AD-A053 183 TERECO CORP COLLEGE STATION TX F/G 13/2

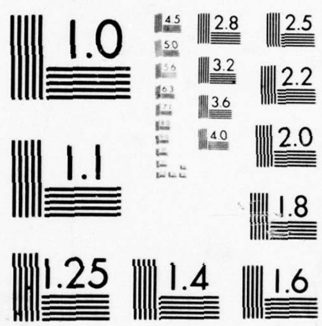
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)

JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL DACW39-76-C-0125

UNCLASSIFIED WES-TR-D-78-2 NL

1 OF 7

AD
A053183



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

12

DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-78-2

AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPOSAL IN THE OPEN OCEAN

by

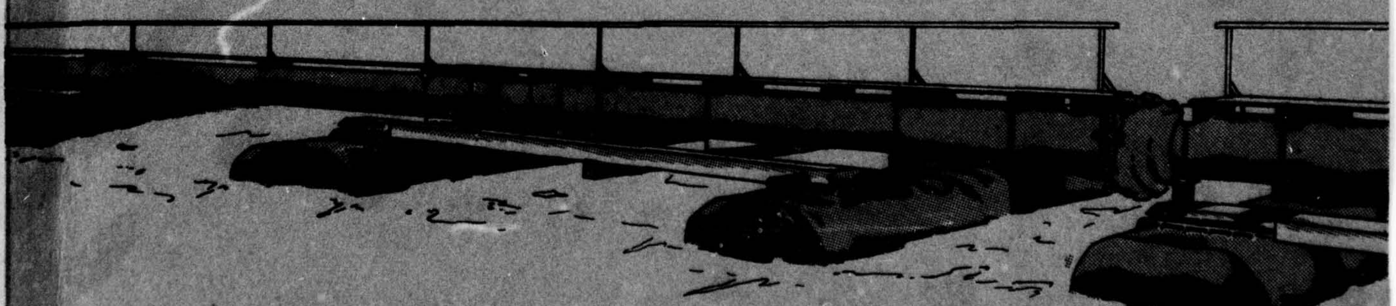
Willis E. Pequegnat
TerEco Corporation
College Station, Texas 77840

in collaboration with
David D. Smith, Rezneat M. Darnell
Bobby J. Presley, Robert O. Reid

January 1978

Final Report

Approved For Public Release; Distribution Unlimited



Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under Contract No. DACW39-76-C-0125
(DMRP Work Unit No. 1A11)

Monitored by Environmental Effects Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESYV

15 February 1978

SUBJECT: Transmittal of Technical Report D-78-2

TO: All Report Recipients

1. The technical report transmitted herewith represents the results of one of several research efforts (Work Units) undertaken as part of Task 1A, Aquatic Disposal Field Investigations, of the Corps of Engineers' Dredged Material Research Program. Task 1A is a part of the Environmental Impacts and Criteria Development Project, which has as a general objective determination of the magnitude and extent of effects of disposal sites on organisms and the quality of surrounding water, and the rate, diversity, and extent such sites are recolonized by benthic flora and fauna.

2. The study reported on herein was conducted as Work Unit 1A11 to provide background information on the deep ocean as a disposal alternative to nearshore, estuarine, and inland dredged material disposal sites. In order to provide interim guidance for Corps of Engineers' Districts to design research studies, to develop site-selection criteria, and to assess the environmental consequences of deep ocean disposal of dredged material, it was necessary to review and evaluate the available literature on oceanic environments and oceanic processes, to define technical issues and concerns, and to document the potential research needs and the environmental parameters to be considered.

3. The report discusses factors that indicate that deep ocean disposal of dredged material may have to be used more extensively in the future than now. The literature analyzed relative to the disposal of dredged material or any similar solid waste material in the open ocean includes studies of the distribution of benthic populations, plankton, fisheries, and chemical species in the water column and in the associated sediments; oceanic currents and water masses; and the physical properties of the sea water. The report further categorizes oceanic environments and identifies by category those oceanic regions that may be better suited for continued disposal operations and those that have a greater potential for short-term and/or long-term detrimental or positive impacts.

WESYV 15 February 1978

SUBJECT: Transmittal of Technical Report D-78-2

4. Results emphasize the need for use of oceanographic information in the selection of disposal sites and the belief that effective management of the use of deep ocean sites will require a basic understanding of marine ecological systems. Therefore, the report provides a working knowledge of the marine environment and its function to facilitate effective selection and use of disposal sites by the managers of deep ocean disposal sites.

5. The results of this study are particularly important in determining sites for deep ocean disposal of dredged material. Referenced studies, as well as the ones evaluated in this report, will aid in determining the optimum disposal conditions and site selection for minimum environmental impact and maximum site use.

John L. Cannon

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

(18) WES (19) TR-D-78-2

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report D-78-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPOSAL IN THE OPEN OCEAN.		5. TYPE OF REPORT & PERIOD COVERED (9) Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Willis E. Pequegnat, ~~in collaboration with~~ David D. Smith, Rezneat M. Darnell, Bobby J. Presley, Robert O. Reid		8. CONTRACT OR GRANT NUMBER(s) Contract No. (15) DACW39-76-C-0125 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS TerEco Corp~~oration~~ College Station, ~~Texas~~ TX 77840 410658		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DMRP Work Unit No. 1A11
11. CONTROLLING OFFICE NAME AND ADDRESS Office, Chief of Engineers, U. S. Army Washington, D. C. 20314		12. REPORT DATE (11) January 1978
		13. NUMBER OF PAGES 645 (12) 659 p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) U. S. Army Engineer Waterways Experiment Station Environmental Effects Laboratory P. O. Box 631, Vicksburg, Miss. 39180		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Dredged material disposal Environmental effects Marine environment Ocean waste disposal		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

At the outset the report contains a discussion of several factors which indicate that deep ocean disposal of dredged material may need to be utilized much more extensively in the future than now. There follows a delineation and preliminary evaluation of the potential physical, chemical, and biological impacts that may occur from the disposal of dredged material in the deep ocean at and beyond the outer edge of the continental shelves of the United States and its possessions. A substantial part of the report is then devoted
(Continued)

next page

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

410658 bb

20. ABSTRACT (Continued).

to the selection and description of oceanic areas (not sites) off eleven subdivisions or sectors of the U. S. coasts in which District Engineers or other Corps of Engineers officials may select specific disposal sites.

The main body of the report is composed of two multipartite sections: ~~Section A~~. Deep Ocean Disposal Perspectives, and ~~Section B~~. Deep Ocean Disposal Environmental Considerations.

The three major parts of Section A are (1) the basis for and objectives of the study together with an overall evaluation of the need for and impacts of deep ocean disposal of dredged material; (2) a discussion of the dredging-disposal process and the nature of dredged materials; and (3) the actual designation of favorable and poor deep ocean areas for disposal of dredged material, as well as the criteria upon which each selection was based. Emphasis is placed upon the need for utilization of oceanographic information in the selection of disposal sites within these areas, and the belief that effective management of the use of deep ocean sites will require a basic understanding of marine ecological systems. These units are followed by a set of conclusions and a summary of the principal findings. In brief, it is concluded that deep ocean disposal of dredged material can be carried out without appreciable damage to any aspect of the marine environment.

Section B is devoted to (1) a discussion of the workings of marine ecological systems, (2) the essential oceanographic conditions existing off the coasts of all geographic sectors of the United States and its possessions, and (3) an analysis of the fate of dredged material disposed in the deep ocean and the potential impacts that it may generate. Thus, this section of the report was designed to provide the managers of disposal sites in the Corps of Engineers with a working knowledge of the marine environment and its functions in their Districts in order to facilitate effective selection and use of disposal sites.

PREFACE

The work conducted for preparation and completion of this report was performed under Contract DACW39-76-C-0125, as amended, entitled "An Assessment of the Potential Impact of Dredged Material Disposal in the Open Ocean," dated 30 June 1976, between the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi and TerEco Corporation, College Station, Texas. The project was sponsored by the Office, Chief of Engineers (DAEN-CWO-M) as part of the general civil works research program, Dredged Material Research Program (DMRP).

The research was conducted by and under the supervision of Dr. Willis E. Pequegnat, who wrote the Summary and the following parts of Sections A and B: (A) Parts 1 and 3, and the Summary Conclusions; (B) the introductions to Parts 1, 3, and 5. Dr. David D. Smith prepared Part 2 of Section A; Dr. Rezneat Darnell wrote Part 2 of Section B as well as the Ecosystem Dynamics unit of Part 4; Dr. Bobbie Joe Presley wrote the units on chemical impacts, and Drs. Robert O. Reid, Andrew Vastano, and Bela M. James the physical impacts in Parts 1 and 2 of Section B; Drs. E.A. Kennedy, Roger Fay, Jean P. Sikora, and Linda H. Pequegnat prepared the materials in geology, pelagic biology and fisheries, benthic biology, and neuston, respectively, in various parts of Section B. Dr. Jefferson T. Turner prepared the illustrative materials and Ms. Patricia Catron and Isabel Hine aided in manuscript finalizations. We also acknowledge gratefully the assistance of the members of our two advisory panels (see Appendix A) who helped shape our views on the issues involved in the study.

The study was conducted under Task 1A, "Aquatic Disposal Field Investigations," as part of the Environmental Impacts and Criteria Development Project, DMRP, managed by Dr. Robert Engler. The contract was managed by Mr. Barry Holliday under the general supervision of Dr. John Harrison, Chief, EEL. COL J.L. Cannon, CE, was Director of WES during the period of this contract and Mr. F.R. Brown was the Technical Director.

CONTENTS

	Page
PREFACE	1
LIST OF TABLES	7
LIST OF FIGURES	10
CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT	16
SUMMARY	17
General	17
Study Objectives	18
Volumes of Material Dredged in the United States	18
Receiving Environments for Dredged Material	19
Some Pros and Cons of Deep Ocean Disposal	21
Evaluation of the Potential Impacts of Deep Ocean Disposal	22
Selection of Deep Ocean Disposal Sites	23
Conclusions	28
Recommendation	29
SECTION A. DEEP OCEAN DISPOSAL PERSPECTIVES	31
PART 1: INTRODUCTION	33
A. Nature of the Present Study	33
General	33
Objectives	33
Study Approach Philosophy	35
B. Toward An Understanding of Open Ocean Disposal	38
Some Factors Favoring Oceanic Zone Disposal	38
Evaluation of the Potential Impacts of Deepwater Disposal	44
C. Background	46
Need for Disposal of Dredged Material	46
Volumes of Material Dredged in the United States	48
Feasibility of Deepwater Disposal	49
D. The Management Role	51
Policy on Ocean Disposal	51
Legislative Basis	51
E. Related Disposal Considerations	55
Resistance or Opposition to Some Conventional Sites	55
Regional Aspects of the Disposal Problem	59
An Alternative Solution: Open Ocean Disposal	59
PART 2: DREDGING AND DREDGED MATERIALS	63
A. Introduction	63

	Page
B. Dredging and Disposal Methods	64
Types of Dredging	64
Types of Disposal	68
C. Dredged Material Volumes, Sources, and Disposal Practices	71
Volumes	71
Source Areas for Ocean Disposal	73
Disposal Practices	79
D. Characteristics of Dredged Material	86
General	86
Before Dredging	86
During Dredging	95
During Transport	97
During Disposal	99
E. Classes of Dredged Material	104
F. Potential for Deepwater Ocean Disposal of Dredged Material	104
PART 3: SELECTION OF FAVORABLE AND POOR DEEP OCEAN DISPOSAL AREAS	107
A. Introduction	107
Need for Alternative Disposal Areas	107
Sources of Site Selection Criteria	108
Sector Definition	109
B. Selection of Areas	116
Gulf of Mexico (Sectors 4 and 5)	116
East Coast: The Atlantic Ocean (Sectors 1, 2, and 3)	121
West Coast: The Pacific Ocean (Sectors 6, 7, and 8)	132
The Gulf of Alaska (Sector 9)	142
The Hawaiian Islands (Sector 10)	142
Puerto Rico and the U.S. Virgin Islands (Sector 11)	143
C. Guides for Selection of Specific Disposal Sites in the Deep Ocean	143
PART 4: SUMMARY CONCLUSIONS	149
SECTION B. DEEP OCEAN DISPOSAL ENVIRONMENTAL CONSIDERATIONS	153
PART 1: FACTORS CONTROLLING SPATIAL DISPOSITION AND CHEMICAL FATE OF DREDGED MATERIAL IN THE DEEP OCEAN	154
A. Introduction	154
Settlement Characteristics	154
Factors Modifying the Spatial Disposition of Dredged Material on the Deep Ocean Floor	160
Importance of Long-Term Vs. Short-Term Bottom Influences	165
B. Physical Controls	170
Descent of Dredged Material Through the Water Column	170
Bottom Contact and the Physical Aftermath	180
C. Chemical Controls	182
During Water Column Passage	182
After Bottom Contact	195

	Page
D. Biological Considerations	210
During Water Column Passage	210
After Bottom Contact	211
PART 2: DISPOSAL ENVIRONMENTS IN THE DEEP OCEAN	213
A. Introduction	213
Location	213
Hydrodynamics	213
Biodynamics	215
B. Marine Ecological Systems	218
Components of the Marine Ecosystems	219
Matter and Energy Transfers	239
The Sea as an Open Ecosystem	242
Marine Systems Under Stress	244
PART 3: ENVIRONMENTAL IMPACTS OF THE DISPOSAL OF DREDGED MATERIAL IN THE DEEP OCEAN	249
A. Introduction	249
General Nature of Impacts in the Deep Ocean	249
Temporal Aspects of Impacts and/or Effects	251
Direct Vs. Indirect Impacts	254
B. Physical Impacts	254
Turbidity Increases	254
Inputs to the Nepheloid Layer	257
Landward Return of Material to Shoal Water	260
Topographic Modifications	261
C. Chemical Impacts	263
Dissolved Oxygen	264
Uptake and Release of Nutrients	267
Uptake and Release of Toxins	274
D. Biological Impacts	297
Water Column Effects	297
Benthic Effects	312
Conclusions	317
PART 4: HYDROBIOLOGICAL ZONES AS DISPOSAL ENVIRONMENTS	319
A. Nearshore - Offshore Trends	319
Trends in Environmental Factors	319
Trends in Biological Factors	320
B. Zonal Analysis	334
Outer Continental Shelf Zone	334
Continental Slope Zone	349
Continental Rise - Abyssal Zone	361
C. Ecosystem Dynamics	382
The Water Section as an Ecological Unit	383
Exchange Processes	383
Residence Vs. Transience of Species	383

Page

Internal Dynamics: Production, Consumption, and Decomposition 385
Internal Dynamics: Vertical and Horizontal Transport 386
System Coordination and Regulation 387
Geographic Variation 387
D. Chapter Summary 388

PART 5: REGIONAL ASSESSMENT OF DEEP OCEAN DISPOSAL RECEIVING ENVIRONMENTS 391

A. Introduction 391
Need for Regional Organization 391
Approach to the Solution 392
Sector Synthesis 394
B. Ocean Disposal Sectors of the United States 395
C. Gulf Coast (Sectors 4 and 5) 399
Geomorphology 399
Oceanography/Meteorology 409
Fisheries Resources 425
D. Atlantic Coast (Sectors 1, 2, and 3) 430
Geomorphology 430
Oceanography/Meteorology 446
Fisheries Resources 462
E. Pacific Coast (Sectors 6, 7, and 8) 473
Geomorphology 473
Oceanography/Meteorology 490
Fisheries Resources 501
F. Sectors of Minor Importance 507
Alaska (Sector 9) 507
Hawaii (Sector 10) 513
Caribbean Territories of the United States (Sector 11) 522

PART 6: SUITABILITY OF SPECIFIC ENVIRONMENTAL AREAS FOR DISPOSAL OF DREDGED MATERIAL 529

A. Introduction 529
General View of Suitable Vs. Unsuitable Environments 529
Categories for Ranking Disposal Areas 533
Need for Criteria as Guidelines 534
B. Development of Criteria for Site Selection 534
Physical Oceanographic Considerations 534
Chemical Oceanographic Considerations 539
Geomorphic/Geologic Considerations 541
Biologic Considerations 545
Resource Utilization Conflicts 547
Conflict by Proximity of Other Disposal Sites 550
C. Analysis of Suitability By Sector: Application of Criteria to Sectors 551
Gulf Coast (Sectors 4 and 5) 551
Atlantic Coast (Sectors 1, 2, and 3) 556

Page
Pacific Coast (Sectors 6, 7, and 8) 560
Gulf of Alaska (Sector 9) 562
Hawaiian Islands (Sector 10) 563
Puerto Rico - U.S. Virgin Islands (Sector 11) 564

LITERATURE CITED 567

BIBLIOGRAPHY 609

APPENDIX A: ROSTER OF ADVISORY PANEL MEMBERS

APPENDIX B: EPA 1977 OCEAN DUMPING REGULATIONS AND CRITERIA

LIST OF TABLES

Table		Page
SECTION A.		
1	Projected Average Annual Corps of Engineers Dredging Requirements (1974-76)	72
2	Ocean Disposal of Dredged Material in Calendars 1974 and 1975 by Corps of Engineers Division	74
3	Comparison of Data on Dredged Material Volumes for FY 1969 and 1974-76	76
4	Geographic Distribution of Sites Designated for Ocean Disposal of Dredged Material	84
5	Sectors of the United States and Territories Showing Their Geographic Limits, Geomorphic, Physical, and Biological Characterizations	111
6	Principal Dredging Sites in the South Atlantic Bight	128
7	Factors to be Considered in Selecting a Deep Ocean Disposal Site for Dredged Material	144
8	Seasonal Concerns in Site Selection and Site Use	146
9	Seasonal Changes in Wind Speed and Wave Height Along Coasts of the United States	148
SECTION B.		
10	Amount of Solar Radiation Reaching Various Depths for Different Types of Seawater	223
11	Classification of Benthic Animals on the Basis of Size	238
12	Classification of Benthic Organisms by Depth Zones in the Sea	238
13	Generalized Biological Response Patterns to Increased Levels of Environmental Stress	245
14	Comparison of Short-term Effects of Dredged Material Disposal Between Shallow Water and the Deep Ocean	252

Table		Page
15	Percent Transmission of Normal Sunlight Through a Metre of Ocean Water	256
16	Heavy Metal Production and Potential Ocean Inputs	275
17	Leachable Heavy Metal Concentrations for Sediments from San Antonio Bay, Galveston Bay, and the Houston Ship Channel	277
18	Estimated Production and Environmental Leakages of Some Synthetic Organic Chemicals	288
19	Budget of Petroleum Hydrocarbons Introduced into the Oceans	292
20	Areas of the Pacific Ocean with Different Zoo- and Phytoplanktonic Biomass in the 0-100m Layer	323
21	Vertical Distribution of Copepods in the Northwestern Pacific	326
22	Distribution of the Production of Aquatic Items over Different Depths in 1966	328
23	Distribution of Benthic Biomass by Faunal Groupings According to Hydrobiological Zones	331
24	Common Genera Collected from World Oceans in Neuston Samples	367
25	Comparison of Daytime Classification of Species Reported from North Atlantic Neuston with Reports of Day-Positive Occurrence of Some Species in Literature	369
26	A Summary Comparison of Regional and Diel Differences in Neuston Biomasses as Wet Weights	370
27	Distribution of World Catch in 1966 by Oceanic Zones	372
28	Relative Abundance of Nektonic Groups in Different Biotopes	374
29	Wind Conditions within Sector 1, Northeast Atlantic Coast	456
30	Wind Conditions within Sector 2, Mid-Atlantic Bight	459

Table		Page

Table	Title	Page
31	Wind Conditions within Sector 3, South Atlantic Bight	463
32	Annual Average Fish Landings in the Northeastern U.S. for the Years 1970-73	464
33	Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to the Northeastern U.S. Fishery	467
34	Annual Average Fish Landings in the Mid-Atlantic States for the Years 1970-73	469
35	Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to the Mid-Atlantic Fishery	470
36	Annual Average Fish Landings in the South Atlantic States for the Years 1972-74	472
37	Frequency of Wind Direction by Speed - Annual Percentage	497
38	Monthly Average Wind Conditions for Onshore Sites in Sectors 6 and 7, Southern California Bight and Northern California Shelf	500
39	Offshore Average Monthly Wind Speed for Sector 8, Northwest Shelf	502
40	Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to California Fisheries	504
41	Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to the Northeast Pacific Fisheries	505

LIST OF FIGURES

Figure		Page
SECTION A.		
1	World Distribution of Primary Production	42
2	Types of Dredges	65
3	Locations of Maintenance Dredging Projects in Coastal Districts Showing Annual Quantities of Dredged Material by Location Type	77
4	Maintenance Dredging Volumes in Coastal Districts by Dredge Type	81
5	Maintenance Dredging Volumes in Coastal Districts by Disposal Category	82
6	Grain-size Classification and Volumes of Materials Excavated in Maintenance Dredging Operations in Coastal Districts	90
7	Exchanges of Matter in an Idealized Estuarine System	93
8	Sectors of the United States Showing Their Geographic Limits and Geomorphic Regions	110
9	Locations of Favorable Areas for Dredged Material Disposal Areas in the Northern Gulf of Mexico	117
10	Location of Favorable Disposal Areas for the Gulf of Maine, Northeast Coast, Sector 1	123
11	Location of Favorable Disposal Areas for the Middle Atlantic Bight, Sector 2	126
12	Location of Favorable Disposal Areas for the South Atlantic Bight, Sector 3	131
13	Geomorphology of the Southern California Bight Area, Sector 6, Showing Favorable Disposal Areas	133
14	Location of Favorable Disposal Areas for the Northern California Shelf, Sector 7	136
15	Locations of Favorable Disposal Areas for the Northwest Shelf, Sector 8	140

SECTION B

Figure		Page
16	A Schematic Picture of the Disposal of Hopper-Dredged Material into a Two-Layered Deepwater System with Strong Thermo-pycnocline	156
17	Fall Velocity of Spherical Particles	174
18	Schematic of Relative Circulation in a Vertical Plane through a Cloud of Moderately Dispersed Slurry	176
19	Copper Adsorption from Sea Water and 0.70 M NaCl onto 1000 ppm Illite as a Function of pH	187
20	Cobalt Adsorption onto 1000 ppm Illite at pH 8 as a Function of Mg^{2+} Concentration	187
21	Percent Variation of Desorption of Zinc in Seawater of Different Salinities at Different pH	189
22	Dissolved Iron Vs. Chlorinity of Samples from the Mullica River and Great Bay, New Jersey	189
23	(A) Interstitial Sulfate and Ammonium and (B) Phosphate Concentrations for Anoxic Sediments	200
24	Typical Interstitial Manganese Profiles Showing Variations in the Anoxic-Oxic Boundary and the Regions of Maximum Manganese Remobilization that Vary as a Function of Sediment Redox Conditions	202
25	Interstitial and Sediment Manganese Concentrations for a Mississippi Delta Sample	204
26	Pore Water and Sediment Manganese Concentrations for a Mississippi Fan Sample	205
27	Diagrammatic Illustration of Possible Patterns of Environmental Areas Influenced by Disposal at Sea	216
28	Diagrammatic Section of the Marine Environment Showing Zonation	220
29	Diagrammatic Section of Outer Continental Shelf Waters of the Temperate Zone Under Summer Vs. Fall-Winter-Spring Conditions	224
30	Vertical Distribution of Major Physical and Chemical Factors in the Ocean	226

Figure		Page
31	Examples of Marine Phytoplankton Organisms	229
32	Examples of Marine Zooplankton Organisms.............	231
33	Examples of Marine Nekton Organisms..................	233
34	Examples of Marine Neuston Organisms.................	235
35	Examples of Marine Benthic Organisms.................	237
36	Diagrammatic Representation of the Food Chains of the Sea..	241
37	Phosphorus Release Under Oxic and Anoxic Conditions: Houston Ship Channel Turning Basin Sediments.........	270
38	Changes in Nitrate and Ammonia with Time After Discharge in the Water of the Sediment-Water Slurry Discharged from Dredge Pipeline....................	272
39	Zinc/Iron Scatter Plot for NW Gulf of Mexico Sediments..	278
40	Selective Extraction Scheme for Sediment Metal Partitioning Studies	283
41	Partitioning of Nickel in Three Distinct Sediment Samples..	284
42	Iron and Zinc Concentrations in Sediment Leached by Various Buffer Solutions after 6 and 24 Hours Equilibration	286
43	Hydrocarbon Concentrations in Sediments Including Alkanes, Alkenes, and Two- to Six-Ring Aromatic Hydrocarbons	293
44	U.S. Production of Bulk Tetracyclines...............	296
45	Geographic Distribution of Phytoplankton Production in the World Oceans..................................	322
46	Geographic Distribution of Zooplankton Biomass in the World Oceans..................................	324
47	Model of a Single Section of Ocean Water to Show Exchange Processes..................................	384

Figure		Page

48 Sectors of the United States in Relation to Biological Provinces 396

49 Sectors of the United States in Relation to Corps of Engineer Districts 397

50 Topographic Divisions of the Gulf of Mexico 401

51 Geologic Provinces of the Gulf of Mexico 402

52 Dynamic Topography of Surface Relative to 1000-db Surface in the Gulf of Mexico 411

53 Comparative Characteristics of Water on the Right-Hand and the Left-Hand Side of an Observer Facing Downstream in the East Gulf Loop Current 412

54 Temperature Section Across the East Gulf Loop Current Based Upon Bathythermograph Data August 8 and 9, 1966 413

55 Isotachs of Geostrophic Speed Relative to 1350-db Surface, Running Nearly East-West Across the Loop Current 414

56 The Spring Intrusion of 1966 as Indicated by Overlays of the 150-Metre Contour Lines from the 22°C Topographies of all Spring Cruises of 1966 416

57 Depth of the 22°C Isothermal Surface from BT Observations, and Selected GEK Surface Current Measurements in the Eastern Gulf of Mexico 417

58 Dynamic Topography of Sea Surface Relative to the 1000-db Surface in the Gulf of Mexico in March 1962 419

59 Gulf Coast Zone Subdivisions Showing Total Hurricane Occurrences 1900-1956 424

60 Physiographic Provinces of the Continental Margin Off the East Coast of the United States 432

61 Geomorphology of Sector 1, Northeast Atlantic Coast 433

62 Submerged River Channels, Shorelines, Canyons, and Deltas of Hatteras-Cape Cod Shelf Region 439

Figure Page

63 Sediments Off the Atlantic Coast of the United States Classified by Texture, Contributing Agent, and Age 440

64 General Circulation of the North Atlantic Ocean 447

65 Surface Water Provinces Between the New England Coast and Bermuda 448

66 A Schematic Representation of the Path of the Gulf Stream and the Distribution and Movement of Rings 452

67 Locations of Offshore Regions Providing Weather Conditions as Tabulated in Table 30 460

68 Continental Borderlands Off Southern California Showing Basins, Canyons, and Escarpments 475

69 Relative Positions of Major Submarine Canyons in Sectors 6 and 7, Southern and Northern California Bights 478

70 Physiographic Provinces of the Sea Floor Off California, Sectors 6 and 7 480

71 Physiographic Provinces of Sector 8, Off Northwest Pacific Coast 483

72 Relative Positions of Major Submarine Banks and Canyons Within Sector 8 485

73 Approximate Locations of Major Submarine Physiographic Features in Sector 8 489

74 Mean Annual Dynamic Topography of the Pacific Ocean Sea Surface Relative to 1000 db 491

75 Geostrophic Flow at the Surface Off the U.S. Pacific Coast in Late Spring 493

76 Geostrophic Flow at the Surface Off the U.S. Pacific Coast in Fall 494

77 Annual Average Winds, Velocity and Direction, of Southern California Coastal Region 498

78 Gulf of Alaska Geomorphic Features 509

Figure		Page

Figure	Title	Page
79	Hydrologic Conditions Seaward of Kodiak Island, Gulf of Alaska, June 1967	512
80	Map of Hawaiian Islands	516
81	Depth of Principal Water Masses Off the Hawaiian Islands	518
82	Physical and Chemical Properties of the Water Column Off the Hawaiian Islands	518
83	Resulting Drift or Average Vector Velocity For Current Meter Stations in the Western Part of the Hawaiian Archipelago	519
84	Schematic Picture of the Disposal of Hopper-Dredged Material into a Two-Layered Deepwater System with a Strong Thermo-Pycnocline	532
85	Diagram of Ekman Transport of Surface Water at Right Angles to Wind Direction	538

CONVERSION FACTORS

U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

MULTIPLY	BY	TO OBTAIN
acres	4046.856	square metres
cubic yards	0.764555	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
fathoms	1.828	metres
feet	0.3048	metres
feet per second	0.3048	metres/second
knots	0.5144444	metres/second
miles (U.S. statute)	1.609344	kilometres
miles (U.S. nautical)	1.852	kilometres
miles per hour	1.609344	kilometres per hour
pounds (mass)	0.45359237	kilograms
square miles	2.58999	square kilometres
tons (2000 pounds)	907.1847	kilograms

*To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

SUMMARY

GENERAL

Structured in this report is the basic premise that, environmental constraints or related considerations notwithstanding, the United States will continue to dredge new and existing waterways to assist in achieving safe passage for vessels of commerce. This will be done, not only because the export and import cargoes are vital to maintenance of a sound and growing economy, but also because accidental spillage of some cargoes due to poorly maintained channels could have far more profound effects than dredging on marine ecological systems and, thus, on the welfare of the American people.

Anticipating that public pressures against continuing use of some present-day types of environments for disposal of dredged material will increase, this report evaluates the potential impacts and viability of disposing of some of this material in a little-used environment--the deep ocean. Throughout the report it is implicit that good management of the dredging-disposal process is essential to the continued welfare of the marine environment, and that to achieve this goal the good manager must understand the scope of the problem, the nature of the dredging process, and command a basic understanding of the composition and functioning of marine ecological systems. He can then apply this knowledge to the task of selecting and using disposal sites in the deep ocean. Accordingly, Section A of this report discusses the potential need for deep-ocean disposal and the extant methods of dredging and disposing, and it recommends disposal areas in all coastal regions of the United States. Section B has been designed to assist the manager in increasing his working knowledge of marine environments with particular emphasis on the deep ocean.

STUDY OBJECTIVES

A comprehensive study of this type can have many objectives, but the overriding ones of this report are (1) to evaluate the future need for deep ocean disposal, region by region, in the United States, (2) to assess the capacity of deep-sea environments to receive dredged material without direct or indirect damage of consequence to its biological components, and (3) to designate with documentation those marine areas and environments that are favorable receiving environments and those that are not.

VOLUMES OF MATERIAL DREDGED IN THE UNITED STATES

PRESENT AMOUNTS

It is estimated that each year in the United States new and maintenance dredging carried out under permit from the Corps of Engineers produces between 350 and 450 million cubic yards of sediment. From this, we can calculate that in a single decade the amount of dredged material requiring utilization or disposal could cover an area as great as 4,500 square miles with a foot-thick layer of sediment. Furthermore, it appears likely that the annual volumes of dredged material will increase during the next decade.

POSSIBLE FUTURE AMOUNTS

Plans for deepening and widening harbor channels to accommodate deep-draft vessels carrying petroleum or liquid natural gas or even dry cargoes, as in Corpus Christi and Matagorda Bays of Texas, are already well along. These will require dredging channels for distances up to 11 miles on the continental shelf and can be expected to produce in total well over one hundred million cu yd of sediment. On the Pacific coast new installations such as in Grays Harbor, Oregon, will likely be commenced within five years or less and will produce an estimated 16 million cu yd of sediment.

Thus, even if we limit our planning only to the most likely of present new projects, we must find ways of coping with the millions of cubic yards of new material that will have to be disposed of in an environmentally sound manner. There can be no doubt, then, that problems associated with the disposal of dredged material will confront us for years to come.

RECEIVING ENVIRONMENTS FOR DREDGED MATERIAL

PRESENT SITES

In the years immediately ahead, the numbers and kinds of acceptable places in which to dispose of this mounting volume of dredged material will inevitably decrease. Among the several factors that will cause this decrease are the following:

1. Movements of populations to once low density coastal regions, especially along the entire Gulf of Mexico, will bring intensive utilization of upland areas for industry, housing and services, and recreation. This will result in usurpation of agricultural land, and the heightened competition for space will mean that usage of upland areas for disposal of dredged material will surely be curtailed if not eliminated.
2. Sooner or later use of estuaries and even bays as receiving environments for disposal of dredged material may be reduced as it becomes evident that continuing deposition of dredged material in them may accelerate their demise.
3. Creation of planned marshes and sea grass beds, although presently a justifiable practice in appropriate places, must eventually cease if it requires shoaling, because this process will only accelerate total sedimentation of the estuary.
4. The estuary and the innermost aspect of the continental shelf, especially in the Gulf of Mexico, comprise an integrated environment that is necessary for the continuing welfare of

numerous organisms of commercial value, e.g., white shrimp of the genus Penaeus and various finfish. Considering the multiple and sometimes stress-inducing uses of the inner shelf, such as harvesting seafood, exploiting increasing amounts of gas, oil, and other minerals, disposing of large quantities of industrial and municipal wastes, and pursuing recreational activities, if future dredged material disposal sites are to be placed on the inner shelf, they must be located with great care.

5. The outer continental shelf may provide acceptable disposal sites in some regions, e.g., off the U. S. southeast Atlantic coast, but not in others. For instance, the middle and outer continental shelf of the Gulf of Mexico sustains the great brown shrimp fishery.

FUTURE SITES

As man is forced to study more penetratingly his relationship to the global environment by one untoward circumstance or another, hopefully he will learn not to rely solely on costly technology to minimize the effects of his waste products on ecosystems. Instead, he should move toward recognition of the natural ecosystems that have the capacity to serve as effective processors of his wastes. The deep ocean already assimilates the millions of tons of riverborne sediments brought to it each year, and its capacity for handling additional sediment is apparently very great.

With the present concern for conservation of all of the Nation's resources, it is logical that steps should be taken to utilize or recycle, where possible, waste materials that were once disposed of with reckless abandon. But, if no present economical use can be made of certain dredged material, it is also logical that final receiving environments should be found, rather than transient disposal sites that can mean shifting the waste problems from one ecosystem to another.

The thrust of the present report concerns evaluation of the impacts likely to accompany the disposal of dredged material of all types in the deep ocean seaward of the shelf break. Certainly the deep ocean can be considered to be a terminal receiving environment.

SOME PROS AND CONS OF DEEP OCEAN DISPOSAL

At present there are two cogent arguments that are often raised against deep ocean disposal, viz., an increase of project costs due to longer haul distances, and a presumed lack of knowledge of the deep sea. Nevertheless, other factors can mitigate the influence of these points. Very likely the economic factor will become a criterion of lesser importance when some presently acceptable disposal sites are no longer favored. Moreover, it is probably reasonable to assume that when the need is evident cost-saving improvements in the dredging-disposal process will be brought forth.

Several reasons can be advanced in support of open ocean disposal. The most important of these are related to biological considerations. Among these are the fact that pelagic life, including that of fishery importance, is markedly reduced in oceanic vs. inshore waters. The deep ocean pelagic fishery, which is composed primarily of tunas and sharks, forms less than 5 percent of the tonnage of the shelf-slope bottom catch. The abundance of bottom-dwelling life becomes greatly reduced as one moves from shore into deeper water. The biomass of benthic life in the deep ocean is only a small fraction of that found on the continental shelf. Also, at present relatively little bottom fishing occurs on the continental slope and none occurs deeper than the 1000-m isobath--and probably never will. About 90 percent of the total bottom or demersal fish catch comes from the shelf. And equally important, it takes only 5 percent of the time to catch a ton of fish on the shelf as on the slope. Finally, the deep ocean has a demonstrated ability to receive and assimilate terrigenous sediments, including dredged material, without losing its capacity to sustain the life processes in kind and amount characteristic of the receiving region.

EVALUATION OF THE POTENTIAL IMPACTS OF DEEP OCEAN DISPOSAL

NATURE OF DEEP OCEAN IMPACTS

There are multiple impacts that dredged material can exert upon any region or ecological system of the marine environment. Therefore, if one is to be definitive as to the effects of deep ocean disposal of dredged material, it is necessary to know how much of what kind of material is being disposed and the nature of the water column and of the final receiving environment. The position taken here is that chemical changes resulting from the disposal of dredged material in deep water and the effects that these changes have upon both the pelagic and benthic biota is the single most important category of impacts at issue, including the potential impacts that these biotal changes may have on the welfare of man. Except under the most unusual of circumstances, there seems little probability that most dredged material would have any but transitory, and then only relatively harmless, effects on the generally sparse pelagic biota in offshelf waters.

MITIGATING FACTORS

There are valid reasons why it is believed that impacts of dredged material will not create severe stresses in the deep ocean. For one thing, we are dealing with large areas and immense volumes of water, even in reasonable distances seaward of the shelf break. For another, as noted above, we know that the deep ocean continues to receive through natural processes large quantities of sediment without any but temporary deleterious effects. For yet another, we know that the deep ocean supports a small biomass, and much of it consists of deposit-feeders, many of which are burrowers that are often not long affected by sediment mounding.

Then too, the deep ocean is little used by man today and, at least for food production, will not be used to a greater degree in the future. Finally, it should be noted that exchange rates in the deep ocean are much more uniform and probably considerably slower than on the shelf.

THE ROLE OF MANAGEMENT

The key to environmentally sound dredging-disposal practices is sound management. The manager must develop a basic fund of knowledge about the environments and ecological systems in his jurisdiction. He must be conversant with water movements on transient and long-term scales and, above all, he must familiarize himself with the biological components of each of the systems available for selection of disposal sites. Some of the basic information required to attain a working knowledge of the components and functioning of the ocean systems can be found in several parts of Section B of this report.

SELECTION OF DEEP OCEAN DISPOSAL SITES

NEED FOR CRITERIA AS GUIDELINES

Criteria are needed as guidelines for both selection of suitable areas in which to locate sites and for the final site-selection process. In this study we are concerned primarily with the finding and description of disposal areas not sites. If it is true that deep ocean disposal can, under proper management, obviate most of the environmental concerns expressed by the general and specific site selection criteria in the Environmental Protection Agency's "Regulations and Criteria for Ocean Dumping" (Federal Register, Part VI, January 11, 1977), then we propose to base the weight of our decision as to selection of suitable vs. unsuitable areas and environments for dredged material disposal on oceanographic considerations. Among these are such phenomena as up- and down-welling, strong or irregular currents, persistent eddies that can transport material shoreward, oxygen-minimum zones, zones of metal-rich surficial sediments, low-oxygen submerged basins, submarine canyons, and hard banks with biota of special scientific significance. Certainly many of these will also be used for site selection. However, to select or reject an area may require only a broad brush treatment of the issue, whereas selection of a definitive site will require more detailed information. Foremost here is the generation of an accurate description of the dredged material and the conduct of appropriate bioassays from which to estimate its probable impact on the indigenous fauna.

APPROACH TO THE PROBLEM OF SELECTION OF DISPOSAL AREAS AND SITES

In order to organize the delineation and description of selected disposal areas, the coastal regions of the U. S., including those of Alaska, Hawaii, and the Caribbean possessions, have been divided into eleven sectors. The geographic limits of these sectors are not wholly arbitrary. In fact, there is a unifying concurrence among Geomorphic Regions, Circulation Regimes, and Biological Provinces and the designated sectors. Thus, any given sector should be thought of as a part of the coastal zone, continental shelf, and contiguous slope whose land boundaries are marked primarily by prominent capes or other geomorphic features, whose current regime differs from that of adjacent sectors and the biota of which has the status of a biogeographical province. It is also considered that a sector includes the encompassed Corps Districts and their dredging activities. The oceanography of each sector is discussed in sufficient detail in this report to permit the effective application of oceanographic criteria in selecting the disposal areas.

SELECTION OF FAVORABLE AND POOR DEEP OCEAN DISPOSAL AREAS

The concluding part of the report is devoted to selection of deep ocean areas in which a District Engineer may wish to locate one or more disposal sites. It is recommended, however, that an oceanographer be involved in the final phase of the decision process. Since by far the bulk of dredged material produced in the United States in any one year comes from New Orleans, Galveston, and Mobile Districts, the Gulf of Mexico sectors are considered first.

Gulf of Mexico (Sectors 4 and 5)

Three areas for deep ocean disposal of dredged material are recommended. These are an area in the northeast gulf around De Soto Canyon, an area over and adjacent to the Mississippi Trough and an area in the northwest gulf somewhat northwest of Alaminos Canyon. Each of these areas covers approximately 9000 km^2. The remainder of the upper continental slope of the northern gulf between and outside of the three favorable areas has both neutral and poor disposal areas, depending upon the proximity of the coral- and algal-covered hard banks (e.g. West Flower Garden Bank), the royal red shrimp grounds, or the potential tilefish fishery.

Atlantic Ocean (Sectors 1, 2, and 3)

Northeast Coast (Sector 1). The problem of disposal of dredged material in this sector is compounded by the great width of the continental shelf and the presence of very productive banks and basins. It is recommended that the entire continental slope region beyond the 300-m isobath can be considered appropriate for disposal of dredged material. Although it is not anticipated that serious biological consequences would actually develop from disposing material in the larger canyons, it would be unwise to dispose in those canyons on the outer flank of Georges Bank that incise the 100-m isobath.

Middle Atlantic Bight (Sector 2). There is an alternating series of favorable and unfavorable disposal areas stretching along the precipitous shelf-slope junction and upper slope from the southern boundary of the present 106-mile industrial site, just south of Hudson Canyon, to Cape Hatteras. Although it is not considered essential for environmental preservation, it is recommended that no disposal take place in those large canyons whose heads incise the continental shelf, viz., Wilmington, Baltimore, Washington, and Norfolk Canyons.

South Atlantic Bight (Sector 3). In this bight there are large stretches of the Florida-Hatteras slope that are favorable for deep ocean disposal of dredged material. Except for certain hard bank areas that are located off the southern aspect of Cape Lookout and Cape Fear, the shallow limit of the favorable areas can run along the shelf-slope junction around the 100-m isobath. In the vicinity of the hard banks, which are favored sports fishing grounds, the shallow limit should be shifted seaward to the 200-m isobath.

Pacific Ocean (Sectors 6, 7, and 8)

Southern California Bight (Sector 6). In this bight the mainland shelf and basin slope are furrowed by over 30 submarine canyons. The principal source of dredged material is the Los Angeles Harbor complex with lesser amounts from San Diego Harbor, Port Hueneme, and other small embayments such as Newport Harbor. Disposal sites can be found within a few kilometres of shore throughout the bight. If submarine canyons are to be utilized for disposal, it seems essential that such a decision be made only after careful study on a case by case basis. Recommended disposal areas are on the seaward face of the Coronado Escarpment and along the San Pedro Escarpment.

Northern California Shelf (Sector 7). The area recommended here for deep ocean disposal of dredged material lies about 10 km west of the Farallon Islands beginning on the 200-m isobath and, on the north-south axis, running between the North Traffic Shipping Lane (inbound) and the Main Traffic Shipping Lane (outbound) to the south. This area is essentially bounded by Pt. Reyes to the north and Pigeon Pt. to the south, with the proviso to avoid the shipping lanes.

The Northwest Shelf (Sector 8). There are several important harbors of moderate size in this sector. Recommended disposal areas for each are:

Humboldt Bay. The continental shelf off Humboldt Bay is about 21 km wide. Because of the importance of the demersal fishery in this area, it is advised that a site should not be established shoreward of the 300-m isobath.

Coos Bay. The continental shelf is about 32 km wide at Coos Bay. It is recommended that material scheduled for ocean disposal not be dumped inside of the 500-m isobath.

Grays Harbor. The continental shelf off Grays Harbor is about 46 km wide. Again, because of the important demersal fishes in this area, it is not advisable to establish a deep ocean site inside of the 500-m isobath.

Puget Sound/Strait of Juan de Fuca Complex. There are numerous acceptable deepwater areas for disposal sites in the Puget Sound and Whidbey Basins (depths to 280 m) and the adjacent Strait of Juan de Fuca. It is suggested that consideration be given to establishing sites over deepest waters where the currents do not reach peak velocities (less that a knot as compared with 5 or more knots in inlets and narrows). Furthermore, although extensive mixing of waters occurs over sills supplying dissolved oxygen to subsurface waters of most of the Sound, there are places where dissolved oxygen levels reach very low levels in summer (avoid Daboh Bay).

The Gulf of Alaska (Sector 9)

Deep ocean disposal of dredged material from Valdez and Anchorage in the Gulf of Alaska is not considered feasible. Consider the fact that it is about 260 km from Anchorage to the entrance of Cook Inlet before the depth increases to 180 m. Also, navigation in Cook Inlet, especially with barges, is very difficult because of a large tidal range, unpredictable currents, and boulder strewn shoals.

Hawaiian Islands (Sector 10)

There are five harbors in the Hawaiian Islands that are maintained by the Corps of Engineers, and Pearl Harbor for which the U. S. Navy is responsible. Three of these harbors already have interim dredged material disposal sites that are in deep water:

Honolulu Harbor in 460 m

Naiwiliwili Harbor in 1000 m

Port Allen in 1540 m

All of these are interim dredged material sites. Final site selection for Pearl Harbor will be under study in spring and summer of 1977 when the harbor will undergo extensive dredging.

Puerto Rico-U.S. Virgin Islands (Sector 11)

There are four harbors in Sector 11 that are relevant to the present study. However, only the material from San Juan Harbor has been disposed of in the deep ocean in 260-300 m of water off the north coast of the island.

CONCLUSIONS

Although deep ocean disposal of dredged material is today practiced only in a few places, especially off the Hawaiian Islands, it is anticipated that it may become a more common practice within the next decade, as various public pressures increase against continuing use of present-day types of sites. The economics of the situation, which are today an important deterrent to deep ocean disposal, will become less so due to increasing environmental pressures and reduction of costs through anticipated improvements in dredging-disposal technology.

Based upon the literature and personal observations and knowledge of the authors, it is concluded that deep ocean disposal of dredged material in present or foreseeable future amounts will cause no serious impacts upon the offshelf marine environment including its living components.

RECOMMENDATION

In view of the dearth of critical information on the economics, fate, and bio-environmental impacts of the disposal of dredged material in the deep ocean, it is recommended that the Corps of Engineers authorize and underwrite a carefully conceived and controlled study having three important facets:

1. Deriving a careful comparison of costs between deep ocean and upland disposal preferably at some point in the Gulf of Mexico where haul distances range from average to long.
2. Determining the fate of the dredged material disposed of in three controversial receiving environments, viz.,
   a. a submarine canyon,
   b. at the shelf break, and
   c. in a low-oxygen environment.
3. Ascertaining through in situ pelagic and benthic bioassay studies the impact of contaminated and polluted dredged material upon the biota of the water column and the bottom at and around the disposal site.

SECTION A

DEEP OCEAN DISPOSAL

PERSPECTIVES

PART 1. INTRODUCTION

A. NATURE OF THE PRESENT STUDY

GENERAL

This report deals with the topic of deep-ocean disposal of dredged material.* Subsequent sections will explore some of the pros and cons of the issue, but after a careful study and evaluation of the literature the authors of this report favor disposing of many wastes, including dredged material, in the oceanic waters of the United States. The authors believe that there are many general areas within which environmentally sound disposal sites may be selected and designated and at which dumping can be carried out with no environmental damage of consequence. It is stressed, however, that good management of the dredging-disposal process is essential to the continued welfare of the marine environment. The good manager will be one whose judgment requires neither too much nor too little environmental concern. To do this, he must either understand the receiving environment or have advisors at hand who do. Section B of this report has been designed and compiled to assist one in attaining a working knowledge of the marine environment. Good management is among the objectives of this study.

OBJECTIVES

1. Examine the functioning of marine systems in appropriate parts of

---

* Dredged material is the term applied to the mix of sediment and water generated as waste by the dredging operation. According to the EPA 1977 Ocean Dumping Regulations and Criteria, 40CFR, Section 227.13, "Dredged materials are bottom sediments or materials that have been dredged or excavated from the navigable waters of the United States, ... Dredged material consists primarily of natural sediments or materials which may be contaminated by municipal or industrial wastes or by runoff from terrestrial sources such as agricultural lands." (Appendix B)

the deep ocean in sufficient detail to permit delineation of generalized and specific responses to the introduction of dredged material.

2. Estimate the need for ocean disposal and evaluate the capacity of the deepwater marine ecosystems to receive dredged material with environmental impunity.

3. Discuss those physical and other oceanographic properties and processes of the deep ocean that will act upon and control the spatial distribution and chemical fate of dredged material following release.

4. Point out and delineate by region and environment those data gaps that would need to be filled by special research efforts before a satisfactory Environmental Impact Statement supporting designation of a disposal site could be prepared.

5. Identify those regions most likely to require deepwater disposal and within them designate areas and environments that are suitable receiving environments and those that are not.

6. Analyze and predict how the disposal activity would or would not impinge upon present and planned multiple use of designated deepwater areas by other interests.

7. Provide the basis for formulation, to the extent possible, of an ordered set of criteria to permit the Corps to identify and possibly select deep ocean disposal sites.

8. Finally, prepare from extant literature an authoritative report on those oceanographic characteristics common to that part of the open ocean overlying the continental terrace of the U.S. and its stipulated territories, and highlight relevant regional features.

STUDY APPROACH PHILOSOPHY

GENERAL

As man is forced to study more penetratingly his relationship to the global environment by one untoward circumstance or another it is hoped that he will learn not to rely solely on costly technology to minimize the effects of his waste products on ecosystems. Instead man should move toward recognition of the natural ecosystems that have the necessary capacity to serve as effective processors of his wastes, perhaps even putting them to use at no monetary or environmental cost. The authors believe that the deep ocean may present this opportunity if it is properly managed.

With the present concern for conservation of all of the Nation's resources, it is logical that steps should be taken to utilize or recycle as much material as possible that was once disposed of with some reckless abandon. But if no present economical use can be made of the material, then final receiving environments should be used rather than transient disposal sites that often have meant shifting the problems associated with the waste from one ecosystem to another.

COMPLEXITY OF AQUATIC SYSTEMS

Concerning the marine environment, it has been stated with some reason that aquatic systems are not only more complex than is realized, but they are more complex than ever will be realized. Fortunately, this study deals with the deep ocean at considerable distances from shore. It is characteristic of the ocean that many of its systems become simpler as one moves substantial distances from shore -- currents are more predictable, salinities and temperatures are less variable, and biota is simpler and generally less abundant. Thus, although aquatic systems may be unfathomable, they are not impossible to work with in the practical vein. The crux of the environmental protection problem is the basic understanding of the healthy environmental systems, recognition of general symptoms of environmental disturbance, and the further appreciation of the particular symptoms of specific types of environmental stress.

The regional (Corps District) environmental manager, in assessing his data needs, can call for special research efforts to fill specific gaps, brought to his attention in this report, prior to selecting a specific site for deepwater disposal.

EXTRAPOLATION FROM SHALLOW WATER DATA

A gap in oceanographic information exists primarily in the area of the open ocean. In contrast, because of the easy access, the intertidal has been studied intensively. During the three decades following World War II, the Office of Naval Research supported a great deal of deep ocean research. In the past five years the Bureau of Land Management has supported comprehensive oceanographic studies on the continental shelves, chiefly of the Gulf of Mexico, southern California, and more recently parts of the Atlantic Coast.

Very little concerted effort has been spent in recent years on the oceanography of the continental slope. In 1975 TerEco Corporation completed an oceanographic study of the upper continental slope (Pequegnat et al., 1975) of the northern Gulf of Mexico. Aside from this and few isolated studies on all coasts, the authors have found a dearth of useful information. Thus, where possible, data from near-shore or deep water or both have been extrapolated into the area of the open ocean.

SCOPE LIMITATIONS PRECLUDE ENCYCLOPEDIC TREATMENT OF ENVIRONMENTS

Attempts have been made in subsequent chapters of this report to provide District personnel with sufficient oceanographic information pertaining to offshore areas of their locale to make intelligent application of suggested criteria in selecting and designating a deep ocean disposal site. Unfortunately, the scope of this study and the financial resources provided have not permitted development of oceanographic atlases for each coast and regions therein. In fact, in many instances the task is made all the more difficult if not impossible because critical data, especially on currents and general circulation in the offshelf areas, are virtually non-existent.

In place of this detailed treatment, this report points out the common features of, say, the outer continental shelf on all U.S. coasts. Then, as data have permitted, certain unique features of a given region, e.g. New England with very broad shelves, that bear on disposal activities and disposal-site selection are highlighted.

USE OF REGIONAL ADVISORY PANELS AND OTHER ADVISORS

Early on in this study TerEco Corporation established two regional advisory panels with the aid of certain WES personnel and then convened them for discussion of the project. The West Coast group met in San Diego, California on 17 August 1976 and the East Coast group met a week later in Key Biscayne, Florida. The authors are grateful for the candid remarks and sound advice given forth during these meetings. Participants were drawn from marine science in university departments, marine laboratories, state agencies, consulting firms, Environmental Protection Agency (EPA), National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), and the U.S. Army Engineer Waterways Experiment Station (WES). The roster of panel members is given in Appendix A.

B. TOWARD AN UNDERSTANDING OF OPEN OCEAN DISPOSAL

SOME FACTORS FAVORING OCEANIC ZONE DISPOSAL

DEFINITIONS

In this report the term open ocean has been interpreted by TerEco Corporation personnel to mean the deep ocean at and beyond the outer edge of the continental shelf. This deepwater area of the ocean is referred to as oceanic in contradistinction to the neritic waters that lie over the continental shelf. The outer edge of the shelf, which is ordinarily marked by a noticeable change of slope, is referred to as the "shelf break." The depth of this break varies considerably around the shelves of the U.S., but Shepard (1963) defines the shelf as "those platforms bordering a continent that terminate oceanward at depths of less than 300 fathoms (about 550 m)." Some breaks occur at depths little more than 10 m depth, but generally they occur in anywhere from 60 to 200 m of water (Emery and Uchupi, 1972). It is at breaks of this latter depth or more, depending upon other topographic features, that the authors propose that some dredged material disposal sites should be located.

RELATIVE AREAS OF CONTINENTAL SHELF AND DEEP OCEAN

Continental and Insular Shelves

The combined worldwide area of the continental shelf constitutes somewhat less than 8 percent of the ocean floor. Perhaps of greater significance is the fact that less than 0.1 percent of the ocean's waters lie over the shelf. Yet it is on this narrow, shallow ledge that people harvest most seafood, exploit increasing amounts of gas, oil, and other minerals, dispose of large quantities of industrial and municipal wastes, and cause ocean-going and recreational vessels to converge as they prepare to enter narrow harbor channels. Accordingly, if future disposal sites are to be placed on the shelf, they should be located with great care.

Area of the Deep Ocean

Beyond the continental shelf the ocean floor dips to form the continental slope, the lower part of which, called the continental rise, grades into the deep ocean basin or abyss. Most people are aware that about 71 percent of earth is covered by the oceans, but few realize that more than half the globe (57 percent) is covered by water of abyssal depths, that is, over 2000 m deep (Bruun, 1957). This concept of area impinges upon two of the most cogent reasons for thinking of the deep ocean as a terminal receiving environment for dredged material. For one thing it has great capacity for receiving sediments, since it is doing so already. For another the deep ocean has little capacity for food production.

ASSIMILATIVE CAPACITY OF THE DEEP OCEAN

The term assimilative capacity has connotations for engineering and physiology as well, perhaps, as for other fields. Here it is used as a measure of the ability of the deep ocean to receive dredged material without losing its capacity to sustain the life processes in kind and amount characteristic of the receiving region. The amount of terrigenous material normally reaching the ocean by natural means has an important bearing on this topic. Accordingly, this discussion will examine the sources and amounts of sediment reaching the ocean each year, and then will compare the food-producing capabilities of the continental shelf and deep ocean by way of demonstrating how little biomass there is in deep water to be affected.

River Transport of Sediments

Most of the fine-grained sediment reaches the ocean via rivers. Holeman (1968) estimated an annual river runoff of 18×10^9 metric tons of suspended solids. Data from McCave (1975) indicate that about 90 percent of modern riverborne solids are deposited on the shelf, slope, and rise -- the remainder reaching the ocean ridge system and the abyss. Drake (1976) estimate that 8×10^9 metric tons are being deposited annually on the continental slope and contiguous rise. At least 40 percent of this is being carried by about a dozen major rivers. By far the largest of these is the Yellow River of China, but the Mississippi River transports on the order of 310 million metric tons of sediment to and beyond its delta each year. This approximates the total of material produced in one year by maintenance dredging in the entire United States.

The distribution of riverborne sediment over the sea floor is very different from that of maintenance dredging. Shepard (1960) estimated that substantial amounts of the Mississippi fine material were deposited within 12 miles of the Mississippi, whereas the maintenance dredgings are deposited around the perimeter of the U.S. No matter how regionally disproportionate this deposition is, it certainly is not as concentrated as the material distributed across the delta and into deeper water of the Mississippi Trench and Fan.

As to the effects of river sediment material on the benthic life, there is no control; hence it is difficult to draw sound conclusions. Still, it is germane to note that St. Amant (1971) estimated than in 1971 the total fish catch in Louisiana shelf waters was about 900,000 metric tons (includes trash fish, shrimp, and recreational fishing totals). This is particularly interesting because the tonnage quoted is about 20 percent of the U.S. total, and because it was fished from waters west of the Delta, which is downstream of the main current in the region. It is not unreasonable to conjecture from this that the disposal of sediments in the deep ocean probably will have neutral environmental influences.

PRODUCTIVE CAPACITIES OF THE LAND AND SEA

Plant Biomass of Land and Sea

The total phytomass (weight of plant tissue) present on the land is estimated to be 2.4×10^{12} metric tons dry weight. Total phytomass in the world's oceans amounts to 1.7×10^{8} metric tons, which is about 15,000 times smaller than that of the land (Rodin et al., 1975).

Plant Production on Land and in the Sea

Perhaps a more meaningful gauge of the relative importance of land vs. sea can be developed if the rate of production of organic matter (primary production) by natural communities on land and in the sea is examined. The total primary production of the land is estimated to be 1.72×10^{11} metric tons/year, whereas that of the sea is about an average of 5.8×10^{10} metric tons/year (Bogorov, 1959). Hence, the oceans with about three times the area of the land contribute approximately one-third as much primary production as do terrestrial plant communities (Figure 1).

Total Living Matter on Land and the Sea

According to Duvigneaud and Tanghe (1968) the earth's total living matter is equal to 2.42×10^{12} metric tons. As might be expected, the living matter of the land exceeds by 750 times that of the world's oceans, including animals from protozoa to whales.

Food Producing Capacities of Land, Shelf, and Deep Ocean

The marine 71 percent of the earth's surface produces no more than 1.5 to 2.0 percent of the world's food supply. Some five years ago Boyd et al. (1972), in referring to the deep ocean, stated "from the standpoint of commercial fisheries, these areas are of virtually no value, either now or in the future." The immediate prospect of obtaining greater quantities of food from marine sources seems to lie mainly in

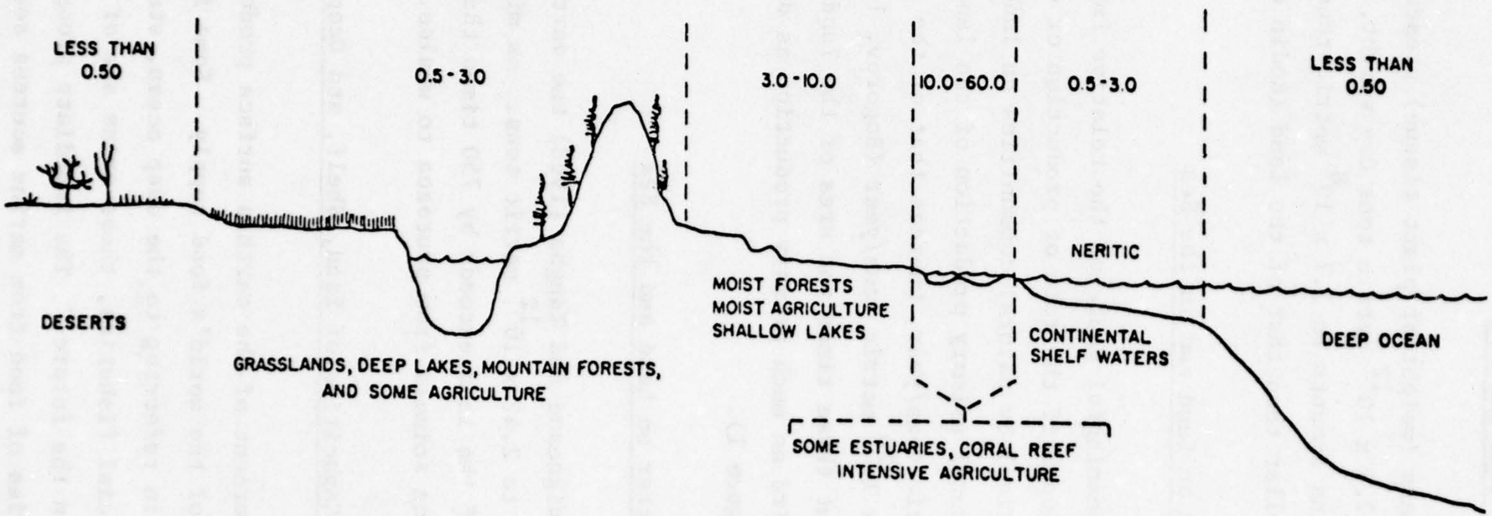


Figure 1. World distribution of primary production. The units are grams of organic matter per m^2 per day (adapted from Odum, 1959).

the possibility of wider, controlled exploitation of natural stocks. As McHugh (1976) points out, some species are overfished while others are not, but the overall view seems to be that there can be some increase in annual tonnage, but not from the deep sea. After a scholarly review of the energy relationships involved in marine production, Tait and De Santo (1972) predict that the deep ocean will never contribute over 1 percent of the total world fish catch, and that will be entirely of pelagic origin. This view is shared also by Moiseev (1971) who has concluded that the abyssal depths show no potential at all for the development of a commercial fishery. Apparently, there is no demersal (bottom) fishery in the United States today below 1000 m, and what there is at that depth forms a rather insignificant part of the total catch. Moiseev (1971) reports that the same depth limit holds in all areas outside the U.S.

The Food and Agricultural Organization (FAO) Yearbooks of Fishery Statistics show that in the year 1850, man took about 1.5 to 2.25 million metric tons of food from the sea. In the 110 years to 1960 it had grown to 33.4 million metric tons. In 1976 the annual world catches of marine fish and other animals amounted to some 62 million metric tons. FAO estimates that the potential catch, considering only the types of animals currently harvested, can be something over 100 million tons. Contrariwise, several U.S. fishery experts consider it more realistic to estimate 70 million metric tons by 1980 as a likely prospect. Moreover, they believe shelf fishes not now utilized will have to be caught to achieve even this increase.

Next to the land, then, the estuarine-shelf complex is the best food producer. About 90 percent of the total bottom or demersal fish catch comes from the shelf (worldwide). Equally important, it takes only 5 percent of the time to catch a ton of fish on the shelf as on the slope.

The deep ocean pelagic fishery, which is composed primarily of tunas and sharks, forms less than 5 percent of the tonnage of the shelf-slope bottom catch. There are those who point out that although the oceans supply only 1 to 2 percent of the world's food supply, that this can amount to almost 10 percent of the protein supply. Unfortunately much of this protein is not consumed in underdeveloped countries where it would do the most good. Rather it is reduced to fish meal and returned to the well-fed nations as poultry supplements. Although the U.S. continental shelves are credited with producing 7.8 million metric tons of fish per year, in recent years 60 percent of this has been taken by foreign fleets.

The Invertebrate Benthos

One reason there are few fishes on the bottom in the very deep ocean is the lack of food. There is a remarkable reduction of invertebrate bottom life (benthos) biomass with increasing depth (Moiseev, 1971; Rowe and Menzel, 1971; Thiel, 1975). On a worldwide basis the average benthonic biomass on the floor of the deep ocean is no more than 0.01 percent that of the continental shelf.

From the above it may be concluded that there is very little bottom life in the deep ocean that could be affected by the discharge of dredged material (see Part 4B, Section B).

EVALUATION OF THE POTENTIAL IMPACTS OF DEEPWATER DISPOSAL

There are manifold impacts that dredged material can exert upon any region or ecological system of the marine environment. Therefore, if one is to be definitive as to the effects of deep ocean disposal, it is necessary to know how much of what kind of material is being disposed and the nature of the water column and the final receiving environment. Some of these specifics are discussed in considerable detail in subsequent chapters. Hence it is proposed here to provide an anticipatory distillation of the bare essentials to undergird a philosophical position vis a vis deep water disposal.

Physical oceanographic effects on dredged material are to a large extent distributive, determining the final resting place of the disposal materials. They are closely related to geological effects and, indeed, there are some interactions. Currents and other physical discontinuities in the water column can modify in what form and concentration dredged material of any type will reach the bottom. Ordinarily one considers physical oceanographic effects to be operative while the material is in the water column and geological ones once it is on the bottom. Thus, geological processes may be distributive if one wishes to so categorize turbidity flows resulting from downslope mass movements.

The position taken here is that chemical changes resulting from the disposal of dredged material in deep water and the effects that these changes have upon both the pelagic and benthic biota is the single most important category of impacts at issue. Except under the most unusual of circumstances, there seems little probability that the material would have any but transitory, and then only relatively harmless, effects on the generally sparse pelagic biota in offshelf waters.

The literature contains considerable documentation of some harmful biological effects of dredged material in marine waters, but the effective studies of the environmental impacts of the dredging-disposal process have been carried out in the shallow waters of the estuarine-inner shelf ecological complex. It is unknown to what extent the conclusions drawn therefrom would apply to deep ocean conditions.

The ultimate fate of the dredged material disposed in the deep ocean is the bottom sediments. Here, potentially toxic elements and compounds may be subjected to conditions that greatly differ from those in the overlying water column and thereby may be released and made available to the benthic community. Thus, it is easier to visualize harmful impacts of the deposition on the benthos than on the pelagial. In fact, the literature is replete with such findings, but the majority of them deal with relatively shallow offshore waters (Rounsfell, 1972;

Thompson, 1973) or with bay waters (Cronin et al., 1970) or estuarine conditions (Sherk, 1971). The magnitude and duration of these effects range from very little to substantial amounts, depending on the amounts and types of materials involved and the ways in which they are disposed. Discussions of acute or short-term effects are common, but very little fieldwork has been done up to now on chronic effects. Nevertheless, it can be anticipated that either long- or short-term effects will be modulated in deep water.

C. BACKGROUND

NEED FOR DISPOSAL OF DREDGED MATERIAL

MAN'S USE OF THE DEEP OCEAN

For all of its vastness, the water column of the deep ocean has actually served man in very few ways and then only on the surface or in a thin layer underneath. For one thing, it has been used as an important transport medium. For another, it has been both a protective physical barrier against hostile invasion and an arena for naval battles. For yet another, and in a more esoteric way, it has been the principal objective of a few major scientific investigations. On the negative side of the ledger, its most disappointing shortcoming is the fact that it never has, and probably never will, provide man with substantial amounts of food, taking full cognizance of the tuna and shark fisheries of the high seas.

Soon the bottom of the deep ocean will undoubtedly supply quantities of important metals associated with manganese nodules. But its most environmentally valuable contribution to the welfare of man may be yet to come. More than a few informed, serious-minded, and environmentally responsible marine scientists and ocean engineers are of the opinion that the deep ocean can receive and assimilate many kinds of wastes, including dredged material, with impunity. In fact, the deep ocean has been doing so for eons and, hopefully, will continue to do so for millenia to come.

MAINTENANCE DREDGING AND THE ENVIRONMENT

Structured in this report is the basic premise that, environmental constraints or related considerations notwithstanding, the United States will continue to dredge existing marine waterways to assist in achieving safe passage of vessels of commerce. This will be done not only because the vessels' export and import cargoes are vital to maintenance of a sound and growing economy but also because accidental spillage of some cargoes in poorly maintained channels could have far more profound effects than dredging on marine ecological systems and, thus, on the welfare of the American people.

NEW PROJECT DREDGING AND THE ECONOMY

Equally patent is the likelihood that new marine projects requiring both new and subsequent maintenance dredging will continue to arise far into the future. Generated by and for an expanding economy, as well as by population movements from the U.S. interior to the coasts, some of these projects now only at various levels of the planning or permit processes, will involve the initial dredging of enormous amounts of sediment. Periodically their maintenance will add to present amounts of material dredged each year from existing channels.

There can be no doubt, then, that problems associated with the disposal of dredged material will persist for years to come. It is the disposal aspect of the total dredging-disposal problem and the justification for serious consideration of a little-used receiving environment that will orchestrate the principal theme of this report. No problem can forever defy solution, but a serious barrier to achieving wholly satisfactory solutions to dredged material disposal is the magnitude of material involved.

VOLUMES OF MATERIAL DREDGED IN THE UNITED STATES

PRESENT AMOUNTS

Each year in the United States, maintenance dredging carried out under permit from the Corps of Engineers produces about 315 million cubic yards of sediment (Arthur D. Little, Inc., 1974). Huge as this volume seems to be, estimated to equal one-third the amount dredged in cutting the Panama Canal, it is certainly not the grand total. New projects are undertaken annually that require dredging of wholly new channels or modifying old ones in various new ways. In 1975, for example, the Corps estimates that new projects required removal and disposal of at least 140 million cubic yards. Thus, U.S. annual production of dredged material is projected to be no less than 450 million cubic yards. In a single decade, then, the amount of dredged material requiring utilization or disposal would cover an area of 4,500 square miles with a foot-thick layer of sediment. This expanse is approximately equal to the combined areas of the state of Delaware and two Rhode Islands!

POSSIBLE FUTURE AMOUNTS

It seems likely that the annual volumes of dredged material will increase during the next decade. Plans for deepening and widening harbor channels to accommodate deep-draft vessels carrying petroleum or liquid natural gas or even dry cargoes, as in various bays of Texas, are already well along. On the Pacific Coast new installations such as in Grays Harbor, Oregon will likely be commenced within five years or less. Then, too, there are plans little more than in the discussion phase, such as the deep-draft channel and turning basin in Corpus Christi Harbor, Texas. Some of these will require dredging channels on the continental shelf if they actually come to pass. In any event, if only the most likely of present new projects are considered, ways must be found to cope with the millions of cubic yards of new material that will have to be disposed of in an environmentally sound manner.

FEASIBILITY OF DEEPWATER DISPOSAL

It is extremely interesting to note the following statement in Boyd et al. (1972), "virtually without exception, the spoil disposal problem foremost in the minds of the Corps District and Division office personnel contacted during this study was the availability of sites for confined land disposal." In the interim, great strides have been made in finding some new uses for dredged material and in reducing the general environmental impact of land disposal. This is all well and good, but, in general, transitional and not final solutions to the problem are being dealt with.

THE ECONOMICS AND ECOLOGY OF THE ISSUE

Undeniably in the present day the hauling of dredged material for disposal in the deep ocean will, in most regions of the U.S., increase the cost of projects well above those involving more conventional disposal sites. The latter often means open water in a bay or the inner shelf or even more frequently a diked containment site on land. But, as pointed out earlier, there is no doubt that for ecological reasons, conventional sites on land are becoming less and less acceptable.

The basic question, then, is this: Just how much more costly would deep ocean disposal be than producing a diked containment? Obviously, a simple answer cannot be provided at this time. However, it should be pointed out that previous cost comparisons between offshelf disposal and land containment have been very much biased in favor of the latter site. Most calculations are based on distances involved and the difference in cost between a hopper dredge for deep ocean disposal and a pipeline dredge for land containment. This, however, is not the full story. Unless the land site is to remain a useless, unsightly, and soggy quagmire beneath a hardened crust, it must be manipulated by heavy machinery, the leachate controlled, perhaps nutrients added, and then, perhaps, planted. These are cost factors that are seldom added. Possibly the most telling cost, especially as time goes on, will be purchase of the land on which the dike is built. On the other hand, when the material is hauled to the deep ocean and disposed, it is gone in a more or less permanent way.

REGIONAL IMPLICATIONS

The seriousness of both aspects of the dredging-disposal process varies greatly by region in the United States. The concern here, however, is with the disposal problem. Perhaps it goes without saying that it should be easier to dispose of material in deep water where the continental shelf is only 5 or so miles wide, as in Miami, as compared with more than 200 miles off Massachusetts. Two other regional factors complicate the problems of the District engineers. One of these is public awareness of what projects are being contemplated and to what extent the public judges them to be in their best interests. Finally, of course, the volumes of material dredged each year will sooner or later have to be reckoned with.

IMPORTANCE OF GOOD MANAGEMENT

The key to environmentally sound dredging-disposal activities involves sound management -- that of including but going beyond the public relations mentioned above. The manager must develop a basic fund of knowledge about the environments and ecological systems in his jurisdiction. He must be conversant with water movements on transient and long-term scales and, above all, he must familiarize himself with the biological components of each of the systems available for selection of disposal sites.

Obviously, also, the dredging-disposal manager must be conversant with the legislation that requires him to control all aspects of the process. Some relevant aspects of the legislation now in force will be examined briefly in the next section.

D. THE MANAGEMENT ROLE

POLICY ON OCEAN DISPOSAL

Management of any function or activity must be undergirded by effective and lucid policy. Although there is ample room for interpretive action among its phrases, the United States does have a policy governing ocean disposal. It is stated in Sec. 2 (b) of the Marine Protection, Research, and Sanctuaries Act of 1972, as follows:

> "The Congress declares that it is the policy of the United States to regulate the dumping of all types of materials into ocean waters and to prevent or strictly limit the dumping into ocean waters of any materials which would adversely affect human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities."

This policy statement leaves no doubt that Congress has recognized that informed American people are concerned about the welfare of the environment and that they are themselves an integral part of that environment. Effective regulation of the disposal of dredged material will depend upon the legal tools provided to the manager of these affairs.

Although regulation of commerce on the Nation's waterways was vested in the Federal government upon ratification of the Constitution, and was extended by the Supreme Court to cover navigation in 1824, it was not until the decade of the 1970s that truly effective legal tools with which to protect the environment of waterways was provided by Congress.

LEGISLATIVE BASIS

Federal legislation controlling waste disposal in the marine environment appears to have started with the Rivers and Harbors Act of 1899. For a long time pursuant to that enactment, control of disposal of dredged material was vested in the Corps of Engineers (Pararas-

Carayannis, 1973). The record seems to show that with only occasional exceptions the principal criteria for issuance of disposal permits were concerned with whether or not hazards to navigation or other impediments to transportation would be created (Smith and Brown, 1971).

In 1958 Congress passed the Fish and Wildlife Coordination Act. It attempted to prevent the disturbance or destruction of aquatic nursery and feeding areas caused by dredging or fill actitivites. It required consultation with applicable state agencies and the United States Fish and Wildlife Service prior to any environmental alteration subject to Federal permits.

In 1970 the Council on Environmental Quality (CEQ) issued its now landmark report on ocean disposal. Since its preparation was stimulated in large measure by the articulate environmental concerns of marine scientists in universities and the Government (largely NOAA) as to the effects of the disposal of sewage sludge and acid wastes in the New York Bight, the CEQ stressed the need for regulation of ocean disposal based upon environmental matters.

CRITICAL NATIONAL LEGISLATION

The 1970 CEQ report carried certain recommendations that were incorporated into the Marine Protection, Research, and Sanctuaries Act of 1972 (MPRSA; PL92-532), that regulates the disposal of wastes into ocean waters. This law is organized into three major titles of which Title I and parts of Title II are germane to this report. The following six sections are worthy of statement here.

Title I - Ocean Dumping

Sec. 101. Bans the transportation for the purpose of dumping and the dumping of radiological, chemical, and bacteriological warfare agents and high-level radioactive wastes.

Sec. 102. Authorizes the Environmental Protection Agency to issue permits for the transportation and dumping of all other material except dredged and fill material, and to establish criteria for reviewing and evaluating such permits and designating sites and times for dumping.

Sec. 103. Authorizes the Corps of Engineers to issue permits, or regulations for Federal projects, for the transportation of dredged material for ocean dumping in accordance with criteria established by EPA (under Sec. 102 of MPRSA).

Sec. 107. Requires the Coast Guard to conduct surveillance of dumping activities and enforce all regulations controlling the transport of materials to be dumped as well as the dumping activity.

Title II - Comprehensive Research on Ocean Dumping

Sects. 201 and 202. Authorizes the Department of Commerce (NOAA) to initiate a comprehensive and continuing program of monitoring and research regarding the effects of ocean dumping.

With the passage of PL92-532, as well as the Federal Water Pollution Control Act Amendments of 1972 (PL92-500) the Congress provided the basis for protection of "ocean waters over which the United States has jurisdiction or over which it may exercise control, under accepted principles of international law, in order to protect its territory or territorial sea." (MPRSA, 1972). Thus, most of the CEQ recommendations were embodied in the Act. However, the international facets of the problem were still awaiting approval of various governments including the U.S.

INTERNATIONAL CONVENTION

One of the CEQ 1970 recommendations stressed the need for broad geographic coverage of the ocean disposal. This together with articulate advocates of the environmental movement served to apprise knowledgeable public officials that effective management of resources and environments inevitably requires one to deal with whole systems. Such a holistic approach certainly applies to the oceans.

The International Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter was developed in the intergovernmental conference held at London in the fall of 1972. The U.S. Senate gave its approval for ratification of this convention on August 3, 1973, but deposition of the ratification was not made until April 29, 1974. The Convention entered into force during August 1975 at the time that the minimum of 15 nations had ratified it.

Meanwhile, in March 1972 an amendment (PL93-254) to MPRSA brought the 1972 Act into full compliance with the Convention. Finally, by publication of the Final Ocean Dumping Regulations and Criteria in the Federal Register of January 11, 1977, EPA has carried out its mandate under Title I of MPRSA and the U.S. Government is in full compliance with the Convention.

THE LATEST APPLICABLE NATIONAL LEGISLATION OF IMPORT

Very likely the most urgent fishery problem facing the Nation today is the great responsibility assumed when the President signed into law PL94-265, the Fishery Conservation and Management Act of 1976. Title III of the Act sets out National standards for fishery conservation and management within the extended zone of jurisdiction (200-mile zone), and outlines procedures by which these standards shall be put into effect. To administer the provisions of this law, which became operative on March 1, 1977, there will need to be understandings among the U.S., the coastal states, and those foreign nations that wish to continue fishing on the U.S. outer continental shelf and upper continental slope. In any event, it is certain that another council will have been brought into existence with stronger than ever concerns about the biological welfare of the continental shelf. This, it seems, is another cogent reason for minimizing the amounts of dredged material to be disposed on the continental shelf.

One among several good reasons often cited for the present plight of the American fisherman is that many other users of the environment are interfering with fishing operations or creating hazards for the resource. Another, of course, is that foreign fishermen are subsidized directly by their governments. A widely held view is that PL94-265 means an end to foreign fishing off U.S. shores, but this is not true. Until the Law of the Sea is concluded and ratified, the U.S. will have only limited control over foreign fleets (the U.S. must demonstrate that it is fully utilizing the living resource in the 200-mile zone). This is an important issue because foreign fleets are presently taking 60 percent of the total catch off U.S. shores. The U.S. fishery can be aided, however, by not disposing in important areas.

E. RELATED DISPOSAL CONSIDERATIONS

RESISTANCE OR OPPOSITION TO SOME CONVENTIONAL SITES

Public awareness, albeit the informed fraction of the population, of the profound biological value of salt marshes, estuaries, and shallow embayments to both shellfisheries and finfisheries is becoming widespread. Both those who fish for a living and for recreation are becoming more deeply and vociferously concerned about the welfare of these resources. As yet this is not true of all coasts or of all parts of a single coast, but areas of apparent unconcern can change very quickly when spurred on by organized leadership.

Today, there are essentially three major categories of disposal environments for dredged material of marine origin: the land or upland areas, the estuarine-continental shelf complex, and the offshelf deep ocean. It is beyond the scope of this report to discuss the first two in any detail, but enough must be said in order to put the third in proper perspective.

RECEIVING ENVIRONMENTS ON LAND

In recent years sponsors of dredging projects have made increasing use of land sites for disposal purposes. Boyd et al. (1972) believe that this trend arose in part because of concern over open-water disposal of contaminated sediments. But there are increasing signs that land disposal has not been the ideal solution. There are many problems associated with confining dredged material on land (Meccia, 1975). Among these are deterioration of dike integrity, long duration of fluidity of the dredged material unless additional expenditures of time and money are made, loss of sediment from the containment area into the waterway, and quite frequently there are both sight and smell indignities -- not to mention health hazards in some areas as a result of the breeding of mosquitoes. In spite of these difficulties and others not mentioned, upland disposal is a viable alternative disposal option in some places, e.g., the Pacific Northwest and, up to now, some areas of the Gulf of Mexico. But with no intention of sounding a doomsday claxon, it seems only fair to say this cheap and easy land disposal may not always be available. In fact, it is almost a certainty that it will not be.

Unless demonstrable beneficial circumstances prevail, the assumption seems to be untenable that the land is the best of possible disposal environments, even for some kinds of polluted sediments. As coastal populations continue to grow, and the rate seems now to be accelerating into the Sunbelt, the need for living space and the utilization of coastal regions for industry and recreation will press harder against food-producing acreage. This is not idle rhetoric. About 65 million people now live within the Coastal Zone (50 miles inland from the shore) of the United States. Thus, roughly 30 percent of the population lives in only 8 percent of the total land area! Perhaps more alarming is the fact that whereas in 1972 the coastal population was estimated to be growing at an annual rate of 2.5 percent, it is now increasing at anywhere from 3 to 5 percent. The recent unseasonably cold winter of 1976-77 may even cause acceleration of this rate.

Unless it can benefit agriculture, which will inevitably suffer a land squeeze in this demographic explosion, the disposal of dredged material on land will become less acceptable. Let no one think that the areas involved in land disposal are small. Mallory and Meccia (1975) estimate on the basis of past dredging volumes that no less than 7000 acres of new land will be required each year for the containment of material generated from maintenance dredging operations of the Corps of Engineers. Obviously, suitable land disposal sites will become as difficult to obtain in many places as they already are, say, in parts of New England, New York, and Baltimore.

In any event, the best land is already being tilled and the remainder tends to be marginal (Borgstrom, 1969). Owing to mismanagement the world over, even the quality of presently cultivated land has deteriorated over the years (see below).

Quality Classification of Tilled Land*

	1882 %	1952 %
Good	85	41
Half of original humus lost	10	39
Marginal soils	5	20

*From Doane, World Balance Sheet, 1957
Reprinted by permission of Harper & Row.

Perhaps even more alarming is the fact that population and related industrial pressures are actually working each day to reduce the amount of arable land. Borgstrom (1969) estimates from data supplied by the

Department of Agriculture that over 2 million acres of rural land are turned over every year to urban development, airports, highways, reservoirs and other flood control measures, parks, wildlife refuges, and the like. Anyone who has seen the irrevocable sprawling of cities such as Washington, D.C., Los Angeles, Phoenix, and Houston (to mention only a few) since, say, as late as 1960, will find these figures credible. Good as these facilities are, there must be some tradeoffs, because the trend cannot go on forever. Most of all, more land in the coastal zone should not be usurped for dredged material unless it can be reclaimed as top soil.

THE ESTUARINE - CONTINENTAL SHELF COMPLEX FOR DISPOSAL

Various authors, among them McHugh (1976), have estimated that something over three-quarters of the weight of finfishes and shellfishes landed in the United States by domestic fishermen are dependent upon an estuary. The telling point, however, is that the major contributors to this living weight (biomass) are species that are not solely dependent upon the estuary or the continental shelf but must live part of their life cycle in each area.

McHugh (1967) makes it clear that the oceanic phases of the life histories of living marine resources that are of highest importance (e.g. shrimp) are equally as important as the estuarine phase. This only points up the folly of shifting a waste disposal problem from one habitat to another. Species of animals or plants cannot be preserved one by one; rather environmental systems must be preserved that in toto are of value to many species.

In some places the creation of artificial marshes in shallow portions of estuaries or embayments by placing dredged material in the intertidal and subsequently planting it may improve the quality of the environment. It must be realized, however, that only certain types of organic and nutrient-rich dredged materials lend themselves to this development (Meccia, 1975). It has been suggested that one good use of dredged material might be to create artificial barrier islands off appropriate coasts as storm wave buffers to heavily populated mainland areas. Although this idea seems quite feasible, careful studies of normal circulation and probable modifications would have to be carried out to determine what potential deterioration of the environment might occur.

REGIONAL ASPECTS OF THE DISPOSAL PROBLEM

The volumes of dredged material produced each year vary greatly on a regional basis. For instance, about 2.4 million cubic yards are produced each year in the New England Sector (see Part 2, Section A, and Part 5, Section B) from Cape Sable to Cape Cod, whereas the northern Gulf of Mexico generates over 100 times that much (ca. 251.6 million cu yd). Still, it must not be assumed from these very disparate figures that it is proportionately easier to find suitable disposal sites in New England than in the Gulf of Mexico. Indeed, for several reasons, the reverse appears to be true at present. But there are very strong evidences that this will not always be so. When it becomes as difficult in the future to dispose of dredged material by conventional means in the northern Gulf of Mexico as it is in New England today, the Corps and other regulatory agencies may be forced to utilize disposal methods that are judged today to be unacceptable for economic or other reasons.

AN ALTERNATIVE SOLUTION: OPEN OCEAN DISPOSAL

In discussing deep ocean disposal, Boyd et al. (1972) note:

> "Differences in opinion as to the environmental impact of deepwater disposal are widespread and reach the proportion of major controversy when polluted and/or toxic substances are involved. Investigations aimed at the controversial issues have proceeded slowly largely because large-scale deepwater disposal operations have not been economically feasible to date. However, with

> alternative solutions to currently unsatisfactory disposal operations standing to increase unit costs by several orders of magnitude, deepwater disposal appears to reenter the realm of economic reality."

Fortunately, the authors have had an opportunity since inception of this project to poll a large cross-section of informed scientists and engineers as to their feelings about deepwater disposal of dredged material. A clear majority of these people, representing all phases of oceanography and related water-quality endeavors (Appendix A) are not opposed to deepwater disposal of dredged material, especially if it is contaminated. Smith (1973) represents this view succinctly when he says "that the oceans' vast space resource is potentially of major value to man for use in waste disposal and that properly managed this use need not damage the marine environment."

Bascom (1974) has phrased a question that in some ways lies at the heart of this matter, indeed, of the entire environmental movement of the 1970s:

> "How unchanged should man try to keep an environment that nature is changing anyway?"

The way nature is changing the deeper aspects of the ocean will be discussed in considerable detail in later sections. If man were the chief cause of these changes, they would constitute pollution. Perhaps, then, a working definition of pollution should be sought.

Marine pollution has been defined by the UNESCO Intergovernmental Commission as:

> "Introductions by man, directly or indirectly, of substances into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities (including fishing), impairing the quality for use of seawater and reduction of amenities."

A definition that cuts to the core of the problem in few words is one often given by Dr. Athelstan Spilhaus (Personal Communication, 1976, and elsewhere), viz., "a pollutant is anything that by its excess reduces the quality of living." Obviously most of the substances usually called pollutants are present in the ocean from natural sources.

Finally, the authors agree with the thrust of a statement emanating from the Coastal Zone Workshop held at the Woods Hole Oceanographic Institution in 1972 (Ketchum, 1972), viz.,

> "There is a prevailing opinion in our society that all contaminants introduced into the environment are bad and that waste disposal into the coastal environment* is to be avoided. This misleading and unrealistic concept must have clarification in order for society to establish acceptable criteria for management of its resources at the same time it provides for a continuing, healthy environment. Most wastes have a level of concentration which can be reached in the environment without significant alteration to the functional parts of the system; in fact, wastes such as nutrients and, sometimes, heat can be beneficial, if properly interfaced with biological, chemical, and physical features. Wastes added under these conditions should be considered contaminants, not pollutants."

Dangerous synthetic molecules and high-level radioactive compounds clearly must be ruled out for regular disposal, as they are by various national and international acts and conventions. But sediment input to the ocean, some of which is highly polluted from natural sources or from man's activities, is a naturally occurring phenomenon. Some sort of answer as to how much more the open ocean can tolerate without unusual change should be sought.

---

*This can be said of the deep ocean even more definitively.

PART 2. DREDGING AND DREDGED MATERIALS

A. INTRODUCTION

In order to develop and maintain the navigable waterways of the United States, the Corps of Engineers is responsible for dredging on the order of 350 to 450 million cu yd of sediment each year at a cost of over $200 million. In addition, privately sponsored dredging projects typically add about 70 million cu yd to the total volume dredged annually.

Disposal of the dredged material presents various environmental, economic, and operational problems because of the enormous volumes of sediment and water involved. These problems are considered in some detail in the landmark report by Boyd et al. (1972), and in a number of subsequent studies and reports sponsored by the Dredged Material Research Program of the U.S. Army Corps of Engineers.

This report examines various aspects of potential deepwater ocean disposal of dredged material. Within this context, Part 2 includes a brief review of typical dredging and disposal methods, and a discussion of the sources and volumes of dredged material, followed by sections emphasizing: a) the characteristics of the materials generated by various types of dredging, b) the disposal practices typically used today, and c) how the characteristics of dredged material and the disposal methods bear on potential ocean disposal.

This part focuses largely on the Corps' dredging activities, and the data used and conclusions reached refer to Corps sponsored projects. Except where otherwise specifically noted, data on private sector dredging projects are not included.

For reasons explained in part in Huston (1970), in spite of the magnitude and cost of dredging activities in the U.S., much of the operational and technical literature is piecemeal and scattered, and most of the statistical data on dredging and disposal operations are unpublished. As a result, in some sections of Part 2, it has not been feasible to provide as balanced a treatment of all topics as might otherwise been desirable.

B. DREDGING AND DISPOSAL METHODS

This section is intended as an abbreviated and selective primer on dredging to familiarize the lay reader with the more important aspects of dredges, dredging methods, and dredged material disposal.

For detailed discussions of the technical and operational aspects of dredging and disposal methods and practice, the reader is referred to Huston (1970); Boyd et al. (1972); Herbich (1975); Gren (1976); and Mohr (1976). For general discussions of the environmental, legal, institutional, and economic considerations and problems involved in this technology, see U.S. Army Corps of Engineers (1976); Saucier (1976); Wakeman (1976); Hackenjos (1976); Smith and Graham (1976); various papers in Krenkel et al. (1976); and the specific papers cited in following sections of this part.

TYPES OF DREDGING

Basically, dredging is the technology of excavating submerged materials (most commonly unconsolidated sediment) in order to create or maintain waterways or to gather bottom material for fill or commercial use (Gren, 1976). In simplest terms, dredges are earth moving machines designed to excavate subaqueous bottom material (Mohr, 1976).

Nearly all existing dredges may be divided into two basic categories: namely, hydraulic and mechanical. Hydraulic dredges lift the dredged material by means of pumps, and mechanical dredges lift by buckets of various designs. The two basic categories of dredges have developed into several distinct types, as outlined in Figure 2.

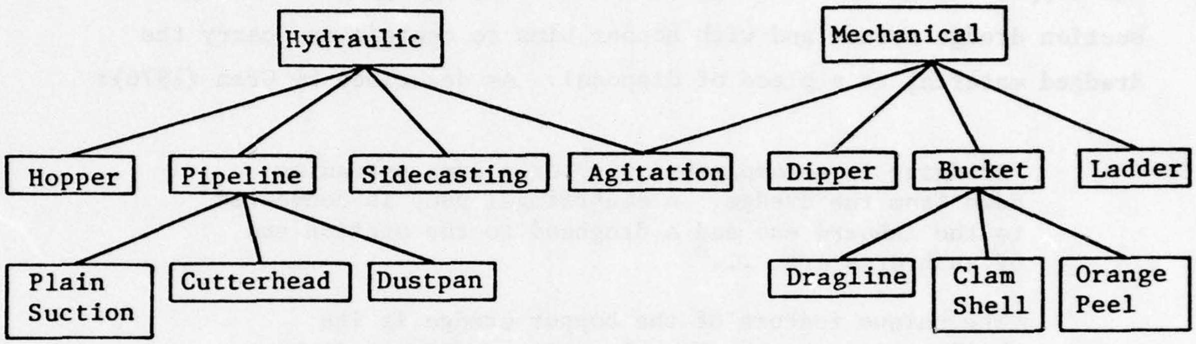


Figure 2. Types of Dredges (modified from Mohr, 1976. Mechanical Dredges, pp. 125 - 138, Dredging and its Environmental Effects)

The operational applications of the various types of dredges overlap to some extent. Thus, for the purposes of this report, the following three dredge types can be considered to be representative of the various types currently used in the U.S.:

hopper dredges (Hydraulic)
pipeline dredges (hydraulic)
bucket dredges (mechanical)

According to Corps of Engineers data presented by Arthur D. Little, Inc., (1974), in 1973 hydraulic dredges accounted for 99 percent of total yards dredged as follows: Hopper dredges - 57 percent; cutterhead and dustpan pipeline dredges - 42 percent. Bucket and other types of dredges accounted for only 1 percent of the total yardage dredged.

A brief description of hopper, pipeline, and bucket dredges follows. For a more detailed description, see Huston (1970), Mohr (1974), Herbich (1975), and Gren (1976).

HOPPER DREDGE

The hopper dredge is a self-propelled vessel, equipped with a hydraulic suction dredge system and with hopper bins to contain and carry the dredged material to a place of disposal. As described by Gren (1976):

> "Dredging is accomplished with drag arms extending down from the dredge. A centrifugal pump is connected to the inboard end and a draghead to the suction end of each drag arm. ..."
>
> "The unique feature of the hopper dredge is its ability to excavate channels while underway, without anchors or other moorings. The hopper dredge is thus highly mobile and provides a minimum interference with passing vessels while operating in the channel to be dredged. This type of dredge is normally employed where the water is too rough for a pipeline dredge, where spoil disposal areas for use by a pipeline dredge are not available within economic pumping distances, or in areas of high vessel density where the pipeline dredge would present a navigational hazard."

According to Boyd et al. (1972), hopper

> "...dredges are all Corps-owned and operated, are confined primarily to the coastal zone and Great Lakes, and are used chiefly in maintenance dredging operations."
>
> "Although the situation is changing somewhat, hopper dredges have traditionally disposed of their materials in open water. Disposal has been accomplished by traveling to the disposal site and, while circling in the disposal area, opening the bottom doors on the hoppers and releasing the spoil materials in a relatively short time. Depending on the dredge used, this discharge can range from 500 cu yd to 8000 cu yd."

PIPELINE DREDGE

The cutterhead-equipped hydraulic suction pipeline dredge is the most widely used type of dredge in the United States and is the basic tool of the private dredging industry (Gren, 1976). This dredge utilizes a rotating cutter on the end of a truss-like ladder to excavate physically in situ material and mix the material with dilution water. The material-water slurry is pumped hydraulically to the surface and then into a pontoon-supported pipeline for discharge at a disposal site.

Cutterhead pipeline dredges are used for both maintenance and new work projects and are capable of dredging consolidated as well as unconsolidated granular materials. Unlike the hopper dredge, pipeline dredging is almost continuous and disposal operations take place concurrently. For this reason, disposal areas normally are located relatively close to the dredge. However, with the aid of booster pumps along the pipeline, the slurry can be pumped to disposal sites located at substantial distances (perhaps 5 to 15 miles) from the waterway being dredged. Because rough water may cause the pipeline components to uncouple, use of pipeline dredges normally is limited to relatively protected waters, such as bays, estuaries, lakes, and rivers.

BUCKET DREDGE

In its simplest form, a bucket dredge consists of a drop bucket (for instance, a clamshell) attached by cables to a winch-equipped boom and lifting system mounted on either a floating platform (e.g. barge or pontoon) or a tracked or tired mobile base. Large modern bucket dredges are considerably more complicated, but the basic components are essentially as described.

According to Boyd et al. (1972),

> "Most mechanical dredging is done for the Corps by private contractors. [These dredges] ... are generally mounted on a barge and are used in both maintenance and new work projects. Although the rate at which the materials are removed by these dredges is small compared to hydraulic dredges, they are ideally

suited for working in small areas such as harbors, slips, etc. The dredged materials are usually placed in barges and scows and transported to the disposal site, ..."

DILUTION WATER

As Mohr (1976) points out, one of the most fundamental differences between mechanical and hydraulic dredging is the amount of water picked up with the dredged sediment.

Mechanical dredges drain off most of the water when picking up sand and coarser materials, and thus furnish bottom material at densities close to those found in situ.

Hydraulic dredges, on the other hand, have to add dilution water to form a slurry. As a general rule, hydraulic dredges add between one and three volumes of diluting water to a given volume of bottom material. Only in very dilute bottom materials, under ideal conditions, and with special equipment, is it possible for hydraulic dredges to handle bottom material at in-place density.

Mohr (1976) emphasizes that the addition of dilution water substantially increases the quantity of dredged material handled. This increase in volume increases operating costs and fuel requirements. As will be shown in later sections, moisture content of the slurry also affects the way the material descends to the bottom when dumped in open water.

TYPES OF DISPOSAL

Dredged material disposal procedures can be readily subdivided into two broad categories: open water and on land. The major subcategories within the two headings can be categorized as follows:

Open Water	On Land
Ocean	Unconfined
Deep	Beach Nourishment
Shallow	Fill
Bays, Sounds	Other
Estuaries	Confined
Inland Rivers	Water Level
Lakes	Upland

Before concern arose regarding possible adverse environmental effects of dredging and disposal, cost was the primary factor in selecting disposal sites for dredged materials. Therefore, sites generally were selected that required minimum transport of the materials -- other factors being equal, the closer the disposal site, the lower the cost. Accordingly, open-water disposal was standard practice, except in relatively uncommon cases in which another type of disposal proved to be less expensive.

Within this framework, the type of dredging method used generally predetermines the type of disposal. Hopper dredges, within the bottom dump gates, are designed to discharge in open waters; the same is true for bottom dump barges. On the other hand, pipeline dredges can pump the dredged material either to open-water sites or to on-land sites.

Other factors, such as the location of the area being dredged, also serve to determine the type of dredges used and, thus, the type of disposal. For example, because of the rough waters in the seaward sections of entrance channels, dredging generally is carried out by hopper dredges that typically travel to and discharge their loads at shallow nearshore ocean disposal sites in the vicinity of the channel being dredged. By contrast, most dredging in more protected waters (such as estuaries) characteristically is done by cutterhead hydraulic dredges that discharge via pipeline either into open water sites in the estuaries or to unconfined or confined sites on land.

On the other hand, mechanically dredged materials typically are loaded into barges and discharged at an open-water disposal site; in many coastal dredging projects, the barges are discharged at one or more shallow water ocean disposal sites a few miles to perhaps tens of miles offshore.

The discussion of Boyd et al. (1972) of disposal methods is particularly informative and is excerpted as follows:

> "Although the situation is changing somewhat, hopper dredges have traditionally disposed of their materials in open water. ..."
>
> "Recently, due primarily to environmental concerns over open water disposal, several hopper dredges, especially those operating in the Great Lakes, have been modified for sidecasting, to allow such disposal procedures as beach nourishment."
>
> "[For the various types of]...pipeline dredges... the dredging and disposal operations are simultaneous and almost continuous. This has resulted in the spoil areas being located relatively close to the dredge. In open water disposal, three different discharge techniques are used. In some cases, the slurry is merely discharged, with no alterations, from the end of the floating pipeline. In other instances, a splash plate is installed at the end of the pipe to deflect the slurry, causing a large spray. As the incident angle of these plates to the slurry can be controlled, the hydraulic force against the plate is often used to move or guide the floating pipeline. Finally, elbows are often installed at the end of the discharge pipe in such a manner as to allow injection of the hydraulic slurry beneath the water surface."
>
> "There are several methods in which materials dredged mechanically and transported by barges are disposed of in open waters. In some types of barges, bottom doors are opened and the spoil materials are dumped in a manner of minutes. They resemble hopper dredges in this sense. In some instances, these materials are dumped over underwater sumps, containment areas, or rehandling basins. Often, materials placed in these rehandling basins are redredged by pipeline dredges and discharged into diked disposal

> areas on land. On deck-type barges, the piled spoil materials are either mechanically pushed over the side or washed overboard with high pressure water jets."

The regional variations in dredged material disposal practices are examined in some detail in a later section on Disposal Practices.

C. DREDGED MATERIAL VOLUMES, SOURCES, AND DISPOSAL PRACTICES

This section addresses the "how much?," "from where?," and "how disposed of?" aspects of dredged material with focus on the volumes, source areas, and disposal practices along the coasts of the United States with reference to potential for deepwater ocean disposal.

VOLUMES

According to a study by Arthur D. Little, Inc. (1974) the Corps was expected to dredge on the order of 450 million cu yd annually for the years 1974 through 1976 (see Table 1).* Of the total volume, about 315 million cu yd, or about 70 percent, would be generated by maintenance dredging activities in existing waterways, and about 140 million cu yd, or 30 percent, would result from so-called "new work" dredging.

Although privately sponsored dredging projects may add yardage amounting

---

*As pointed out by Boyd et al. (1972),

> "...the magnitude of the Corps' annual maintenance and new work dredging operations varies significantly from year to year primarily because of variations in new work quantities. Furthermore, methods of disposal vary with time because of changing attitudes and constraints. Therefore, any average figures pertaining to the Corps' dredging and disposal operations should be viewed both in light of the annual variations in the size of operations and the types of dredge spoil disposition."

Table 1

Projected Average Annual Corps of Engineers

Dredging Requirements (1974-76)*

DISTRICT	TOTAL (Cu. Yds.)	MAINTENANCE	NEW WORK	M/NW %'s
Alaska	458,000	192,000	266,000	42/58
Los Angeles	3,298,000	1,880,000	1,418,000	57/43
Portland	16,433,000	15,283,000	1,150,000	93/07
Sacramento	3,035,000	2,155,000	880,000	71/29
San Francisco	10,063,000	7,346,000	2,717,000	73/27
Seattle	3,786,000	3,483,000	303,000	92/08
Pacific Ocean	438,000	0	438,000	0/100
Jacksonville (G)	12,807,000	3,586,000	9,221,000	28/72
Galveston	70,364,000	53,477,000	16,887,000	76/24
Mobile	35,602,000	25,277,000	10,325,000	71/29
New Orleans	145,610,000	84,454,000	61,156,000	58/42
Huntington	716,000	630,000	86,000	88/12
Kansas City	2,108,000	1,813,000	295,000	86/14
Little Rock	2,570,000	2,570,000	0	100/0
Louisville	2,571,000	2,210,000	361,000	86/14
Memphis	29,311,000	29,018,000	293,000	99/1
Nashville	990,000	396,000	594,000	40/60
Omaha	6,000	6,000	0	100/0
Pittsburgh	134,000	125,000	9,000	93/07
Rock Island	1,250,000	1,250,000	0	100/0
St. Louis	7,862,000	7,862,000	0	100/0
St. Paul	2,280,000	2,189,000	91,000	96/04
Tulsa	1,000,000	1,000,000	0	100/0
Vicksburg	14,830,000	10,974,000	3,856,000	74/26
Buffalo	3,932,000	3,617,000	315,000	92/08
Chicago	1,893,000	1,723,000	170,000	91/09
Detroit	3,217,000	3,217,000		100/0
Jacksonville (E)	15,298,000	3,519,000	11,779,000	23/77
Baltimore	1,674,000	1,540,000	134,000	92/08
Charleston	10,510,000	8,933,000	1,577,000	85/15
New England	2,397,000	1,270,000	1,127,000	53/47
New York	12,561,000	5,527,000	7,034,000	44/56
Norfolk	4,421,000	4,288,000	133,000	97/03
Philadelphia	10,048,000	9,445,000	603,000	94/06
Savannah	8,991,000	8,991,000	0	100/0
Wilmington	13,270,000	5,972,000	7,298,000	45/55
	455,734,000	315,218,000	140,516,000	
		69%	31%	

*Table compiled by Dr. R.T. Saucier, Dredged Material Research Program, Waterways Experiment Station, from data presented in the National Dredging Study by A.D. Little (1974). The figures shown represent an average of the figures for dredging requirements projected for 1974, 1975, and 1976 by A.D. Little. Actual value probably falls between 350 and 455 million cu yd annually.

to perhaps 10 to 15 percent of the total volume dredged in some years, this privately sponsored work is not addressed in this section.

According to U.S. Environmental Protection Agency (1976a, p. 45), the volumes of dredged material discharged in the ocean annually (based on 1974 and 1975 figures) are on the order of 90 to 100 million cu yd (Table 2). Thus, of the roughly 450 million cu yd projected annual dredging only about 20 to 22 percent is presently disposed of in the ocean.

In view of the above, a logical question is "how much of the remaining 78 to 80 percent of the 450 million cu yd volume is a likely candidate for ocean disposal?" Further, "how much of the 90 to 100 million cu yd now going to the ocean is a likely candidate for deepwater ocean disposal."*

Because of the generalized nature of the data available on dredging (and for other reasons), answering these questions with any degree of precision is not possible within the scope of this report. However, the following discussion of dredged material volumes from different source areas should provide some insight to the questions.

SOURCE AREAS FOR OCEAN DISPOSAL

The logical source areas for contribution of dredged material to ocean disposal are considered to be the coastal sections of the 48 contiguous states, i.e. Atlantic, Gulf, and Pacific coasts, and the urbanized localities of coastal Alaska and the Hawaiian Islands.

---

*Although pertinent yardage figures are not available, based on the shallow water locations of almost all the ocean disposal sites authorized for discharge of dredged material, probably only a very small fraction (say, a few percent) of the 90 to 100 million cu yd going to the ocean presently goes to deepwater sites.

Table 2

Ocean Disposal of Dredged Material in Calendar Years 1974 and 1975 By Corps of Engineers Divisions (cubic yards)

		Calendar Year 1974				Calendar Year 1975			
	Division	Corps of Engrs.	Permits	Total		Corps of Engrs.	Permits	Total	
Atlantic	New England Division	1,340,400	921,800	2,262,200		551,000	331,500	882,500	
Atlantic	North Atlantic Division	8,234,543	3,475,849	11,710,392		10,500,000	3,100,000	13,600,000	
Atlantic	South Atlantic Division	5,911,248	-	-		11,715,250	-	-	
	Atlantic	(4,961,248)	-	4,961,248		(10,015,250)	-	10,015,250	
	Atlantic Total and %			18,938,840	19%			24,497,750	28%
	Gulf	(950,000)	-	950,000		(1,700,000)	-	1,700,000	
Gulf	Lower Mississippi Valley Division	54,600,000	-	54,600,000		33,508,087	12,000	33,520,087	
Gulf	Southwestern Division	9,743,982	-	9,743,982		8,581,253	None	8,581,253	
	Gulf Total and %			65,293,982	66%			43,801,340	50%
Pacific	South Pacific Division	7,162,918	1,292,500	8,455,418		2,516,000	190,480	2,706,480	
Pacific	North Pacific Division	5,982,280	-	5,982,280		7,473,792	135,000	7,608,792	
Pacific	Pacific Ocean Division					30,000	9,182,000	9,212,000	
	Pacific Total and %			14,437,699	15%			19,527,272	22%
		92,975,371	5,690,149	98,665,520		74,875,382	12,950,980	87,826,362	

Based on U.S. Environmental Protection Agency, 1976, Figure 6, with additional data from Corps of Engineers

The following brief discussion of source areas is based on the data on annual volumes of dredged material (presented in Table 1) furnished by the 20 Engineer Districts responsible for these coastal areas and summarized by Arthur D. Little, Inc. (1974).

Based on data presented in Table 1, the largest volume of dredged material (on the order of 264 million cu yd per year, or 69 percent) is generated along the Gulf coast; the second largest volume (79 million cu yd per year, or 21 percent) is generated along the Atlantic coast area; and 36.5 million cu yd per year (or 10 percent) are generated along the Pacific coast. Only about half a million cu yds are generated in Alaska, in spite of its lengthy coastline; and in Hawaii, which is of particular interest for this study because of its location in deep water, an equally small volume is generated. Thus, a first approximation of the total volume generated in U.S. coastal areas (and, therefore, subject to consideration for ocean disposal) is about 380 million cu yd per year, or roughly 83 percent of the 450 million cu yd projected annual volume generated nationwide by the Corps. The 90 to 100 million cu yd actually being disposed of at sea thus comprise roughly one quarter (about 23 to 26 percent) of the total projected annual volume generated in coastal districts.

However, it is evident that a portion of the yardages reported by coastal districts is dredged in areas relatively remote from the ocean. Thus, at least a second refinement of the volume figures is necessary to determine more realistically the volume of dredged material potentially available for ocean disposal.

Unfortunately, the Arthur D. Little, Inc. 1974-76 data on dredged material volumes (presented in Table 1) are too generalized to lend themselves to such an analysis. For this reason, the more detailed FY 1969 data from Boyd et al. (1972) were used, even though they only account for maintenance dredging yardage and do not include figures for new work. Review of the FY 1969 data indicates that the total volume of maintenance for that period was 298 million cu yd and, of this, some 205 million cu yd was generated in the 20 coastal districts. Comparison of the Arthur D. Little, Inc. 1974-76 data and the Boyd data from FY 1969 is shown in Table 3.

Table 3

Comparison of Data on Dredged Material Volumes for FY 1969 and 1974-76

Basis for Comparison	FY 1969*	1974-76**
Total Volume Dredged	not given	456 million cu yd
Total Volume Maintenance	298 million cu yd	315 million cu yd
Total Volume New Work	not given	141 million cu yd
Total Volume 20 Coastal Districts	not given	381 million cu yd
Maintenance Volumes 20 Coastal Districts	205 million cu yd	247 million cu yd

*Boyd et al., 1972

**A.D. Little, Inc., 1974

Within the 20 coastal districts, examination of the general locations of maintenance dredging (and yardage generated) provides a rough measure of the volumes that are not a likely candidate for ocean disposal. The yardage volumes for different types of dredging locations are shown graphically in Figure 3. Inspection of this figure shows that for a number of the coastal districts -- particularly Galveston, New Orleans, and Mobile (which together account for two-thirds of the total maintenance yardage from coastal districts, i.e. some 247 million cu yd); about one quarter to one half of the volume comes from river

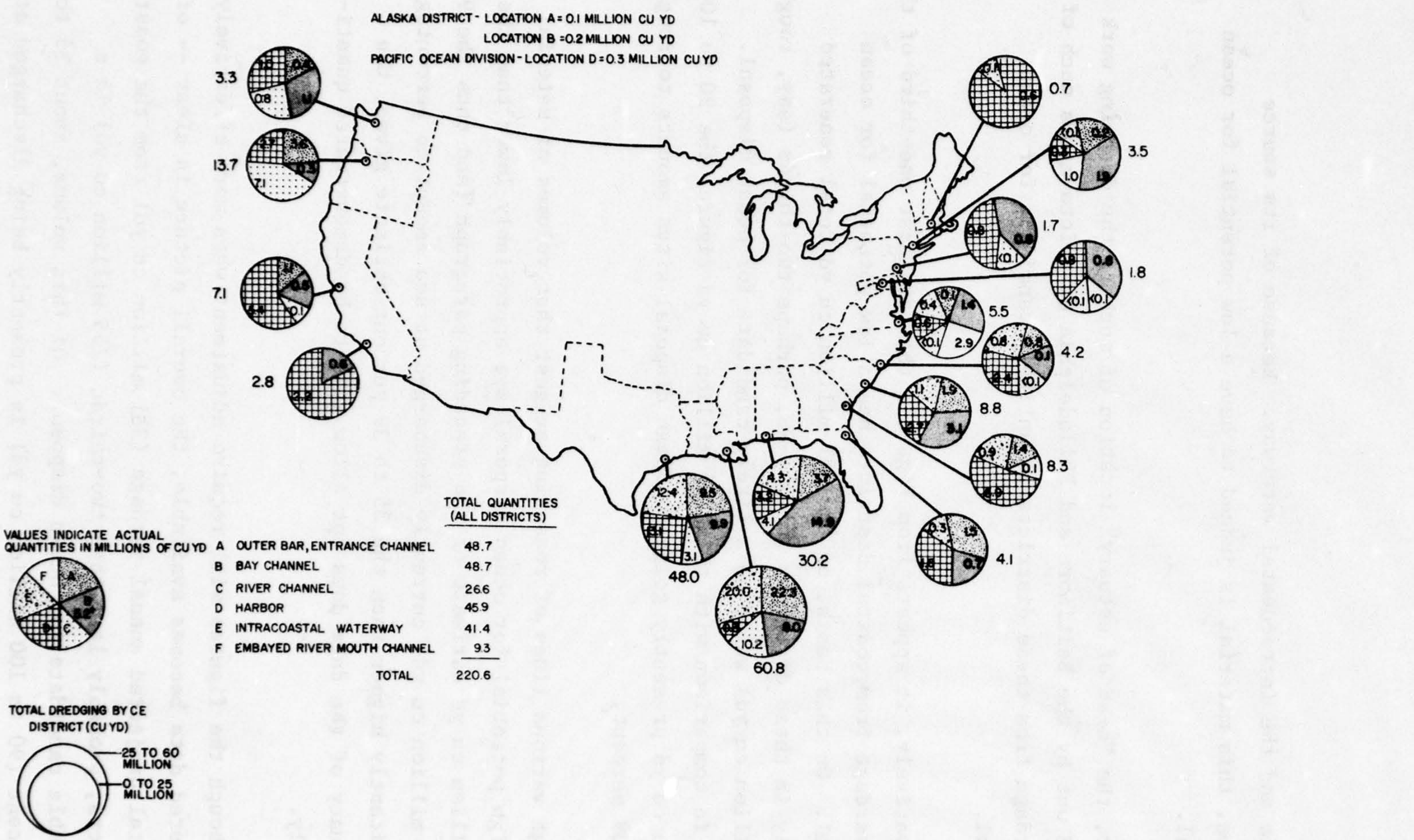


Figure 3. Locations of maintenance dredging projects in coastal districts showing annual quantities of dredged material by location type (modified from Boyd et al., 1972, Figure 5).

channels and the intracoastal waterway. Because of its source location, this material is judged to have a low potential for ocean disposal.

Further, the "head of estuary" location of much of the dredging work carried out by the Baltimore and Philadelphia districts makes much of the yardage from these districts an unlikely candidate for ocean disposal.

Conservatively, it appears from Figure 3 that at least one-third of the total yardage from coastal districts has a low potential for ocean disposal. On this basis, of the 381 million cu yd total generated annually in these districts in 1974-76, perhaps two-thirds (say, roughly 255 million cu yd) would be a likely candidate for ocean disposal. Viewed in comparison with this 255 million cu yd figure, the 90 to 100 million cu yd presently going to ocean disposal sites amounts to roughly 35 to 39 percent.

Although various lines of reasoning suggest that volumes of material with high potential for ocean disposal are appreciably lower than the 255 million cu yd estimate of the preceding paragraph (and thus the 90 to 100 million cu yd) currently discharged at sea amount to percentages significantly higher than the 35 to 39 percent estimate given, the inadequacy of the data does not allow this to be demonstrated quantitatively.

Even though the figures will require adjustment when more effectively structured data becomes available, the overall picture is clear -- of the total projected annual yardage (381 million cu yd) from the coastal districts, probably less than two-thirds (255 million cu yd) is a reasonable candidate for ocean disposal. Of this volume, about 35 to 40 percent (90 to 100 million cu yd) is presently being discharged at sea.

Further, it is clear that dredging along the Gulf coast generates by far the largest volumes of yardage that can be considered a candidate for ocean disposal. For maintenance dredging, the Gulf generates three times the volume of the Atlantic coast, which in turn is about double that of the Pacific coast.

In calendar 1974, the Corps districts in the Gulf coast accounted for more than two-thirds of the total national volume of dredged material discharged at sea (Table 2). The Atlantic coast accounted for about 19 percent, and the Pacific coast accounted for about 15 percent. As evident, these volumes are roughly proportional to the total volumes dredged in each of the three areas.

However, for a number of reasons developed in the last section of this part, of the yardage that has high potential for ocean disposal, only a small fraction is a likely candidate for deepwater ocean disposal. One of the most important reasons is haul distance (which equates with cost). For the Gulf, Atlantic, and Pacific coasts, the haul distances to shelf edge, deepwater sites are, unfortunately, roughly proportional to the volumes of dredged material generated. The shelf edge (and deep water) is as much as 60 to 100 miles offshore in the Gulf, at intermediate distances along much of the Atlantic coast, and generally close inshore along the Pacific coast. It should be pointed out, however, that there are potential sites in the Gulf less than 50 miles offshore.

DISPOSAL PRACTICES

Dredged material disposal practices vary widely, depending upon a number of factors, including: a) the type of dredge in use, b) the category of the work (maintenance versus new work), and c) the geographic region, d) various environmental and geographic characteristics of the area being dredged, and e) various institutional and economic factors. Examples of some of these variations follow.

Consider the marked regional variations in maintenance dredging and disposal in the coastal districts of the Corps. As shown in Figure 4, for the Gulf coast districts (Galveston, New Orleans, Mobile, and part of Jacksonville) taken as a whole, roughly three-fourths of the yardage is moved by pipeline dredges and the other fourth by hopper dredges. Along the Atlantic coast, the southern three districts have roughly the same ratio, but the more northern districts have much larger proportions of hopper dredging. The Pacific coast districts vary widely. As presented earlier, pipeline dredges may discharge into open water or unconfined basins, but most hopper dredges discharge at open-water sites near channels in large bays or offshore.

As to types of disposal (see Figure 5), open-water disposal typically accounts for half or more of the yardage for the four Gulf coast districts and in Wilmington, Norfolk, and Baltimore districts. Only in the Savannah, Charleston, and Philadelphia districts does confined disposal account for 50 percent or more of the yardage. Again, on the west coast, the types of disposal vary widely from district to district.

It should be noted that, as used for Figure 5, the term open-water disposal includes disposal in bays, estuaries, and river mouths. Only about 50 to 60 percent of the yardage shown as open-water disposal in Figure 5 actually goes to ocean disposal sites (see discussion of sources and volumes in the preceding section).

According to data presented in a 1970 study of ocean disposal of waste (Smith and Brown, 1971), there were at that time some 160 active disposal sites for dredged material in coastal waters, over 90 percent of which were along the Atlantic and Gulf coasts. This number did not include disposal sites in coastal bays, sounds, or estuaries. Of the 160 sites, 60 percent were located within three miles of the coast in water depths less than 100 ft.

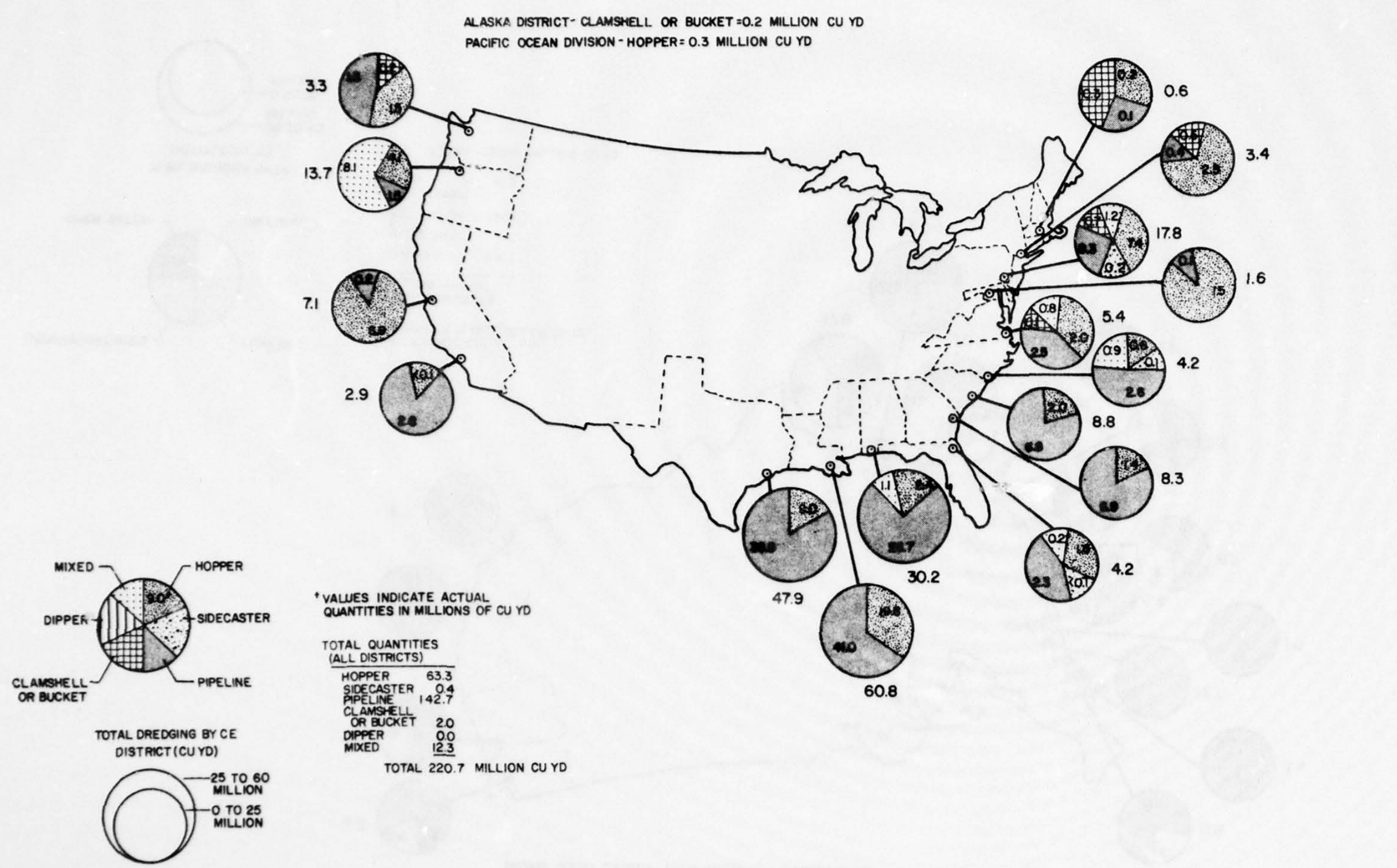


Figure 4. Maintenance dredging volumes in coastal districts by dredge type (modified from Boyd et al., 1972, Figure 1).

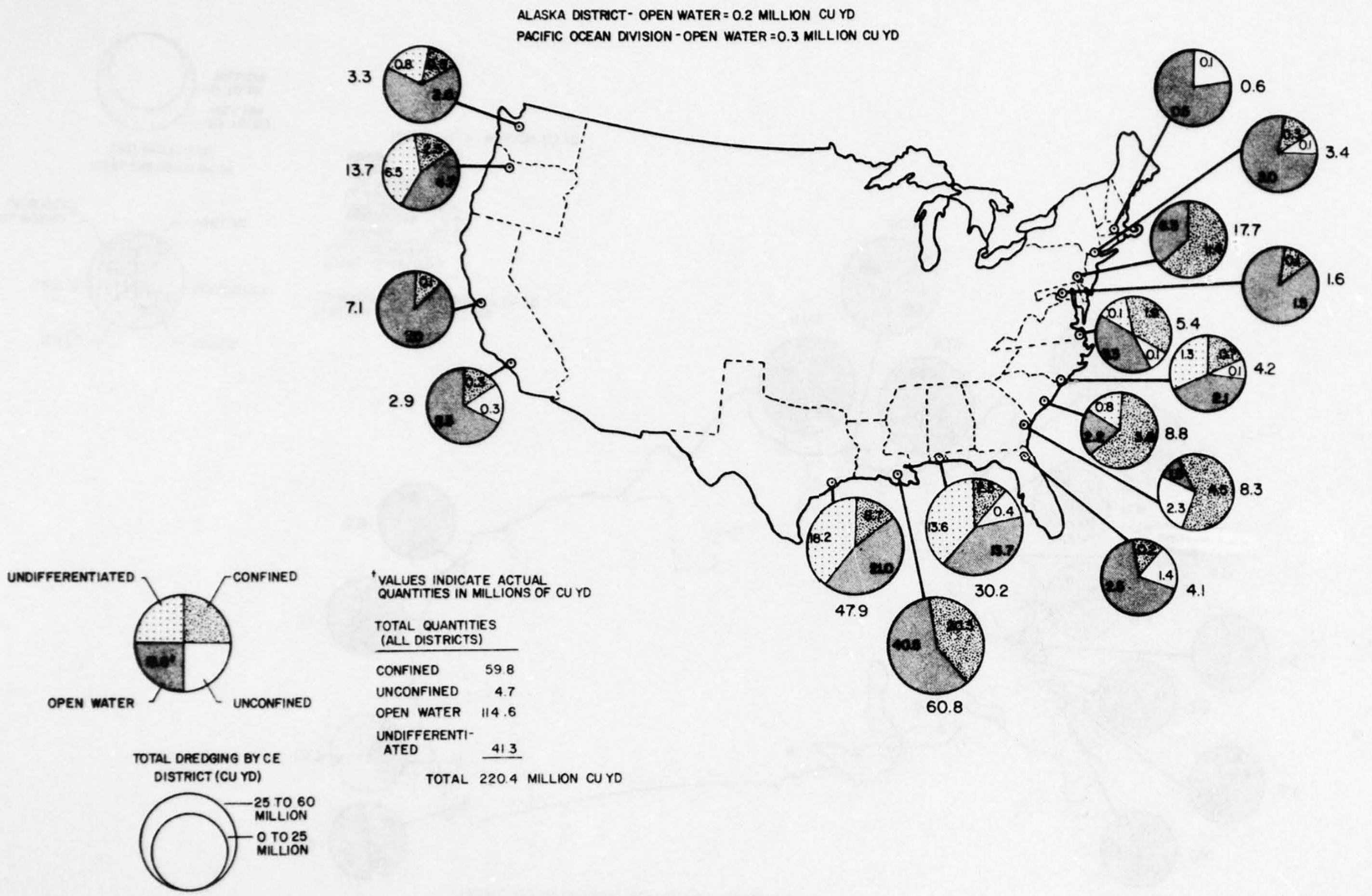


Figure 5. Maintenance dredging volumes in coastal districts by disposal category (modified from Boyd et al., 1972, Figure 2).

As pointed out in Boyd et al. (1972):

> "The principal criterion in the selection of these sites, many of which have been in use for 40 or more years, was disposal costs or economics. Selected locations were usually those closest to the dredging project that offered reasonable assurance that (a) the disposal material would not return directly to the dredged channel, (b) accumulating spoil would not restrict navigation, (c) known fishing grounds would not be destroyed, and (d) spoil would not adversely affect beaches, water intakes, and other coastal facilities. Considerations of environmental impacts seldom were employed in site selection procedures."

The January 1977 Ocean Dumping Regulations and Criteria (U.S. Environmental Protection Agency (1977), contain a list of 127 dredged material disposal sites, many of which are identical to sites listed in the 1970 study by Smith and Brown (1971). The geographic distribution of these sites is summarized in Table 4. Examination of the table shows that the following patterns characterize the distribution of present ocean disposal sites for dredged material.

Although the Gulf coast is the source of about 70 percent of the total volume of dredged material generated by the coastal districts, and accounted for 66 and 50 percent of the total U.S. volume disposed at sea in 1974 and 1975, this coastal area has less than 40 percent of the U.S. ocean disposal sites. The Gulf coast sites clearly receive greater volumes on a per site basis than sites on the Atlantic and Pacific coasts, but this may be offset by the fact that Gulf coast sites tend to be larger in area individually.

The Atlantic coast is the source of about 21 percent of the total dredged material generated by the coastal districts and, in 1974 and 1975, accounted for 19 and 28 percent of the dredged material disposed at sea; it has nearly 30 percent of the ocean disposal sites.

Table 4

Geographic Distribution of Sites Designated for Ocean Disposal of Dredged Material*

Area	Sites Number	%
Gulf Coast	49	38.6
Atlantic Coast	37	29.1
Pacific Coast	30	23.6
Alaska	2	1.6
Hawaii	3	
Pacific Islands	2	7.1
Puerto Rico	4	
	127	100%

*Based on Federal Regulations, January 11, 1977.

Although the Pacific Coast is the source of only 9.5 percent of the total volume generated by the coastal districts, it had about 23.6 percent of the ocean disposal sites and, in 1974 and 1975, discharged from 15 to 22 percent of the total dredged material disposed at sea from the United States.

In proportion to the volumes dredged (a fraction of one percent), Puerto Rico, Hawaii, and Guam together have substantially more sites (seven percent) than other areas.

Based on data from Franks (Personal Communication, Interstate Electronics Corporation, Anaheim, California, 1977), about 60 percent of the sites are within three miles of the coast. According to Musser (Personal Communication, Interstate Electronics Corporation, Anaheim, California, 1977) the balance are all within 12 miles of the coast.

Inspection of bathymetric charts indicates that about 13 (10 percent) of the ocean disposal sites designated for dredged material are at or near the shelf edge. Only these 13 sites can be considered analogues of the potential deepwater ocean disposal sites being examined conceptually in this study.

Examination of charts in EPA's atlas of ocean disposal sites (Interstate Electronics Corporation, 1973) and of unpublished Corps data discloses a broader pattern worthy of note. At the present time, the bulk of the ocean disposal yardage apparently goes to shallow water ocean disposal sites relatively near shore -- this would be expected based on the nature and location of the material dredged and the cost of hauling. Phrased differently, the only yardage taken to sea is that which can be transported conveniently and economically because of the location and manner of dredging. A key exception to this generalization has been dredged material too contaminated for disposal in bays and estuaries. Until recently, such dredged materials (generally small volumes) from coastal projects commonly have been designated for ocean disposal regardless of hauling costs.

In what way are these present patterns of ocean disposal likely to change? This question is addressed in the closing section of this Part.

D. CHARACTERISTICS OF DREDGED MATERIAL

GENERAL

The following sections present a brief, summary description of the characteristics of typical dredged material in four situations: 1) before dredging (in place), 2) during dredging, 3) during transport, and 4) during disposal. Although the characteristics during disposal are of the most direct interest for this report, the characteristics of the material in the three other situations also are of significance.

In general terms, the dredging process hydraulically or mechanically removes in-place material from the bottom and transports it to a discharge point. Depending on the dredging mode used, the effect of dredging on the physical characteristics of the in-place sediment may be large or small. In certain situations, some of the chemical characteristics of the sediment also may be altered.

When examined more closely, it is evident that the dredging process *per se* involves three relatively distinct phases (JBF Scientific Corp., 1975, and Mohr, 1976): a) the dredging phase, b) the transport phase, and c) the disposal phase. A brief description of the characteristics of these phases is incorporated in subsequent paragraphs. Further information on the subject is contained in Herbich (1973), JBF Scientific Corp. (1975), and the references cited therein.

BEFORE DREDGING

For convenience of discussion, the material in place can be considered as a mix of two principal components: solids and water. The solids component typically consists of solid inorganic particles (soils) ranging in size from molecular dimensions up to large rocks and boulders, together with an organic fraction. The soils generally consist of fine- through coarse-grained mineral particles occurring in every conceivable textural arrangement. In addition to the mineral soils, the material commonly contains other solids such as wood and man-made debris (pieces of metal, broken glass, etc.). Additionally, relatively minor amounts of contaminants (heavy metals, pesticides, algal nutrients, oil and grease, etc.) may also be present.

Texturally, the solids constitute the matrix, and the water fills the pore spaces. The amount of water present (i.e., the moisture content) depends on the size, shape, and packing arrangement of the particulate matrix.

According to Boyd et al. (1972),

> "Based on the assessment of the reported materials currently being dredged by the Corps, there is no standard method used to identify and classify dredged ...material. Terms used to identify...[material]... range from the basic terminology (gravel, sand, silt, clay, or combinations thereof) to less descriptive terms such as mud, topsoil, and muck. The basic terminology is derived from the Unified Soil Classification System which is based on the size of the particles, the amounts of the various sizes, and the characteristics of the fine grains. This system provides a standard method of classification and should be used for reporting types of...materials [to be dredged]."

In new work dredging, any type of bottom material occurring in nature may be found -- ranging from hard rock to very soft mud, or any intermediate material. By contrast, in maintenance dredging, the material typically consists of silt, mud, or sand with varying amounts of organic materials, debris, and other foreign materials inter-mixed (Mohr, 1976).

As Boyd et al. (1972) summarize it,

> "[Material] from new work often has appreciably better physical, engineering, and chemical properties than maintenance dredge spoil. Maintenance dredge materials from the coastal zone generally comprise the fine-grained materials such as silt and clay from surface runoff and sludges from municipal and industrial sewage. Consequently, there are probably more environmental problems involved in dredging and disposing of maintenance dredgings."

Some of the more important aspects of the physical and chemical properties of the in-place material are discussed briefly in following sections.

PHYSICAL PROPERTIES

According to Boyd et al. (1972), grain size, moisture content, and plasticity are the important physical properties of the in-place material that affect dredging rates, types of dredging equipment needed, and method of disposal. Grain size is also one of the key factors controlling the amount of turbidity associated with the disposal operation and the rate at which solids settle.

Grain Size

For engineering purposes, material can be divided into three principal types: coarse-grained, fine-grained, and organic materials. The coarse- and fine-grained types can be further divided into descriptive terms on the basis of grain size. According to Boyd et al. (1972), normally it is the fine-grained and organic materials, and not the coarse-grained, which may cause environmental problems relating to dredging.

A summary of quantities of material of different grain sizes excavated by the Corps of Engineers in maintenance dredging work is presented in

Figure 6. The types of material reported by the Corps Divisions were grouped into five related groups as follows:

Group A - Mud, clay, silt, topsoil, shale

Group B - Silt, sand

Group C - Sand, gravel, shell

Group D - Peat, organic muck, sludge, municipal and industrial wastes

Group E - Mixed types

According to Boyd et al. (1972),

> "By far the largest category (approximately 153,000,000 cu yd per year) is that classified as mixed sand and silt [see Figure 6]. About half this value is associated with the coastal areas of the United States, and the other half the inland rivers. ... Of the category including sand, gravel, and shell...22,000,000 cu yd is dredged from the coastal zone. The ill-defined materials mud, clay, silt, topsoil, and shale account for 80,000,000 cu yd per year, all but 8,400,000 cu yd of which are dredged from the eastern one-third of the United States. Finally, although the group including organic muck, sludge, peat, and municipal-industrial wastes accounts for only 1,400,000 cu yd per year, some of the more pressing environmental problems are associated with this group. Generally speaking, ... in lakes, harbors, and many areas of the coastal zone where the carrying capacity of the water is quite low, the dredged materials often consist of small, light particles such as clays and silts. ..."

Moisture Content

Moisture content of in-place material may range from very low in rock, to 25 to 30 percent in sands, to 60 percent and higher in soft soupy muds characteristic of near surface bay floor sediments. The consistency of soils is markedly affected by changes in water content. Normally, the degree of firmness of a fine-grained soil decreases as the water content increases.

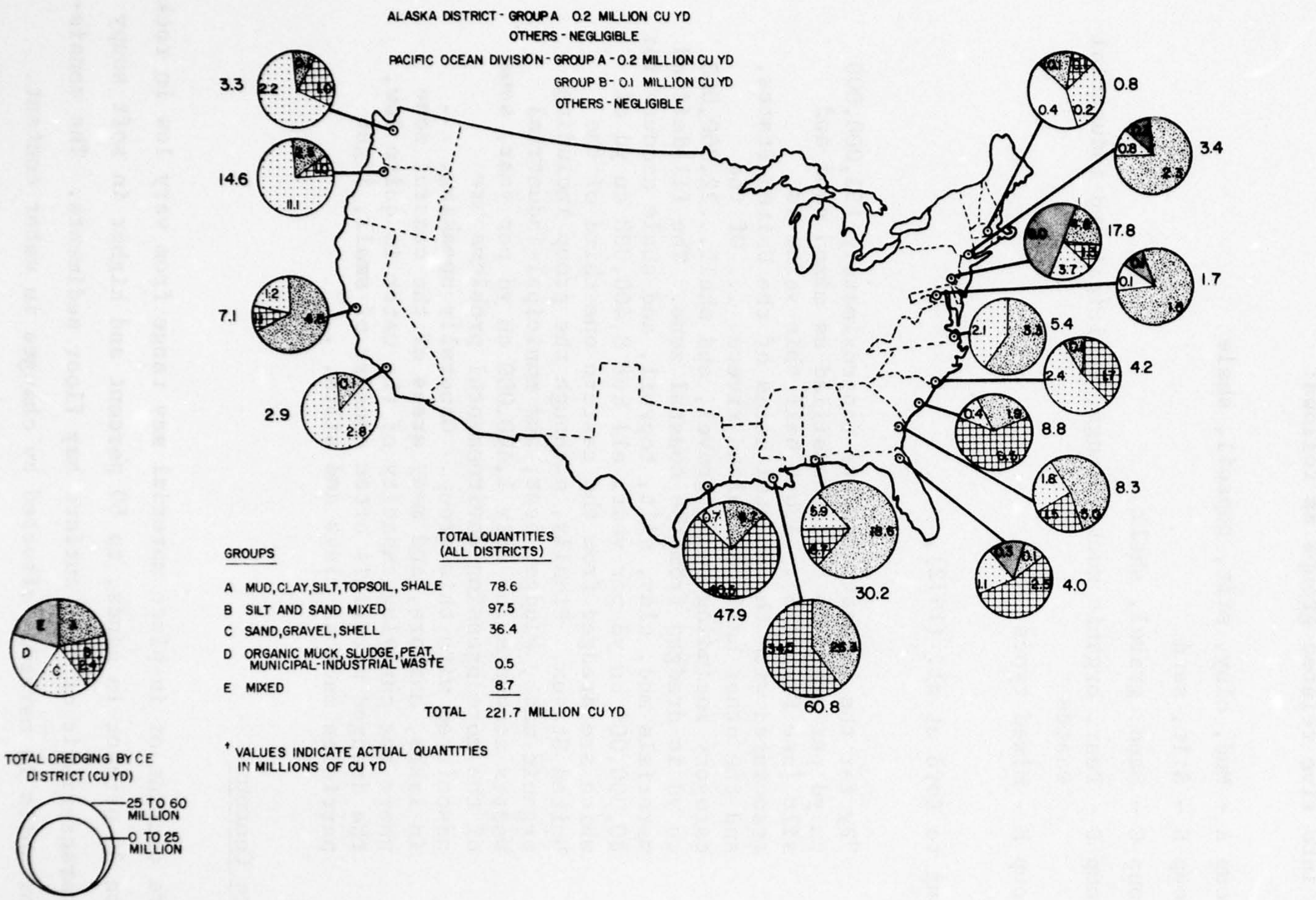


Figure 6. Grain-size classification and volumes of material excavated in maintenance dredging operations in coastal districts (modified from Boyd et al., 1972, Figure 3).

According to Mohr (1976, p. 127):

> "With the exception of rock, the bottom materials in most dredging projects range in density from slightly less than 1,300 g/l to slightly more than 2,000 g/l and occur frequently near both ends of this range. The upper end consists predominantly of sand and the lower end of silt or mud. Since the particle density of all dredged materials varies little from 2,600 g/l, the lighter bottom materials must contain more interstitial water and less solids per unit volume."

As an example, JBF Scientific Corp. (1975) reports *in situ* moisture contents of 124 to 173 percent in fine-grained sediment in the Alameda area of San Francisco Bay.

Organic Content

Organic content of material *in situ* tends to correlate with grain size, the finer the grain size, the higher the organic content. Some sedimentary materials have such high organic contents that they are classed as peat and organic muck. Soils with high organic contents generally have poor engineering properties, in part because of their high water content. When disposed of in open water, organic materials can cause adverse effects such as temporary depletion of dissolved oxygen. This can be accentuated by the presence of reduced inorganic elements such as S^{--}, Mn^{++}, and Fe^{++}.

According to Boyd et al. (1972),

> "The assessment of maintenance dredging according to types of material...[Figure 6] indicates that more than half of the material dredged in the New England Division and Chicago District has a high organic content. All Districts reported the presence of organic materials in maintenance dredging but in most cases, not in large enough quantities to be shown in...[the Figure]."

Other Physical Properties

Plasticity and such soils engineering properties as shear strength, compressibility, and permeability are not discussed in this report.

CHEMICAL CHARACTERISTICS

Bottom deposits (i.e., materials in place before dredging) typically result from suspended material settling from the overlying water body. The factors controlling settlement and deposition are discussed in various references (in particular, see Folger, 1972a and b, and Meade, 1972). In simplest terms, the bulk of the suspended material generally is sediment particles most commonly composed of silicon dioxide (quartz) and of complex, layered silicates (the clays). Therefore, the chemical characteristics of the in-place bottom sediments should be those of these mineral components, and other materials contributed to the sediment mass, in combination with the chemistry of the pore waters and the dynamics of the sediment-water system. Thus, the chemical characteristics of the in-place material depends upon the complex interaction of a number of factors as is lucidly summarized below for Chesapeake Bay sediments by Bricker and Troup (1975):

> "Estuaries are complex systems which receive chemical inputs from a variety of different sources [Figure 7]. River run-off contributes dissolved species derived from chemical weathering of rocks in the watershed, suspended material from mechanical weathering of terrigenous matter, and dissolved and particulate organic material of biogenic origin. The influx of sea water provides a strong electrolyte solution of nearly constant relative composition with respect to the major ions Ca^{++}, Mg^{++}, Na^{+}, K^{+}, Cl^{-}, and SO_4^{+}, dissolved and particulate organic material, and suspended sediment. Superimposed on the natural sources are inputs resulting from the activities of man.

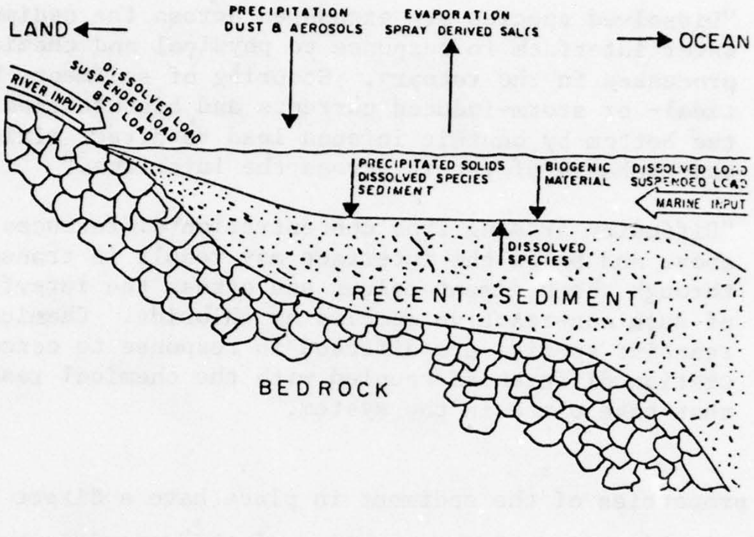


Figure 7. Exchanges of matter in an idealized estuarine system. Reproduced from Bricker and Troup (1975).

> "The estuary is an open system in which the inputs are balanced by outputs in the form of flow through the system and sinks within the system. Some of the more soluble elements pass through the estuary to the ocean essentially unchanged, whereas others combine and precipitate as solid phases or settle to the bottom sorbed on particulate matter to be stored in the sediment reservoir. ..."
>
> "The least understood component of the system is the influence that sediment reservoir has on the chemistry of estuarine waters. The sediment and its contained pore waters may be either a source of dissolved species or a sink for them, depending upon the reactions that take place between pore fluids and sediment and the direction of transfer of material across the sediment-water interface."
>
> "...In the Chesapeake Bay diagenetic reactions in the pore water-sediment environment result in many dissolved species being enriched by one or more orders of magnitude above that of their concentrations in the overlying water. Rapid exchange between overlying water and the upper part of the sediment column lends to the establishment of strong gradients in dissolved species extending to depths of at least 30 cm beneath the sediment-water interface."

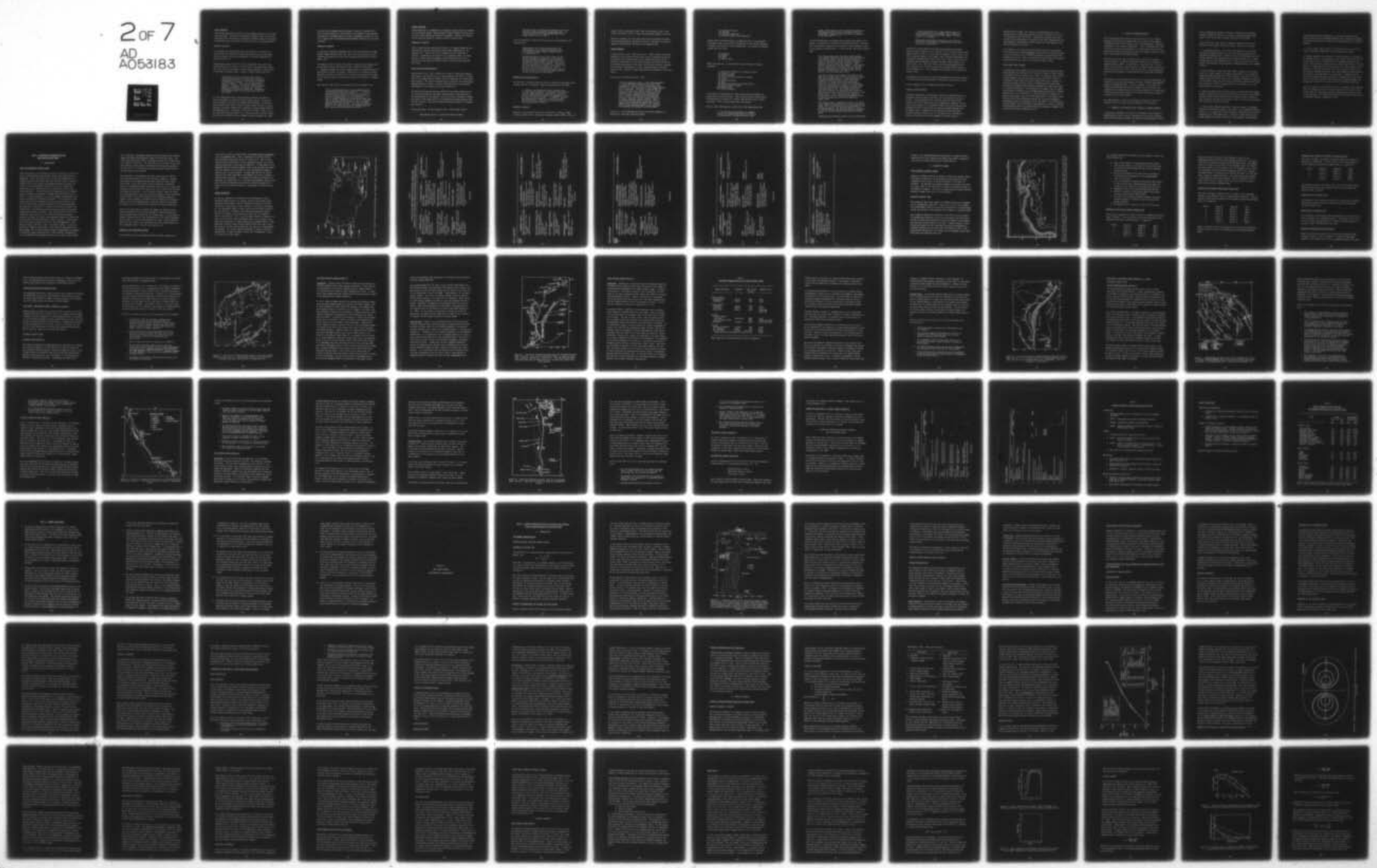
> "Dissolved species are exchanged across the sediment-water interface in response to physical and chemical processes in the estuary. Scouring of sediments by tidal- or storm-induced currents and bioturbation of the bottom by benthic infauna lead to direct mixing and exchange of waters across the interface."
>
> "Diffusion arising from concentration differences above and below the interface may result in transport through the sediment column and across the interface of such non-reactive species as chloride. Chemically reactive species are diffused in response to concentration differences coupled with the chemical reactions that take place in the system."

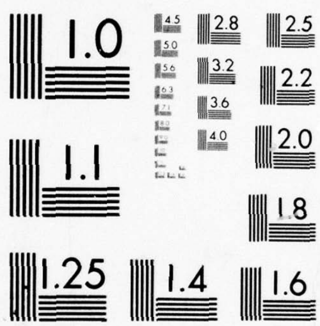
Chemical properties of the sediment in place have a direct bearing on the physical and engineering properties of the material when dredged (Boyd et al., 1972). For example, each of the clay mineral groups (kaolinites, illites, and montmorillonites) has different behavioral characteristics that affect the behavior of dredged material and the uptake and release of contaminants.

As pointed out in Boyd et al. (1972), the amount of technical literature dealing with the physical and chemical composition of coastal and offshore sediment, as well as with distribution, texture, origin, age, movement, and related considerations is enormous. Thus, it is not surprising that there is no convenient summary of chemical properties of bottom sediments that is particularly pertinent to dredging. Lacking a convenient summary, the reader is referred to the more fundamental or comprehensive books and papers dealing with the chemical characteristics of coastal and marine sediments. Some of these include: Ott (1970); Berner (1971); Windom (1972, 1973, 1976a); Duchert, Calvert, and Price (1973); Lee and Plumb (1974); Bricker and Troup (1975); Thompson et al. (1975); Brannon et al. (1976); Chen et al. (1976a); and Gambrell et al. (1976a and b).

AD-A053 183 TERECO CORP COLLEGE STATION TX F/G 13/2
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)
JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL DACW39-76-C-0125
UNCLASSIFIED WES-TR-D-78-2 NL

2 OF 7
AD
A053183





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DURING DREDGING

This section addresses the effects of the dredging operation on the materials excavated. The effects of hydraulic dredging, which are much more significant than the effects of mechanical dredging because of the degree of disturbance and the addition of dilution water, are discussed first.

HYDRAULIC DREDGING

In the hydraulic dredging operation, the material is saturated to a liquid state, the structure is destroyed as particles are rearranged, and oils, grease, and other contaminants in the water sometimes are mixed with the soil.

Hydraulically dredged materials contain considerably more water than solids and exist as a slurry. It is because of the high water content that this slurry can be pumped readily through pipelines to hopper bins or directly to disposal areas. However, as Mohr (1976) points out:

> "The addition of [this] dilution water tends to process the material. This processing consists of segregating the material by grain size and washing out fines and pollutants. ...soils vary little in particle density. ...when they are hydraulically dredged, ...(adding up to several 100% of diluting water) the turbulence associated with hydraulic dredging will separate the particles. Subsequently, the coarser particles will settle faster than the finer ones."

In soils engineering terms, during hydraulic dredging the moisture content increases to as much as several hundred percent, the percent solids decreases, and the shear strength drops markedly. According to JBF Scientific Corp. (1975), "There is every indication that the shear strength in material dredged with a pipeline or hopper dredge should be approximately zero." According to JBF Scientific Corp. (1975), it is not clear which soils parameter (i.e., percent moisture, percent solids, dry density, wet density, shear strength, bearing strength, etc.) best describes those dredging induced changes in physical characteristics that are most important to the behavior of the material during dumping. The behavior of dredged material in these circumstances appears to fall into a region that is interdisciplinary between classical soil and fluid mechanics.

MECHANICAL DREDGING

In contrast to hydraulic dredging, when soils are mechanically dredged without adding dilution water, the bulk of the soil particles are not separated and generally retain their _in situ_ distribution and texture (Mohr, 1976).

For example, based on studies of clamshell dredging in the Alameda area of San Francisco Bay, JBF Scientific Corp. (1975) concluded that "...clamshell dredges can recover dredged material at approximately the same moisture content as _in situ_." Specifically, the moisture content measured in material in place on the bottom was approximately the same as the moisture content in the material placed in a barge by a clamshell dredge.

JBF Scientific Corp. (1975) also found that for the Alameda study,

> "Shear strength measurements in the dredged material were highly variable in the clamshell... . Since the _in situ_ values of moisture content are close to, or above, the liquid limits for the materials measured, the shear strength must be low by definition. ... With a clamshell dredge, the values should range from zero to _in situ_, depending upon the way the clamshell obtains and releases the material. Shear strengths generally were under 100 psf. Shear strength does not appear to be a good descriptor for dredged materials due to their relatively high water content. ..."

DURING TRANSPORT

Dredged material is transported to a disposal location either by mechanical or hydraulic means. Hopper dredge or barge transfer of material are the most common mechanical methods of transport. Delivery via pipeline is the principal hydraulic transport method currently used.

MECHANICAL TRANSPORT

After a barge has been mechanically filled, or a hopper dredge has been hydraulically filled, the disposal vessel moves immediately to the disposal site. Travel time to the disposal site is a function of distance. Depending on the width of the continental shelf and other factors, transit time for deepwater ocean disposal may vary from a fraction of a day along the Pacific coast to a day or more along the Gulf coast.

Hydraulically Dredged Material

JBF Scientific Corp. (1975) carried out a study of open-water disposal operations in San Francisco Bay to examine whether the effects of transport of the dredged material might alter the dispersion of the materials when disposed. The effects considered were compaction and consolidation during transit as a result of static conditions (time in the hoppers) and dynamic factors (vessel motions and vibrations).

The JBF study found that moisture content in the hopper dredge was low in the lower portions of the hopper and exhibited a steep gradient in the upper portion of the hoppers. At one of the two localities studied, the values in the lower portion of the hoppers approached in situ value for that locality. The actual condition observed, however, is strongly site specific.

More specifically, the JBF Scientific Corp. (1975) report states:

"The hoppers appear to contain two discrete layers.

> "The bottom layer is relatively homogeneous and of low moisture content approaching the <u>in situ</u> value. On top of this layer is a high gradient layer which slowly settles out over time."

As to the effects of time and of vessel motions and vibrations, JBF reported that:

> "Measurements over 24 hours demonstrated that thixotrophy is not an important parameter over the time periods that dredges normally transit to a disposed area."
>
> "Vibrations appear to have little effect on the moisture content of the material in the hoppers but ship maneuvering appears to cause shifting of the material which releases pockets of water and results in settling of the material. Settling of the high gradient upper volume of the hopper takes place but this effect requires time. Over a period of one hour after dredging ceases, this can add several feet of low moisture content material to that in the bottom of the hopper."

Mechanically Dredged Material

The JBF work at Alameda showed the moisture content found in situ and in a barge filled by a clamshell dredge were approximately the same.

> "...However, the variability within a barge pocket is quite high and depends on the degree of disturbance that the dredge imparts to the material. Moisture content within the barge pockets is dependent on the way that the barge is filled. ...In general, [however], the mean moisture content for a total barge load when filled with a clamshell can be quite close to the in situ moisture content."

HYDRAULIC TRANSPORT

Transport of solid/liquid slurrys via pipeline is a complex, highly technical subject that is described at length in Nardi (1959), Zandi and

Govatos (1967), Weidenroth (1968), Bain and Bonnington (1970), Shen (1970), and Herbich (1975) to which the interested reader is referred.

Because of pumping costs and rough water-caused operational problems with floating pipelines, pipeline transport is unlikely to be used for deepwater ocean disposal and thus is not addressed here.

DURING DISPOSAL

As JBF Scientific Corp. (1975) points out: "There is very little data available in the literature which can be used to quantify the hypothesized behavior of dredged material when disposed of in open water." Laboratory simulations of bottom dump disposal operations carried out by JBF under sponsorship of the Corps' San Francisco District examined the dispersion and mounding of typical dredged materials from San Francisco Bay. Details of these simulations are presented in the cited report.

According to JBF Scientific Corp. (1975):

> "The most important factors...[affecting] dispersion ...and the subsequent potential for erosion and resuspension...[are] the size distribution of the particles and the bulk density of the dredged material. Size is important...[because] it affects both the particle settling rate and the degree of cohesion among particles. Bulk density...determines the rate of descent immediately following the dump and is a function of the density of individual particles, the water content, and the proportion of lighter materials such as organics. Water content and cohesion affect the behavior of the dumped material during the descent and collapse phase by controlling the growth of the cloud and the spreading rate during the collapse phase."

Clark et al. (1971) describe the total post-release transport as divided into four basic transport phases:

(1) Convection descent
(2) Collapse
(3) Long-term dispersion
(4) Bottom transport and resuspension

Gordon (1977) studied placement of dredged material at six different ocean waste sites, using acoustic reflections in the 200 kHz frequency to observe the descent of the discharged mass. He divides the disposal process into four steps:

(1) Insertion
(2) Descent
(3) Impact
(4) Bottom surge

These four steps are in turn dependent upon some eleven "process variables":

(1) Mechanical properties of dredged material
(2) Insertion speed
(3) Volume released
(4) Solids fraction in material released
(5) Current
(6) Density gradients
(7) Depth
(8) Impact properties of clods and bottom
(9) Bottom erosion strength
(10) Bottom slope
(11) Bottom roughness

A discussion of these phases or steps and the process variables is beyond the scope of this report. The interested reader should consult the discussions in Clark et al. (1971), JBF Scientific Corp. (1975), and Gordon (1977), and the references cited therein.

The test tank investigations carried out by JBF demonstrated that:

> "...the physical characteristics of dredged material are highly significant as related to the dispersion of the material when bottom

dumped. There appears to be a significant difference in parameters such as descent and impact velocity, cloud radius, mounding, and bottom flow as a function of moisture content. ..."

In the JBF simulation, the descent phase showed three distinct sub-phases: an acceleration sub-phase, an equilibrium velocity sub-phase, and a deceleration sub-phase, the duration of which depended in part on the material characteristics. In this context, JBF (1975) reported that:

"The collapse phase and bottom flow phase appeared to be highly dependent on the material characteristics. Low moisture content resulted in mounding directly under the dump point, little horizontal transport of material, and low bottom flow velocities. High moisture content was just the opposite. There appears to be a transition zone between these two extremes and its size appears to be related to the material physical characteristics, the dump volume, and the depth in which the dump takes place."

"The size (volume) of the dump and the depth of the water that it takes place in have a significant effect upon the dispersion pattern. Volume and depth are intimately related and may be scaled under many conditions of interest using the Froude number. While the effects are also related to the moisture content of the material, it appears as though descent velocities increase and entrainment decreases with increasing dump volume. The average bottom flow velocities increase with increasing dump volume, as does the percentage of material in the vicinity of the impact point. ... For a given volume, dumping in shallow water results in a smaller dispersion pattern on the bottom than is achieved when dumping in deeper water."

"For materials with...[moisture content] in the solid range, dumps are characterized by a very rapid descent phase, little cloud growth and little spreading of the material on impact. The material falls as a block, at equilibrium velocity, and entrainment is negligible. Most of the material mounds directly under the dump point.

"[Materials with moisture contents in] the liquid phase

...[are] characterized by a slower descent phase, the cloud expanding due to entrainment, and a rapid flow of material across the bottom after impact. There is little, or no mounding."

"[Materials with moisture contents in] the transition phase [are] characterized by conditions that vary from the solid to liquid phase."

Various field investigations and monitoring programs for dredged material disposal operations are reported in the literature (Great Lakes Research Center, 1968; U.S. Army Corps of Engineers, 1969; Cronin et al., 1970; Ecker and Sustar, 1972; Gordon, 1974; National Oceanographic and Atmospheric Administration, 1976; Proni et al., 1976) as are studies of disposal sites subsequent to disposal (Harrison, 1967; Gordon et al., 1972; Saila et al., 1972; May, 1973; U.S. Navy Oceanographic Office, 1973; Slotta et al., 1973; U.S. Army Corps of Engineers-San Francisco, 1975; Thompson et al., 1975; Yamamoto and Alcauskas, 1975; Wilkins and Persuad, 1976).

A comparison of the results of these investigations with the JBF laboratory simulation work just described is beyond the scope of this report.

A brief synopsis of two representative studies follows:

FARALLON ISLAND DISPOSAL

Literature discussing truly deepwater disposal of dredged material is extremely limited in amount and scope, but two studies are worthy of mention. During September 1974, the Naval Undersea Center (under contract with the San Francisco Corps of Engineers) conducted a field study of the impacts of the disposal of 4000 cu yd of San Francisco Bay sediments in 183 m of water near the Farallon Islands (Yamamoto and Alcauskas, 1975). Compaction of the material in the hopper bins occurred during the 35-mile trip to the disposal site, probably as a function of time for the buried sediments to hydrate (water of imbibition) and expand. As a result of consolidation much of the material fell in clumps and covered only about 26 percent of the area of the disposal site (11,500 m^2). Although the affected areas were covered to an average depth of one-third m and some organisms must have been smothered, photographic evidence shows very little damage to the bottom communities as a whole.

It is important to point out that some photos taken at the disposal site show fish of the genus _Sebastes_; these would be strongly attracted to any structuring of the otherwise featureless and unstructured environment at the site. There is no doubt that such clumps could increase sports fishing in the area by structuring the water column.

PORT ALLEN, KAUAI DISPOSAL

A potentially more valuable but far less satisfactorily monitored deep-water disposal was carried out off Port Allen, Island of Kauai, Hawaii, in November 1972 (R.M. Towill Corp., 1972). The disposal site was only 3 miles offshore, but the water depth varied from 1275 to 1640 m or from seven to nine times the depth of the Farallon site. Because of repeated equipment failures the best estimates derived from bottom deposition of sediment were derived by mathematical computations based on limited observations. It was deduced, for example, that the cumulative release of 250,000 cu yd of dredged material resulted in a maximum deposition of $4.25 \times 10^{-3} g/cm^2$ (ca. 0.002 cm thick) of sediment at a distance beginning no less than 20 km downcurrent of the disposal site. This is all the more interesting because the calculated geological sedimentation rate is estimated to be on the order of $4 \times 10^{-4} g/cm^2/yr$. If these figures are any reasonable approximation of reality, then deep ocean disposal would not be adding significant amounts of sediment over and above the normal sedimentation rate.

E. CLASSES OF DREDGED MATERIAL

One of the intended objectives of this Part was to set up a simple, working classification of dredged material in terms of, for example, contaminant content, with classes such as "uncontaminated," "moderately contaminated," and "highly contaminated." Such a classification could facilitate reference and discussion in following Parts of this report, particularly those addressing the various environmental aspects of deep-water ocean disposal of dredged material.

The logical basis for such a classification and thus for disposal classes should be the Federal regulations governing ocean disposal of dredged material, namely, "Ocean Dumping - Regulations and Criteria" (Title 40 CFR Chapter I, Sub-chapter H), the final revision of which was issued in January 1977 by EPA. (The key sections of these Regulations and Criteria pertaining to dredged material are reproduced in Appendix B).

Unfortunately, the complexity and scope of the pertinent Regulations and Criteria do not permit establishment of simple, readily distinguishable classes of dredged material. As will be evident to the reader who reviews the Regulations set forth in Appendix B, the decision as to acceptability of dredged material for ocean disposal is to be made using a multi-part evaluative process that includes a hierarchical sequence of chemical tests and bioassays.

For these reasons, it was not practicable to establish a series of disposal classes for ready reference elsewhere in this report.

F. POTENTIAL FOR DEEPWATER OCEAN DISPOSAL OF DREDGED MATERIAL

A substantive assessment of potential for deepwater ocean disposal of dredged material would require a comprehensive multi-factor analysis that carefully examined a number of important non-environmental factors such as dredging and transport economics, modification in existing dredging technology, and use of alternative disposal methods, among others. Such an analysis is beyond the scope of this study.

On the other hand, some intuitive insights regarding potential for deepwater ocean disposal seem worth noting. These are as follows:

1. As presented earlier, of the 127 ocean disposal sites currently authorized for dredged material by EPA, only 13 (10 percent) can be considered deepwater sites. Further, of the 90 to 100 million cu yd of dredged material being discharged in the ocean annually, only a small fraction goes to these deepwater sites. Thus, it is clear that at the present time deepwater ocean disposal of dredged material is an uncommon practice.

2. Haul distances to deep water (shelf edge or beyond) for the three major U.S. coastal regions are roughly proportional to the volumes of dredged material generated in the three regions: deep water is close inshore along the Pacific coast, is at intermediate distances along much of the Atlantic coast, and is as much as 120 miles offshore in the Gulf. Thus, where the volumes of dredged material are greatest, so are the haul distances to deep water.

3. Based on probable haul distance alone, it would appear that dredged material disposal in deep water would be most attractive off the Pacific islands, and next most attractive off the Pacific coast; it would be less attractive off much of the Atlantic coast, and with some exceptions least attractive off the Gulf coast.

4. Given present dredging technology, pipeline transport of dredged material from hydraulic dredges to deep water is not considered feasible because of: a) rough water-caused operational problems with the surface pipeline, and b) the pumping costs. Further, it seems doubtful that hopper dredges can operate efficiently using deepwater ocean disposal

sites because the time-consuming run to and from deep water would substantially reduce the yardage dredged per day. Barging is considered the most likely means of transport of dredged material for deepwater disposal.

5. At the present time, however, less than one percent of the total volume of material dredged each year is transported by barge.

In summary, deepwater ocean disposal of dredged material at present is an uncommon practice, and accounts for only a small fraction of the 90 to 100 million cu yd of dredged material discharged annually in the ocean. Haul distances to deep water are roughly proportional to dredged material volumes generated along the major U.S. coastal regions, with distances to deep water along the Gulf coast generally the greatest. With present dredging technology, only barge transport appears feasible for delivery of dredged material to deep water. Yardage costs for mechanical dredging and barge transport of dredged material are three to five times more expensive than hydraulically dredged yardage, even though most delivery is to relatively close-in shallow water sites.

For these reasons, it would appear that use of deepwater ocean disposal sites for dredged material will remain minimal for some time to come unless either a) technological advances substantially reduce the cost of such disposal, or b) tightening regulatory constraints force the use of deepwater disposal, regardless of cost.

PART 3. SELECTION OF FAVORABLE AND POOR DEEP OCEAN DISPOSAL AREAS

A. INTRODUCTION

NEED FOR ALTERNATIVE DISPOSAL AREAS

Before delving into the principal objective of this part of Section A, that of selecting deep ocean disposal areas, three points must be emphasized. First, this report does not advocate disposing of all dredged material in the deep ocean, now or in the future. Rather, it predicts that it will become increasingly difficult to acquire and continue to use conventional disposal sites in the Coastal Zone, whether they are in upland areas or in estuaries or on the inner continental shelf. This problem will be aggravated by the estimated future increases in the amount of dredged material produced in U.S. waters. A viable alternative to the increasingly unsatisfactory disposal operations will eventually be needed. It is concluded in this report that deep ocean disposal sites will meet this need and that their use will impose only minor stresses on deep ocean ecosystems. The importance of this point is underscored by marine biologists who believe that our productive estuaries should be spared from as much human-related stress as possible. Also, selected parts of the inner continental shelf adjacent to the estuaries should be preserved because, as pointed out earlier, many important species of finfish and shellfish must have both habitats in order to survive. Unfortunately, most of the major estuaries of the U.S. have been degraded to some degree by human action (U.S. Dept. of Interior, 1970b). In fact, 23 percent are judged by authorities to have suffered substantial ecological damage, and 50 percent moderate damage, principally by containing low dissolved oxygen concentrations or high bacterial contamination. It is not implied that dredging has caused all or most of this damage, but it has been a contributor because it does influence both dissolved oxygen and bacterial populations, albeit for short time spans. The outer continental shelf offers a reasonable alternative in some places, but in others it does not. For instance, the outer shelf of the southeast Atlantic region supports small fisheries of nominal importance, but the outer shelf off western Louisiana and Texas supports part of the great brown shrimp fishery.

The second point is an admission that this report may be viewed by some as being visionary or, at the very least, premature. Perhaps the authors can be charged with discussing solutions before needs have arisen. But on this latter point we encounter a dichotomy. There are knowledgeable people who believe that the need for deep-ocean disposal is here and that the time is not far off when it will be used more generally than now. In all fairness it must be said that there are others who counter that such a position ignores economic realities. In this context it can only be hoped that as dredging techniques improve, such as making it possible by direct pumping into sea-going barges to free the dredging vessel of whatever type from also being the hauler, the cost of deep-ocean disposal will become competitive.

Finally, the third point is simply that areas, not specific sites, deemed satisfactory for deep-ocean disposal of dredged material are being delineated and described in the ensuing pages. The selecting of specific disposal sites is the responsibility of the District Engineer and his staff. To do this intelligently one needs to know something about the ocean itself, how its systems work, and something about its most vulnerable facet -- the life that exists in it.

SOURCES OF SITE SELECTION CRITERIA

For those who are not conversant with these concepts, Section B of this report contains an authoritative description of the oceanography of the recommended areas. Also, a discussion of criteria used in area selection is presented in Part 5 of Section B. Some of these criteria will be appropriate for site selection as well, but in most cases more detailed criteria may be called for. In this event, it is suggested that the District Engineer refer to the criteria for selecting waste disposal sites discussed in the 1976 National Academy of Science study of ocean disposal. In some cases the use of locally generated and often unpublished environmental data may be valuable in reaching final decisions. If it appears that extant information is inadequate for preparation of an acceptable Environmental Impact Statement, the District Engineer may authorize carefully designed field studies that will yield information to supplement the deficient data base.

SECTOR DEFINITION

In order to regularize the delineation and description of these potential disposal areas, the coastal reaches of the United States, including Alaska, Hawaii, and the Caribbean possessions, have been divided into eleven spatial units referred to as sectors (see Figure 8). The geographic limits of these sectors are not wholly arbitrary. In fact, there is a unifying concurrence among Geomorphic Regions, Circulation Regimes, and Biological Provinces and the designated sectors (see Table 5). Thus, any given sector should be thought of as a part of the Coastal Zone, continental shelf, and contiguous slope whose land boundaries are marked primarily by prominent capes or other geomorphic features, whose current regime differs from that of adjacent sectors, and the biota of which has the status of a biogeographical province. For a more complete discussion of sectors and their incorporation of Corps Districts, turn to the "Introduction" of Part 5 of Section B of this report.

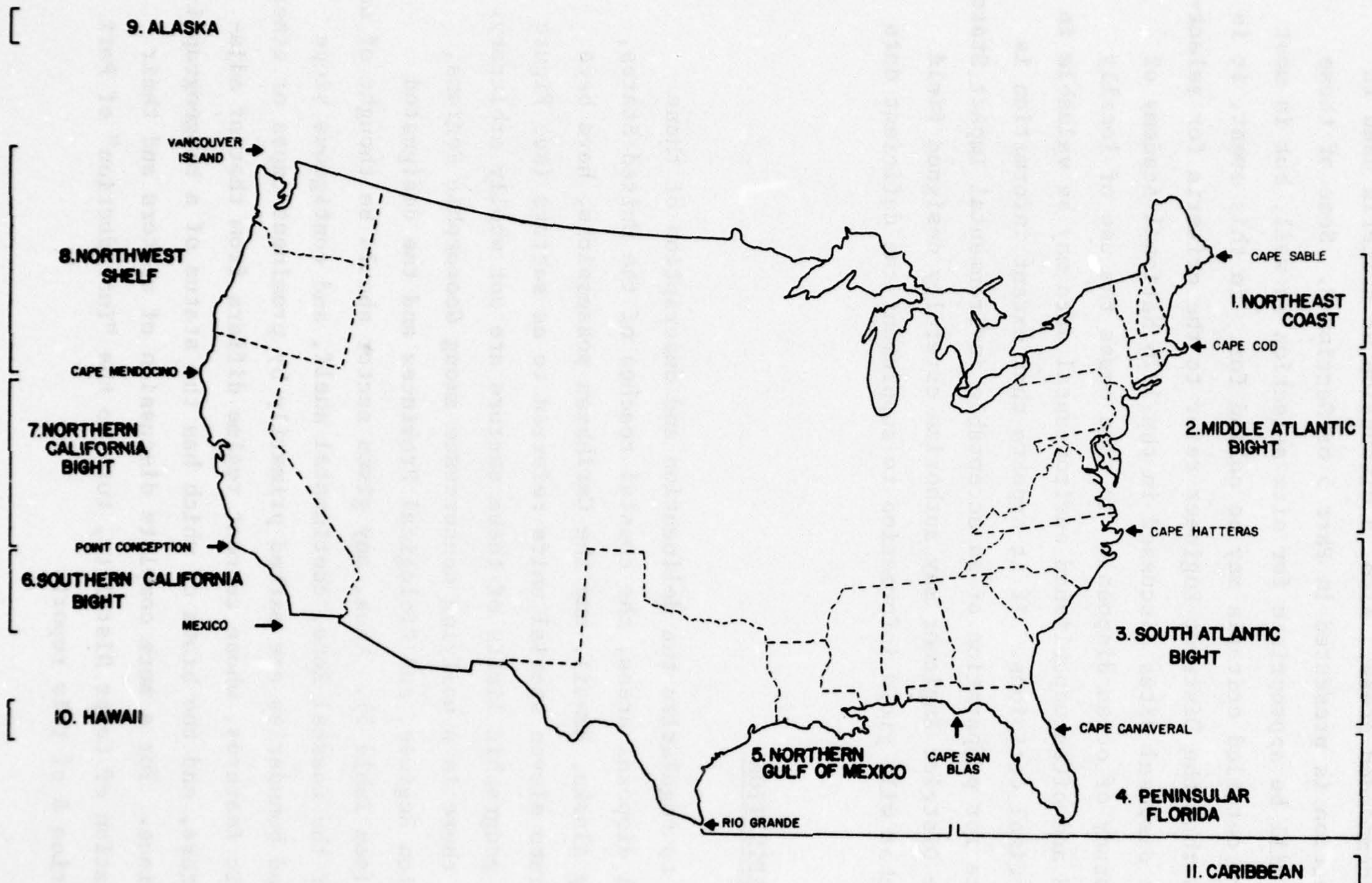


Figure 8. Sectors of the United States showing their geographic limits and geomorphic regions.

Table 5

Sectors of the United States and Territories, Showing their Geographic Limits, Geomorphic, Physical, and Biological Characterizations

SECTOR NUMBER	GEOMORPHIC REGIONS	CIRCULATION REGIMES	BIOLOGICAL PROVINCES
1.	Cape Sable to Cape Cod	Gulf of Maine	Arcadian
	Rocky glaciated shoreland and submarine topography Deep basins and broad banks Steep slopes Very wide shelf	Seasonal counterclockwise eddy Southern limb of this eddy conforms to a clockwise eddy over Georges Bank Slope water moves into Gulf through Northeast Channel	Biota is generally boreal
2.	Cape Cod to Cape Hatteras	Middle Atlantic Bight	Virginian
	Lowland streams, coastal marshes, and muddy bottoms increasing Shelf smooth and wide Slopes dissected by many canyons	Inshore flow generally southerly but may become northerly in summer Offshore drift of waters south of 37°N Bottom water moves southwest	Biota primarily temperate with some boreal species
3.	Cape Hatteras to Cape Canaveral	South Atlantic Bight	Carolinian
	Extensive marshes and cypress swamps, muddy bottoms very important. Shelf narrowing Slope has steps Blake Plateau	Tendency toward a slow southerly drift over the inner shelf with intrusions of Florida Current waters Slow northerly drift on outer shelf	Inshore biota is temperate with some subtropical forms Offshore it is tropical

(Continued)

Table 5 (Continued)

SECTOR NUMBER	GEOMORPHIC REGIONS	CIRCULATION REGIMES	BIOLOGICAL PROVINCES
4.	<u>Cape Canaveral to Dry Tortugas</u> Trend toward very narrow shelves Florida Straits Channel	<u>East Florida Shelf</u> Summer upwelling on the northeast Florida Shelf To the south, the flow is dominated by the Florida Current and the Gulf Stream	<u>Floridian</u> (Canaveral to Tampa Bay)
	<u>Dry Tortugas to Cape San Blas</u> Carbonate rocks prominent Coral reefs extensive in the southern part Wide shelf Steep escarpment	<u>West Florida Shelf</u> Generally northerly drift inshore Locally affected by winds Major influence is the East Gulf Loop Current	Peninsular Florida Biota tropical and subtropical Sea grass beds common
5.	<u>Cape San Blas to Mississippi Delta</u> End of carbonates at DeSoto Canyon and beginning of quartz sediments Smooth slope	<u>MAFLA Shelf</u> General westward flow inshore but strong southwest flow in winter Strong influence of Loop Current from April-October	<u>Louisianian</u>
	<u>Mississippi Delta to Rio Grande</u> Muddy (silty clays) sediments Wide Shelf Mississippi Trough	<u>Texas Shelf</u> Predominant westward flow Generally a short reversal in June-July	Tampa Bay to Rio Grande Biota similar to Carolinian but more tropical elements

(Continued)

Table 5 (Continued)

SECTOR NUMBER	GEOMORPHIC REGIONS	CIRCULATION REGIMES	BIOLOGICAL PROVINCES
6.	<u>Punta Eugenia to Pt. Conception</u> Shoreland generally mountainous General absence of marshes, swamps, and calcareous bottoms Shelf narrows Troughs, basins, banks, and offshore islands Canyons common	<u>Southern California Bight</u> Southward moving California current well offshore Northwest flowing countercurrent Countercurrent either joins Davidson Current (winter) or turns southeast completing the Southern California Eddy North flowing undercurrent (150-800 m)	<u>Californian</u> Biota tends toward tropical Some kelp beds
7.	<u>Pt. Conception to Cape Mendocino</u> Shoreland predominantly mountainous Shelf widens but still narrow compared to Gulf and parts of East coast Steep slope Large stretches without canyons	<u>Northern California Shelf</u> Southward moving California Current 0.2 kt. Northward moving Davidson Current (Nov.-Feb.) Upwelling from late winter to late summer	

(Continued)

Table 5 (Continued)

SECTOR NUMBER	GEOMORPHIC REGIONS	CIRCULATION REGIMES	BIOLOGICAL PROVINCES
8.	Cape Mendocino to Vancouver Island	Northwest Shelf	Columbian
	Rocky coast common Puget Sound a major feature Submarine canyons common	Weak and ill-defined surface currents California Current far to sea Davidson inshore: north in winter; south in summer On Washington coast downwelling in winter and upwelling in summer	Extensive kelp beds, especially in the southern part
9.	Alaska	Gulf of Alaska	Aleutian
	Fiords common Wide shelf to southern Alaska, but narrows toward the Aleutians Slope steepens toward Aleutian Chain	Dominated by the Gulf of Alaska Gyre, the northern branch of the west wind drift crossing the Pacific	Boreal and polar biota
10.	Hawaii	Hawaiian Islands	Pacific
	Volcanic and carbonates Narrow insular shelves Coral reefs	Circulation tends to be dominated by tidal currents Local and submarine topography and winds important	Insular Tropical

(Continued)

Table 5 (Concluded)

SECTOR NUMBER	GEOMORPHIC REGIONS	CIRCULATION REGIMES	BIOLOGICAL PROVINCES
11.	Virgin Islands and Puerto Rico	Caribbean	Tropical (Caribbean)
	Shoreland low-lying (karst) limestone varying to mountainous but distinctly calcareous	Flow predominantly to the northwest throughout the year	Biota tropical
	Foreshore and seabed with calcareous marls, sands, and coral reefs	Inshore flow follows isobaths	

Because of the disproportionately large amount of dredged material produced in the Gulf of Mexico, the authors have opted to begin the area selection process with the Gulf's three sectors.

B. SELECTION OF AREAS

GULF OF MEXICO (SECTORS 4 AND 5)

Disposal of dredged material in the Gulf of Mexico was started around 1926 and has continued up to the present and now constitutes some 43,800,000 cu yd per year (or about 50 percent of the total U.S. disposal). The material was normally disposed of in waters less than 30 m deep. Most of this disposal is carried out by hopper dredges or occasionally by barges. The trend in dredged material volumes produced annually is upward (see Part 2 of this section).

FAVORABLE DISPOSAL AREAS

Three areas for deep ocean disposal of dredged material are recommended for consideration (Figure 9). These are an area in the northeast Gulf around DeSoto Canyon, an area over and adjacent to the Mississippi Trough, and an area in the Northwest Gulf northwest of Alaminos Canyon.

Even though the shelves are very wide in the Gulf and one is mindful of reducing haul distances, use has not been made of the shelf-slope junction to reduce haul distances because such disposal could impinge upon the major shrimp fishery on the shelf. Perhaps, however, future studies may reveal that the intermittent disposal and dispersal of compatible sediments on the outer shelf will create no more or less environmental deterioration for shrimp than the dragging of huge otter trawls over the bottom day after day.

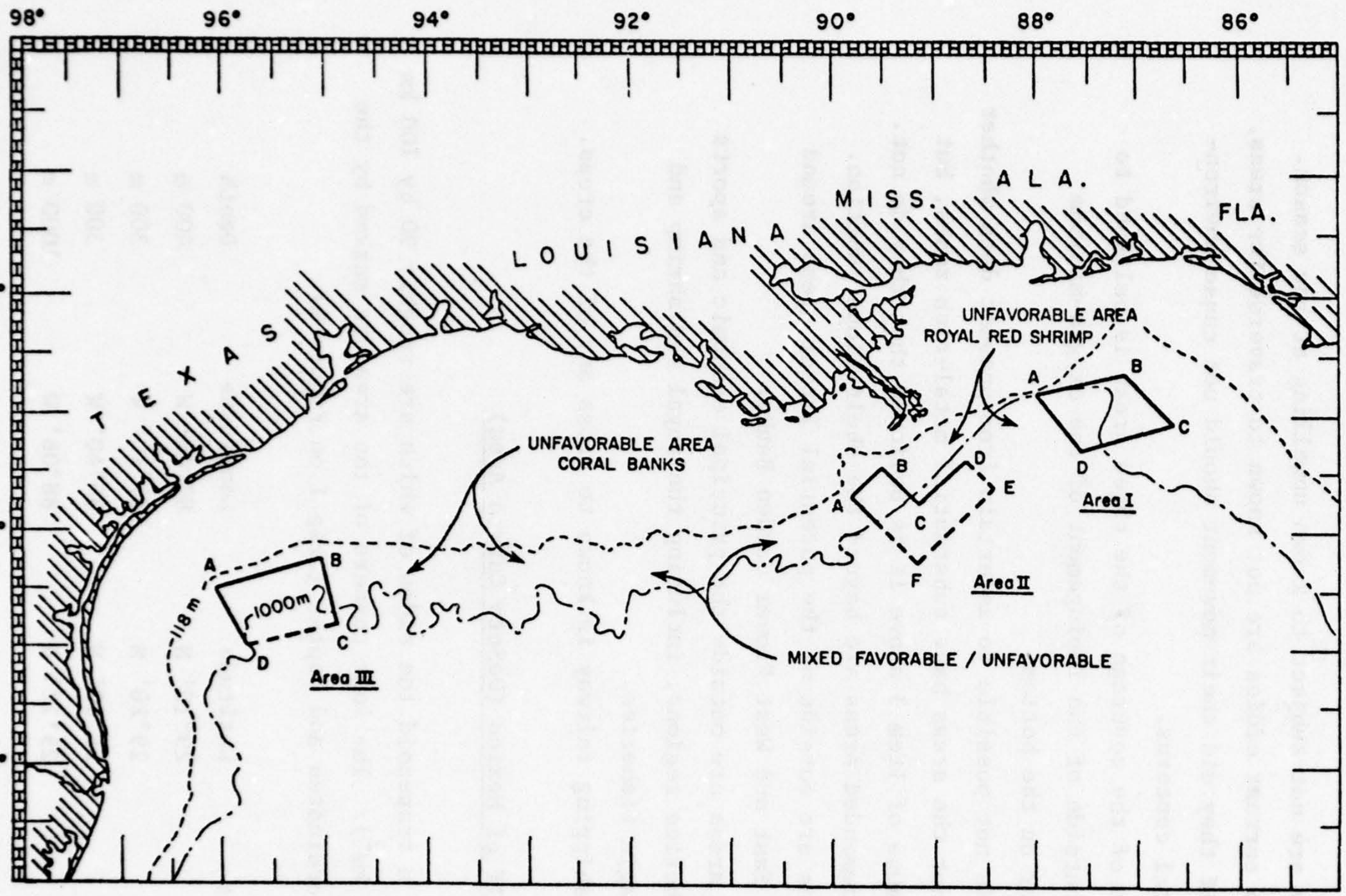


Figure 9. Locations of favorable areas for dredged material disposal areas (Areas I, II, and III) in the northern Gulf of Mexico. Solid lines denote more or less strict boundaries, dashed lines are optional (see text for coordinates at A, B, C, etc.). General locations for several unfavorable areas are also shown.

The criteria employed in selecting the three favorable areas in the Gulf of Mexico are:

1. They are not subject to known upwelling at any season.
2. Loop current eddies are not known to traverse the areas, or if they did their movement should not cause environmental concerns.
3. Much of the coverage of the three areas is believed to be outside of the impingement of the oxygen-minimum layer on the bottom.
4. It is not possible to ascertain from present data whether or not the areas have substantial metal-rich zones, but because of Item 3 above it is believed that they do not.
5. Recommended areas are beyond the shelf-slope junction.
6. Areas are outside of the potential impact areas around the East and West Flower Garden Banks.
7. All areas are outside the principal economic and sports fisheries regions, including the royal red shrimp and pelagic fisheries.
8. No shipping fairway is known to cross any of the areas.

Northeast Gulf of Mexico (DeSoto Canyon Area)

This area is a trapezoid the sides of which are roughly 90 by 100 km (area - 9000 km^2). The four corners of the area are marked by the following coordinates and depths (Area I on Figure 9).

Corners	Latitude	Longitude	Depth
A	29°10' N	88°00' W	400 m
B	29°20' N	87°10' W	300 m
C	28°50' N	86°40' W	300 m
D	29°12' N	88°06' W	1000 m

The west corner (A) is about 95 km from Pass a Loutre of the Mississippi Delta and 105 km from the Mobile Bay sea buoy. The north corner (b) is also about 105 km from the Mobile sea buoy. The deepest point of the area is about 2000 m on the southwest line; the shallowest point is 160 m on the northwest line. W. Pequegnat et al. (1972) have published a series of bottom photographs of the area, showing a reasonable amount of biological activities on the walls, but they show also a jumble of sediment material in the canyon bottom that appears to have resulted from recent slumping. This is confirmed by work of James (1972), based on finding displaced bivalve shells of species that live only in much shallower water.

Central Gulf of Mexico (Mississippi Trough Area)

This area is roughly L-shaped in order to remain clear of shipping fairways, other disposal sites, and some potential fisheries. The six corners of this area are marked by the following coordinates and depths (Area II on Figure 9).

Corners	Latitude	Longitude	Depth
A	28°20' N	89°50' W	500 m
B	28°35' N	89°30' W	600 m
C	27°15' N	89°10' W	1200 m
D	28°35' N	88°45' W	1400 m
E	28°20' N	88°25' W	1900 m
F	27°45' N	89°10' W	1700 m

Corner B is about 50 km from Southwest Pass and 65 km from South Pass. This is an area of fairly rapid sedimentation and slumping (Shepard, 1960).

Northwest Gulf of Mexico (Area West of Alaminos Canyon)

This area is roughly a rectangle the sides of which are roughly 90 x 100 km (area = 9000 km^2). The four corners of the area are marked by the following coordinates and depths (Area III on Figure 9).

Corners	Latitude	Longitude	Depth
A	27°30' N	96°00' W	200 m
B	27°45' N	95°00' W	300 m
C	27°10' N	94°50' W	1500 m
D	27°00' N	95°45' W	1000 m

The northwest corner of the area is about 100 km from Corpus Christi Harbor entrance whereas the northeast corner is about 170 km from Galveston Harbor sea buoy.

NEUTRAL AND POOR DISPOSAL AREAS

The remainder of the continental slope of the northern Gulf of Mexico between and outside of the three favorable areas has both neutral and poor disposal areas.

Brownsville to Northwest Area

The continental slope between offshore Brownsville, Texas and the Gulf Area III (Figure 9) is considered neutral. In general, most of it is too far from the principal centers of origin of dredged material to be given further consideration at this time.

Between the Northwest and Central Areas

There are both neutral and poor areas along the continental slope between the Areas II and III (Figure 9). Certainly those areas adjacent to the seaward side of such topographic features as the East and West Flower Gardens, Three Hickey Rocks, etc. should be considered poor. The remaining areas are neutral, although if sites were to be selected, they should be well beyond the shelf-slope junction.

Between the Central and Northeast Areas

The prograding delta front, between Areas II and I (Figure 9) including the Mississippi Fan and the slope between the Central Gulf area and the DeSoto Canyon should be judged to be poor because of the adjacent royal red shrimp grounds and possible tilefish regions.

EAST COAST: THE ATLANTIC OCEAN (SECTORS 1, 2, AND 3)

Dredged material accounts for the major amount of wastes of all types disposed along the entire Atlantic coast. In calendar year 1975 about 1 million cu yd were dredged in the New England Division, 13.6 million cu yd in the North Atlantic Division, and 10 million cu yd in the South Atlantic Division (see Part of this section). Probably only a quarter of this was disposed of in the ocean. So far as is known, the only part of it that was placed in the deep ocean beyond the shelf break was off San Juan, Puerto Rico in about 260 m depth.

FAVORABLE DISPOSAL AREAS

Northeast Coast (Sector 1)

The problem of disposal of dredged material in this sector is compounded by the great width of the continental shelf and the presence of very productive banks and basins. The Gulf of Maine is a more or less enclosed coastal sea rimmed by shallow sills that have three narrow passages interconnecting it with the Atlantic. Its circulation is, therefore, essentially estuarine. Considering the value of the invertebrate fishery to the area, there is no alternative to eventual deep ocean disposal of dredged material.

Giving consideration to the currents and to the history of disposal in the entire slope area, it is recommended that the entire continental slope region beyond the 300-m isobath can be considered appropriate for disposal of materials (Figure 10). Although it is not anticipated that any serious biological consequences would actually develop from disposal of material in the larger canyons, it would be unwise to discharge in those canyons on the outer flank of Georges Bank that incise the 100-m isobath. The homarid lobster is the chief species of concern here, but the relatively small amount of dredged material involved would have little or no impact on this deep fishery.

Arrival at the above for Sector 1 has been guided by the following:

1. Circulation in the Gulf of Maine is dominated by a cyclonic gyre that persists throughout the year, although it varies in both velocity and extent seasonally. It is most variable in winter and reaches its greatest extent in summer. Spring runoff from rivers tends to give it estuarine qualities.

2. Marine waters enter across Browns Bank and move into and out of the Bay of Fundy, from which part is then entrained in the gyre and the rest moves out of the Gulf of Maine via Great South Channel and over Georges Bank.

3. Both the banks and basins are important to fisheries.

4. The four most important fishery species from their dollar value are the American Lobster (Homarus americanus), the Caridean Shrimp (Pandalus borealis), the Soft-shell Clam (Mya arenaria), and the Ocean Perch (Sebastus marinus). The major amounts of these species are taken at or above the 300-m isobath.

5. As elsewhere, the benthic biomass decreases rapidly near and beyond the shelf-break.

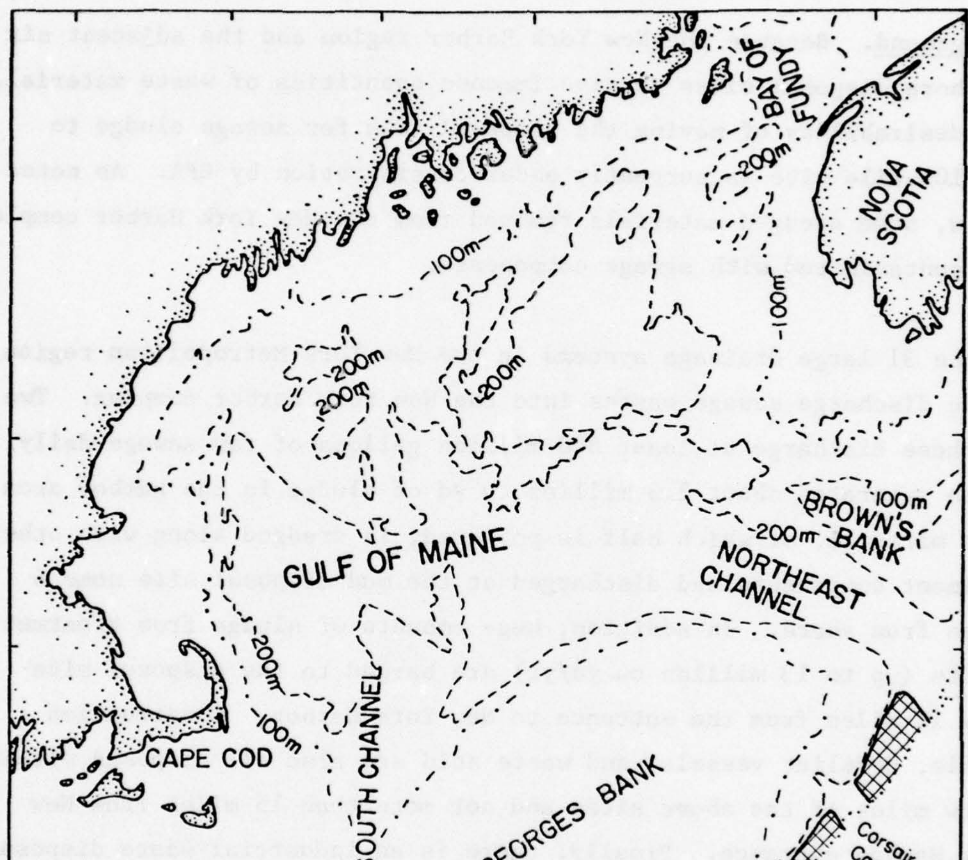


Figure 10. Location of favorable disposal areas for the Gulf of Maine, Northeast coast, Sector 1. Crosshatching indicates areas considered favorable for deep ocean disposal of dredged material.

The Middle Atlantic Bight (Sector 2)

Background. Because the New York Harbor region and the adjacent six offshore disposal sites receive immense quantities of waste material, the desirability of moving the disposal area for sewage sludge to the 106-mile site is currently under consideration by EPA. As noted below, some dredged materials removed from the New York Harbor complex are contaminated with sewage components.

Of the 31 large drainage systems in the New York Metropolitan region, three discharge sewage wastes into the New York Harbor complex. Two of these discharge at least 500 million gallons of raw sewage daily, which generates about 2.3 million cu yd of sludge in the harbor area. This material, of which half is polluted, is dredged along with other sediment components and discharged at the mud disposal site some 6 miles from shore. In addition, huge amounts of sludge from treatment plants (up to 13 million cu yd/yr) are barged to the disposal site only 12 miles from the entrance to New York Harbor. Construction rubble, derelict vessels, and waste acid are also all disposed within a few miles of the above sites and not more than 15 miles from New York Harbor entrance. Finally, there is an industrial waste disposal site about 106 miles offshore just south of Hudson Canyon. As a result of activities at these sites, it is estimated that 80 percent of all ocean disposal of municipal sludge, waste acid, and industrial wastes in the U.S. occurs off the coasts of New York and New Jersey. It is remarkable that more difficulty has not arisen from materials (especially floatables) being carried to the New Jersey coast at times when a strong northeasterly wind combines with reduced fresh water discharge from the rivers. The Coriolis effect would cause the currents to hug the coast and possibly impinge upon the shore at times of low river outflow. The fact that this has not happened (or at least has not happened often) is attributable to the major flow of fresh or low-salinity water moving out of the harbor area and turning southward around Sandy Hook.

As has been pointed out, the level of waste solids discharged by the New York Metropolitan area approaches the sediment load of some of the huge rivers in India and China except that the latter do not carry all of the contaminants found in the Bight. Unfortunately, for the Bight region, however, very little riverborne sediment enters the western North Atlantic because it is captured by the estuaries. Hence, there is little native sediment available to cover and sequester the waste mounds. Apparently, an important environmental factor that has prevented a more serious degradation of the coastal ecosystem south of the disposal sites is the active circulation found there (Ketchum et al., 1951). It is a matter of conjecture, however, as to how the system will fare with time and, especially, if there is any increase in disposal of both dredged material and sewage sludge.

Disposal Areas. There is an alternating series of favorable and unfavorable disposal areas stretching along the precipitous shelf-slope junction and upper slope from the southern boundary of the present 106-mile industrial site (just south of Hudson Canyon) to Cape Hatteras (Figure 11). Although it is not considered essential for environmental preservation, it is recommended that no disposal take place in those large canyons whose heads incise the continental shelf. From north to south the major ones of these are Wilmington, Baltimore, Washington, and Norfolk Canyons. Judging from the best available bathymetric charts and fisheries data, disposal can be carried out in the intervening stretches between the above canyons at and beyond the 150-m isobath. It is anticipated that the material will be dispersed down the slope, essentially as is the natural fate of large amounts of sediment deposited naturally by rivers on their prograding deltas.

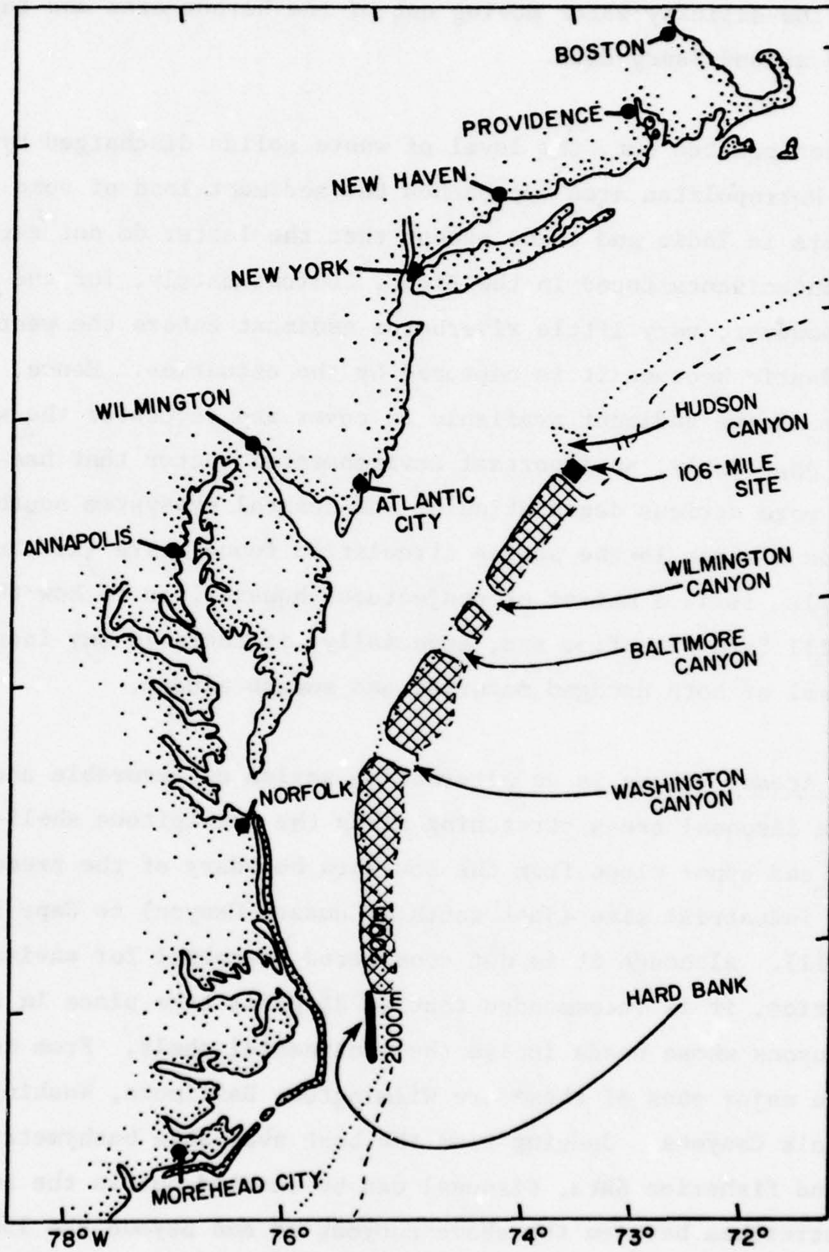


Figure 11. Location of favorable disposal areas for the Middle Atlantic Bight, Sector 2. Those areas considered favorable for deep ocean disposal of dredged material are crosshatched. Note the 106-mile industrial dump just south of Hudson Canyon and the hard bank (solid) near Cape Hatteras.

South Atlantic Bight (Sector 3)

Background. Dredging of the principal ports and shipping channels in the South Atlantic Bight produces about 80 percent of the volume of dredged material generated in the Middle Atlantic Bight. A substantial portion of the nearly 25 million cu yd is disposed of in the ocean on the inner continental shelf without any evidence of unfavorable environmental effects. However, apparently only occasional monitoring studies have been carried out. The major dredging sites and the volumes produced in 1975 are presented in Table 6. All of the above disposal sites range in depth from 6 to 15 m.

As noted in Table 6, Charleston is the principal harbor utilizing ocean disposal of dredged material in this bight. About 20 percent of the total material is disposed close to the south jetty in about 15 m of water. The rest is taken to sea. Since the material thus far is largely clean silt and sand, it is believed that no serious environmental effects have resulted from these modes of disposal. It is anticipated, however, that the harbor will undergo enlargement in a matter of a few years by dredging the inner reaches. Some of the sediments there are suspected of being contaminated by toxic wastes discharged into the feeder rivers (the Cooper and Ashley) by various industries. Should such a project be undertaken, it is quite likely that a deeper disposal site will have to be designated. The remainder of the waterway dredging is carried out in connection with pipeline dredging, and the material is deposited on Folly Island. Some alternative methods of disposal, such as tidal marsh formation and land fill, have been utilized, but the future of these methods of disposal is under evaluation and probably would not be used for contaminated materials without extensive tests. By the same token, it is unlikely that the use of natural marshland for continuing disposal of dredged material will be given favorable consideration.

Table 6

Principal Dredging Sites in the South Atlantic Bight

State and Harbor	Frequency	Cubic Yards* (x 10^3)	Disposal Area
North Carolina			
Morehead City	Annual	800	ocean
Wilmington	Annual	1000	ocean
South Carolina			
Georgetown	Annual	2500	ocean
Port Royal	Annual	500	ocean
Charleston	Annual	8500	ocean 80% Dikes 20%
Georgia			
Savannah Harbor Entrance	Continuous	1000	ocean
Inner Savannah Harbor		6000	harbor and dikes
Brunswick	6 months	1500	ocean and dikes
Florida			
Jacksonville Harbor	2 years	599	ocean
St. Augustine	Annual	128	ocean
Cape Canaveral	Annual	ave. 600	beach
Large job in 1971 produced 2,870,833 cu yds.			ocean

*Data supplied by relevant districts, Corps of Engineers.

Smaller amounts of material are produced during maintenance dredging in Port Royal and Georgetown Harbors. The material is relatively clean silts and sands that are disposed of at shallow sites on the shelf.

The Savannah Barge Channel is the outer portion of Savannah Harbor. Approximately a million cu yd of material are dredged in the channel and disposed of in the ocean sites. The inner harbor is subject to continuous pipeline dredging and the resulting 6 million cu yd of material are disposed of in five large sites in the harbor proper. It is doubtful that this process can continue indefinitely without eventual severe environmental degradation.

Brunswick Harbor is subject to dredging twice a year, during which time the outer part yields about 700,000 cu yd that are disposed of at sea. The nearly 800,000 cu yd produced from the inner harbor are deposited in diked areas on Andrews Island.

The principal dredging operations in the Florida portion of Sector 3 are in Jacksonville, St. Augustine, and Cape Canaveral Harbors. About 50 percent of the material produced in these three harbors (a little less than 1 million cu yd/yr) is disposed of on the shallow parts of the shelf. Most of the Cape Canaveral material is used for a kind of beach nourishment.

No serious environmental degradation appears to have resulted from most ocean disposal in this bight, but harbor enlargement and increasing industrial development along the waterways can change the quality of the dredged material very quickly. Perhaps, though, deep ocean disposal will be unnecessary for a long time. Dr. Herbert Windom (Personal Communication, 1976), a chemical oceanographer from the Skidaway Marine Laboratory has no serious reservation about deep ocean disposal of dredged material, provided it is well managed. He considers deep ocean disposal unnecessary at this time for the quality of material being dredged in Georgia embayments. Rather, he would dispose of it on the outer part of the shelf, which in this area is not very productive.

Disposal Areas. In the South Atlantic Bight there are large stretches of the Florida-Hatteras slope that are favorable for deep ocean disposal of dredged material. Except for certain hard bank areas located off the southern aspect of Cape Hatteras, and opposite Cape Lookout and Cape Fear, the shallow limit of the favorable areas can run along the shelf-slope junction around the 100-m isobath. In the vicinity of the hard banks, which are favored sports fishing grounds, the shallow limit should be shifted seaward to the 200-m isobath (Figure 12).

Arrival at the above for Sectors 2 and 3 has been guided by the following facts:

1. The shrimp fishery is located at or shoreward of the 40-m isobath.
2. The principal commercial finfishery is located at or shoreward of the 80-m isobath (much of it to the south is inside the 40-m isobath).
3. The Lithothamnion Reef and Black Rock Reefs are to be avoided, but much of their coverage is inside the 200-m isobath.
4. The sandstone ledges supporting hard bottom communities are discontinuous and lie within the 100-m isobath.
5. Little concern has been expressed about the possibility of disposal affecting the potential harvest of manganese nodules on Blake Plateau.

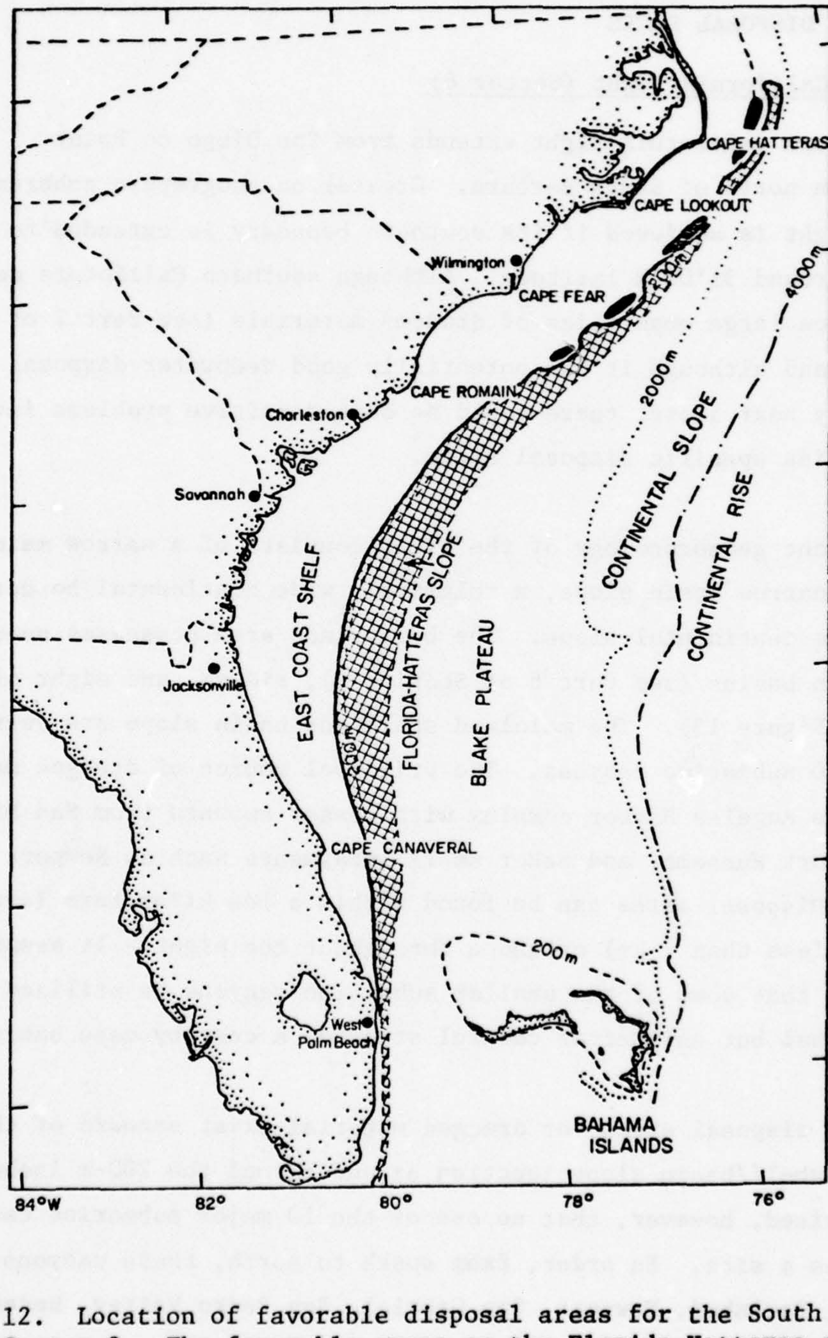


Figure 12. Location of favorable disposal areas for the South Atlantic Bight, Sector 3. The favorable areas on the Florida-Hatteras slope for deep ocean disposal of dredged material are crosshatched. Note the hard banks in solid black.

WEST COAST: THE PACIFIC OCEAN (SECTORS 6, 7, AND 8)

FAVORABLE DISPOSAL SITES

Southern California Bight (Sector 6)

The Southern California Bight extends from San Diego to Point Conception north of Santa Barbara. Greater oceanographic coherence in the Bight is achieved if its southern boundary is extended to Cabo Colnett around 31°00'N latitude. Although southern California does not produce large quantities of dredged materials (see Part 2 of this section) and although it has potentially good deepwater disposal sites relatively near shore, there could be some sensitive problems involved in selecting specific disposal sites.

The relevant geomorphology of the bight consists of a narrow mainland shelf, a narrow basin slope, a relatively wide continental borderland, and a true continental slope. The borderland area possesses numerous low-oxygen basins (see Part 6 of Section B), ridges, and eight offshore islands (Figure 13). The mainland shelf and basin slope are furrowed by over 30 submarine canyons. The principal source of dredged material is the Los Angeles Harbor complex with lesser amounts from San Diego Harbor, Port Hueneme, and other small embayments such as Newport Harbor. Disposal sites can be found within a few kilometers (average width is less than 7 km) offshore throughout the bight. It seems advisable that some of the smaller submarine canyons be utilized for disposal but only after careful study on a case by case basis.

Favorable disposal areas for dredged material exist seaward of the mainland shelf/basin slope junction at and beyond the 200-m isobath. It is advised, however, that no one of the 10 major submarine canyons be used as a site. In order, from south to north, these canyons are La Jolla, Carlsbad, Newport, San Gabriel, San Pedro Valley, Redondo, Santa Monica, Dume, Mugu, and Hueneme.

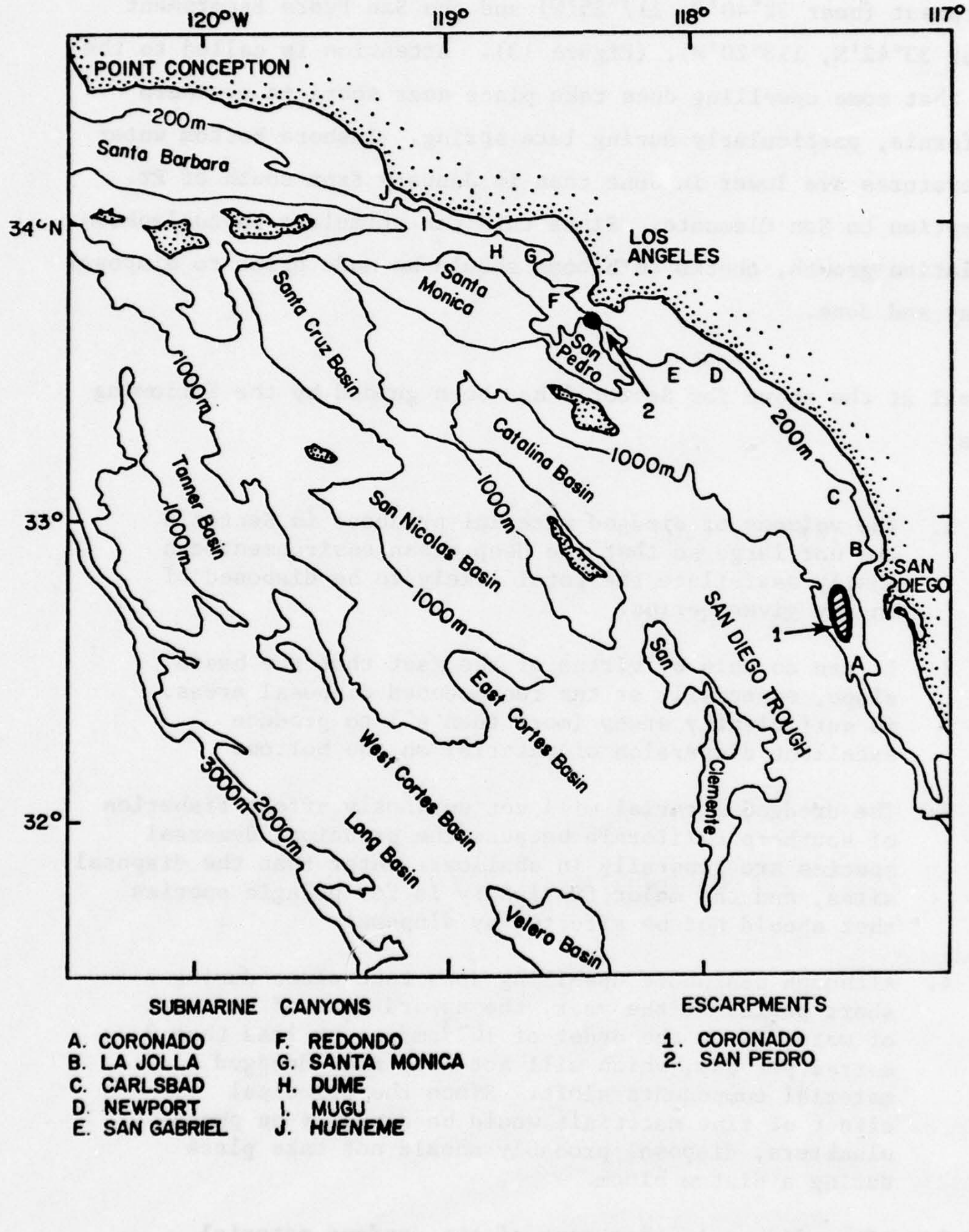


Figure 13. Geomorphology of the Southern California Bight area, Sector 6, showing favorable disposal areas (crosshatched area on the Coronado Escarpment, 1; and solid black area on the San Pedro Escarpment, 2).

Highly recommended areas are on the seaward face of the Coronado Escarpment (near 32°40'N, 117°25'W) and the San Pedro Escarpment (about 33°42'N, 118°20'W), (Figure 13). Attention is called to the fact that some upwelling does take place near shore in southern California, particularly during late spring. Inshore bottom water temperatures are lower in June than in January from south of Pt. Conception to San Clemente. Since this can stimulate phytoplankton population growth, checks on blooms should be made prior to disposal in May and June.

Arrival at the above for Sector 6 has been guided by the following facts:

1. The volumes of dredged material produced in Sector 6 are not large so that the deep ocean environment can easily assimilate the total likely to be disposed of in any given period.

2. It can do this by virtue of the fact that the basin slope, especially at the recommended disposal areas, is sufficiently steep (more than 4°) to produce excellent dispersion of material on the bottom.

3. The dredged material will not seriously affect fisheries of southern California because the principal demersal species are generally in shallower water than the disposal sites, and the major finfishery is for pelagic species that should not be affected by disposal.

4. Although nearshore upwelling does take place during a short period of the year, the upward rate of movement of water is on the order of 10^{-3}cm/sec or less than 3 metres per day, which will not keep most dredged material components aloft. Since the principal effect of fine materials would be directly on phytoplankters, disposal probably should not take place during a diatom bloom.

5. After disposal, that part of the dredged material remaining aloft in the water column would be transported northwestward more or less parallel with the coastline by both the Counter Current, which is part of

the Southern California Eddy, and the California Undercurrent, which is present below the Counter Current at depths between 150 and 800 m. Both currents move at speeds between 5 and 40 cm/sec.

6. The southward-flowing California Current is too far offshore (200 km) in southern California to have any direct effect on the dredged material.

Northern California Shelf (Sector 7)

Sector 7 extends from Pt. Conception to Cape Mendocino. San Francisco Harbor is the only major port in the sector, although there are relatively minor embayments to the south at Monterey Bay and to the north at Tomales Bay. There are three interim dredged material sites (1977 Regulations and Criteria) in the region: Moss Landing on the 183-m isobath, San Francisco Channel Bar, and the Farallon Islands on the 183-m isobath. The latter is the most important, being situated about 65 km west of the Golden Gate. In September 1974 the San Francisco District supported a field study of the disposal of 3000 cu yd of San Francisco Bay sediment at an experimental site on the 183-m isobath about 20 km northwest of the designated site. Photographs of the bottom following disposal showed that most of the material fell directly under the barges and, because of its consolidation, formed jumbled mounds on the bottom.

The area recommended here for deep ocean disposal of dredged material lies about 10 km west of the Farallon Islands beginning on the 200-m isobath and on the north-south axis running between the North Traffic Shipping Lane Inbound and the Main Traffic Shipping Lane Outbound to the south (Figure 14). This area is essentially bounded by Pt. Reyes to the north and Pigeon Point to the south, with the proviso to avoid the shipping lanes.

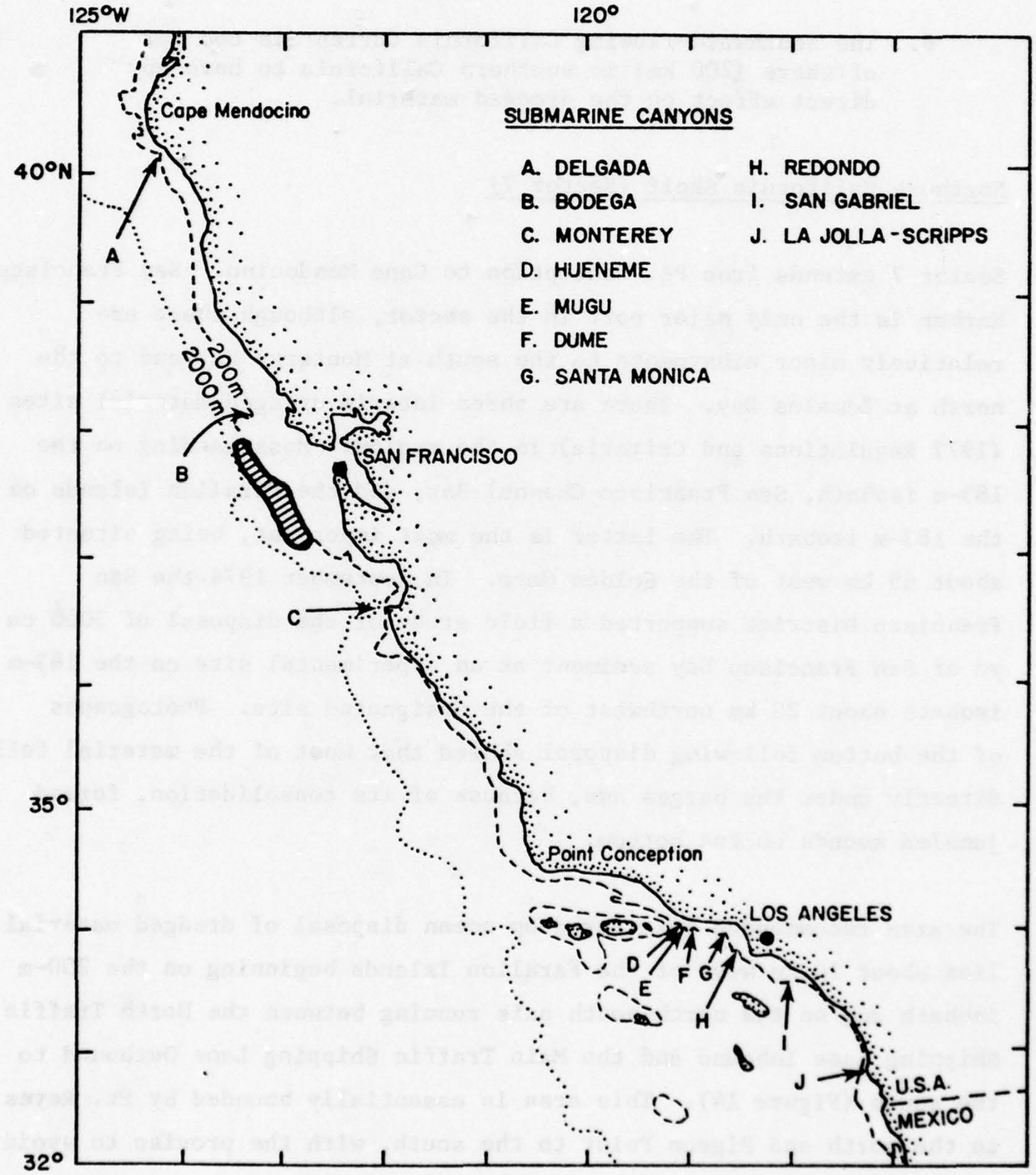


Figure 14. Location of favorable disposal areas for the Northern California Shelf, Sector 7. (Favorable locations are shown by crosshatched areas.)

Arrival at the above for Sector 7 has been guided by the following facts:

1. The 200-m isobath is outside of the principal sports and commercial sports fisheries for Chinook Salmon, English Sole, and other flatfishes.

2. Many of the rockfish of the genus Sebastes (e.g., Bocaccio, Chilipepper, Blue Rockfish, etc.) exist along this isobath and deeper, but any mounding in the area might well serve as habitat for several species of the genus.

3. The experimental study noted above observed numerous decapod crustaceans at the disposal site. These were very likely the near-bottom caridean decapod shrimp of the genus Pandalus (probably jordani). They should not be seriously affected by periodic disposals.

4. The current regime is reasonably favorable, being southerly in summer and northerly in winter.

5. Upwelling occurs in the area but is limited to February to July and much of it is inside of the proposed site.

6. Ample potential sites can be located in such manner as to avoid the shipping fairways.

The Northwest Shelf (Sector 8)

Background. Sector 8 runs from Cape Mendocino to Cape Flattery. There are three Corps districts involved: San Francisco, Portland, and Seattle. Only five major dredging areas are involved in this large stretch of coast that includes northern California and all of Oregon and Washington. These are California's Humboldt Bay (San Francisco District), Oregon's Coos Bay and Columbia River (Portland District), and Grays Harbor and the Puget Sound complex that are in the Seattle District. At the present time at least the Columbia River does not appear to be in need of ocean disposal in deep water whereas the others either are or soon will be.

Although Humboldt Bay has not produced very large volumes of dredged material in the past, a six-mile channel is now projected for 1977-78 that will produce about 2.41 million cu yd in 1977. Of this, some 200,000 or more cu yd are scheduled for hopper dredging and ocean disposal. The bulk of the remainder may be used for beach nourishment, but this can pose problems that are not easy to solve. For instance, it may not be possible to place large amounts on or near the dunes because to do so would increase the vertical distance to the water table, resulting in possible death of native vegetation.

Coos Bay is the largest and most industrialized bay in Oregon. It covers about 10,000 acres of which about half are tidelands (Slotta et al., 1973). Continued dredging is necessary to permit medium draft (30-40 ft) vessels to enter the harbor. Annual maintenance dredging averages about 1.8 million cu yd. In 1972 a team of Oregon State University engineers and scientists studied the biological effects of hopper dredging and in-channel disposal in the bay. The disposal of about 8000 cu yd by the HARDING was monitored on October 4, 1972. It was concluded that many factors have contributed to the somewhat depauperate infauna, and that small-scale maintenance dredging may have only a temporary effect on the benthic infauna. Moreover, it was stressed that the effects of dredging operations cannot be compared with the results that dredging permits, namely, increasing commercial ship traffic, industrialization, and urbanization.

The Columbia River appears not to be a likely source of dredged material for deep ocean disposal in the foreseeable future. One of the main concerns of the Portland District is maintenance of channels in the Columbia River in the 100-mile run between Portland and Astoria. While the river transports an estimated 18 million cu yd a year, the Corps dredges about 5 million cu yd. They are attempting to stabilize river erosion by using a method based on the assumption that the river will remove from banks every yard that the Corps dredges from the bed. The method employed, called flow-lane dispersion, calls for redistributing the sand dredged from shoals at erosion areas in bends of the river.

Within a year or two Grays Harbor will be the site of a major project that will entail production of a planned 16 million cu yd. It is anticipated that some of this will have to be disposed of in deep water off the coast.

The Seattle District dredges on the order of 2.5 million cu yd a year. Much of this is being placed in upland areas or discharged in deep water in Puget Sound.

Favorable Areas. The favorable disposal areas of Sector 8 are shown on Figure 15. These areas are in Humboldt Bay, Coos Bay, and Grays Harbor, and the Puget Sound/Strait of Juan de Fuca complex. The continental shelf off Humboldt Bay is about 21 km wide. However, because of the importance of the demersal fishery in this area, it is advised that a site should not be established shoreward of the 500-m isobath.

At Coos Bay, the continental shelf is about 32 km wide. It is recommended that material required for ocean disposal not be disposed inside of the 500-m isobath.

The continental shelf off Grays Harbor is about 46 km wide. Again, because of the important demersal fishes in this area, it is not advisable to establish a deepwater site inside the 500-m isobath.

The disposal of dredged material into Puget Sound began around 1920 at

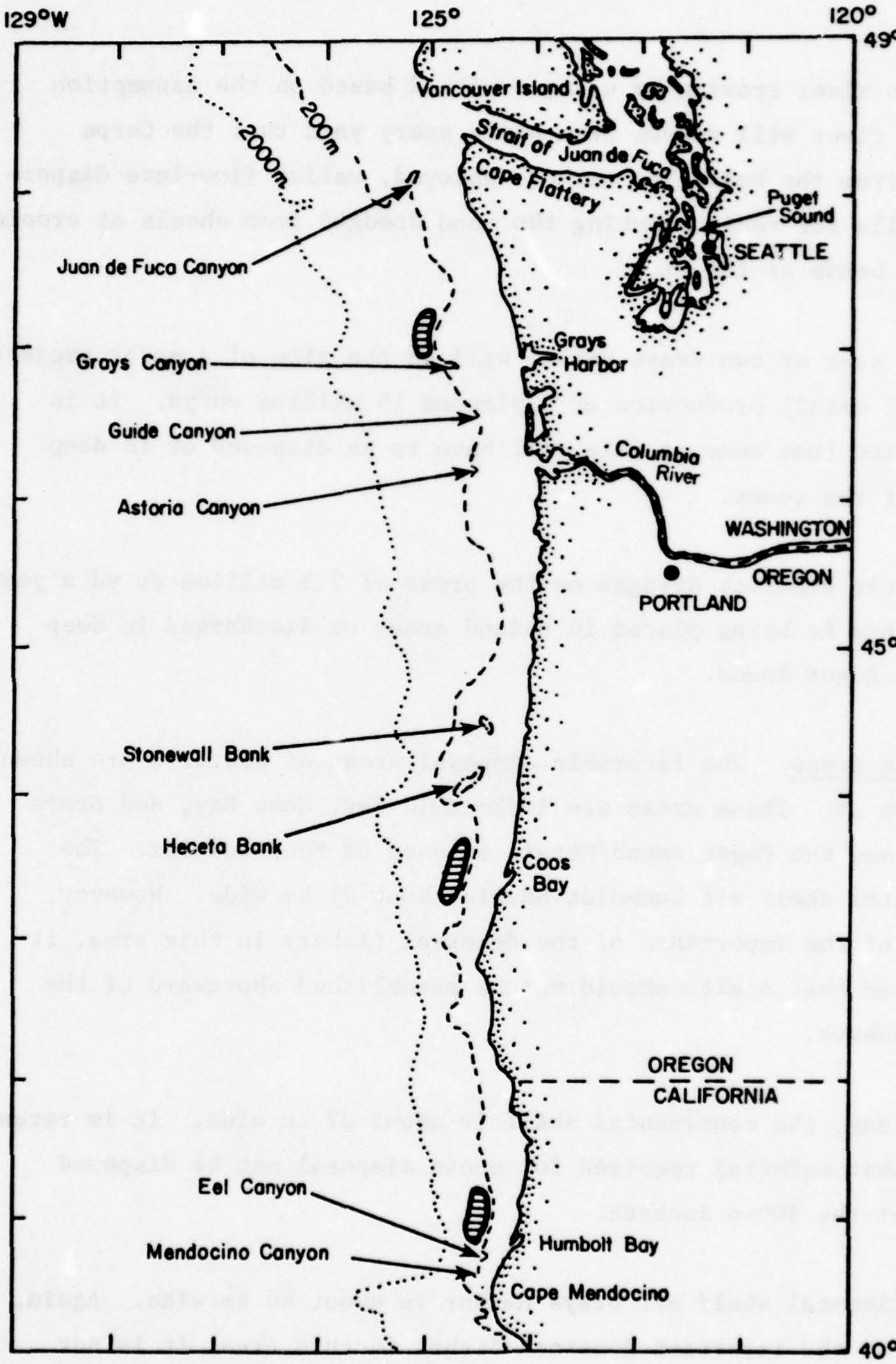


Figure 15. Location of favorable disposal areas for the Northwest Shelf, Sector 8. (Favorable locations are shown by crosshatched areas.)

the time that the entrance to Gambel Harbor was deepened. Today, on the order of 250,000 cu yd are disposed in the waters of Puget Sound and the Strait of Juan de Fuca. Most of the areas require maintenance dredging only once every ten years because of the dynamic tidal action. Bellingham and Tacoma Harbors have needed dredging about every five years. Some of the sediments in the region have very high BOD levels and are thought to require land disposal. Special problems exist in disposing of certain sediments from harbors into which pulp mills discharged waste sulfite liquors and settleable suspended solids. These sediments are truly toxic and have high BOD ratings. Such materials persist in such harbors as Tacoma, Everett, and Anacortes.

There are numerous acceptable, deepwater disposal site areas in the Puget Sound and Whidbey Basins (depths to 280 m) and the adjacent Strait of Juan de Fuca. It is suggested that consideration be given to establishing sites over deepest waters where the currents do not reach peak velocities (less than a knot as compared with 5 or more knots in inlets and narrows). Furthermore, although extensive mixing of waters occurs over sills supplying dissolved oxygen to subsurface waters of most of the Sound, there are places where dissolved oxygen levels reach very low levels in summer.

Arrival at the above in Sector 8, has been guided by the following facts:

1. The circulation regime over the proposed disposal sites is weaker than on the east coast with the Gulf Stream, but it is fairly predictable.
2. The important flow is southward in the spring and summer and, with formation of the Davidson Current, northward in winter.
3. Although upwelling occurs throughout the Sector,

it is not as prevalent to the north and tends to be a coastal but not nearshore event.

4. The continental slope appears to be a good place to dispose of dredged material.

5. However, because of the importance of the demersal fishery in this sector and because many of its constituent species live on the upper shelf, it is advised that disposal should not occur in large amounts above the 500-m isobath except in Puget Sound.

6. The circulation and high dissolved oxygen levels in most basins (avoid Daboh Bay) of the Puget Sound create good receiving environments for dredged material.

THE GULF OF ALASKA (SECTOR 9)

As will be explained in Part 6 of Section B, it is impractical to consider deep ocean disposal of dredged material from Anchorage, which is located many miles up Cook Inlet from the Gulf. Not only is distance to deep water from the harbor source a factor but also navigation in Cook Inlet, especially with barges, is very difficult because of unpredictable currents and boulder strewn shoals.

THE HAWAIIAN ISLANDS (SECTOR 10)

As will be mentioned in Part 6 of Section B, deep ocean disposal of dredged material is already being practiced, viz., off

Honolulu Harbor in 460 m
Naiwiliwili Harbor in 1000 m
Port Allen in 1540 m.

All of these are interim dredged material sites. Final site selection for Pearl Harbor will be under study in spring and summer of 1977 when the harbor will undergo extensive dredging. These harbors are on a 5-year dredging cycle.

PUERTO RICO AND THE U.S. VIRGIN ISLANDS (SECTOR 11)

As will be explained in Part 6 of Section B, there are four harbors in Sector 11 that have undergone significant dredging in the last eight years. However, only the material from San Juan Harbor, Puerto Rico (877,760 cu yd) was disposed of in the deep ocean in 260-300 m of water off the north coast of the island.

C. GUIDES FOR SELECTION OF SPECIFIC DISPOSAL SITES IN THE DEEP OCEAN

Three tables have been constructed to provide guides to the administrator, who must select specific sites for the disposal of dredged material in the deep ocean. Each factor has been ranked in accordance with its estimated general importance to site selection. It is recognized, however, that regional considerations can modify the ranking given in the table.

The factors to be considered in selecting a deep ocean disposal site for dredged material are tabulated in Table 7. In Table 8 seasonal concerns both in regard to selection and especially to use of a site are provided. Finally, as an example of seasonal constraints on site usage and their regional intensification and amelioration, Table 9 shows the mid-winter and mid-summer differences in high waves and winds in all of the sectors.

Table 7

Factors to be Considered in Selecting a Deep Ocean Disposal Site for Dredged Material

Consideration	Information Source	Degree of Importance to Siting: High	Medium	Minor
A. Present Uses of the Site Area				
1. Navigation				
Shipping Fairways	U.S. Coast Guard and National Ocean Survey Charts		+(amount of traffic)	
Offshore Terminals	U.S. Coast Guard (when beyond 3 mi) Corps of Engineers (in territorial sea)		+	
2. Fisheries				
Economic	National Marine Fisheries Service	+(seasonal)		
Sports	U.S. Fish and Wildlife Service			+
Exploratory	National Marine Fisheries Service		+	
3. Waste Disposal				
Ocean Incineration	EPA, Marine Protection Branch	+		
Sewage Sludge	EPA, Marine Protection Branch	+		
Other (Industrial)	EPA, Marine Protection Branch	+		
4. Military Uses				
Explosive Dumping	National Ocean Survey Charts		+	
Other Activities	Department of Defense	+		
5. Industrial				
Petroleum	Bureau of Land Management			+
Submarine Cables	Federal Communications Commission		+	
6. Special Scientific Areas	Regional Oceanographic Institution		+	

(Continued)

Table 7 (Concluded)

Consideration	Information Source	Degree of Importance to Siting: High	Medium	Minor
7. Recreation				
Aquatic Monuments	National Park Service			+
Boating, etc.	State Chamber of Commerce			+
Shipwreck and Other Fishing Reefs				+
8. Preservation Activities	Department of Commerce Office of Coastal Zone Management	+		
B. Oceanographic Criteria of Receiving Environment		HIGH	MEDIUM	MINOR
1. Density Structure of Water Column				
Temperature, Salinity, Sigma-t		+(for fines)		
2. Submarine Morphology		+		
3. Sedimentology (Chemical Features also)		+		
4. General Ocean Circulation				
Upwelling		+(seasonal)		
Downwelling		+(seasonal)		
Eddy Formation		+(seasonal)		
5. Currents				
Surface			+	
Midwater			+	
Bottom			+	
6. Deep Ocean Marine Life (Non-fisheries)				
Pelagic				+
Benthic			+	
7. Dissolved Oxygen (Bottom Waters)			+	
8. General Winds and Sea States			+ (seasonal)	

Table 8

Seasonal Concerns in Site Selection and Site Use

Thermocline

a. Greatest seasonal cycle of thermocline occurs in temperate latitudes

b. Winter - deep mixed layer with weak thermal structure

c. Spring - thermocline shallows and strengthens

d. Summer - generally maximum stratification of water column with shallow mixed layer

Density

a. Influenced mainly by temperature structure

b. Winter - may reach maximum value but only a weak pycnocline because of mixing

c. Summer - density of surface waters may become only 0.3 - 0.5 that of underlying waters - sharp pycnocline - strong stratification - little mixing

d. Upper 100 m or so generally has homogeneous density

Meteorology

a. Sea states (wave heights, etc.) generally change markedly with season (see Table 9)

b. Wind conditions are very seasonal in most places - affect the general sea conditions

c. Visibility - seasonal, generally poorest in fall and spring

General Circulation and Currents

a. Currents - currents change markedly with season on all coasts - there may be complete reversals. Even tidal currents change with time of year

b. Both surface and subsurface circulation can change markedly.

Table 8 (Concluded)

Upwelling and Downwelling

a. Upwelling is a seasonal phenomenon on both the Gulf and Pacific coasts

b. Downwelling is a seasonal phenomenon - see Davidson Current on Pacific coast

Changes in Biological Activity

a. Primary productivity of phytoplankton reaches a peak in early spring in offshore waters - reaches a general low level with water column stratification - builds up in fall for short period with increased mixing maintains low level in winter

b. Movements of many finfishes and some shellfishes are related strongly to season; includes oceanic as well as anadromous species; often species have distinctly different spawning and "feeding" grounds; protection of migratory pathways

c. Spawning season with release of planktonic larvae of important species

Seasonal Changes in Commercial Fishing Activity

Table 9

Seasonal Changes in Wind Speed and Wave Height Along Coasts of the United States

Place	Wind (34 kt or more)		Wave Height (3 m or more)	
	Jan.	July	Jan.	July
Atlantic Coast				
Gulf of Maine	7.4	0.1	8.0	0.0-0.5
Nantucket (40°-42°N)	4.9	0.1	13.4	0.2
New York (40°N)	3.4	0.2	5.6	0.0-0.5
Delaware-New Jersey	9.3	0.3	6.0	0.2
Maryland-Virginia	6.0	0.2	11.9	0.5
Cape Hatteras to Lookout	8.8	0.2	15.2	0.9
Cape Fear to Savannah	5.6	0.5	13.2	1.8
Savannah to Ponce de Leon	2.4	0.4	8.5	1.1
Ponce de Leon to Florida Keys	0.8	0.1	3.8	0.6
Straits of Florida	0.6	0.1	2.3	0.3
Gulf of Mexico				
Tampa	1.1	0.0	7.5	0.0
Mobile	1.2	0.1	5.4	0.2
New Orleans	1.1	0.1	4.7	0.2
Galveston	1.1	0.1	3.8	0.1
Brownsville	1.4	0.0	6.0	0.0
Pacific Coast				
San Diego	0.0	0.0	1.4	0.6
San Francisco	1.5	0.8	15.6	7.9
Eureka	4.8	2.4	34.6	3.3
Astoria	6.3	0.0	35.4	1.4
Seattle	4.3	0.0	11.1	4.5
Hawaii (Windward)	1.0	0.0	10.6	2.6
Hawaii (Leeward)	0.0	0.0	7.3	1.5
Gulf of Alaska	11.7	0.5	27.5	7.2

Source: United States Coast Pilots, National Ocean Survey, NOAA.

PART 4. SUMMARY CONCLUSIONS

1. The Corps of Engineers is presently responsible for dredging between 350 and 450 million cu yd of sediment at a cost of over $200 million in order to develop and maintain the navigable waterways of the United States. In addition, privately sponsored dredging projects typically add about 70 million cu yd to the total volume dredged annually.

2. At least this level of dredging will be maintained in future years, or it will increase substantially if plans for some major harbor developments are carried out. Among these plans are those for the Harbor Island Deepwater Terminal in Corpus Christi, Texas and Grays Harbor, Oregon, which together will require dredging of an estimated 115 million cu yd of sediment during construction. In addition, the new channels will require a substantial amount of maintenance dredging.

3. Dredging must be continued to insure safe passage of vessels of commerce. Not only are their export and import cargoes vital to maintenance of a sound and growing economy, but also accidental spillage of some cargoes because of poorly maintained channels could have far more profound effects than dredging on marine ecological systems and thus on the welfare of the American people.

4. The most difficult problem of the dredging-disposal process is the disposal aspect. There is an increasingly urgent need to develop ways of coping with the millions of cubic yards of new as well as maintenance dredged material that will have to be disposed of in an environmentally sound manner. The disposal problem is accentuated by the fact that in some places sites for confined land disposal are virtually impossible to acquire or are at least becoming scarce. Moreover, leaching of such disposal sites into ground or surface waters can result in severe degradation of the environment. In

other words, some past solutions to the disposal problem have proved to be less than ideal.

5. There are three major categories of disposal environments for dredged material, viz., the land or upland areas, the estuarine-inner continental shelf complex, and the offshelf deep ocean. In recent years increasing use has been made of land sites, but there are clear signs that the practice can be less than ideal. Moreover, land for disposal of any type of dredged material is becoming difficult to acquire in the coastal zone. It is estimated that no less than 7000 acres of new land will be required each year for containment of material generated by maintenance dredging operations of the Corps of Engineers. Population pressures are making the search for suitable land disposal sites more difficult. The population of the Coastal Zone (50 miles inland from the shore), already between 65 and 70 million people, is increasing at an annual rate of 3 to 5 percent. Accordingly, a third of the U.S. population now lives on 8 percent of the land -- and the trend continues.

6. The use of land for disposal has an even more significant factor. On the order of 98 percent of man's food supply comes from the land and the small remainder from the sea. And expert estimates point to the likelihood that the sea will not ever supply much more than the present 2 percent. Hence, if the dredged material involved will in any way degrade potential or actual agricultural land, perhaps it should be disposed of in an appropriate part of the ocean.

7. The estuary and inner continental shelf provide an essential habitat for numerous species of valuable shellfish and finfish, as evidenced by the fact that some 75 percent of the U.S. seafood comes from this complex. This suggests that these areas should be avoided for disposal, particularly if the dredged material is

contaminated or polluted. The outer continental shelf may be satisfactory for disposal of dredged material in some regions (e.g., the South Atlantic Bight) but not in others, such as the western Gulf of Mexico where the great brown shrimp fishery exists.

8. It is concluded in this report that deep ocean disposal of dredged material is an environmentally sound alternative to presently unsatisfactory disposal operations. Given time and some technological improvements it will become economically feasible as well, as it already is in some insular areas.

9. The physical facts that support this conclusion are (a) that about 92 percent of the ocean floor and over 99 percent of the oceans' waters lie beyond the shelf break, (b) there are then huge areas and great volumes of water to receive and dilute any except the most hazardous wastes cast into the ocean, and (c) the deep ocean has a demonstrated assimilative capacity to receive huge volumes of sediment without losing its capacity to sustain the life processes in kind and amount characteristic of the receiving region.

10. The biological facts that support the above conclusion are (a) that the deep ocean does not have much capacity to produce food for man either in the water column or, particularly, on the bottom -- indeed, it does not support much macroscopic life of any kind on the bottom, and (b) that estimates of informed specialists indicate that the deep ocean, particularly beyond the 1000-m isobath, will never contribute over one percent of the total world fish catch, and that will be entirely of pelagic origin.

11. Although there are multiple effects that dredged material can and will exert upon any region or ecological system, it is concluded generally that these impacts will be less severe in the deep ocean than elsewhere in the marine environment. Even so, to evaluate

these impacts one must know a good deal about the nature of the dredged material involved, how much is to be disposed of at a time and how frequently, and the nature of the final receiving environment. Certainly chemical changes resulting from the disposal of dredged material in deep water and the effects that these changes have upon both the pelagic and benthic biota is the single most important category of impacts at issue. But, as mentioned above, there is not only a paucity of life in the deep sea to suffer impacts, but the impacts themselves will be weakened by water transit.

12. No matter what the receiving environment, the key to environmentally sound dredging-disposal activities involves sound management. To achieve this, the manager must develop a basic fund of knowledge about the environments and ecological systems in his jurisdiction. He must be conversant with water movements on transient and long-term scales and, above all, he must familiarize himself with the biological components of each of the systems available for selection of disposal sites. Section B of this report was prepared to provide this basic information in ready form for the District Engineer who, in most instances, will be the dredging-disposal manager.

13. Lastly, it is concluded that the deep ocean can be a final receiving environment for dredged material. Thus, its use will permit man to solve two important environmental problems. First, he will have found a natural ecosystem that has the necessary capacity to serve as an effective processor of most of his wastes without huge technological and monetary outlays. Second, by utilizing an essentially terminal receiving environment, he will no longer -- at least for dredged material -- be shifting the problems associated with the waste from one ecosystem to another *ad seriatum*.

SECTION B

DEEP OCEAN DISPOSAL

ENVIRONMENTAL CONSIDERATIONS

PART 1. FACTORS CONTROLLING SPATIAL DISPOSITION AND CHEMICAL FATE OF DREDGED MATERIAL IN THE DEEP OCEAN

A. INTRODUCTION

SETTLEMENT CHARACTERISTICS

PHYSICAL FACTORS OPERATING DURING DISPOSAL

Adaptation of Stokes' Law

The settling rate of small particles through the water column follows Stokes' law:

$$Ws = \frac{\rho_1 - \rho_2 \ gd^2}{18 \ V}$$

where Ws is settling rate, ρ_1 is particle density, ρ_2 is fluid density (i.e. water column), V is the viscosity of the fluid, g is the acceleration due to gravity (980 cm/sec^2) and d is the particle diameter in centimetres.

The actual behavior of dredged material in the deep ocean is controlled by several important factors. For one thing, much of the material does not fall as individual particles but as a density current wherein a high percent of composite particles is formed. Thus, on the average, from Stokes' law, particles around 3μ will settle less than a metre per day in a water column that is motionless and well mixed. However, application of the law is modified by physicochemical flocculation in the immediate period following dumping (Krone, 1976). As will be shown later, those fines that do remain in the water column can (and frequently do) undergo agglomeration through biological activities.

Descent of Dredged Material Through the Water Column

Several intrinsic factors will determine in part the spatial disposition and ultimate physical fate of dredged material pursuant to disposal. The most important of these are the spectrum of particle size at the time of and shortly after the disposal and the overall or bulk density of the dredged material. The latter, which will fix the initial rate of descent, is determined by the percentage of moisture (PCM), the "lights" such as organic detritus, and the density of various kinds of sediment particles.

As the material drops from the container vessel it possesses a bulk density greater than the ambient water and thus it acquires a downward momentum causing it to act as a cloud of dense liquid. Within seconds, shear stresses develop at the fluid/fluid interface reducing the momentum and raising turbulence that entrains sea water. If the container vessel is moving at the instant of disposal, imparting a higher momentum to the cloud, there will be even more thorough invasion of sea water. Gordon (1973a, 1973b) estimated the initial descent speed of silty material discharged in shallow water from a scow to range up to 5 m/second but it decreases to 1 m/sec near the bottom. There are, of course, good reasons why this speed will not be maintained to the bottom by all the material discharged into deep water.

As the material is discharged from the container vessel it will be accelerated by gravity and reach its maximum speed in the first few metres. It then gradually slows down due to entrainment of ambient water. The latter process decreases the cloud's density at the very time the density of the ambient water will very likely be rising as an indirect effect of depth increase. Descent of the cloud will be slowed and it can suffer dynamic, vertical collapse and horizontal spreading upon encountering a strong pycnocline, which it will inevitably do in deep ocean disposal (Figure 16). Settling velocities calculated for individual particles do not apply in the case of average dredged material up to the point of collapse; thereafter, however, rates for particulates, although they may be compound particles, are more generally applicable. Thus, the denser particles, individually or

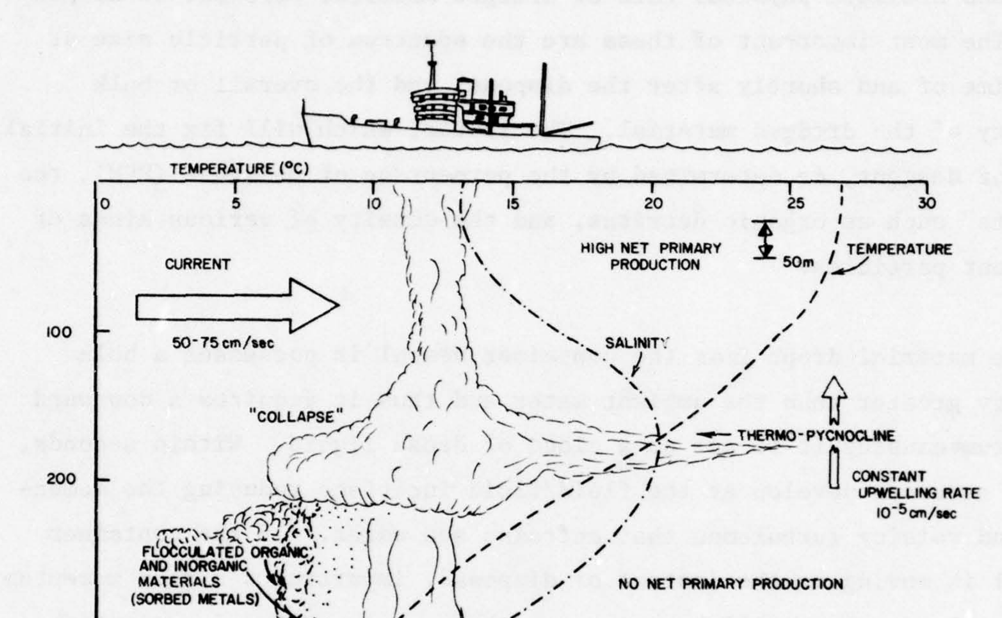


Figure 16. A schematic picture of the disposal of hopper-dredged material into a two-layered deepwater system (1000 m) with a strong thermo-pycnocline. Note the depth of high net primary production (25-50 m), the spreading of some fine material on the thermocline, and the minimal effect of upwelling as material passes through the thermocline.

as floccules, pass on through to the bottom, while the remainder, which will undoubtedly be a small percentage by weight, enter a long-term dispersion and settlement of the cloud. If an initial collapse occurs at a pycnocline, the fine materials that spread out on the density discontinuity are subject to ingestion by filter-feeding organisms (particularly small copepod crustaceans that abound in all oceans). These organisms, among others, take particles ranging in size from 1 to 50 μ and eject them in fecal pellets that range from 30 to 3000 μ (Haven and Morales-Alamo, 1972). These pellets have a density of about 1.2 and sink at rates of from 0.02 to 2 cm/sec (Smayda, 1969), which are rates typical of coarse silt or fine sand grains.

Krone (1976) has cited the effect of flocculation on sedimentation and demonstrated how it is affected by organic and inorganic salts. But physicochemical flocculation is not only a function of salinity (Krone, 1962) but also of the cohesive nature of the particles (Einstein and Krone, 1962) and the concentration and chemical nature of the fine material (e.g. illite or montmorillonite), as determined in part by Whitehouse et al. (1960). Turbulence of a certain strength may bring an increase of flocculation by increasing frequency of interparticle collisions, but beyond some critical point an increase of turbulence actually leads to disaggregation.

There is considerable evidence mounting that physicochemical flocculation is not the predominant process for the formation of composite particles (Schubel, 1971). In support of the importance of organisms in composite particle formation, Manheim et al. (1972) found that copepods are important in flocculation in the northern Gulf of Mexico. It is important to note that these larger particles will settle faster than would individual particles.

It is quite evident that much fine silt and clay does not settle as single grains in marine waters, whether the input is riverine or from dredging-disposal operations. As Drake (1976) concluded, physicochemical flocculation can and does produce settling rate increases that range up to about one order of magnitude, whereas biological processes can account for increases of up to several orders of magnitude. Accordingly, these physicochemical and biological factors will be acting upon the residue of fine particles (the plumes) that is left at the surface, that marks the vertical trail of the "slug", that accumulates at the pycnocline, and that arises following bottom contact.

The effects of currents are discussed in a later section of this part in a discussion of factors modifying the spatial disposition of dredged material on the deep ocean floor.

CHEMICAL FACTORS OPERATING DURING DISPOSAL

Changes During Descent

The chemical and physical characteristics of dredged material will almost always be very different from those of sediments lying in deeper and more open oceanic environments. The same factors that affect material during natural transport will also affect dredged material during and after disposal. These issues are discussed in considerable detail in later sections of this report. Nevertheless, a cursory overview at this time may be helpful to the reader. At this time, the two items of concern are that the dredged material will suffer some changes in water column transit and that these changed materials (whatever the percentage of the total discharge may be) will have some impacts on the disposal environment including, of course, the biological component.

Oxygen Depletion. Considering the small ratio between the disposal volume and the receiving water column it is unlikely that the disposal of dredged material into deep ocean water would result in significant oxygen demand represented by most dredged material that possesses increments of organic matter and reduced substances. However, some rather substantial changes in the dredged material itself can take place, as is discussed later in this chapter.

Change in pH. Removing dredged material from an estuary or bay and discharging it into the deep ocean will generally involve exposing it to a higher pH. This can be very significant because adsorption-desorption reactions involving trace metals are controlled by specific pH-dependent surface reactions wherein metal ions are exchanged for surface-bound hydrogen ions. In general metals will be adsorbed with increasing pH (surface seawater pH = 8.2) and desorbed with decreasing pH, which may go as low as pH 5.0 in natural environments.

Salinity Changes. In most situtations one can expect that dredged material, when discharged into the deep ocean, will be exposed to a higher salinity than at its point of origin. This can change the net result of the adsorption-desorption process mentioned above. If there is concern for changes in metal availability in a specific dredging-disposal situation, then the effect of the salinity change factor in the intended receiving environment must be taken into consideration, as is discussed in some detail in a later section of this chapter.

Anoxic-H_2S-Rich Environments. Several closed basins that are anoxic, or nearly so, and rich in H_2S are known in the world ocean. In fact, there are several off the Texas-Louisiana coast. These are considered by some to be favorable receiving environments for seriously contaminated material, in that the discharged dredged material will end up as reduced bottom sediments chemically similar to the starting material. Moreover, the anoxic condition results in the absence of most benthic organisms that ordinarily rework and mix sediments.

Bottom Contact and the Chemical Aftermath

Chemical diagenesis in sediments is a relatively straightforward topic, but it is so multifaceted that few useful generalizations can be made. In other words, each major disposal operation should be studied thoroughly prior to developing a release program. Standard water-quality analyses such as the elutriate test (Keeley and Engler, 1974) approximate the sorptive capacities of particulates falling through an oxygenated water column. This topic is discussed in considerable detail in subsequent sections of this part. Suffice it to state here that whatever chemical changes do occur that can produce deleterious effects on the infaunal and demersal biota will have a far lesser impact (if any) in the deep ocean than on the continental shelf or most shallower marine environments.

FACTORS MODIFYING THE SPATIAL DISPOSITION OF DREDGED MATERIAL ON THE DEEP OCEAN FLOOR

VARIATIONS OF DREDGED MATERIAL

Dredging Methods

At the present time the only dredged materials that will be candidates for deep ocean disposal are those produced and transported by such hopper dredges as the BIDDLE or the HARDING or by a clamshell dredge, such as the BOSTON. The latter type of dredge will fill a bottom-dumping barge, which will then be moved to the disposal site by a sea-going tug. In the future it may be desirable to develop systems whereby either a hopper dredge (or possibly a pipeline dredge) can fill sea-going barges instead of its bins so that it can dredge continuously without the necessity for disposal interruptions. This would simply mean outfitting a hopper dredge with pump-out capabilities to a barge similar to the beach nourishment activity off Long Beach, New Jersey in 1966 (Mauriello, 1967).

In February 1977 (personal communication, W. E. Pequegnat, TerEco Corporation, College Station, Texas) it was observed that one complete cycle of the hopper dredge CHESTER HARDING working in Honolulu Harbor was about 3 hrs and 15 mins, i.e., from completion of a disposal in the deep ocean (457 m) steaming back to the harbor, filling the hopper bin (2709 cu yd) steaming to the disposal site, and discharging. This in spite of the fact that the disposal site was only 3.6 nautical miles from the sea buoy, and it took only on the order of 2 minutes to empty the hoppers (with a flushing discharge). About seven complete cycles could be completed in a 24-hour day. This certainly falls within the critical economic distance for the haul of a hopper dredge, which is considered to be between 20 and 25 miles.

Clamshell dredges are not given much consideration here, simply because they presently carry out such a small percentage of the total dredging done in the United States today. Nevertheless, some consideration will be given to the fate of clamshell dredge material after disposal.

Percent of Moisture

For slurry consisting mostly of silts and clay (particle diameters of 4 μ to 60 μ and less than 4 μ, respectively), the studies by JBF Scientific Corporation (1975) indicate that the initial dilution of the slurry is critical with respect to the behavior of material in the water column. If the percent moisture content (PCM) of the slurry is less than 100, then the bulk of the material will fall essentially intact rapidly through the water column with little if any entrainment of fluid. If the initial PCM is above 200 for silts or above 300 for clays, then the slurry will act essentially like a dense fluid at least initially.

Mineralogy of the Dredged Material

In general one would prefer during the disposal phase to have the material retain a small volume prior to passing through the photic zone (or possibly the seasonal thermocline, which will be shallower) and then increase its dispersion prior to hitting the bottom. Such action would minimize any biological impacts. Fortunately this scenario is very likely what will eventuate to much of the dredged material (assuming it will be a mixture of silt and clay) discharged in the deep ocean. As indicated above, the water content has a very pronounced effect on dispersion and subsequent mounding. Below a critical moisture content the mass of particles can act as a single unit, settling with little dispersion. As the moisture content is increased (at the time of disposal) the material breaks up in the water column and also upon impact yielding widespread and generally uniform dispersion. But it is to be noted here that the nature of the dredged material can also modify this mounding vs. dispersion mode. For instance, the JBF (1975) report demonstrates a tendency for silt to disperse at a lower water content than clay, due very likely to considerably lower cohesive forces between the silt particles as compared to the clay particles.

Even though the JBF tests were run in very shallow tanks, so that it is probably unwarranted to transfer the above conclusion to the field in the case of very deep water, it is possible to reinforce previous observations that cohesive forces will very much influence the behavior of dredged material as it falls through the water column and during and after bottom contact.

MOVEMENTS OF THE DISPOSING VESSEL

Movements of the vessel containing the dredged material to be disposed prior to and during the instant of disposal can affect the spatial disposition of the material on the ocean floor.

In a hopper dredge some consolidation and decrease of PCM in materials has been noted as a function of time. However, direct measurements by JBF Scientific Corporation's 1975 report reveal that the effects are not significant in running times less than about one hour and then only in regard to the material in the upper half of the hopper. This consolidation occurs more as a result of maneuvering of the ship (probably allowing water pockets in the bin to escape to the surface) than of vibrations. Time also may permit greater amounts of water of imbibition to be picked up by individual particles creating a gel state, which will permit the "slug" to act more as blocks.

The method of disposal can influence the ultimate fate of the material to a greater or lesser extent. Again the statements apply only to disposal from hopper dredges or from bottom-opening barges. Two variables are involved, viz., the container can discharge underway or while stationary and water can be pumped into the bins during or after the drop.

During the February 1977 dredging of Honolulu Harbor referred to previously (Personal Communication, W. E. Pequegnat, TerEco Corporation, 1977), it was noted that the hopper dredge HARDING was moving at less than 0.3 kn in a long radius turn during the two minutes required to discharge the 2709 cu yd of material from the eight hopper bins, including the simultaneous rinse with seawater. The only surface manifestation of the disposal was a slightly crescentic turbid streak estimated to be 75 ft wide (vessel's beam is 56 ft) and about 350-400 ft long (vessel's length is 308 ft). It was observed for approximately 20 minutes, during which time it did not appreciably change shape or coloration. Much of this was very fine-grained material undoubtedly derived from the rinsing process. Since the vessel draws about 21 ft of water when loaded, the fact that any material reached the surface is probably attributable to the rapid rise of the vessel as it lightens and the upwelling created by its sideslipping during the turn. If the vessel discharged slowly while at rest very likely little or no surface effects would have been noted. In any event, what there was would cause no appreciable impacts on the pelagial zone.

EFFECTS OF CURRENTS

It is generally agreed that currents exert minimal effects on the deflection of the main mass of dredged material when it is discharged in shallow water. Obviously the fine materials that form a turbid cloud in the water column and the spreading cloud upon bottom impact will be carried for some days or months in the water mass. Also, bottom currents will affect the bottom mass in due time. But this discussion is concerned with the transit of material from the container vessel to the bottom in deep water. In these cases currents can be expected to have graded effects. Certainly dense clumps of material very likely will plunge to the bottom with minimal deflection, but the material that suffered "collapse" at the pycnocline will undoubtedly be carried by the moving water mass. The question arises as to just how much horizontal deflection from the vertical drop-line the material will undergo. This will depend principally upon the vertical distribution of water movement and partly upon the amount of time the material remains aloft.

Drift currents caused by the wind over deep water in the northern hemisphere will move somewhat to the right of the wind (Coriolis effect) at a speed roughly 3 percent of the speed of the wind. This shift to the right becomes more and more pronounced with depth. Wind starts the thin surface layer in motion, this in turn drags on the one below setting it in motion but with a further deflection to the right. Current direction at a certain depth below the surface will be 180° out of phase with the surface. Also, because of the inefficiency of the transfer of momentum, the current velocity decreases with depth. This phenomenon is called the "Ekman spiral." Even under strong winds these effects are not noticeable below

30-m depth. Generally when the current has been completely reversed, the current speed will be about 1/25 that of the surface.

Obviously other currents may well be involved below the 100-m isobath. Other intermediate currents and bottom currents, caused principally by density differences, can have displacement effects on the dropping dredged material. These too can vary in magnitude and direction with depth, but on a much greater depth scale than the Ekman layer.

IMPORTANCE OF LONG-TERM VS. SHORT-TERM BOTTOM INFLUENCES

SHORT-TERM EFFECTS

Bottom Currents

Since the definition of deep ocean used here includes that water lying over the shelf break and beyond, and since the depth of the break may in some cases be over 200 m, some attention will be given to the effects of bottom currents on recently disposed dredged material. Southard and Stanley (1971) believe that there is no need to consider that movement of mud and sand off the shelf break onto the continental slope is restricted to canyons. The accepted view is that the shelf edge possesses stronger currents than either the shelf proper or the upper slope. These will tend to keep fine sediment in suspension or perhaps resuspend it frequently so that fine material coming from nearshore areas is transported to the continental slope or beyond without permanent deposition near the shelf break.

There are numerous causes of the bottom currents observed at or near the shelf break and the upper continental slope, among which are:

1. Occurrence of internal waves--these tend to have rather long periods, i.e., interval between waves, (10 min to 12 pendulum hr).
2. Tidal motions, which may be twice daily (semidiurnal) or diurnal.

3. Propagation (passage) of normal surface waves, which generate oscillatory movements of rather short periods.
4. Wind-driven currents, produced either by steady winds or accentuated by storm conditions.
5. Temperature-salinity (thermohaline) circulations that generally influence large areas, including the shelf break and beyond.

Some of these currents are sufficiently strong as to activate both bed load transport of coarse sediment and resuspension of any fine sediment that has settled during quiescent periods. Komar et al. (1972) have noted that surface waves may have oscillatory ripple effects on the bottom to depths of at least 200 m. Ewing (1973) reported that refraction of large waves by irregularities in the trace of the shelf edge can produce a pattern of augmented and depressed oscillatory bottom currents resulting in much stronger or weaker bottom sediment transport.

In many areas there appears to be a maximum in tidal current velocities near the shelf break (Fleming and Revelle, 1939; Kuenen, 1939). Maximum tidal velocities are proportional to distance from shore divided by local water depth. This ratio is often greatest at the shelf edge.

Galt (1971) has found that under certain conditions a moving storm can produce a wave that will generate bottom currents concentrated at the shelf break. The current extends throughout the water column and parallels the bottom contours. Calculated speeds are on the order of 10 cm/sec, which could augment tidal and wave-produced currents to the point where they could resuspend fine materials and aid bed load transport of coarse sediment near the shelf break (Southard and Stanley, 1971).

If there is density stratification over the shelf break and the continental slope, as there often is, internal waves with a wide range of amplitudes and periods can be present (LaFond, 1961 and 1962).

It is thought that both standing and progressive internal waves might move sediments on the continental shelf or slope (Emery, 1956; LaFond, 1961), but this seems unlikely unless there is interaction with bottom topography (breaking of the waves).

The ultimate effect of any or all of the above water movements on the dredged material will depend in part upon the relative difference between the discharged sediment and that of the receiving bottom environment. For instance, Sternberg et al. (1976) found that they could still identify a dredged sediment deposit even though during winter storms it was being covered by migration of the native sediment. On the other hand, others have reported that storm-wave induced currents have moved dredged sediment mounds several kilometres across the shelf in relatively shallow water. This would not occur on the continental slope or deeper bottoms.

Currents in Submarine Canyons

If dredged material were to be discharged into submarine canyons, recent textural evidence and direct observations show that currents are strong enough in upper parts of the canyons to provide for a net downslope transport of the sediment. Shepard and Marshall (1973) and Shepard et al. (1974 a, b) have reported currents with speeds of up to 38 cm/sec moving both up and down canyons off the California coast. Downcanyon velocities are higher and of longer duration than upcanyon, indicating that net transport of sediment will be toward the ocean floor. Similar observations have been made in Wilmington Canyon off the East Coast by Stanley et al. (1972) and Lyall et al. (1971).

LONG-TERM EFFECTS

Biologic Processes

Progressing into the deeper reaches of the ocean, higher percentages of deposit-feeding invertebrate animals are found. The activities of these organisms, skimming off the thin layer of organic matter in the surficial sediments or burrowing various depths into the sediment bed engulfing sediments more or less indiscriminately, undoubtedly lead to important long-term effects in the deeper zones of the ocean.

Bioturbation. Various kinds of benthic organisms possess the capability of reworking soft sediments to considerable depths beneath the sediment surface. Pequegnat et al. (1972) show large burrows of animals at depths of over 2000 m in the northern Gulf of Mexico. The suspected burrower in this case is the Giant Isopod (Bathynomus giganteus), which is capable of moving large amounts of sediments in a few moments. Others observed working sediment in deep-sea photographs are holothurians, (sea cucumbers), which pass masses of sediment through the intestines and eject mucus-covered fecal ropes; caridean shrimps such as Glyphocrangon nobile, which create labyrinthine burrow systems in 1200 to 1500 m of water; and even fishes such as the Grenadier, which scoop out sediments with their snouts during feeding activities. Polychaete annelid worms are prominent among deposit-feeding organisms from the inner shelf to the abyssal plain. Pequegnat et al. (1972) have photographed at depths of 3200-3722 m in the Gulf of Mexico polychaetes in the families Ampharetidae and Maldanidae, which build mucus-sediment tubes. These animals and others, including tracks and trails, are only the surface manifestations of the subsurface reworking of sediments going on in the deep ocean at least to depths of 15 or more centimetres (Bruun, 1957; Thorson, 1957; Owens et al., 1967).

There is a good possibility that the activities of burrowing and epibenthic organisms may contribute to the load of suspended sediment found in the bottom water over muddy-clay sediments (Kelling and Stanley, 1976). In fact, Dr. T. Bright (Personal Communication, Dept. of Oceanography, Texas A&M Univ., 1976), while aboard a deep submersible, observed, in summer of 1976, actual resuspension of muddy bottom sediment emanating as a turbid stream from burrows at depths of several hundred feet off the Texas coast. W. Pequegnat (Personal Communication, TerEco Corporation, College Station, Texas, February, 1977) believes that some of the organisms involved are the caridean shrimp, *Glyphocrangon*, and that these and other organisms (including some fishes) may be important contributors to the nepheloid layer in this region (see Part 3B of this Section). When these activities are numerous enough on the continental slope, they may reinforce existing processes of downslope transfer and perhaps provide a triggering mechanism for large-scale sediment movement (Kelling and Stanley, 1976).

Burrowing organisms are also responsible for the construction of mounds, some of which are several centimetres high, and labyrinthine, open burrow systems, the effects of which are to increase the excess pore pressures in fine sediments leading to underconsolidation. All of these activities will contribute to shear failure and possible slumping, which will promote downslope movement.

All of the above activities will very likely be conducted in dredged material discharged on the shelf break or the upper continental slope. It is not anticipated that there will be much fatal smothering of organisms in this environment, both because mounding will not be as severe as in shallow water and because the organisms are often exposed to massive movements of sediment in these environments.

In this context submarine canyons could make good disposal areas because their sedimentary fill is generally regarded as being in an unstable condition (Shepard and Dill, 1966). Apparently, the steepness of the walls of these canyons results from collapse of sediments under the influence of activities of both burrowing and boring organisms. Documentation for this conception comes from observations of Dillon and Zimmerman (1970) in some canyons off Georges Bank, from Stanley et al. (1972a) for Wilmington Canyon off Deleware, and from Shepard (1973) for LaJolla Canyon, California.

Chemical Modifications After Deposition

Dredged material undergoes diagenetic chemical changes after disposal that will eventually bring them into dynamic equilibrium with factors of the ambient environment. There are exchanges in both directions, i.e., from dredged material into the receiving sedimentary and aqueous environments and vice versa. Some of these processes may require on the order of tens or perhaps even hundreds of years to reach equilibrium or completion. As might be expected the activities of organisms can facilitate some of these actions by opening up channels between old and new sediment masses and permitting a freer flow of water. Thus, processes that depend upon diffusion for completion will be speeded up by advective exchanges. Not only are metals involved in these diagenetic processes, but also organic compounds suffer hydrolysis. The organic detritus in dredged material that reaches the bottom may very early be the source of amino acids, simple sugars, and fatty acids that will sustain a microflora and meiofauna that pioneer population of the introduced sediment.

B. PHYSICAL CONTROLS

DESCENT OF DREDGED MATERIAL THROUGH THE WATER COLUMN

GENERAL STATEMENT OF PROBLEM

The spatial distribution, the temporal evolution, and the ultimate fate of material disposed in the deep ocean from a hopper dredge is something that is perhaps impossible to predict in a completely deterministic way because of the great variability of the factors that control its bulk properties and passage through a water column whose current structure is also variable in space and time. In addition even if all the important factors pertaining to the dredged material and the water column were known, at the present time there appears to be no universally applicable model for quantitatively predicting the time history and ultimate fate of typical material released in the sea. Nevertheless one can make useful qualitative statements about the behavior of the released material based on evidence from existing laboratory and field studies, plus certain basic physical principles.

PERCENT OF MOISTURE

In a 1975 report prepared for the San Francisco District, Corps of Engineers, by JBF Scientific Corporation, the results of tank tests and field observations provided some data that are applicable to important aspects of deep ocean disposal. The percent moisture content (PCM) of the dredged material is an important characteristic that varies with

1. the nature of the material being dredged,
2. the type of dredge being used,
3. the vertical position of the material within the bins of a hopper dredge, and
4. the time between dredging and disposal.

PCM is defined as

$$\frac{Ww}{Ws} \times 100$$

Where Ww is weight of water and Ws is dry weight of the solids. It is beyond the scope of this study to discuss the permutations among these parameters in detail, but it must be emphasized that the PCM of the dredged material, other things being equal, will determine (a) the amount of the dredged material that will reach the bottom in a short time, (b) the area on the bottom that it covers, (c) the direct and immediate impact upon the pelagic and benthic fauna, and (d) the effects of the environment upon the disposed material.

When working with clay and silt, or mixtures thereof, disposal characteristics of the dredged material are separable into two distinct classes, solid and liquid, that behave differently upon disposal

(JBF Report, 1975). These are as follows:

Solid Mode	Liquid Mode
1. Low PCM.	1. High PCM.
2. Observed in barge filled by clamshell dredge.	2. Observed in material of the upper few feet of hopper dredge (much affected by transit time).
3. Usually found in the bottom half of hopper dredge.	3. Characteristic of pipeline dredge material.
4. Falls as solid blocks.	4. Falls as a liquid cloud.
5. Rapid descent, no deceleration before impact.	5. Slower descent phase.
6. Little cloud growth.	6. Cloud expands due to entrainment.
7. Trails a small turbidity plume.	7. Deceleration of descent rate is significant.
8. Little spread of material on bottom after impact, but this depends upon cohesiveness of material disposed.	8. Horizontal momentum on bottom considerable, producing laterally spreading cloud.
9. Pycnocline has effect only on small trailing turbidity plume.	9. Pycnocline has effect on falling cloud, possibly producing first collapse.
10. Generally some mounding on bottom, even in deep water.	10. Little or no mounding on bottom.

The criticality of PCM to the behavior of any particular dredged material is also dependent upon dump size and water depth. Accordingly, any material that has a PCM within the solid mode but near the solid-liquid transition value(s) may shift to liquid behavior, involving entrainment, when dropped in deeper water and possibly even if dropped in small volumes.

No hard and fast rule can be given for prediction of this behavior in specific cases, but the JBF tests (JBF Scientific Corporation, 1975) seem to indicate that no entrainment (and all the associated water column effects that entrainment implies) will occur in either silt or clay up to PCM = 100. But beyond that point definite entrainment will occur for silt at PCM = 200 or more and for clay at 300 or more.

For the fluid case, it must be borne in mind that a wide spectrum of particle sizes exists. The density of the individual mineral particles is typically about 2.5 times that of the seawater and hence the negative bouyancy of the individual particles is considerable. The particles will therefore initially be accelerated downwards. If they were very widely dispersed (extreme dilution of the order of 3000 or more PCM or one particle per 30 parts water), then the particles would reach a terminal velocity relative to the water dependent upon their size and relative density (as determined by Stokes' law if sufficiently, small, see Figure 17. The larger or denser particles would fall more rapidly thus tending to sort out the size distribution within the water column. Such a <u>settling phase</u> is expected only in the later stages of the descent of the material, after sufficient entrainment of seawater has occurred to produce the required dilution. In this stage the negative buoyancy force on an individual particle is balanced by the viscous drag exerted by the fluid. This implies in turn that an equal and opposite force is exerted on the fluid by the particle. Because of this, the pressure of the fluid at a fixed level beneath the settling particles is slightly greater than its value in the absence of the particles, but this is essentially a passive effect, the fluid itself being otherwise uninfluenced by the particles.

CONVECTIVE STAGE

In the initial stage of a moderately dispersed ensemble of particles, a similar tendency will exist for the individual particles to try to attain terminal velocity relative to the fluid. However, in this

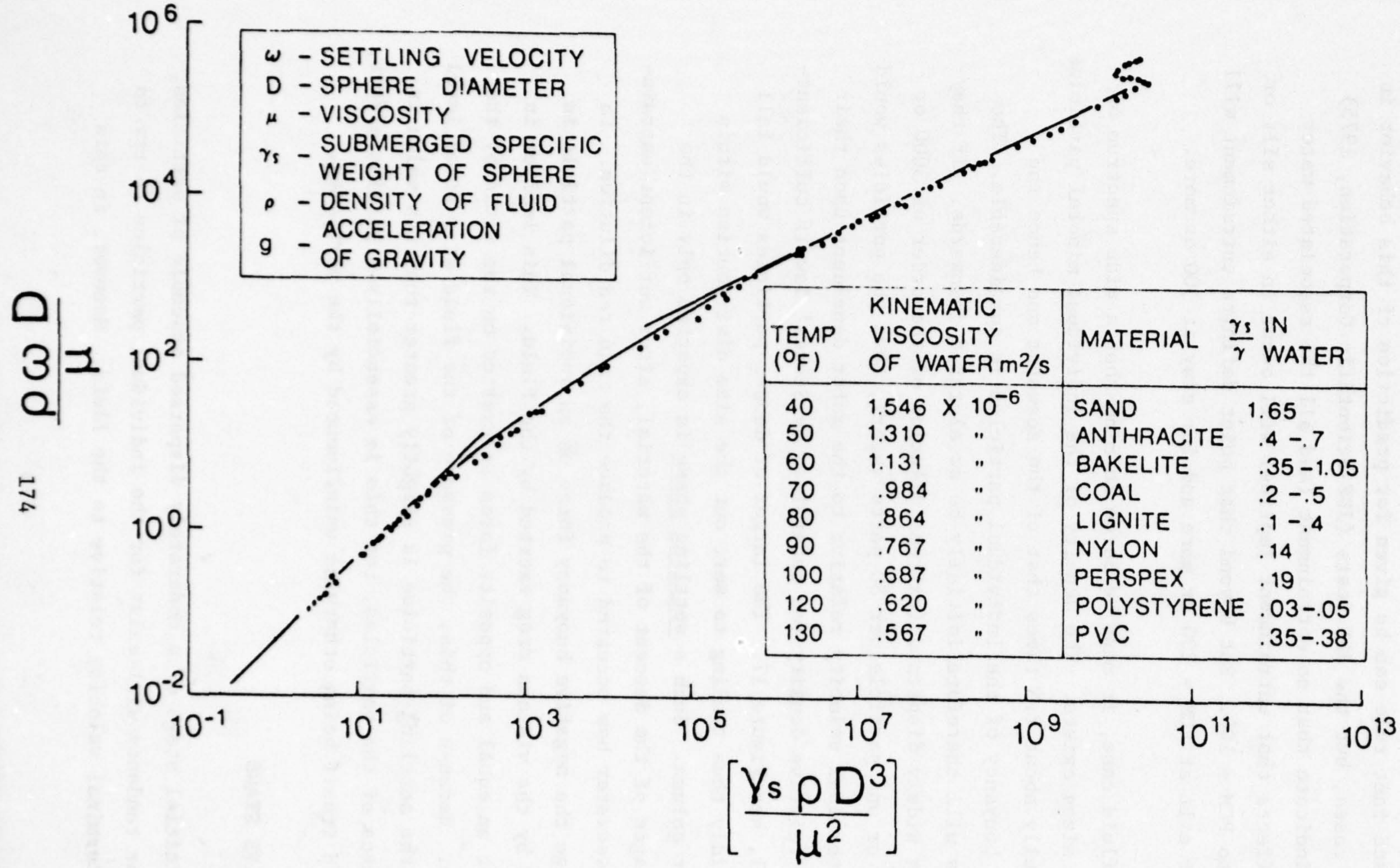


Figure 17. Fall velocity of spherical particles. (From Krishnappan, 1975).

stage the effect of the particles on the fluid acts in a more active manner, producing horizontal and vertical pressure gradients and motion of the fluid that cause the ensemble of particles to act as a dynamic interacting unit, such that the entrained fluid as well as the particles descend at some common speed, which actually exceeds that of the individual particle settling speeds. In essence the ensemble of particles and entrained fluid act like a dense fluid.

An essential feature of this fluid stage is the tendency for a relative motion field* within the cloud to be set up in which downward flow occurs in the central region of the cloud and upward flow exists in the outer regions (just the opposite but otherwise similar to convectively maintained water droplet clouds in the atmosphere, which also possess a wide spectrum of droplet sizes). The above relative motion field is referred to as a vortex ring--it is analogous to the motion in a smoke ring whose axis is vertical. This type of motion is characterized by its azimuthal vorticity, which is associated with a closed circulation (of fluid and particles) in a vertical (γ, z) plane through the center of the cloud (Figure 18). It is this circulation that tends to maintain the cloud as a unit. However, at the same time this circulation also tends to enhance the entrainment of ambient water into the cloud primarily on the top side, where the central motion is into the cloud.

The mechanism responsible for generating and maintaining the vortex ring circulation, in the presence of dissipative effects (resisting torque) due to turbulent mixing of vorticity with the environment, is the <u>radial gradient of effective density</u> within the cloud (density of the fluid-particle mixture). An analogous problem in two-dimensions has been treated by Csanady (1965) and by Crew and Reid (1976) for the descent of a dense effluent continuously injected into a stream.

*Relative to the center of mass of the cloud of material.

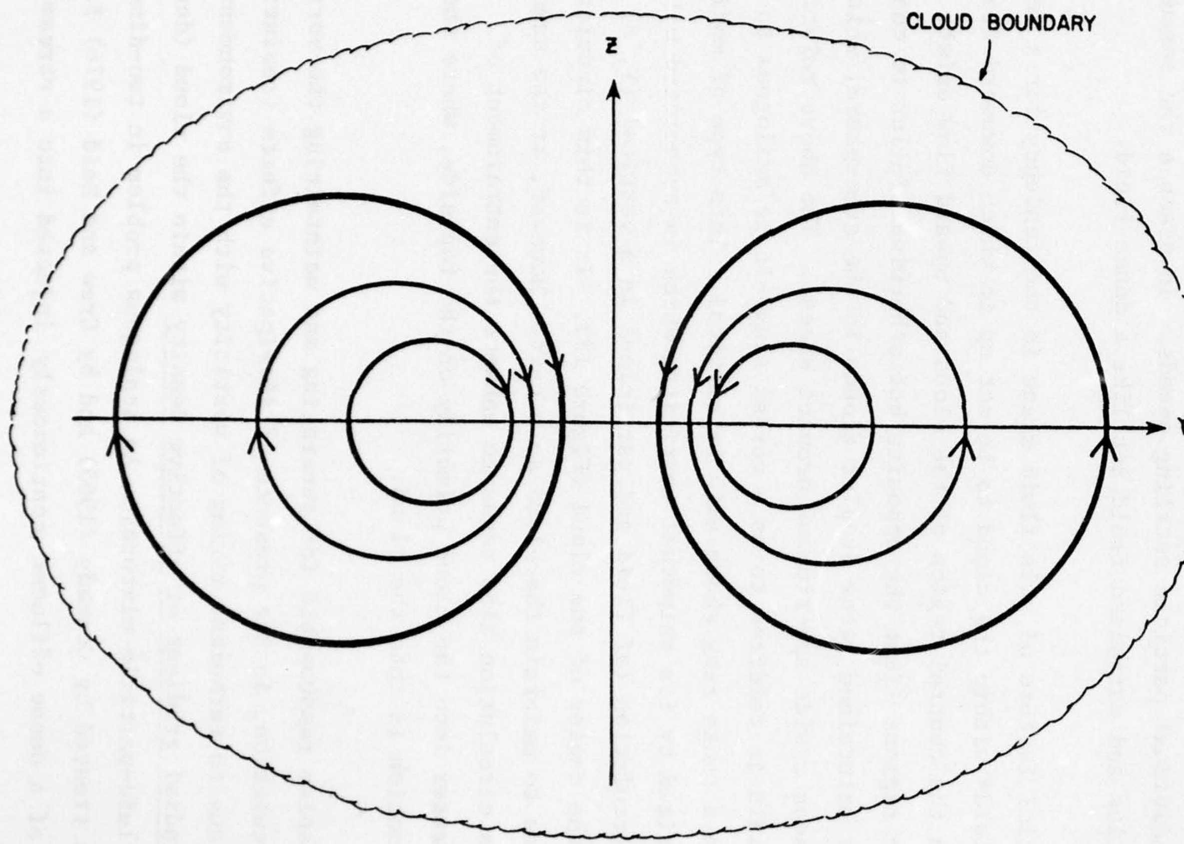


Figure 18. Schematic of relative circulation in a vertical plane through a cloud of moderately dispersed slurry.

These analyses, however, were restricted to the case of a homogeneous environment (i.e., no stratification). The method of analysis in the cited studies contrasts with that of the models of Edge and Dysart (1972), Koh and Chang (1973), Krishnappan (1975), and Brandsma and Divoky (1976), since it employs only the predictive equations for vorticity and negative bouyancy of the cloud, the circulation field and descent rate being implicitly related to the vorticity. The model of Brandsma and Divoky (1976) does include a computation of vorticity of the cloud by a method attributed to Turner (1960); the vorticity in the latter model is employed in estimating an entrainment rate, which is required in the equations of motion and continuity. One of the difficulties of the models that employ the equations of motion directly is that the results are sensitive to assumptions concerning the net pressure forces acting on the cloud. This is avoided in the procedure of Csanady (1965) but is replaced by perhaps an equally difficult problem of assigning meaningful diffusion coefficients for vorticity.

The circulational regime discussed above is associated with greater downward velocity in the center of the cloud that the upward velocities in the outskirts of the cloud, with the result that the net velocity of the cloud is downward as expected. In the case where the cloud descends into a region of greater environmental density (e.g., in the pycnocline region of the ocean), then the lateral density gradient tends to be reduced resulting in a reduction in the maintenance of the vorticity. This results in a slowing of the descent and a lateral spreading of the cloud, which in turn produces a stretching of the vortex filaments. The latter is accompanied by a further catastrophic decrease in the intensity of the vortex ring circulation, which can result in a virtual collapse of the fluid vortex ring regime and set the stage for the settlement regime.

It is understood that any really large conglomerates of particles have already passed through the cloud and by virtue of their large density have penetrated through the pycnocline region. Those particles that may be trapped in the thermocline are the truly fine clays whose size is such that their settling velocity is comparable to the natural upwelling maintaining the thermocline, which is normally of the order of 10^{-5} to 10^{-4} cm/sec. These fine particles can be carried horizontally by the existing currents for large distances before ultimate settling out to the abyssal regions. If the release occurs in regions of intense coastal upwelling where upward currents of 10^{-3} cm/sec (100 m/day) can occur, then some of the medium silts or larger clay particles may remain suspended in the thermocline for some time.

OCEAN DENSITY STRUCTURE

Three factors determine the density of sea water, viz., salinity, temperature, and pressure. At midlatitudes temperature may vary from over 20°C in the surface layers to less than 2°C in the abyssal depths of the ocean with a very rapid decrease in the thermocline region, which usually occurs in the upper 500 metres and much shallower near shore. Salinity usually varies by 1 to 2 g/kg with depth from about 35 g/kg in very deep water to values either above 35 or below 35 in the surface layers depending upon location.

The density of seawater increases by about 0.8 mg/cm^3 with an increase of salinity of 1 g/kg. The temperature dependence is nonlinear. However, for a decrease of temperature of 5°C centered at 15°C the density will be increased by about 1 mg/cm^3. The dependence on pressure is such that an increase in depth of about 250 metres produces an increase in density of 1 mg/cm^3. Normally in most considerations of density the pressure effect can be ignored. In fact the gravitational stability of a column of seawater depends on $d\sigma_t/dz$ where σ_t is the anomaly of density from 1 g/cm^3 expressed in mg/cm^3 and evaluated for 1 atm of pressure. Typical variation of σ_t with depth is from about 24 or 25 mg/cm^3 in the surface mixed layer to 27.8 mg/cm^3 in the abyssal depths. Typical contrast across the thermocline (or pycnocline) is about 1 to 2 mg/cm^3.

When pressure effect is taken into account the seawater density can range from about 1.024 to 1.030 g/cm^3. This variation has very little effect on the settling velocity of mineral particles (silts and clays) since they have a typical density of about 2.6 g/cm^3. A greater effect on the settling rate of fine particles for which Stokes' law is valid is due to variation of viscosity with temperature. Typical values of the kinematic viscosity on the surface layers is about 0.9×10^{-2} cm^2/sec and about 1.5×10^{-2} cm^2/sec deeper than 1000 m where temperatures are less than 5°C. Since Stokes' law indicates an inverse relation to the viscosity, this means that the settling rate of the fine particles is decreased in passing through the thermocline due to the increase of viscosity and not due to the change in density. Of course for light organic material the density contrast across the thermocline might be important.

The primary importance of the pycnocline is in respect to its effect on the cloud of moderately dispersed material whose effective density is comparable to but somewhat larger than the seawater density. As discussed earlier the arresting effect of the pycnocline on the descending cloud can lead to a collapse of the dynamic circulation within the cloud and thus initiate the settling stage in which the silts and possible flocculated clays will rain downwards at their individual terminal speeds. It should not be implied however, that collapse of the cloud necessarily occurs at the thermocline, for if the thermocline is fairly shallow the cloud could pass through intact and possibly make the transit to the sea bed before collapse.

INFLUENCE OF CURRENTS

For the case of the descent of initially low PCM material, the bulk of material presumably will drop essentially like a solid mass through the water column. The transit time for depths of the order of 1000 m will be sufficiently small (of the order of several minutes to tens of minutes) that the influence of currents in transporting the material laterally will be minimal.

On the other hand for the initially moderate to high PCM material which can produce an entraining cloud, which collapses either at the thermocline or at middepth, the fine silts and clays whose settling rate is less than 0.001 cm/sec can clearly be carried large distances (thousands of kilometres) before settling to the bottom, typical subsurface currents approaching 10 cm/sec. In fact, clay particles of the order of 1 micron in diameter might be suspended in the thermocline indefinitely. The reason for this is that throughout most of the ocean where a well-developed permanent thermocline exists, it is generally associated with a slight upwelling rate of 10^{-5} cm/sec (roughly one cm/day). This is sufficient to keep the fine clay particles suspended. One wonders about the implications of this with respect to a possible build-up of turbidity of the upper layers due to continual deepwater disposal. On the other hand such material would be swept by the ocean currents over vast areas of the oceans from a finite number of potential disposal sites. Thus it is improbable that any significant localized buildup of turbidity would occur much above that associated with naturally occurring organic detritus.

BOTTOM CONTACT AND THE PHYSICAL AFTERMATH

The details of the effects of the descending dredged material as it impacts upon the bottom are not fully understood nor can they be delineated easily. Indeed, these effects will vary with the nature of the dredged material, including its mineralogy, grain-size spectrum, its water content (PCM), how it is discharged, and water depth. There will also be interactions with factors of the water column, e.g., density structure and currents, that will determine the amount and dispersion pattern of the "slug" that impacts the bottom. Since these parameters will determine either directly or indirectly much of the overall effect of dredged material disposal, they are worthy of critical discussion, but it is to be remembered that few observations of this bottom contact phenomenon have ever been made in truly deep water. Therefore, one must extrapolate a few points from observation in shallow water (e.g., Bokuniewicz et al., 1975), mindful of the probability that most if not all important effects will be of lesser magnitude in the deep ocean as compared with estuaries or even the continental shelf.

THE BOTTOM CLOUD

That part of the dredged material that penetrates the pycnocline may impact on the bottom and may probably produce a mound and a bottom cloud. The latter will usually contain some resuspended local sediment, particularly when large chunks of consolidated material reach the bottom. These chunks can cause some cratering, with distinct crater rims, as well as mounding. Formation of the bottom cloud may be inferred from observations made in 17 m of water (Gordon, 1974) and 20 m of water (Bokuniewicz et al., 1975). When bottom contact is made a density surge of highly turbid water occurs. Its exact nature will depend of course upon the sedimentary composition of the material that reaches the bottom (more fines will remain aloft in a deepwater column) as well as of the bottom material. The velocity of the vertical falling density cloud will decrease due to entrainment and head drag and to the changes occurring at the pycnoclinal collapse. When bottom contact is made the velocity change is immediate and discontinuous. At this moment horizontal spreading of the bottom turbid cloud begins and lasts for varying but generally short periods. In any event, while the cloud is spreading, it is also thinning; hence its effects on the bottom fauna are rapidly lessening on all radii from the point of bottom contact.

BOTTOM AREA COVERED BY DISPOSED MATERIAL

In shallow water (50 m or so) a high percentage of disposed material falls within a radius of 200 m or less from the impact point. For instance, Bokuniewicz et al., (1975) found that 80 percent or so of the material disposed from a stationary barge reached the bottom (50 m deep) within a radius of 30 m around the dropsite and 90 percent within a radius of 120 m, and that only 1 percent was dispersed over greater distances in the bottom cloud. In such cases neither the pycnocline nor currents would be expected to have substantial effects on the immediate fate of the material. But such may not be the case in much deeper water. In deep water both the pycnocline and currents can be expected to have considerable effects, especially on the fine materials. Thus, the amount of fine material to create the bottom density surge would be reduced. Furthermore, since the water column transit would be greater, the dilution of fines in the water column would be sufficiently great as to cause little or no irreversible effects upon pelagic life.

C. CHEMICAL CONTROLS

DURING WATER COLUMN PASSAGE

Any disposal of dredged material at sea is certain to result in some interaction between the dredged material and seawater, regardless of how rapidly the material sinks to the bottom. Of course, the longer the contact time the more extensive such interaction is likely to be, and the interaction will depend in its detail on the chemical and physical nature of the dredged material. Ideally one could predict the exact nature of all reactions if given a number of measurable properties of the dredged material and the disposal site water. In practice, needless to say, such properties are to some extent unknown, or only partially measurable, and therefore, whereas some predictions of possible behavior can be made, no complete description of what will happen as a given dredged material reacts with seawater can be derived.

Most dredging operations will be conducted for the purpose of removing material that has been rapidly deposited in harbors, bays, estuaries, and other nearshore environments. The chemical and physical characteristics of such material are considerably different from those of material (sediments) lying in deeper and more open oceanic environments. Thus, one can see that natural processes work to chemically and physically alter and fractionate material during its transport to and deposition in deeper water. The same factors that affect material during natural transport will also affect dredged material during and after disposal. For discussion purposes the most important of these factors can be considered under the following headings:

1) Redox and pH changes
2) Salinity changes
3) Minor component concentrations

It is the disposal environment, or more accurately the consequences for marine organisms of environmental change, that is of primary concern in ocean disposal of dredged material. Nevertheless, serious consideration must be given to the reaction of the dredged material itself, because this controls the environmental change. In this report, therefore, two opposite sides of the disposal coin will be considered; first, changes in and the fate of the dredged material, and secondly, in a later section (Part 3), the resulting changes (impact) on the disposal environment. The behavior and fate of dredged material during disposal is, obviously, strongly influenced by physical factors such as water depth and currents, and these are considered elsewhere, but chemical factors are also extremely important, as will be demonstrated below.

REDOX AND pH

The importance of dissolved oxygen in the disposal site water, both to living things at the site and to the behavior of dredged material during disposal cannot be overemphasized. In almost all open ocean environments it is the dissolved oxygen level that determines the reduction-oxidation (redox) character of the environment. Only when circulation and thus atmospheric renewal are restricted or when unusual demands for oxygen exist does its concentration become too low to control the redox level. It seems unlikely that the disposal of dredged material into deep ocean water would result in significant oxygen depletion, despite the potentially large oxygen demand represented by most dredged material, whether clean or contaminated. Even when free from all products of man's activities, nearshore sediments of the type likely to be dredged have a large oxygen demand. This is because the very thing that requires them to be dredged, namely their rapid rate of sedimentation, results in their containing organic matter and other reduced substances that did not oxidize before being cut off from the overlying water by burial. Thus, the re-exposure of these substances to dissolved oxygen at the disposal site will cause additional oxygen uptake. However, as stated above, it is unlikely that this uptake will significantly alter the oxygen content of most deep ocean waters due to the relative magnitudes of the available oxygen and the oxygen demand in the typical case.

If, then, only minor changes in water column oxygen concentrations are likely to result during transport of dredged material to the seafloor, are equally small changes in the chemistry of the dredged material itself to be expected? Here the answer is even less straightforward and once again the time and extent of contact between the material and oxygenated water are critical. Nevertheless, it is probably safe to predict rather extensive changes in the dredged material under many conditions of deep ocean disposal. These changes will in general reverse changes that the material has undergone during its time of residence at the dredge site and depend to a high degree on changes in the redox character in the environment.

Material removed by dredging will normally have arrived at the dredge site in a well-oxidized state, except for resistant organic matter and biological material produced at the site. Burial and isolation of the material from a supply of oxygen then results in reducing conditions and leads to a complex series of reactions that are discussed in detail elsewhere in this report.

As a consequence of reducing conditions in the sediment column certain chemical elements are converted to a lower oxidation state. Quantitatively, the most important of these are nitrogen, sulfur, iron, and manganese, and it is the re-oxidation of these elements during disposal that produces the most immediate oxygen demand on the water at the disposal site, while at the same time changing the chemical nature of the dredged material itself. Organic carbon from the dredged material also oxidizes to some extent in the water column during the disposal operation, but most of it survives to settle to the bottom where it is either oxidized or buried depending on the sedimentation rate, the nature of the organic matter, and other factors.

The re-introduction of oxygen into a mass of organic and inorganic material that has been removed from what were almost certainly reducing conditions at the dredge site can bring about, as briefly noted above, rather drastic chemical and physical changes in the material. A black smelly mud (rich in reduced forms of nitrogen, sulfur, iron, manganese, and perhaps other normally more trace components) may be, if sufficient oxygen and time are available, changed both physically and chemically to what would superficially appear to be a normal open shelf marine sediment. It may be possible to distinguish the dredged material mass from the surrounding sediment by differences in grain size, mineralogy, and chemistry; but depending on the nature of the two materials and the rate of disposal, hence completeness of alteration of the dredged material, the difference may be quite subtle and have little or no environmental quality significance.

Removing dredged material from very near shore and depositing it in deeper open ocean water will almost always result in exposing the material to a higher pH, i.e. to a more basic solution. The pH of surface seawater is kept near 8.2 by the carbonate-bicarbonate, carbon dioxide system, except during times of intense biological productivity when rapid use of carbon dioxide can raise the pH to near 9. Typical river waters and pore waters trapped in nearshore sediments have a lower pH. Nissenbaum et al. (1972) and Ben-Yaakov (1973), for example, calculated that sulfate reduction should lower the pH to near 7.0, and actual measurements made in reducing pore waters generally give values of 7.0 - 7.5 (Manheim and Sayles, 1974 for a review of pore water data).

The importance of pH to dredged material disposal is that adsorption-desorption reactions involving trace metals are controlled by specific pH dependent surface reactions whereby metal ions (Me^{+n}) are exchanged for surface-bound hydrogen ions:

$$Me^{+n} + H\underline{X} = Me\,\underline{X}^{+n-1} + H^{+}$$

where $\underline{X}$ represents the solid phase. In other words, metals will be adsorbed with increasing pH and desorbed with decreasing pH for environmentally encountered values (i.e. pH 5-9). Figure 19 shows this behavior for copper adsorption from seawater and 0.7 M sodium chloride on illite. Removing fluvial and nearshore material to the open ocean would generally tend to increase the pH of the aqueous solution and thus favor adsorption over desorption reactions. However, other

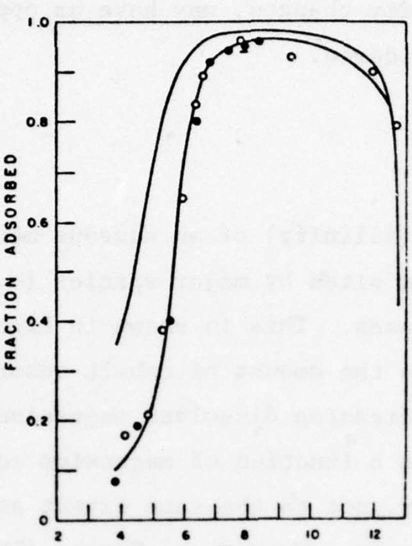


Figure 19. Copper adsorption from seawater and 0.70 M NaCl onto 1000 ppm illite as a function of pH (from O'Connor and Kester, 1975).

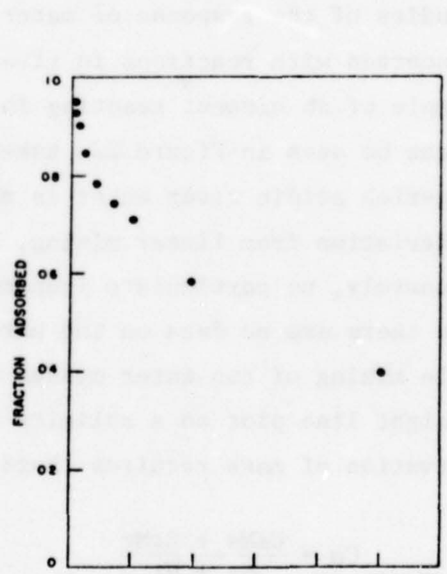


Figure 20. Cobalt adsorption onto 1000 ppm illite at pH 8 as a function of Mg^{2+} concentration (from O'Connor and Kester, 1975).

factors, such as salinity changes, may have an opposite effect and they must also be considered.

SALINITY CHANGES

As the ionic strength (salinity) of an aqueous medium increases, competition for surface sites by major species (e.g., Mg^{+2}, Ca^{+2}, Na^{+} and K^{+}) also increases. This is shown in Figure 20 from O'Connor and Kester (1975) where the amount of cobalt adsorbed on illite at pH 8 decreases with increasing dissolved magnesium concentration. Desorption of cobalt as a function of magnesium concentration was also shown to occur, however, not to the same extent as observed for the reverse adsorption process. Murray and Murray (1973) also show the effect of salinity on desorption of zinc (Figure 21) to be small, expecially when compared with pH effects.

The most extensive studies of the response of materials to change in salinity have been concerned with reactions in river water-seawater mixing zones. An example of an element reacting in the freshwater-seawater mixing zone can be seen in Figure 22, taken from Coonley et al. (1971). Here iron-rich acidic river water is mixing with seawater, and judging from the deviation from linear mixing, iron is being precipitated. Unfortunately, no particulate iron measurements were made in this study, so there are no data on the nature of the solid phase formed. A simple mixing of two water masses with no reaction would result in a straight line plot on a salinity - concentration diagram because conservation of mass requires that:

$$Cm = \frac{CsMs + CrMr}{Ms + Mr}$$

Where Cm is the resultant concentration after mixing masses Ms and Mr of concentrations Cs and Cr. The same relationship holds for total salt (S%) thus:

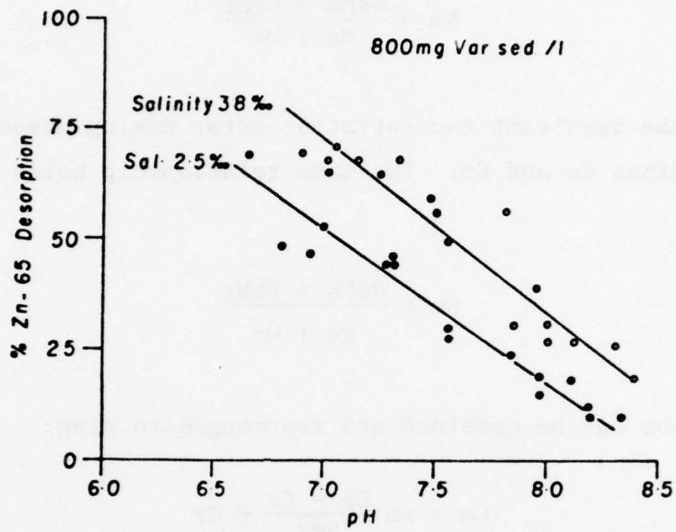


Figure 21. Percent variation of desorption of zinc in seawater of different salinities at different pH (from Murray and Murray, 1973).

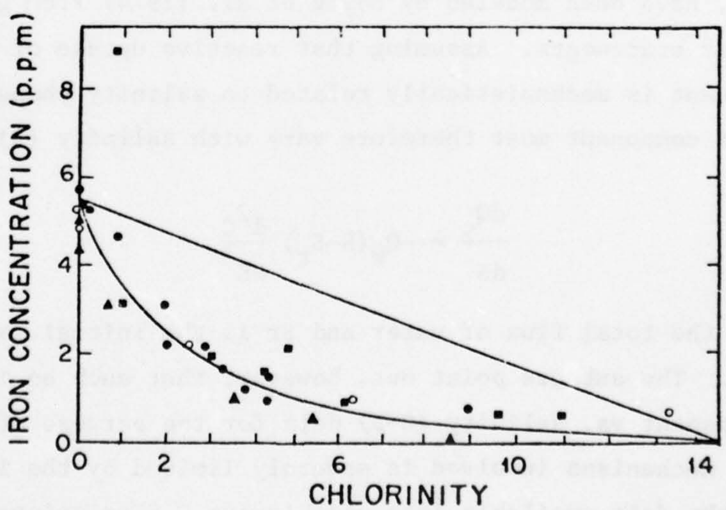


Figure 22. Dissolved iron vs. chlorinity of samples from the Mullica River and Great Bay, New Jersey (Coonley et al., 1971).

$$Sm = \frac{SsMs + CrMr}{Ms + Mr}$$

Where Cm is the resultant concentration after mixing masses Ms and Mr of concentrations Cs and Cr. The same relationship holds for total salt (S%) thus:

$$Sm = \frac{SsMs + SrMr}{Ms + Mr}$$

These equations can be combined and rearranged to give:

$$Cm = Sm \frac{Cs - Cr}{Ss} + Cr$$

Therefore, Cm varies linearly with Sm. Such is clearly not the case in Figure 22, implying reaction in this salinity range.

Non-conservative deviations from linear mixing, as observed for iron (Figure 22), have been modeled by Boyle et al. (1974) from general material flux statements. Assuming that reactive uptake of a river-borne component is mechanistically related to salinity change, the flux (Q_c) of that component must therefore vary with salinity (S):

$$\frac{dQ_c}{dS} = -Q_w(S-S_r)\,\frac{d^2C}{dS^2}$$

where Q_w is the total flux of water and Sr is the initial salinity of river water. The authors point out, however, that such an interpretation of component vs. salinity (C-S) data for the purpose of explaining the removal mechanisms involved is severely limited by the inability to resolve the data available into unambiguous C-S relationships. In fact, they conclude that for several instances of observed removal (e.g., Bien et al., 1958; Wollast and de Broeu, 1971), deviation in the C-S plot can actually be interpreted as two or more straight lines

AD-A053 183   TERECO CORP COLLEGE STATION TX   F/G 13/2

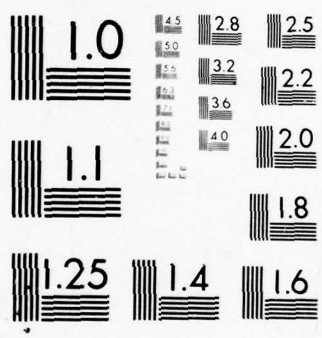
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)

JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL   DACW39-76-C-0125

UNCLASSIFIED   WES-TR-D-78-2   NL

3 OF 7

AD
A053183



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(i.e., more than one mixing regime) and that curvature must be demonstrated in order to establish even an overall removal phenomenon for a particular species.

In addition to the observations of Coonley et al. (1971) discussed above, work by several other investigators bears on the problem of reactions, or lack thereof, at river mouths. Windom (1975), for example, shows an exponential decrease in dissolved iron with increasing salinity in agreement with the above, and Lowman et al. (1966) report that river dissolved metals become predominantly "particulate" upon mixing with seawater. Other workers have considered primarily the solid phase.

In a much-quoted study, Kharker et al. (1968) equilibrated radioactive tracers of cobalt, silver, selenium, chromium, and molybdenum in distilled water with montmorillonite, illite, kaolinite, ferric oxide, manganese dioxide, and peat. The solids were then filtered out and placed in natural seawater. After equilibration with seawater the solids were found to have lost cobalt, silver, and selenium presumably due to displacement of surface held metals by the major cations in seawater. On the basis of their desorption experiments and determinations of dissolved concentrations in several rivers, these authors proposed modified residence times in the ocean for cobalt, silver, and selenium. This study can be criticized because of the short equilibration times used, the failure to monitor pH, the use of distilled water for the uptake process, and the study of each metal individually; nevertheless, desorption did seem to occur and this has been confirmed in other studies.

Evans and Cutshall (1973) observed desorption of ^{54}Mn and ^{65}Zn from river suspended matter, which was mixed with seawater, but saw no loss of ^{51}Cr, ^{124}Sb, or ^{46}Sc. According to DeGroot et al. (1971), Rhine River sediments, which are contaminated with heavy metals, lose a substantial portion of these metals in the Rhine estuary, but attribute the lowering of concentrations to a simple mixing of Rhine River sediments with metal-poor sediment transported into the area by ocean currents.

Trefry and Presley (1976b), in an extensive study of the Mississippi River mixing zone, compared river suspended matter to that in seawater just outside the river mouth. They show that individual particulate metals behave differently upon mixing with Gulf of Mexico water. Iron, aluminum, cobalt, nickel, and chromium concentrations were very similar in river and gulf suspended matter, whereas Mn content generally decreased seaward and zinc, lead, copper, and cadmium concentrations were either similar or higher in gulf samples. These observations argue against extensive desorption of any of these metals except manganese and agree with the laboratory study of O'Connor and Kester (1975). However, the decreased Mn concentrations in gulf suspended matter, which were up to 40 percent lower than those in the river, suggest desorption of manganese similar to that observed by Evans and Cutshall (1973). In a number of instances, the zinc, lead, copper, and cadmium concentrations were higher in gulf suspended matter, suggesting that under certain conditions (e.g., following pH changes from less than 8.0 to 8.5, or during plankton blooms, etc.) uptake of these metals may occur.

It is perhaps not surprising that so much seemingly conflicting data have been published on marine adsorption-desorption phenomena in view of the likely importance of such variables as the nature and concentration of both dissolved and suspended matter, pH, time of equilibration, temperature, etc. These matters are discussed in some detail by Murray and Murray (1973), O'Connor and Kester (1975), and Parks (1975), all of whom stress the need for more work in order to better understand the reactions involved. It may be, then, that each dredged material and disposal environment will have to be considered individually if there is concern for minor changes in the chemistry of the material in response to salinity changes. Certainly no major chemical changes are to be expected.

MINOR COMPONENT CONCENTRATIONS

The concentration of minor or trace components at the disposal site is unlikely to exert much control on the dredged material under most circumstances, although situations can be imagined in which effects might be apparent. For example, if petroleum hydrocarbon concentrations are high enough at the disposal site to cause a surface sheen or slick, then pesticides and other organics might be removed from the dredged material by an in situ solvent extraction action. At the same time, fine-grained material could become coated with the petroleum (or other organic substances at the site) and stay in suspension much longer than would be normal. Other examples of similar, but unlikely situations include cases where trace metals, nutrients or trace organics are unusually high in the water and these are adsorbed or otherwise incorporated into the dredged material as it mixes with and settles through the water column. Such incorporation is possible because active uptake sites from organic matter in the dredged material are exposed to the water, as are new uptake sites produced as iron oxide precipitates form during disposal. It is possible, then, to enrich the dredged material in certain substances by scavenging from the water during disposal, and to thus produce a bottom sediment somewhat different from the starting material. Baseline data on concentrations at the disposal site, coupled with an elutriate test using the material to be dredged should allow prediction of such effects.

One situation in which a minor component could have pronounced effects on the behavior and ultimate fate of dredged material is the one where hydrogen sulfide (H_2S) exists in some part of the water column. Several closed basins are known in the world ocean where such is the case, including the Orca Basin off the Texas-Louisiana coast (Shokes et al., in press). The Orca Basin has 2000 m of well-oxygenated water overlying 200 m of anoxic, H_2S-containing bottom water. A completely different physical situation is exhibited by the well-known Cariaco Basin off Venezuela, where 400 m of oxygenated water overlies 1000 m of anoxic water. Obviously, the reaction of material will be different in the two environments, although in each, the ultimate resting place for the material is in anoxic water and whatever material reaches the bottom will react so as to adjust to the anoxic conditions. No doubt many different combinations of water depths and oxic-anoxic conditions can be found, and each will be to some extent unique with respect to reactions in the water column but will exhibit similar bottom conditions.

Material disposed into anoxic water will end up as reduced bottom sediments similar chemically to the starting material, assuming it to be rapidly deposited nearshore sediment. However, depending on the water depth and currents above the anoxic zone the material might well be subjected to considerable physical fractionation (loss of fines) as it descends and this will affect its chemistry, and it will react to the changes in salinity, redox, etc. discussed earlier in this report during its passage through the oxygenated part of the water column, which can also slightly alter its chemistry. The result, then, is a mass of sediment chemically and physically similar to the starting dredged material in the typical case, but now overlain by anoxic water.

There are several consequences of an anoxic water column, not the least of which is the absence of all but microscopic benthic organisms, and thus the absence of normal biological re-working and mixing of the sediments. Of course, there will also be very little physical re-working of the sediments, because anoxic conditions can only be maintained in the absence of most advective water movement. Thus, the anoxic basin presents both a stable water column and a stable sediment column. Nevertheless, some exchange of material will occur through diffusion from the sediments to the overlying water and slow diffusive and advective exchange between the anoxic water and the surrounding oxygenated water mass and by the normal rain of particulate matter from above. Few studies have been made of the chemistry of anoxic sediments (see Deuser, 1976 for a review), but they do seem to show certain unique characteristics. They are, for example, enriched in sulfur due to sulfate reduction and iron sulfide (FeS) formation and are generally enriched in carbon, phosphorus, and other constituents of organic matter. This latter observation has been attributed to a slower rate of organic degradation in anoxic environments, but this is a matter of considerable controversy (Richards, 1970). Trace elements such as copper, molybdenum, lead, and vanadium also seem to be enriched in anoxic sediments, and the possible impacts that this and the other anoxic characteristics might have on the environment will be discussed in a later section of this report.

AFTER BOTTOM CONTACT

The ultimate fate of waste material disposed in the open ocean is the bottom sediments. Here, elements and compounds may be subject to conditions that greatly differ from those in the overlying water column and thereby be released and made available to the benthic community. Although standard water-quality analyses (e.g., elutriate tests) may well indicate the sorptive behavior of particulates settling through an oxygenated water column, they do not anticipate possible redox and chemical changes in the sediment column. Thus, additional monitoring experiments and further study of post-depositional processes and the potential release of toxins from rapidly accumulating wastes may be warranted. This section briefly reviews the understanding of chemical diagenesis in sediments and then applies this knowledge to predicting chemical behavior in waste deposits.

CHANGE IN REDOX POTENTIAL

Organic material not destroyed during passage through the water column is deposited at the sea floor where it is subject to bacterial decomposition. Diagenetic changes in carbon, nitrogen, phosphorus, sulfur, silicon, iron, manganese, and other element concentrations and speciation are, to some degree, a direct or indirect function of this organic decomposition. Organic molecules themselves are also altered by the diagenetic process with resultant small organic byproducts forming via condensation, deamination, decarboxylation, and other reactions. However, the specific products of sediment diagenesis and the mechanisms leading to their production are only partly understood.

If oxygen is available in a sediment's interstitial water, organic degradation is promoted by heterotrophic bacteria that oxidize carbon and fix carbon dioxide to form cell material. The process may be generalized by the reaction,

$$(CH_2O)_{106}\ (NH_3)_{16}\ (H_3PO_4) + 106\ O_2 \rightarrow$$

$$106\ HCO_3^- + 16\ NH_4^+ + HPO_4^= + 92\ H^+ \qquad (1)$$

which shows that for every mole of carbon oxidized, 1 mole of oxygen is consumed and 1 mole of bicarbonate and lesser amounts of ammonia and phosphate are produced. However, if oxygen has been depleted in the sediment column, organic degradation is mediated by anaerobic bacteria that use electron acceptors other than oxygen, such as NO_3^-, NO_2^-, $SO_4^=$, $SO_4^=$ being quantitatively most important. A general reaction for anerobic decomposition,

$$(CH_2O)_{106}\ (NH_3)_{16}\ (H_3PO_4) + 53\ SO_4^= \rightarrow$$

$$106\ HCO_3^- + 53\ HS^- + 16\ NH_4^+ + HPO_4^= + 39\ H^+ \qquad (2)$$

shows that for every 2 moles of carbon oxidized, 1 mole of sulfate is reduced and in addition to bicarbonate, ammonia, and phosphate, a sulfide species is also produced.

Surface sediments in most continental shelf and slope areas are oxic; however, interstitial waters at a few to several centimetres below the sediment-water interface are often devoid of free oxygen (Kanwisher, 1962), thus an anoxic environment develops at depth. The vertical extent of the oxic zone is a function of sediment accumulation rate (Goldhaber and Kaplan, 1974; Shokes, 1976) and/or the concentration of metabolizable organic matter (Berner, 1971). For example, Trefry (Unpublished Data) found that Mississippi Delta sediments, which accumulated at $>1 g/cm^2/yr$, had essentially no oxidized zone (i.e., $<1mm$) whereas sediments depositing at less than $0.5 - 1.0 g/cm^2/yr$ had measurable oxidized zones, the depth of which increased with decreasing sedimentation rate.

If sizeable amounts of dredged material are rapidly deposited in oxygenated water there will be a limited oxygen supply except in the top centimetres of sediment where biological mixing occurs, and anoxic conditions will develop at depth. With frequent disposal and/or high organic content waste material, it may be possible to generate a completely reducing, anoxic sediment column. When time scales are longer and/or organic content low, the anoxic sediment will be overlain by a variable, but small oxic zone. In the anoxic region, some chemical species may be released to the interstitial water whereas others may be rendered immobile. When the entire sediment column is anoxic there will be a diffusive flux of solubilized species to the overlying seawater. When anoxic sediment is covered by oxic sediment, mobilized species may dissolve at depth, diffuse upward, reoxidize in the surface sediment, and thus greatly concentrate a given species over natural levels in a surface layer. Likewise, species rendered more soluble by oxidizing conditions may be released from sediments where there is a thin oxic zone.

In effect, the above two cases are not any different from those which may be found in the natural marine environment. If a difference is to be noted, it would be that dredged material provides a larger than normal reservoir for release of certain species due to higher organic content. One must also bear in mind, however, that there most likely will be intermediate degrees in the character of oxic-anoxic environment as measured by the redox potential (Eh). Price (1976) notes that Eh and pH in a discrete section of sediment are a function of the balance between the types of bacteria, amounts of metabolizable organic matter, the buffering and poising capacity of the sediments, and the rate of diffusion of oxygen through the sediment.

Nutrients and Sulfur

Of the primary dissolved species in surface sediment interstitial water, it is the nutrient elements (nitrogen, phosphorus, and silicon) that are subject to the greatest concentration changes. Except for silicon, these changes are controlled by the decomposition of organic matter and thus are greatest in sediments that have abundant organic matter and are consequently anoxic.

Idealized kinetic models for the behavior of dissolved species during early diagenesis have followed from the initial work of Berner (1964) and may be expressed by the diagenetic equation (Berner, 1975),

$$\frac{\partial C}{\partial t} = D_s \frac{\partial^2}{\partial x^2} - \omega \frac{\partial C}{\partial x} + \frac{\partial C}{\partial t_\alpha} + R \qquad (3)$$

where C = concentration of dissolved specie (g/cm of pore water)

t = time (sec.); t_α = time for adsorbtive equilibria

D_s = diffusion coefficient (cm^2/sec) corrected for porosity and tortuosity.

x = depth in the sediment column (cm)

ω = sedimentation rate (cm/sec)

R = summation of rate expression for slow chemical reactions involving the dissolved specie ($g/cm^2/sec$).

The terms of the equation (from left to right) account for pore water diffusion, advective supply of the dissolved species by continual sediment accumulation, equilibrium adsorption, and slow chemical reactions affecting dissolved concentrations. Guinasso and Schink (1975) have also incorporated the effects of biological mixing into their diagenetic model and this should be considered where appropriate.

Application of the steady-state diagenetic equation to specific elements involves selecting the appropriate terms, setting boundary conditions, and solving the differential equations to obtain solutions, which may be fitted to actual data. Figure 23 gives typical plots for sufate ($SO_4^{=}$), ammonium (NH_4^{+}), and orthophosphate ($PO_4^{\equiv}$) concentrations in the interstitial water of anoxic sediments and points out the reduction of sulfate and production of ammonia and phosphate.

Hydrogen sulfide, a toxin to all aerobic organisms and perhaps to many anaerobic bacteria as well (Goldhaber and Kaplan, 1974), is also generated under the above conditions. However, sulfide generally precipitates as iron sulfide and thus there are minimum hydrogen sulfide levels in the pore water (Nissenbaum et al., 1972). If very strong reducing conditions were to develop in a high organic content, low-iron waste deposit it may be possible that the kinetics of sulfide removal would allow high levels to be reached and maintained even at the sediment surface, but production of iron sulfide (FeS) is a more common phenomenon.

Production of ammonia and phosphate in anoxic sediments may be considerable (Figure 23) and allow large concentration gradients between the interstitial water and the overlying seawater to be set up. This

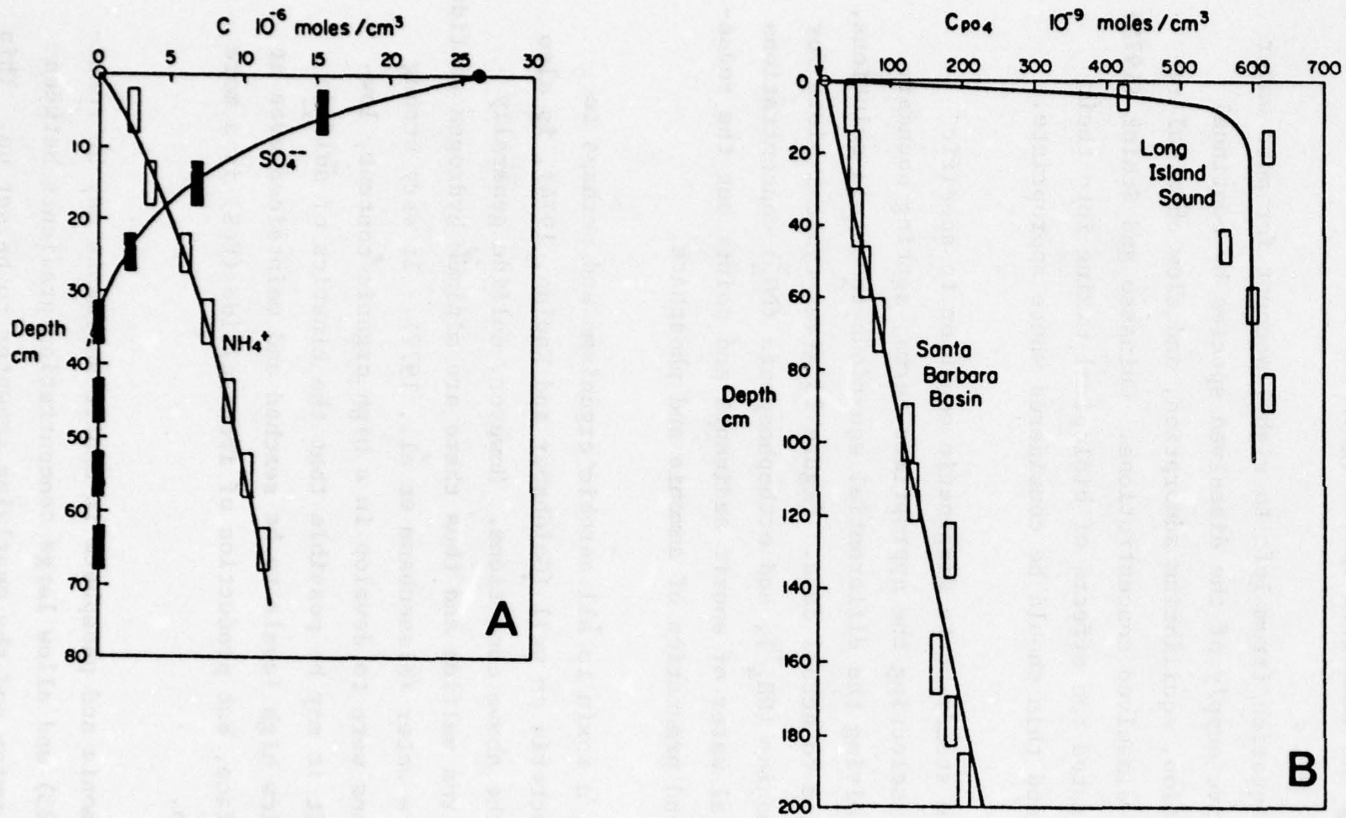


Figure 23. (A) Interstitial sulfate and ammonium and (B) Phosphate concentrations for anoxic sediments (from Berner, 1974).

leads to diffusive fluxes of species across the sediment-seawater interface. These may be quantified by

$$F = D_s \frac{dC}{dx} + \omega C \qquad (4)$$

where C = concentrations of dissolved species (moles/cm^3)

x = thickness of sediment from surface (cm) to the concentration maximum at depth

D_s = diffusion coefficient corrected for porosity and tortuosity (cm^2/sec)

ω = sedimentation rate (cm/yr).

Large gradients, such as that for phosphate in Figure 23B, can support a diffusive flux from sediments on the order of 3 μ moles/cm^2/yr. Anaerobic conditions can likewise support sizeable ammonia and even sulfide gradients within and from the sediment column. These observations will be maximized in areas where large amounts of organic-rich (>3 percent organic carbon) dredged material are disposed, but in any case measurable changes in the solid phase chemistry of the deposit are likely to be small, except from the top few centimetres of sediment where biological mixing and advective processes can aid the slow molecular diffusion. Even relatively small fluxes from the sediment may, however, affect the quality of the overlying water--a point which will be considered in the "impacts" section of this report. (Part 4).

Metals

Iron and manganese are the metals most often cited as being susceptible to dissolution under anoxic conditions. Figure 24 summarizes possible interstitial profiles in oxic and anoxic zones. Case I would be observed where a stratified water column with anoxic bottom water is found (e.g., the Black Sea). Here, iron and manganese and other metals are reduced and solubilized in the water column. For anoxic sediment (Case II), maximum metal remobilization occurs at the

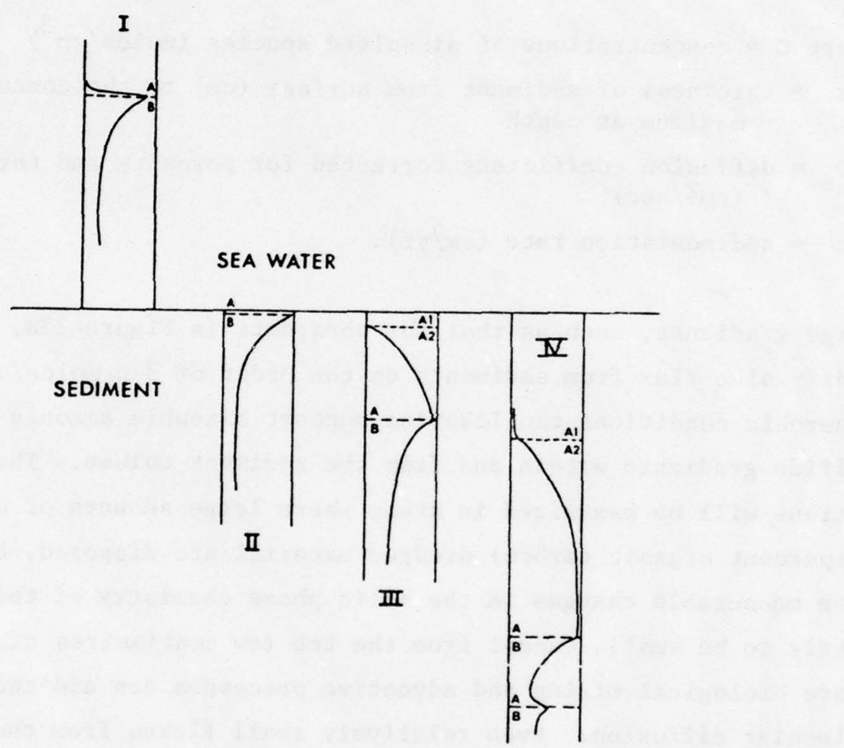


Figure 24. Typical interstitial manganese profiles (from Elderfield, 1976) showing variations in the anoxic-oxic (A-B) boundary (A1-A2 in cases III and IV) and the regions of maximum manganese remobilization that vary as a function of sediment (or water column) redox conditions.

sediment-water interface or in the top millimetres of sediment. The net diffusive flux from the sediment is, of course, an important function of the depth of the oxidized layer. In Case III, mildly reducing conditions allow a well-defined oxic zone (A-1 in Figure 24) to develop, wherein remobilized metals may be trapped and greatly concentrated over natural levels. Finally, Case IV exemplifies the pattern for slowly accumulating deep-sea sediments where there is a thick oxidized zone wherein there may be discrete anoxic segments. Dredged material would most likely set up situations similar to those for Cases II and III. Thus, the magnitude of dissolved interstitial species as well as the biological availability of species remobilized and concentrated in the surface sediments must be considered with respect to the heavy metals.

Data from Trefry (Unpublished Data) in Figures 25 and 26 compare the behavior of manganese in shallow, rapidly accumulating Mississippi Delta sediment with that in deeper water Mississippi Fan sediment. Anoxic conditions are found in both cases; however, the fan sediment has a thin oxic zone (A-1) whereas the delta core is reducing even at sediment-seawater interface. A flux of manganese on the order of 1500 $\mu g/cm^2/yr$ is passing into the overlying water and consequently the bottom sediment has a total manganese concentration ($\sim$660 $\mu g/g$), which is about one-half that in the particulate flux ($\sim$1300 $\mu g/g$) to the sediments. A comparable flux of iron is also passing from these nearshore sediments; however, this study and most others do not allow similar quantification of fluxes of additional metals from nearshore, anoxic sediments.

In deeper waters, slower sedimentation rates permit the formation of a thin oxidized zone, and there is a significant flux of manganese ($\sim$100 $\mu g/cm^2/yr$) into this zone where reoxidation and precipitation of manganese occurs and a very high sediment manganese value is measured. However, within error limits, Trefry (Unpublished Data)

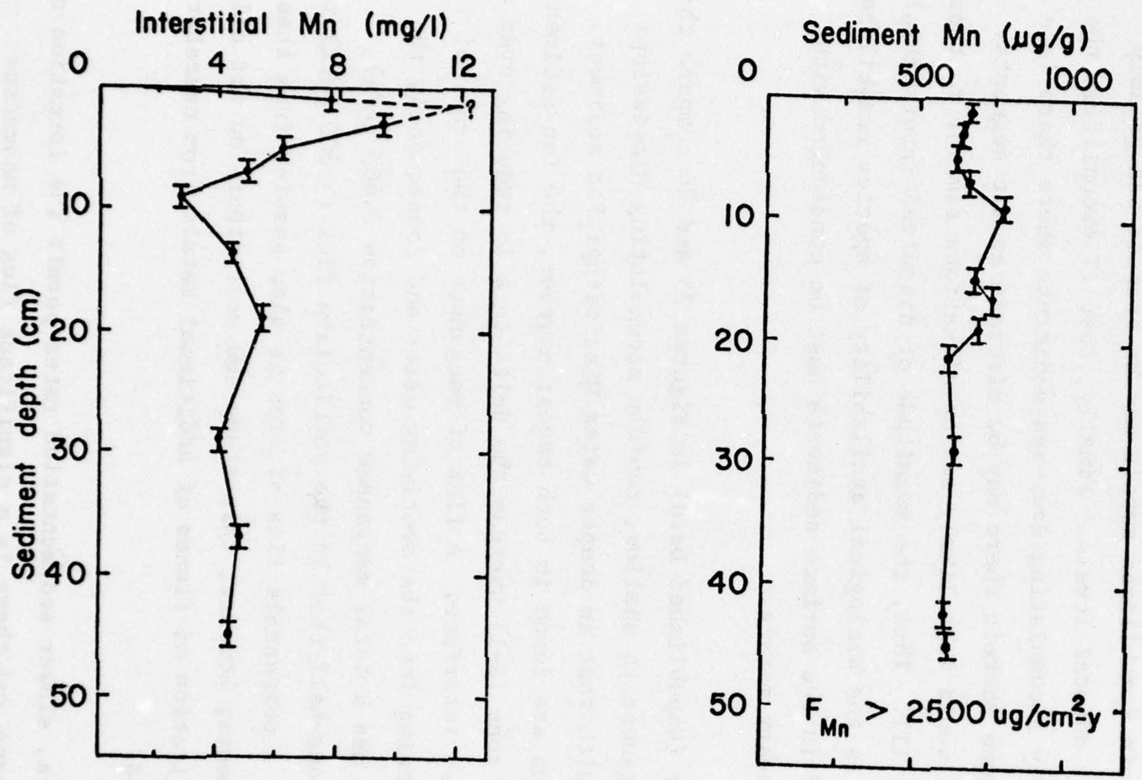


Figure 25. Interstitial and sediment manganese concentrations for a Mississippi Delta sample (from Trefry Unpublished Data).

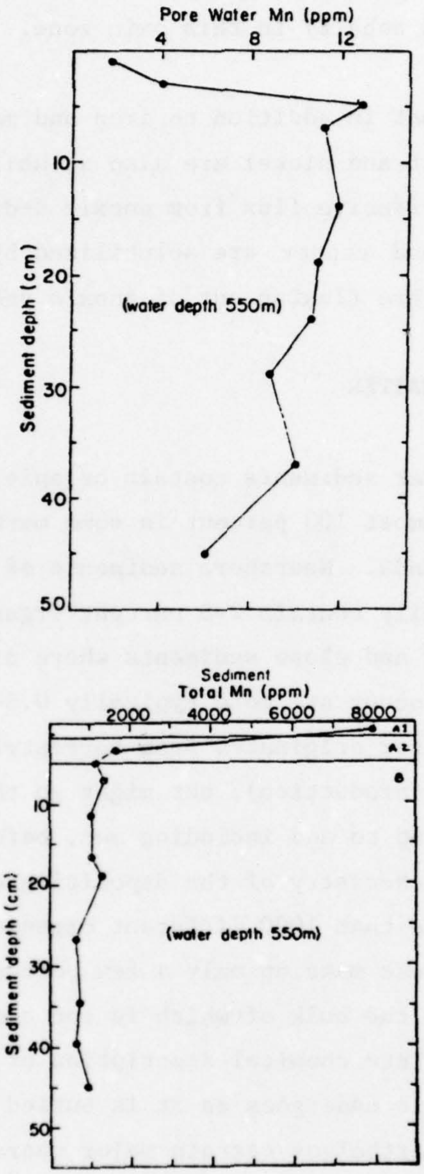


Figure 26. Pore water and sediment manganese concentrations for a Mississippi Fan sample (from Trefry Unpublished Data).

found no similar enrichment of other heavy metals (iron, copper, nickel, zinc, lead, and cobalt) in this oxic zone.

Manheim (1976) notes that in addition to iron and manganese, cerium and perhaps lead, cobalt, and nickel are also solubilized in the reduced state and have a net diffusive flux from anoxic sediments. Furthermore, he suggests that zinc and copper are solubilized by organic complexation and thus they too are fluxing out of anoxic sediments.

DIAGENESIS OF ORGANIC MATTER

All marine and freshwater sediments contain organic matter, but the amount can vary from almost 100 percent in some marsh deposits to almost zero in clean sands. Nearshore sediments of the type likely to require dredging typically contain 2-5 percent organic matter, whereas outer continental shelf and slope sediments where disposal of the dredged material might occur are more typically 0.5-1 percent. Sedimentary organic matter originates from terrestrial and marine photosynthesis (primary production), but might go through a complex food web of organisms, up to and including man, before it is deposited on the sea floor. The chemistry of the depositing organic matter is extremely complex. More than 1000 different organic compounds have been identified, and these make up only a few percent of the total weight of the material, the bulk of which is too complex to chemically characterize. Any complete chemical description of marine organic matter and the changes it undergoes as it is buried with sediment is thus not possible. Nevertheless certain major characteristics and trends can be pointed out.

Marine organic matter, like all organic matter including man, consists mainly of the elements carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus. However, few samples of either plankton or sediments have been analyzed for all of these major elements; usually only one or two of them are determined. This procedure makes it difficult to comment on changes in the elementary makeup of organic matter during diagenesis, but it is generally agreed that phosphorus is regenerated most easily, followed by nitrogen and sulfur. This enriches the residue in carbon, and in some cases hydrogen, and leads ultimately to the formation of coal or petroleum.

Information as to the relative loss or changes in various specific compounds in organic matter is at least as scarce as information on elements. Again the problem is mainly caused by investigators working with only one group of compounds at a time, for example amino acids, and ignoring others. Thus, much data exist on many different compounds, but not from the same sample. It seems clear, however, that amino acids, fatty acids, carbohydrates, and the like decompose more easily than do humic and fulvic acids and that kerogen and lignin-like materials are even more resistant to decomposition. The decomposition takes place through loss of functional groups by deamination, decarboxylation, depolymerization, and oxidation-reduction reactions, most of which are not reversible.

The reactions involved in organic decomposition are almost all mediated by bacteria and related organisms (yeast, molds, algae, etc.), and there is a strong correlation between the number and kinds of organisms in sediments and the rate and nature of organic decomposition. Perhaps the most drastic change in kinds of organisms occurs when all molecular oxygen has been removed from the pore water of sediments through biochemical oxidation of organic matter. Once the oxygen is gone, organisms that use nitrate and sulfate as electron acceptors always develop as a natural consequence of the reducing conditions, and they continue to degrade organic matter until all nitrate and sulfate has been reduced. Nor does organic decay stop when all nitrate and sulfate are gone; rather, various fermentation and carbon dioxide reduction reactions become prominent. The amount of energy obtained by the organisms becomes less and less through the series of reactions described above, while at the same time the organic residue is becoming less and less susceptible to attack. Thus there is a rapid decrease in the rate of decomposition with time (i.e., depth in the sediment column).

In summary, the loss of organic matter in sediments is a complex function of the nature of the starting material (i.e., its susceptibility to decomposition), the rate of sediment accumulation, and the nature of the environment. Maximum decomposition will occur in oxygenated environments where marine organic detritus (rather than land-derived material) is accumulating slowly so as to allow time for decomposition at the sediment-water interface. Large amounts of organic matter and/or poor renewal of bottom oxygen will result in burial of more organic matter and development of reducing conditions. There is little information on the differences in rate or nature of oxic versus anoxic decomposition, but it is generally thought that the latter goes more slowly. Certain potentially toxic substances, especially ammonia and hydrogen sulfide, are stable under reducing but not oxidizing conditions and this should be kept in mind when selecting a disposal site.

CEMENTATION AND COHESION OF SEDIMENTS

The distribution of dredged material at the disposal site will depend in large part on the resistance of the material to erosion and resuspension by bottom currents. The physics of sediment movement by fluid flow is very complex if one takes into account variables such as grain size, grain shape, density, sorting, roughness of the bottom, velocity of flow, etc. Hundreds of scientific papers have been published on the subject, including many good reviews, such as that of Allen (1970). However, even if the physics of sediment movement could be thoroughly understood and therefore predicted, chemical and biological factors can completely alter the actual behavior in nature. Unfortunately, the chemical and biological factors affecting competence (resistance to movement) are even more complicated and less understood than the physical factors.

The fact that chemical processes are active on the sea floor is dramatically illustrated by the presence of hard rocks that are produced from soft mud often at depths so shallow that the pressure from the overlying mud is relatively insignificant. Chemical cements of various kinds bind the sediment particles together, producing in concert with increased pressure, a completely indurated rock as an end product. Common chemical cements include minerals such as quartz, opal, calcite, siderite, limonite, and pyrite, each of which forms under a particular set of physicochemical conditions. Organisms living in the sediment play a major role in determining the physicochemical conditions, and at the same time produce cementing agents themselves. Barnacles and agglutinated Foraminifera are obvious examples of organisms that cement particles together, but such subtle substances as bacterial mucus may also be important. Rhoads and Young (1974) and Hulbert and Given (1975) stress the importance of organic matter in determining the cohesion of sediments.

It seems likely that dredging sediment from harbors, estuaries, and other nearshore areas and disposing of it in more open and deeper water will alter the cohesion of the material due to the changes in physicochemical conditions, as well as the probable loss of fine-grained and organic material during disposal. However, the overall effect and the resultant resistance to movement of material reaching the bottom at the disposal site will have to be evaluated on a case by case basis after consideration of both the dredged material and the environment.

D. BIOLOGICAL CONSIDERATIONS

DURING WATER COLUMN PASSAGE

NEGLIGIBLE EFFECTS

Organisms will have little if any effect on the spatial distribution and chemical fate of the coarse particles and larger components of the dredged material in the water column. However, as noted in the introduction to this part, they can and do modify the behavior of the fine silts and clays.

IMPORTANT EFFECTS

It has already been pointed out that certain filter-feeding pelagic organisms play important roles in forming clay-size particles that would descend extremely slowly in the water column into composite particles and fecal pellets that descend somewhat more rapidly. Important pelletizers, in addition to the extremely abundant copepods, are other small crustaceans such as euphausiids, a host of crustacean larvae, some mollusks such as the pelagic pteropods, and the pelagic larvae of numerous types of bottom-dwelling organisms, including barnacles, clams, crabs, etc. In toto these organisms pass immense amounts of particulate matter through their guts. For example, Moore (1937) found during spring population increases in the Clyde Sea, the fecal pellets from barnacle larvae and euphausiids were deposited at the rate of about 33 mg/cm^2 each week. As a result of these activities, the fines that might remain aloft in the biologically productive upper extension of the water column for months or even years can be brought down in a matter of hours, depending upon the density of particles and filter-feeding organisms. Apparently, this does not happen so readily in the nepheloid layer because of the relative paucity of pelagic filter-feeders in the near-bottom waters. Furthermore, those composite particles found in the nepheloid layer are the finest ones that presumably would sink very slowly.

AFTER BOTTOM CONTACT

PHYSICAL EFFECTS

Bottom-dwelling organisms (benthos) play very important roles in both the distribution and chemical fate of dredged material after it drops to or near the bottom. Although the predominant feeding type among the benthos is usually considered to be deposit-feeders, there are many suspension or filter-feeders as well. The latter filter the lower few centimetres of water and form aggregates and fecal pellets quite as effectively as pelagic forms. The deposit-feeders are of two main types: the selective types, such as many clams, that skim material off the thin upper layer of sediments, and the non-selective types, among them various worms and echinoderms, that literally eat their way through the sediments as they "burrow." In other words, there is a steady movement of sediment through their alimentary canals with a steady production of mucus-impregnated fecal pellets.

Johnson (1974) noted that about 40 percent of surface sediment samples from shallow waters contained animal-formed aggregates. He noted that most of the fine materials in his sediment samples were in composite particles. Moreover, Drake (1976) believes that they remain in composite form when resuspended and their subsequent settlement behavior is thus modified by their aggregate form.

There is considerable evidence that similar processes go on in offshelf waters down to and on the abyssal plain. These activities appear to be most prevalent in muddy sediments where deposit-feeding sea cucumbers (holothurians) are particularly common in deep waters. There are many burrowing species in these deeper waters, many of which, such as polychaete worms and clams, ingest sediments and, along with the sea cucumbers, produce a plethora of fecal pellets. These activities not only modify the physical and geotechnical properties of the sediments but also, as will be discussed, the chemical properties as well. These activities may supply sediments to the nepheloid layer and in places can so change the properties of the sediment bed that it is more susceptible to slumping. This may be aggravated by mounding, which is a common habit of large clams and some crustaceans.

CHEMICAL EFFECTS

In shallow water a host of organisms including various types of bacteria are constantly altering the chemical balance at or below the sediment-water interface. Although the evidence is not as complete, very much the same kinds of changes must be going on in deeper waters. However, it is also evident that except for fecal pellets, much of the organic matter that reached the bottom in very deep water cannot be digested by many metazoan animals. The role of microbial organisms becomes increasingly important to the recycling of such materials in the deep sea.

PART 2. DISPOSAL ENVIRONMENTS IN THE DEEP OCEAN

A. INTRODUCTION

If dredged material is disposed of on land, the environment of the disposal site may be thought of in terms of the specific location, its topography, surface and subsurface geology, and drainage characteristics. However, the marine disposal environment cannot be characterized so simply, and an understanding of the characteristics of the marine disposal environment is essential to the evaluation of the effects of disposal at sea. The three conceptual components of the marine disposal site include: location, hydrodynamics, and biodynamics*. Each of these is considered in some detail below.

LOCATION

If solid, dense material such as concrete is dropped from a surface ship, the material will sink rapidly through the water column and come to rest on the bottom in a position more or less directly below the surface vessel. In this case the disposal material will have a transient effect in its path through the water and a more permanent effect upon the bottom surface (and immediate subsurface) where it comes to rest. The environmental location to be considered is three-dimensional, rather than two-dimensional, as on land. Hence, the characteristics of the water column as well as the bottom are of interest in characterizing the disposal environment.

HYDRODYNAMICS

Now suppose that the material to be disposed of includes a loose assortment of particle sizes ranging from rocks through gravels, sands,

---

* For definitions of ecological terms see Ecology by C. J. Krebs. Harper & Row, Publishers, New York, 1972, 694 pp.

silts, and clays. Each particle tends to sink at a rate dependent upon its size (cross-sectional area) and its density (relative to the densities of the various water masses through which it passes). Actually, many of the particles may adhere to one another and behave as larger particles, and the sinking of the entire mass may create a vertical current, which sucks the smaller and less dense particles downward for some distance. Eventually, however, the size and density of each particle will largely determine its own rate of sinking. To the extent that the smaller and lighter particles are delayed in their vertical passage, their properties and those of the water masses will become more prominent in determining their ultimate fate (see Part 1, A & B, this section).

Within the vertical water column the layers become progressively denser with depth. This will result in a sorting of the particles, with the larger and denser material proceeding fastest and deepest and the smaller and lighter materials traveling most slowly. All the way down particles will be trapped at interfaces and within water masses as each particle type comes into temporary equilibrium with the various forces affecting its descent.

The effect of vertical sorting will be compounded by the hydrodynamic properties of the individual water masses. Most of the water at sea is characterized by horizontal movement. Some also moves with a vertical component (up or down), and turbulent motion may be a factor near the surface or the bottom or at interfaces between water masses.

As a result of vertical sorting and water mass movement, dredged material composed of different size classes of particles will certainly spread over vast areas of sea bottom in a graded series, with the larger, denser materials settling to the bottom more or less directly beneath the ship, and with progressively finer particles distributed in a graded fan extending for many miles downstream. Therefore, the environment affected by the disposal material will not be a simple cylindrical column of water and a specific, discrete bottom site, but it will include something like a cone of water extending downward and outward from the ship. If most of the water masses are flowing in more or less the same direction, then the cone will be highly skewed. The bottom environment affected will be a very large, perhaps round, oval, or fan-shaped area with gradation in quantity and particle size tapering toward the downstream periphery (Figure 27). Under some circumstances this simple scheme may be inappropriate, and it is conceivable that the very fine particles could be transported miles from the original disposal site, as persistent cloudy layers, and eventually deposited in quantity in still bottom areas many miles away. In any event, the importance of water mass dynamics and the degree of compaction of the sediment to be discharged will be critical in determining the distribution and volume of the water column affected, as well as the size, shape, and position of the bottom surface impacted by the disposal material.

BIODYNAMICS

As the disposal material spreads out in its downward cone and finally settles to the bottom, the fine particles, at least, will be affected by the living organisms in their path. Many species produce mucus or other gelatinous substances to which the particles would readily adhere. This would lead to clumping of such material to the surface of marine organisms and aggregation of the fine particulates onto mucous films such as those produced by marine bacteria. Such aggregation would aid in clearing up turbid water and would, for the most part, hasten the removal of fine particulates from the water column. Still other species feed by filtration of large volumes of water. Filter feeders would tend to concentrate fine materials into larger compact fecal pellets, which would definitely have faster sinking rates than the isolated particles.

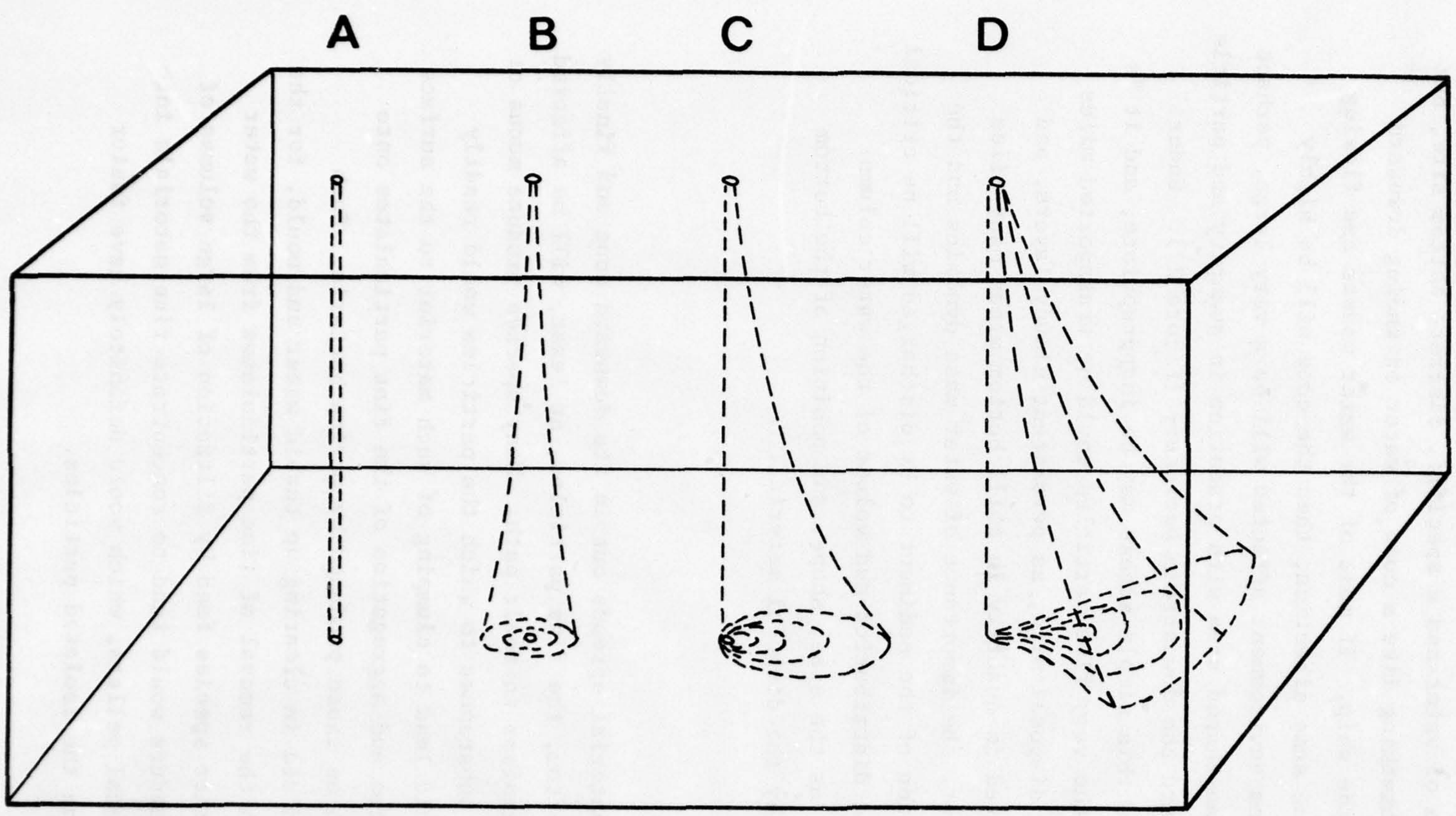


Figure 27. Diagrammatic illustration of possible patterns of environmental areas influenced by disposal at sea. A. The material remains together and impacts a specific bottom site. B. The material spreads somewhat and influences concentric circles of the bottom. C. The material spreads and is moved somewhat by currents, impacting concentric ovals on the bottom. D. The material spreads and is moved by currents, affecting a fan- or tear-shaped area of bottom. Finer materials sink most slowly and impact the bottom farthest from the actual disposal site.

Once on the bottom, the disposal material would be subject to various types of influence by the benthic organisms. Larger materials would be bored and drilled until they were riddled with passages. These would cause structural weakening and eventual collapse of the larger masses. Bore passages would permit water extraction of soluble materials in the mass, a process that might be hastened by activities of the organisms themselves. The same basic processes would occur in finer sedimentary materials widely distributed in thin layers over the bottom surface. Bioturbation would stir and mix the sediments and tend to release into the adjacent water any materials that might be soluble in the water. Even certain materials, such as heavy metals, which arrive on the bottom in insoluble form, may be made soluble and released through biological activity. Subsequent water movement would distribute such materials far downstream. Additionally, the organisms might concentrate certain chemical components of the sediments into their own living protoplasms. These would likely become concentrated through various members of the food chains so that the larger top carnivores might receive very high tissue concentrations of heavy metals and other chemicals, which occur in much lower concentrations in the original dumped materials.

Organisms of the sea determine, in part, the fate of the disposal materials, but they also are affected by the materials. Organisms of the water column in the path of the descending material may become trapped and carried to the bottom. Those on the bottom may become buried. Extensive turbidity in the upper lighted layers (euphotic zone) of the sea would reduce light penetration and lower the level of photosynthesis. Many species of the water column and of the bottom feed by filtration of fine particles. Gill-clogging by the suspended particulate material could become a severe problem resulting in mortality of the filter feeders. If the disposal material had a high chemical or biological oxygen demand it could locally deplete oxygen resources, resulting in the debilitation or death of many marine organisms. Heavy metals and other toxic chemicals removed from the sediments by marine organisms may, in turn, affect the well-being of the organisms themselves. Turbid water and chemicals released from the disposal materials could induce sensory deprivation in the marine organisms as they interfered with sight, smell, taste, or other senses necessary in the location of food, breeding partners, etc. Larger bottom animals, which escape burial, might find difficulty in locating adequate food supplies as the smaller organisms become deeply buried in the sediments.

Thus, in considering the disposal environments of the deep sea, one is forced to take into account not only the specific location of the disposal sites, but also the physical, chemical, and biological processes, which together constitute the dynamic environments of the water column and the bottom sediments. These factors both affect the disposed material and are affected by it. They vary regionally and in respect to the various hydrobiological zones. In order to understand these dynamic systems in relation to disposal, it is first necessary to develop the concept of the marine ecological systems.

B. MARINE ECOLOGICAL SYSTEMS

All ecosystems are major functional organizations involving both living and non-living components. The living components include the various groups of plants and animals that make up the biological communities. The non-living components are the air, water, and soil that collectively comprise the environments of the living systems. The living and non-living components of ecosystems are bound together through the dynamic exchange and recycling of chemical materials and energy, and the patterns of such exchange are determined largely by the controlling factors of the physical and chemical environments.

Since the major physical and chemical factors vary regionally and with depth, so the marine ecosystems display certain basic patterns of composition and process, and these basic patterns will be treated briefly in the sections that follow. The vertical zonation of the sea is shown diagrammatically in Figure 28.

COMPONENTS OF THE MARINE ECOSYSTEMS

NON-LIVING COMPONENTS

The non-living components of the marine ecosystems include the atmosphere above the water, the water column itself, and the floor of the sea. All three components are important in considering the marine ecosystems and the disposal environments of the sea.

The atmosphere above the oceanic water is of primary importance because water mass movement is induced largely by the frictional force of winds passing over the water surface. Wind-driven currents play a major role in the horizontal spread of organisms and of any materials discharged at sea. Turbulence, involving vertical water movement, is largely responsible for bringing nutrients from the deeper waters into the lighted zone of the sea where photosynthesis occurs. Exchange of gases takes place through the air/water interface of the sea surface, and this is greatly facilitated by wave and spray induced by the wind/water interaction. Thus, the concentrations of the gases (oxygen and carbon dioxide) of primary biological importance, are regulated by this air/sea exchange process. The temperature of the air also determines, to a large extent, the temperature of the near-surface water, especially in coastal areas where the water is shallower. Sunlight, transmitted through the atmosphere, penetrates the water surface and supplies the radiant

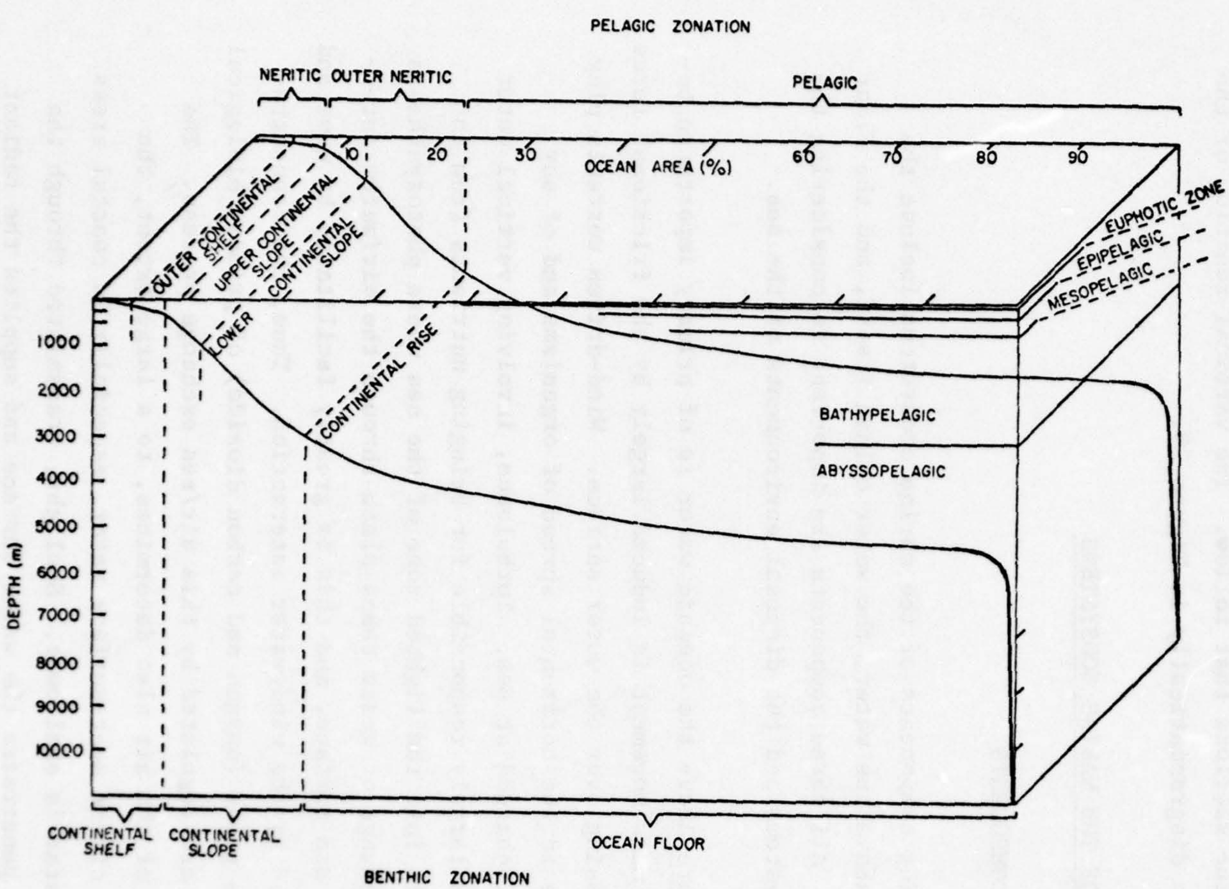


Figure 28. Diagrammatic section of the marine environment showing zonation.

energy required for phytoplankton growth. Cloudy weather interferes with this transmission by shading the water surface. For these and related reasons, the atmosphere is of paramount importance in regulating environmental conditions in the surface waters of the sea, and by so doing, it is largely responsible for the regional differentiation of coastal waters.

The water column itself provides the medium in which most of the marine organisms live and through which they find the means for survival. The conditions of light, temperature, salinity, nutrient concentrations, density, and pressure of each water mass determine the ambient conditions of the environment to which the organisms must adjust if they are to survive in a given area. Since these factors vary with respect to region, distance from shore, and depth, the biological communities will also vary with respect to these circumstances.

The upper layers of the sea are in contact with the atmosphere, and therefore, they are in motion most of the time, primarily as a result of wind disturbance. This fact is especially important during the spring and fall periods when storms and strong winds disturb the surface waters and induce strong currents. To a lesser extent, this is also true of the winter months. During the summer, however, there is generally less wind action, and water movement is at a minimum.

The seasonal progression of the sun determines that greater amounts of heat and light will be received by the surface waters during late spring, summer, and early fall than during the remaining seasons, when the sun is more directly over the southern hemisphere. Much of the sunlight striking the sea surface is reflected back into the atmosphere, and that which does penetrate the sea surface is rapidly absorbed by water molecules and by smaller suspended particles. For these reasons, sunlight is attenuated in seawater a logarithmic function of depth (Table 10). Phytoplankton growth is limited by the quantity of light available for photosynthesis, and phytoplankton generally cannot carry on photosynthesis when the ligh level is less than one percent of the surface value. Therefore, the depth of the euphotic zone (i.e., the upper layer of the sea where light is sufficient to support photosynthesis) tends to be greater in the open sea than in the more turbid coastal waters, greater in the summer than in the winter, and greater in tropical latitudes than in temperate or polar latitudes.

As a result of wind and solar heating, the surface waters may become sufficiently less dense than the deeper layers so that a condition of thermal stratification is established. Under such conditions, which may exist in tropical waters the year around and in temperate waters during the warmer summer months, mixing of surface and deeper waters becomes minimal. In the well-lighted surface waters the phytoplankton grows and uses the available nutrients. Since these are not being replaced from below (and, in fact, they are largely being lost from the euphotic zone), the waters of the euphotic zone become nutrient poor and remain so throughout most of the summer. Lowering of the surface water temperatures associated with stormy weather in the fall, results in breaking of the stratification and more or less complete mixing of nutrients from below. At this time and throughout the winter and early spring the water column of the continental shelf from top to bottom is more nearly homogeneous in temperature and nutrient concentrations, while at sea the upper layers are less stratified than they are during the summer period. These processes are illustrated in Figure 29.

Table 10

Amount of Solar Radiation* Reaching Various Depths for Different Types of Seawater

Depth (m)	Oceanic Water Clear	Coastal Waters		
		Very Clear	Moderately Turbid	Very Turbid
0	100	100	100	100
1	44.5	36.9	33.0	17.6
5	30.2	14.2	9.3	1.0
10	22.2	5.9	2.7	0.05
50	5.3	0.02	<0.01	-
100	0.5	-	-	-

* expressed as percentage of incident radiation at the surface

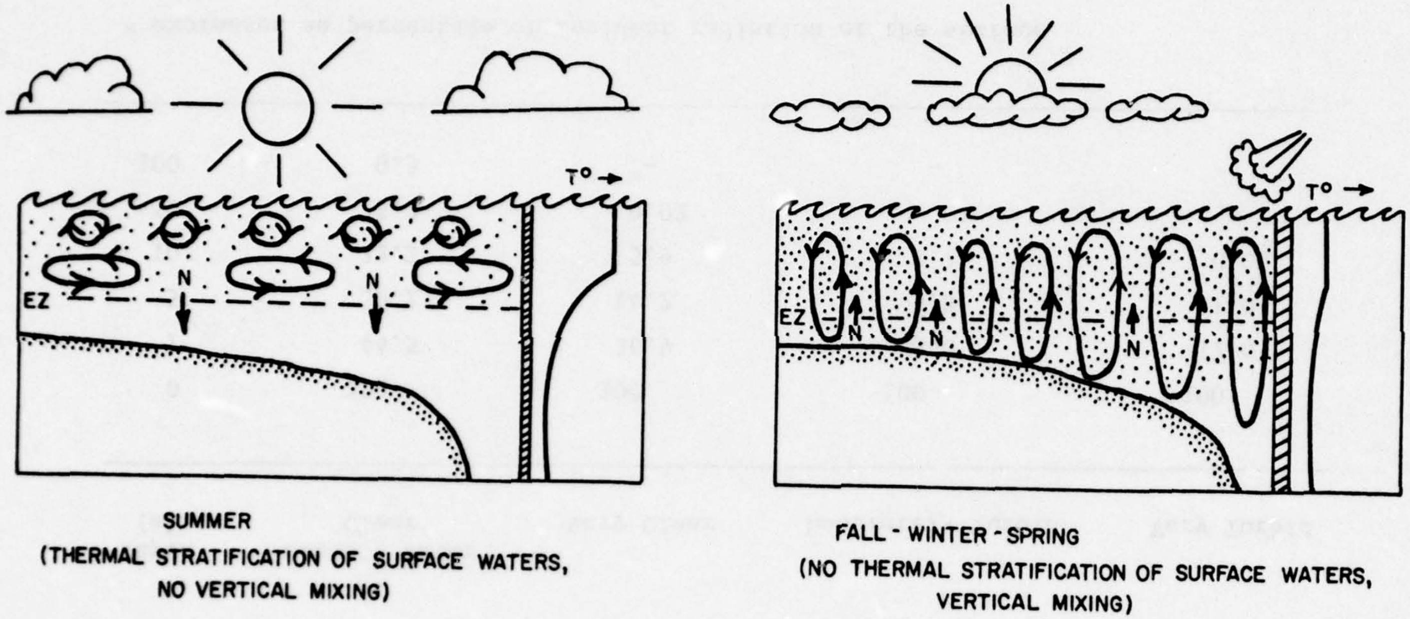


Figure 29. Diagrammatic section of outer continental shelf waters of the temperate zone under summer vs. fall-winter-spring conditions. Water temperature (T°) is shown to the right in each diagram. Circulation patterns are indicated by loops. EZ is the bottom of the euphotic zone. N is the nutrients required to support phytoplankton growth.

As one proceeds deeper into the oceans below the euphotic zone one encounters an environment characterized by absence of surface light, high nutrient concentrations, low temperatures (declining to a constant level of about 4° C in the deeper water), and extreme pressure. Water masses become progressively denser. Furthermore, each water mass in the vertical section has its own unique prehistory, and each is moving in its own specified direction. At a level of about 500-1,000 metres there is encountered a layer of water in which the oxygen content is lower than it is either above or below. This is the oxygen minimum layer of the sea where the lower level of oxygen may limit the vertical distribution of high-oxygen requiring species, which live above or below the zone. Beneath the oxygen minimum layer lies the dark, cold world of the deep sea where environmental conditions are nearly uniform and where seasonal changes, so evident in surface waters, have little meaning. The vertical distribution of a number of environmental factors is shown in Figure 30.

The floor of the sea is called the benthic area. For present purposes it is considered to include the water column for a few metres above the bottom (suprabenthic water), the bottom surface itself, and the bottom muds to a depth of about one metre. These benthic zones form a functional ecological unit, and they are conveniently considered together. The benthic area is the ultimate resting place of all particulate material, which sinks down through the water column, and this includes the river-borne sediments that enter the sea, fecal pellets, the organic and inorganic remains of all plants and animals of the water column, and all non-floating particulate debris of civilization that is dumped at sea. The sea bottom is the ultimate sink for all the land and water areas of the world.

The floor of the sea is not uniform in composition in all of its areas. On the outer continental shelf, where it is often swept by fairly strong water currents, the bottoms are often covered by coarse sands and shell debris. The continental slope tends to be a

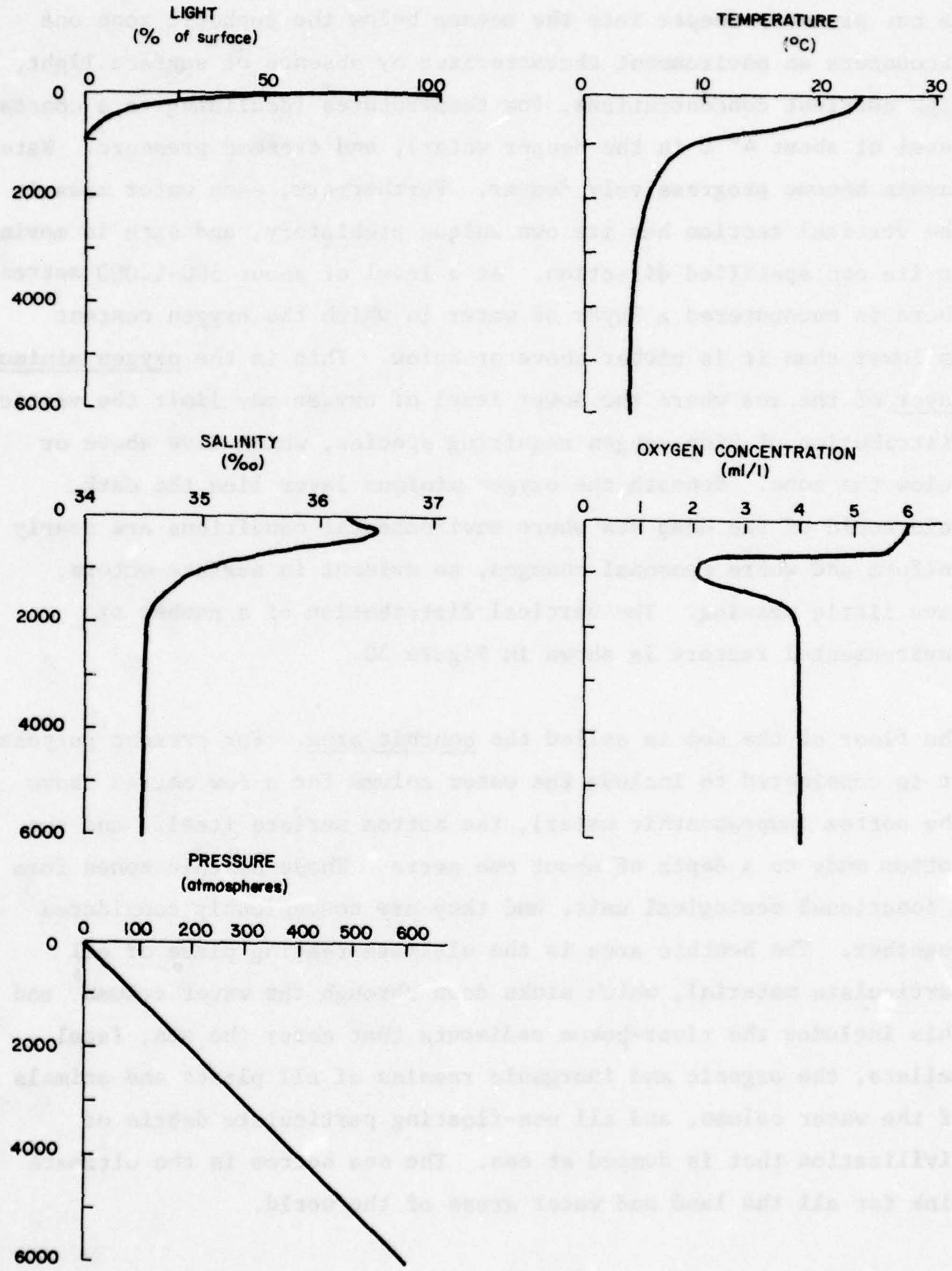


Figure 30. Vertical distribution of major physical and chemical factors in the ocean.

depositional environment where the benthic sediments are composed largely of fine silts and clays. The organic content of the benthic sediment tends to be high on the slope, especially in the zone where the oxygen minimum layer intersects the slope. There the sediments tend to show an increased organic content. Below the oxygen minimum layer and extending down the slope, through the continental rise, and across the abyssal plain, the bottom is made up of finely particulate silts, clays, and marine oozes.

Exceptions to these general patterns do occur. Rock outcrops may be found at any depth. The outer continental shelf and the slope are often dissected by erosional channels and valleys leading to submarine alluvial fans in deeper water. The channels of the slope often show a braided appearance as they connect and disconnect with one another. Local topographic highs may be encountered at any depth. Each of these features is characterized by its own suite of sedimentary environments, which are reflected in the patterns of particle size distribution on the local scale.

The water layer just above the bottom is affected by the proximity of the bottom itself. Any bottom stirring, whether by water currents or the activities of the benthic animals, may disturb the sediments and raise clouds of the powder-fine particles. Some of this material may remain in suspension for considerable periods of time, forming a cloudy or nepheloid layer above the bottom surface.

The bottom itself, down to a depth of about one metre is also considered to be a portion of the benthic environment because this is habitat for a very large variety of microbial and animal species. Through chemical action and through mechanical activities such as burrowing and pumping, these organisms stir and change the sediments and bring to the surface materials formerly buried to a depth of about a metre. The upper one metre of the sediments is, therefore, a dynamic zone, in actual or potential contact with the bottom surface and the suprabenthic waters.

LIVING COMPONENTS

The living components of the marine ecosystem include the plankton, nekton, neuston, and benthos. Each of these is treated briefly below.

Plankton

The plankton of the sea includes the microscopic plants and animals, which possess limited powers of locomotion and which are, thus, at the mercy of the water currents. They are swept wherever the currents take them, and for this reason the plankton of each water mass is indicative of the prehistory of the water. Examination of the plankton for "indicator species" permits identification of the source of the water mass and aids in working out the various current patterns of the seawater. Marine plankton is divided into two main groups: the phytoplankton, or plant plankton, and the zooplankton, or animal plankton. Each of these plays a distinct functional role in the economy of marine ecosystems.

Phytoplankton includes the single-celled organisms, diatoms, dinoflagellates, and others of lesser abundance (Figure 31). These are the producers of organic matter in the sea (comparable to grass and trees on land) upon which all the animals ultimately depend. Since light is required to support photosynthesis, the phytoplankton is essentially restricted to the upper 200 metres of water, where sunlight penetrates. The depth of the euphotic zone varies in relation to latitude, season, time of day, water clarity, and other factors, and the effective depth limit of the phytoplankton varies accordingly.

Phytoplankton is limited not only by light, but also by available nutrients, of which phosphorus and nitrogen are the two chief components.

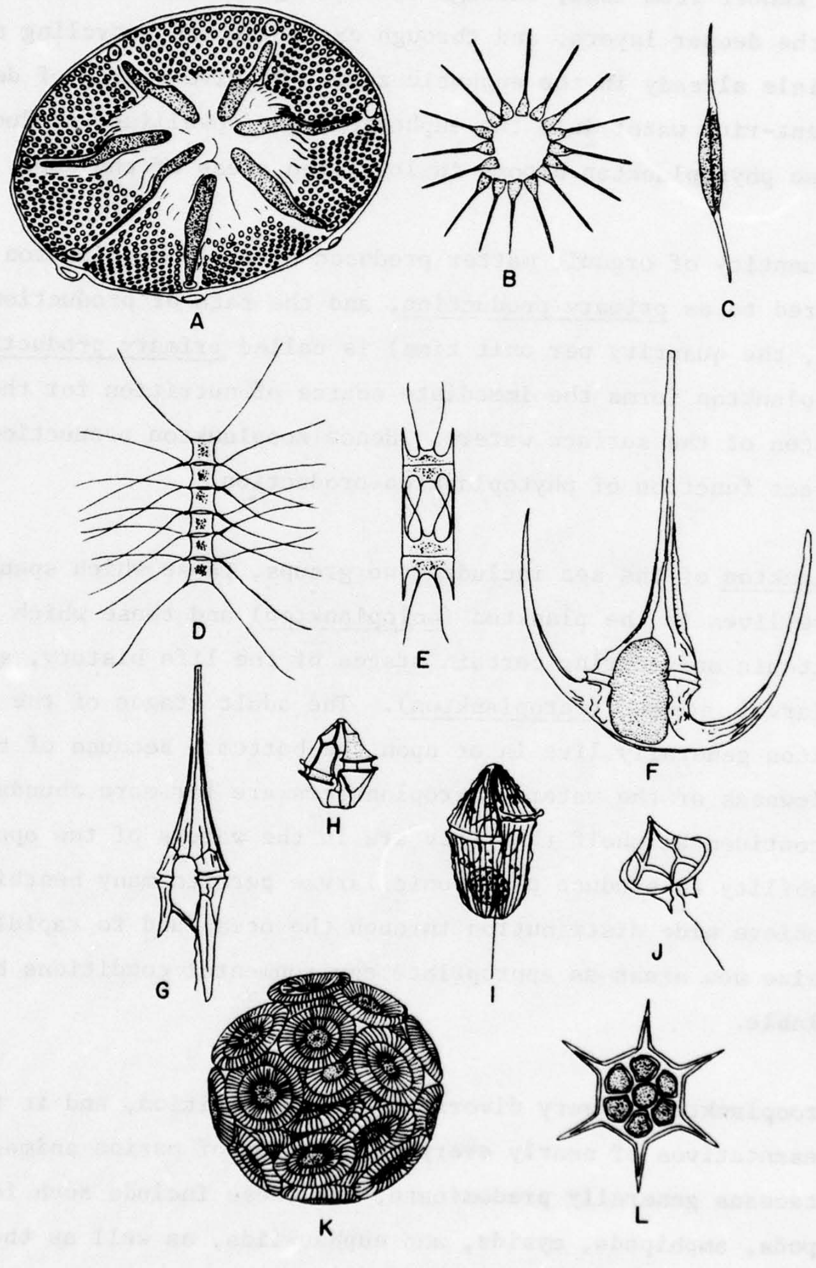


Figure 31. Examples of marine phytoplankton organisms. A, D, E Centric diatoms; B, C Pennate diatoms; F–J Dinoflagellates; K Cocolithophore; L Silicoflagellate.

These elements may become available in the surface waters through river runoff from land, through the rising of nutrient-laden waters from the deeper layers, and through excretion and recycling of materials already in the euphotic zone. Massive rising of deeper, nutrient-rich water into the euphotic zone (upwelling) produces immense phytoplankton blooms in localized areas of the sea.

The quantity of organic matter produced by the phytoplankton is referred to as primary production, and the rate of production (i.e., the quantity per unit time) is called primary productivity. Phytoplankton forms the immediate source of nutrition for the zooplankton of the surface waters. Hence zooplankton production is a direct function of phytoplankton production.

Zooplankton of the sea includes two groups, those which spend their entire lives in the plankton (holoplankton) and those which are planktonic only during certain stages of the life history, generally the larval stages (meroplankton). The adult stages of the meroplankton generally live in or upon the bottom. Because of the shallowness of the waters, meroplankters are far more abundant over the continental shelf than they are in the waters of the open sea. The ability to produce planktonic larvae permits many benthic species to achieve wide distribution through the ocean and to rapidly colonize new areas as appropriate environmental conditions become available.

The zooplankton is very diverse in its composition, and it includes representatives of nearly every major group of marine animals. Small crustaceans generally predominate, and these include such forms as copepods, amphipods, mysids, and euphausiids, as well as the larvae of decapods (shrimp, crabs, lobsters, etc.). Also abundant are protozoans (foraminiferans, radiolarians), chaetognaths (arrow worms), planktonic mollusks (heteropods and pteropods), pelagic tunicates (doliolids and salps), and others (see Figure 32).

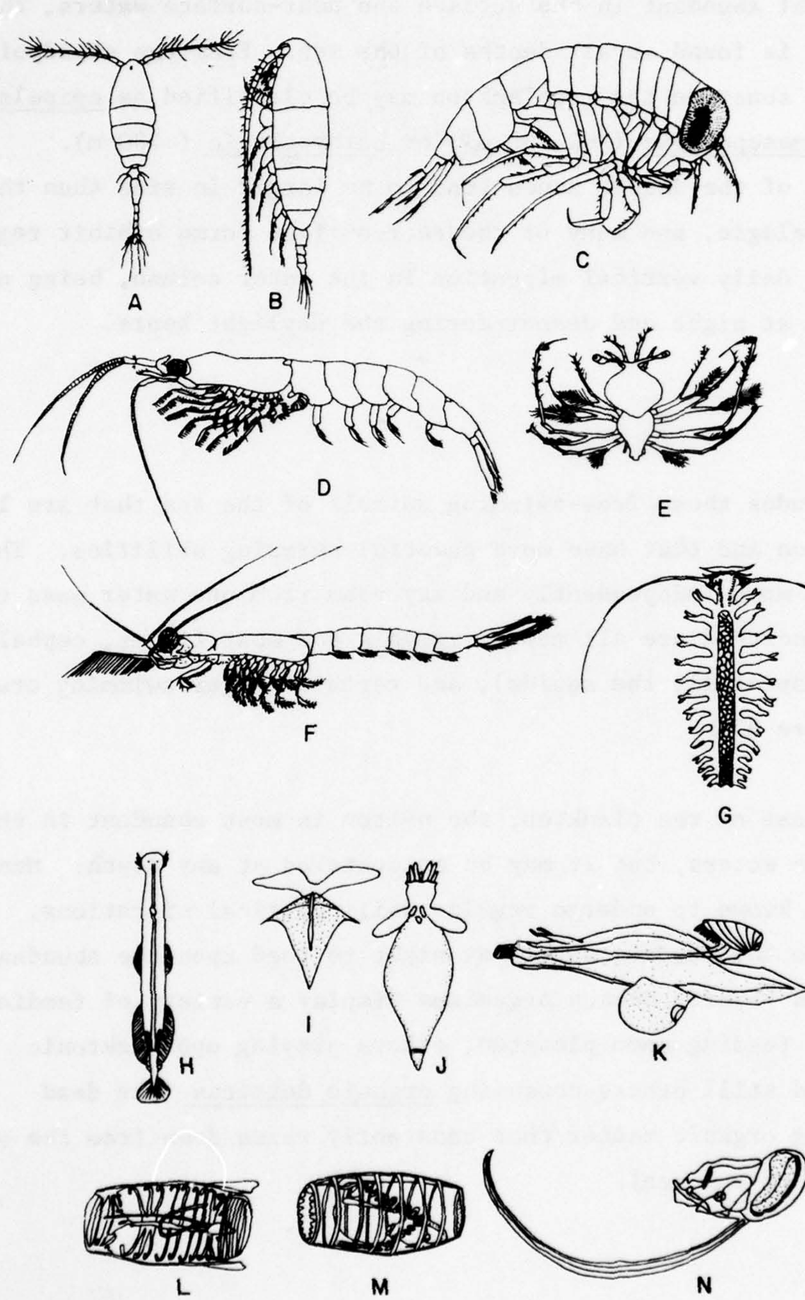


Figure 32. Examples of marine zooplankton organisms. A. Cyclopoid copepod; B. Calanoid copepod; C. Amphipod; D. Euphausiid shrimp; E. Phyllosoma (lobster) larvae; F. Mysid shrimp; G. Pelagic polychaete worm; H. Chaetognath (arrow worm); I-J. Pteropod mollusks; K. Heteropod mollusk; L. Salp; M. Doliolid; N. Larvacean.

Although most abundant in the surface and near-surface waters, the zooplankton is found at all depths of the sea. From the standpoint of vertical zonation the zooplankton may be classified as epipelagic (0-200 m), mesopelagic (200-700 m), or bathypelagic (700 m). Zooplankton of the deeper zones tend to be larger in size than those of the epipelagic, and many of the near-surface forms exhibit regular patterns of daily vertical migration in the water column, being nearer the surface at night and deeper during the daylight hours.

Nekton

Nekton includes those free-swimming animals of the sea that are larger than plankton and that have more powerful swimming abilities. They are able to move independently and may roam from one water mass to another. Included are all marine mammals and most fishes, cephalopod mollusks (especially the squids), and certain larger swimming crustaceans (Figure 33).

As in the case of the plankton, the nekton is most abundant in the near-surface waters, but it may be encountered at any depth. Many species are known to undergo regular daily vertical migrations, ascending to the surface waters at night to feed upon the abundant life in this layer. Nekton organisms display a variety of feeding types, some feeding upon plankton, others preying upon nektonic species, and still others consuming organic detritus (the dead and decaying organic matter that constantly rains down from the surface layers of the sea).

Neuston

Neuston is the group of organisms that lives in association with the upper surface layer of the sea. Some live on the surface, some live in the surface film, and others live just below the surface (i.e., in the top 10-20 cm). The living organisms include many

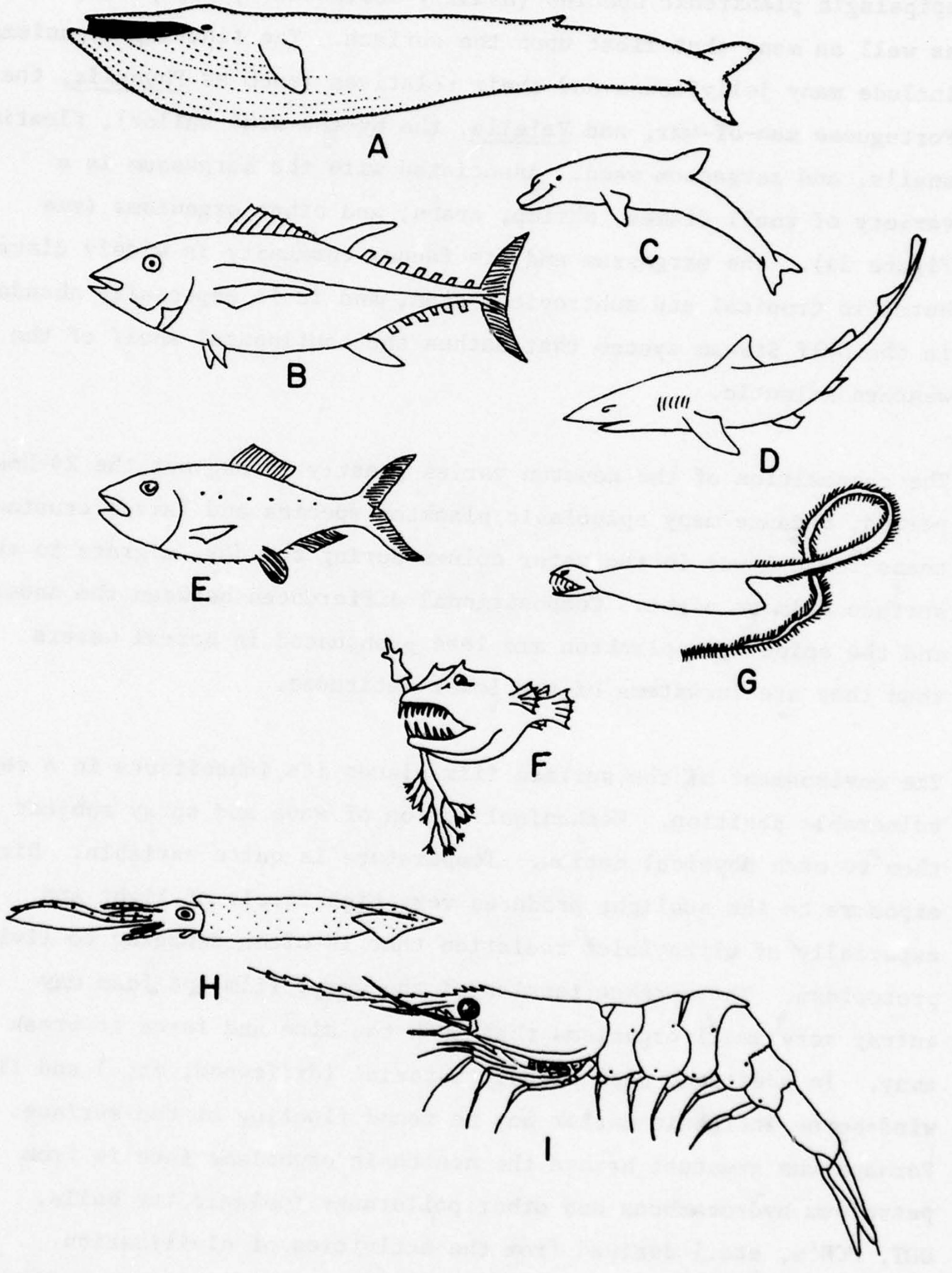


Figure 33. Examples of marine nekton organisms. A. Blue whale; B. Tuna; C. Dolphin; D. Shark; E. Menhaden; F. Angler fish; G. Viper fish; H. Squid; I. Caridean shrimp.

epipelagic planktonic species (usually dominated by copepods), as well as many that float upon the surface. The floating organisms include many jellyfishes and their relatives (such as *Physalia*, the Portuguese man-of-war, and *Velella*, the by-the-wind sailor), floating snails, and sargassum weed. Associated with the sargassum is a variety of small fishes, shrimp, crabs, and other organisms (see Figure 34). The sargassum and its faunal community is widely distributed in tropical and subtropical seas, and it is especially abundant in the Gulf Stream system that bathes the continental shelf of the western Atlantic.

The composition of the neuston varies greatly throughout the 24-hour period, because many epipelagic plankton species and larval crustaceans found lower in the water column during the day, migrate to the surface film at night. Compositional differences between the neuston and the epipelagic plankton are less pronounced in boreal waters than they are in waters of the lower latitudes.

The environment of the surface film places its inhabitants in a very vulnerable position. Mechanical action of wave and spray subject them to much physical motion. Temperature is quite variable. Direct exposure to the sunlight produces very high levels of light and especially of ultraviolet radiation that is often damaging to living protoplasm. The surface tension of the water film and foam may entrap very small organisms that lack the size and force to break away. In addition, much organic material (driftwood, etc.) and fine wind-borne inorganic matter may be found floating at the surface. Perhaps the greatest hazard the neustonic organisms face is from petroleum hydrocarbons and other pollutants (pelagic tar balls, DDT, PCB's, etc.) derived from the activities of civilization. Thus, the organisms that live at the surface must possess special adaptions to survive in this zone of stress.

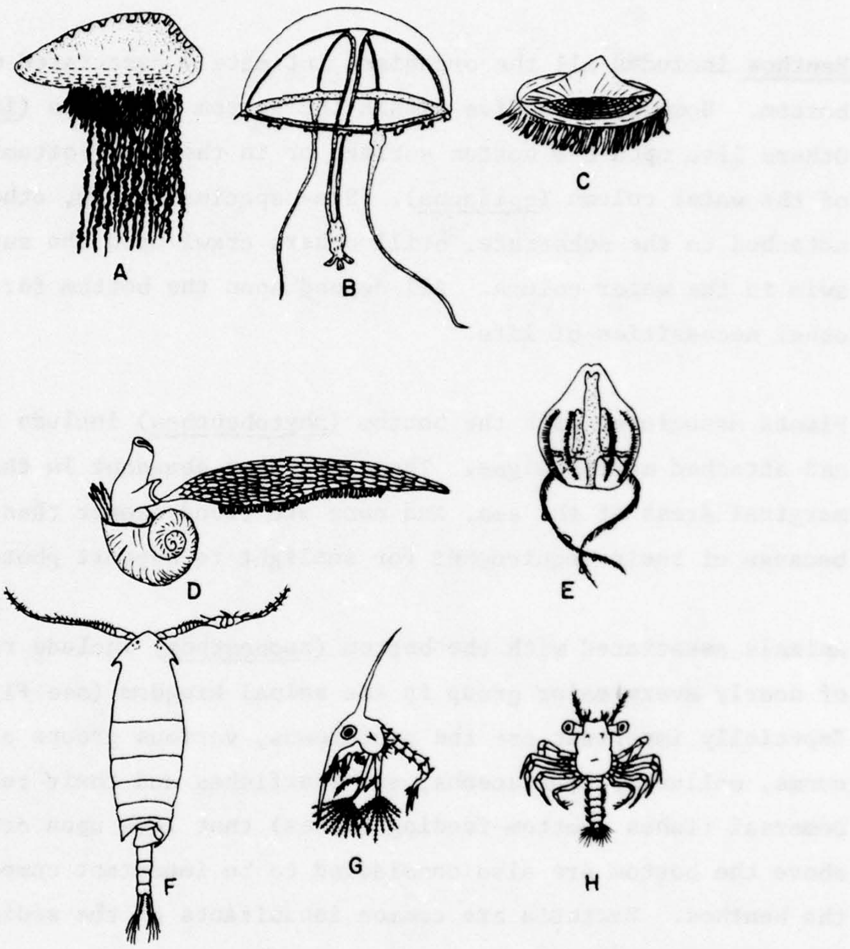


Figure 34. Examples of marine neuston organisms. A. Physalia (Portuguese man-of-war); B. Jellyfish; C. Velella (by-the-wind sailor); D. Janthina (purple storm snail); E. Ctenophore; F. Copepod; G. Crab Zoea larvae; H. Crab megalops larva; I. Sargassum weed community.

Benthos

Benthos includes all the organisms intimately associated with the bottom. Some species live within the bottom sediments (infauna). Others live upon the bottom surface or in the near-bottom portion of the water column (epifauna). Some species burrow, others are attached to the substrate, still others crawl upon the surface or swim in the water column. All depend upon the bottom for food and other necessities of life.

Plants associated with the bottom (phytobenthos) include seagrasses and attached marine algae. These are most abundant in the shallow marginal areas of the sea, and none are found deeper than 200 m because of their requirement for sunlight to support photosynthesis.

Animals associated with the bottom (zoobenthos) include representatives of nearly every major group in the animal kingdom (see Figure 35). Especially important are the protozoans, various groups of marine worms, mollusks, crustaceans, and starfishes and their relatives. Demersal fishes (bottom-feeding fishes) that live upon or just above the bottom are also considered to be important components of the benthos. Bacteria are common inhabitants of the sediments and near-bottom waters.

On the whole, the benthos includes a very diverse group of organisms, and many techniques have been worked out for studying and classifying them. One method of characterizing the benthos is on the basis of size (Table 11). Another way is on the basis of depth distribution in the sea (Table 12). Each type of substratum (mud, sand, gravel, rock, etc.) and each depth zone is inhabited by a special community of benthic species specifically adapted to the prevailing conditions of that particular environment.

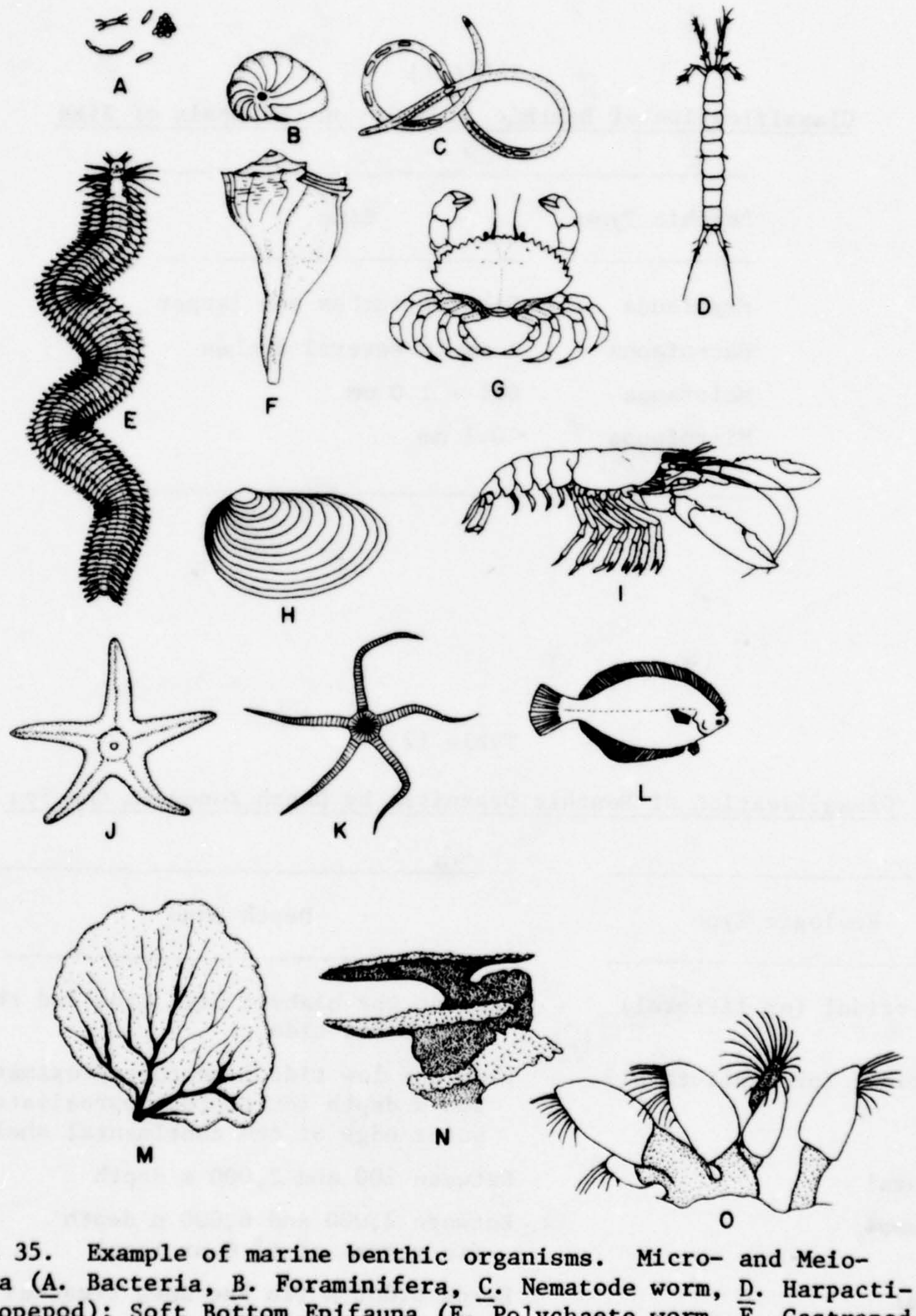


Figure 35. Example of marine benthic organisms. Micro- and Meio-Infauna (A. Bacteria, B. Foraminifera, C. Nematode worm, D. Harpacticoid copepod); Soft Bottom Epifauna (E. Polychaete worm, F. Gastropod mollusk, G. Brachyuran Crab, H. Bivalve mollusk, I. Lobster, J. Starfish, K. Serpent Star, L. Flatfish); Hard Bottom Epifauna (M. Sea fan, N. Stony coral, O. Stalked barnacles).

Table 11

Classification of Benthic Animals on the Basis of Size

Benthic Type	Size
Megafauna	Several inches and larger
Macrofauna	1 mm to several inches
Meiofauna	0.1 - 1.0 mm
Microfauna	$<$ 0.1 mm

Table 12

Classification of Benthic Organisms by Depth Zones in the Sea

Ecologic Type	Depth Zone
Intertidal (or littoral)	Between the highest high tide and the lowest low tide
Subtidal (or sublittoral)	From the low tide line to approximately 200 m depth (or to the approximate outer edge of the continental shelf)
Bathyal	Between 200 and 2,000 m depth
Abyssal	Between 2,000 and 6,000 m depth (in waters of 4° C or less)
Hadal	Below 6,000 m (in the deep trenches of the ocean bottom)

Studies have revealed that benthic organisms are far more abundant in shallow waters than they are in deeper areas. Standing crops in the nearshore waters may reach a kilogram or more per square metre of bottom surface area, whereas in the abyssal zone the living matter may constitute only a gram or less per square metre of bottom. Nevertheless, benthic organisms are found at every latitude and every depth in the sea. In a few areas where the circulation is poor, oxygen is absent, and hydrogen sulfide reaches high levels (such as the Black Sea and some oceanic trenches), animals cannot live, and the only benthic organisms that can tolerate the anaerobic conditions are bacteria and certain other microscopic species.

Coral and algal reefs constitute a special type of benthic community. These are found on hard calcareous bottoms in shallow waters, principally in tropical and subtropical regions. They require sunlight and are especially sensitive to heavy sediment loads in the water column. Marine biofouling organisms represent another benthic community adapted for attachment to hard substrates. These have become secondarily adapted to live on hard man-made substrates.

MATTER AND ENERGY TRANSFERS

Ecosystems exist by repeated cycling and recycling of chemical elements from the environment through various steps of the living systems and back to the environment. By means of photosynthesis and other mechanisms the plants of the sea take up carbon, hydrogen, oxygen, nitrogen, and the various salts and metals required by the living plants. Once these materials become incorporated into the phytoplankton cells, they become available to the animals of the sea that graze upon phytoplankton. Because of their requirement for light, the phytoplankton are restricted to the euphotic zone.

Within the euphotic zone the phytoplankton organisms are consumed by smaller zooplankton organisms, and through a series of eat-and-be-eaten steps the chemical materials are eventually transferred to the largest predatory carnivores. Taken together, these steps form the links of the <u>food chain</u> of the euphotic zone. Some of the phytoplankton sinks to lower levels of the sea where it also forms the base of the food chains of the aphotic zone of the water column and of the benthic zone. However, the food chains of the three zones are not completely independent of one another. Living animals may move up and down between zones and feed or be fed upon by organisms of another zone. Further, the non-living material (organic detritus), which consists of carcasses, fecal material, and the like, may sink (due to gravity), or it may rise (due to buoyancy). These factors tend to interconnect the food chains of the different depth zones (Figure 36). Actually, the situation in nature is more complex than this simple food chain model. At each step in the food chains many species exist, and numerous animals feed at more than one level. This redundancy means that in reality there are many interconnected food chains within each zone. Hence, one must think of complex <u>food webs</u> that exchange the materials through the living part of the marine ecosystems.

In order for the chemical elements to move through the food webs of the sea, there must be a source of power, and this power is derived from the sun. In the process of photosynthesis, phytoplankton cells convert certain wavelengths of solar radiation to chemical energy stored in the cell body as carbohydrates, fats, and proteins. These materials are passed around the living system through the food webs. When plants or animals require energy to support their metabolic activities, growth, and reproduction, they burn (or oxidize) some of the stored chemicals and release the energy for biological work.

According to the second law of thermodynamics, no energy transformation is 100 percent efficient. Some of the energy becomes available for useful work, but the remainder is lost, primarily as heat. The ratio of work output to fuel consumed is a measure of efficiency.

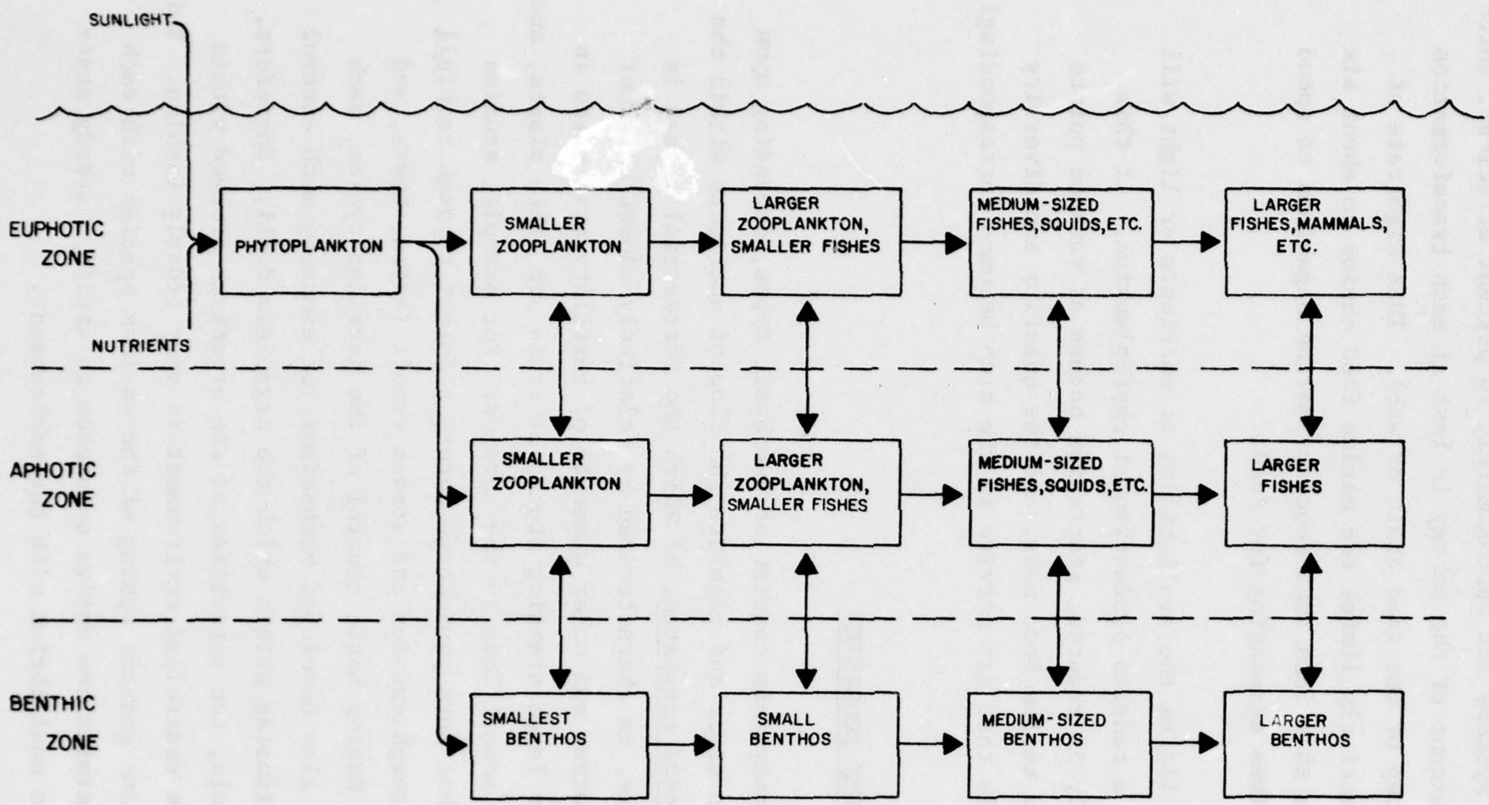


Figure 36. Diagrammatic representation of the food chains of the sea.

Most biological systems are approximately 10 percent efficient, which means that 90 percent of the energy is lost at each transformation (i.e. at each step of the food chain or web). This high rate of energy loss effectively limits the marine food chains to about six links, and it is this loss that requires marine organisms to spend much of their lives scrounging for food.

Any factor that limits the availability of nutrients or light will be reflected in a reduced production of phytoplankton. If this basic food supply is reduced, starvation occurs at various points higher up in the marine food webs, and the quantity and diversity of marine animals that can survive in the area becomes correspondingly restricted.

THE SEA AS AN OPEN ECOSYSTEM

Conceptually, ecosystems consist of two basic types, depending upon their ability to store and regulate the flow of nutrients within the system. The closed ecosystem, of which the terrestrial forest is the prime example, is characterized by relatively closed nutrient cycles. Phosphorus and other elements of fertility are stored in the soil and in large standing stocks of trees and other plants, and there is little annual loss to the outside. For example, studies have revealed that more phosphorus enters a forest through rainfall than is lost through erosion and stream runoff (Ryden, Syers, and Harris, 1973). Having basic control of the nutrient cycles, such ecosystems have also developed mechanisms for exerting much control over the microclimates within which the organisms dwell. Therefore, on an annual basis, the activities of the organisms proceed within the more-or-less controlled environment in very orderly fashion. This order permits fine genetic tuning of the various species with each other, and it permits the entire ecosystem to attain a steady state or thermodynamic equilibrium with the environment.

Aquatic systems in general and oceanic systems in particular are open ecosystems. They cannot store or retain nutrients over long periods of time, nor can they control the flow of nutrients with the same precision as occurs in a forest. Focusing only upon the euphotic zone of temperate marine systems, it is clear the nutrients enter the system seasonally as a result of meteorological and hydrographic factors. Water mass sinking in the fall (due to chilling and increase in surface water density) and water mass stirring (due to storms) result in the raising of nutrients from deeper layers to the surface waters. Nutrients are lost from the surface waters due to gravitational sinking of dead particulate organic matter, solubility and water transport of molecular nutrients, and movement of larger mobile animals out of the area. Marine ecosystems are very much at the mercy of the physical environment, and in a very real sense, they are adapted to respond to rather than control the annual nutrient cycle.

For these reasons, marine ecosystems of the euphotic zone in temperate latitudes exhibit seasonal pulses (in response to nutrient availability) followed by gradual relaxation (as the nutrients become lost to the system). The pulse-relaxation phenomenon, so evident in the surface layers, has not been studied in the deeper layers of the sea. However, these layers are totally dependent on the upper layers for their food supplies. Although some dampening of peaks and timewise spreading must occur, it would be expected that some seasonal changes in productivity must occur, even in the deeper layers, in response to seasonal nutrient availability.

To the extent that the meteorological and hydrographic events recur on a regular seasonal basis, the biological responses also recur regularly. However, it cannot be said that a steady state or a real equilibrium is established with the environment. Rather, it would seem that the marine systems are constantly chasing equilibrium, but never really achieving it, because of the seasonal variability of the physical environment and the absence of real biological control mechanisms.

MARINE SYSTEMS UNDER STRESS

All life on this planet is adapted to survive under the particular set of environmental conditions within which it normally lives and to which it has become genetically and evolutionarily adjusted through eons of time. Marked deviation of an environmental factor from the normal may place a burden upon the biological system, a condition referred to as stress. The factor that induces the stress is the stress agent. In the extreme case the stress agent may exceed the limits of vital tolerance, and death will ensue. For example, the temperature may become too high or too low for survival, or iodine may be present in toxic amounts or be so low that organisms die of deficiency disease. Within the total range of tolerance there is a zone, called the optimum, where the environment is just right, and no burden is placed upon the system. However, between the optimum and the limits of tolerance there exist the upper and lower zones of stress where the system is taxed and where survival is in jeopardy.

Biological response to stress takes many forms, and it occurs at all levels of biological organization. Observations and experiments on terrestrial, freshwater, and brackish-water organisms provide a background of information concerning the responses of biological systems to stress, and generalized response patterns to increased levels of stress are given in Table 13. Mild stress or stress of short duration may produce little permanent biological effect, but severe stress or stress of long duration inevitably takes a significant biological toll. Little work has been done on the effects of long-term low-level stress, and this is an important gap in present knowledge, especially in view of the widespread intrusion of civilization into the formerly natural environments of the world.

Table 13

Generalized Biological Response* Patterns to Increased Levels of Environmental Stress

Degree of Stress	Response at indicated level of organization: Individual organism	Population	Species	Community
Moderate	-Some metabolic and behavioral interference. -Reduced competitive ability. -Reduced resistance to parasites and predators. -Reduced capacity for reproduction.	-Reduced competitive ability of most sensitive individuals. -Some genetic selection for more tolerant individuals.	-Most sensitive populations undergoing selection for hardiest individuals, hence losing genetic diversity. -Most tolerant populations little affected.	-Noticeable shifts in relative species abundance as the most sensitive species suffer reduction in numbers while more tolerant competitor species remain the same or increase in abundance.
Heavy	-Individual under heavy stress load. -Survival not in jeopardy, but individual weakened and susceptible to parasites, disease, and predation. -Reproduction greatly curtailed.	-Elimination of most sensitive individuals. -Increase in more tolerant individuals. -Population level may or may not be affected. -Reduction in genetic diversity.	-Most sensitive populations eliminated. -Most tolerant populations losing sensitive individuals, hence losing genetic diversity.	-Significant shifts in species composition as sensitive species are eliminated and hardy competitors remain and often increase. -New hardy species may enter from elsewhere.
Severe	-Severe metabolic and behavioral interference. -Individual survival in question. -Reproduction no longer possible.	-Survival of only the most tolerant individuals. -Population level may or may not be reduced. -Severe reduction in genetic diversity.	-Only the hardiest individuals of the most tolerant populations still survive.	-Great shifts in species composition. -Most species reduced or eliminated. -Hardy species may become very abundant. -Total system greatly simplified. -Community metabolism greatly modified. -Stability severely reduced.
Total	Death	Elimination	Extinction	Collapse

* Response is given for several different levels of biological organization. Entries within a given vertical column are meant to indicate trends of response pattern. Habitat elimination sends all columns to the bottom entry.

From Darnell et al., 1976

Little is known of the responses of fully marine systems to environmental stress, but the general conclusions drawn from other systems certainly seem to apply when interpreted within the marine context. Marine organisms exhibit ranges of tolerance, and they show graded responses to mild and severe stress. Oil spills and severe domestic waste pollution have been observed to kill individuals, decimate marine populations, and eliminate multi-species communities, and the effects upon benthic systems may persist for many years. Species differ in their tolerances to various types of disturbance, with the most sensitive species suffering the most immediate, widespread, and permanent damage. By implication, the genetic consequences are clear. Darnell et al. (1976) have reviewed the literature concerning environmental impacts of construction activities in wetlands of the United States, and they have amply documented the complex and subtle ways in which specific environmental disturbance agents may affect aquatic environments and eventually species and ecosystems. Odum (1970) has shown the same for estuaries.

A few general conclusions may be drawn concerning the effects of stress upon marine ecosystems. Plankton populations are known to exhibit changes in species composition under mild stress (Mosser et al. 1970, and others), and to be locally wiped out by severe stress. However, due to the dilution capacity of large volumes of seawater, the movement and mixing capacities of water currents, and the widespread distribution of most plankton species, permanent damage to plankton populations by imaginable stress agents appears remote (except, possibly, in the cases of long-lived radioactive chemicals and certain chlorinated hydrocarbons). Neuston would be expected to be more vulnerable. Since the sea surface is an area, not a volume, dilution of floating substances would be less effective. Any deleterious agent that floats and spreads on the sea surface could potentially damage the neuston of a large area. However, like plankton, the species of the neuston are generally widespread, and eventual recovery would be anticipated. Most nektonic species are sufficiently mobile that they may avoid areas of severe stress if it can be sensed as being dangerous. Unfortunately, this is not always the case. Subtle stress agents, such as heavy metals, which become concentrated up food chains, may not induce avoidance reactions, and these could, in sufficient concentrations, damage the nektonic populations. Benthic environments cannot provide for dilution and transport. Many benthic species are of somewhat limited distribution, and most are relatively immobile. Hence, widespread and long-term damage to benthic systems is a definite possibility, although even here the damage is not likely to be permanent unless whole species are eliminated. All the effects of stress agents noted above are likely to be most severe in semi-enclosed bodies of water and in areas with low flushing rates. In dealing with complex material such as dredged material, which may contain a variety of potential stress agents, the above matters must be taken into account.

PART 3. ENVIRONMENTAL IMPACTS OF THE DISPOSAL OF DREDGED MATERIAL IN THE DEEP OCEAN

A. INTRODUCTION

GENERAL NATURE OF IMPACTS IN THE DEEP OCEAN

As was pointed out by Boyd et al. (1972), the ultimate concerns associated with impacts of the dredging-disposal process are the direct and and indirect effects on biological communities. To these may be added the potential impacts that these community changes may have on the welfare of man.

There have been very few truly deep ocean disposals of dredged material that have been studied from the standpoint of impacts on the biota (R. M. Towill Corp., 1972). Nevertheless, there is an impressive amount of indirect evidence that the impacts in the deep ocean will not have serious effects on the fauna. This view was subscribed to by a majority of marine scientists that TerEco Corporation convened at two advisory panel meetings in the fall of 1976. The same sentiment was voiced by K. O. Emery of Woods Hole Oceanographic Institution in 1971 (Andreliunas and Hard, 1972) when he indicated that there is much more ocean floor to waste than dry land and advised that the deep ocean should be used for waste disposal, provided it is done under knowledgeable management to minimize ecological problems. In general, those marine scientists who favor deep ocean disposal base their opinion on the probability that there will be an amelioration of effects during a long transit in the water column and that there is very little life on the deep ocean floor. Those who are equivocal on this issue or oppose it base their opinion on the fact that not as much is known about the deep ocean floor and its relationship to productive parts of the water column as should be. This is a legitimate observation, but more may be known than the non-specialist in deep ocean biology is aware.

Certain natural occurrences in the form of turbidity flows or currents provide some information on the effects of rapid sediment introduction to the ocean floor. Such flows are now known to be a common feature of certain continental slopes. For example, Griggs et al. (1969) found that the Cascadia Channel (2600 m depth) off the coast of Oregon and Washington had been the receiving environment of numerous postglacial-age turbidity currents. Even so, the benthic animal populations were four times as abundant as those of the adjacent Cascadia Abyssal Plain that has not been affected by such currents. Griggs et al. (1969) postulated that the turbidity flows created a superior environment with differences in sediment size (coarser) and composition by increasing the supply of utilizable organic material. This suggests that if done properly, terrigenous sediments, which are relatively rich in organic matter, can enhance the deep ocean environment, especially since the coarser material would tend to aggregate and thus create a coherent environmental "patch."

There are other valid reasons why it is believed that impacts of dredged material will not create severe stresses in the deep ocean. For one thing, as mentioned earlier, the deep ocean has large areas and immense volumes of water, even in reasonable distances seaward of the shelf break. For another, it is known that the deep ocean supports a small biomass and much of it consists of deposit-feeders, many of which are burrowers. Then, too, the deep ocean is little used by man today and, at least for food production, will not be used to a greater degree in the future. Finally, it should be noted that exchange rates in the deep ocean are much more uniform and probably considerably slower than on the shelf.

The rapid introduction of organic matter to the deep ocean floor should be considered an enhancing factor. Deep-sea conditions should facilitate release of phosphate and nitrate. Fillos and Molof (1972) have shown that low levels of dissolved oxygen in overlying waters (and thus into burrows, etc.) increased the release of PO_4-P and NH_3-N from benthal deposits. Pequegnat (1975) postulates that the microflora sustained by these materials and dissolved organic material supports some constituents of the meiofauna that can be a food source for larger invertebrates and, possibly, for some deep-sea fishes (cf. Rayburn, 1975).

TEMPORAL ASPECTS OF IMPACTS AND/OR EFFECTS

SHORT-TERM EFFECTS

The principal short-term impacts of the disposal of dredged material are summarized in Table 14, where a comparison is attempted between the degree of the effects between shallow water and deep ocean disposal. It is noted that the effects are either on the physical environments, which in turn affects the organism, or directly upon the organism. In the present context the latter are usually referred to as acute effects that elicit immediate stress responses from the organism.

LONG-TERM EFFECTS

It is difficult to document long-term impacts of the disposal of dredged material in shallow water let alone the deep ocean. Here again, however, effects can be to modify the physicochemical environment, which in turn will affect the organisms, or to directly impact the organism. In all instances it would appear that the deleterious effects will be less severe and possible beneficial effects will be more pervasive in the deep ocean than in shallow water. For instance, if it is assumed that toxic metals and some organic materials will be sorbed on fine sediments, these will be very widely dispersed and thus diluted, possibly below background levels. On the other hand, the weaker current systems in the deep ocean will have only moderate

Table 14

Comparison of Short-term Effects of Dredged Material Disposal Between Shallow Water and the Deep Ocean

Effect	Shallow Water	Deep Ocean
Turbidity:		
1. Reduce light penetration	Can be important to phytoplankton and phytobenthos	Little phytoplankton and no phytobenthos
	Can have effects on hermatypic corals	No reef building corals
2. Flocculate phytoplankton	Can be important in estuaries and above thermocline in neritic waters	Little effect
3. Aesthetically displeasing	Strong possibility	Little effect
4. Decrease availability of food	May be important Dilution of food particles with useless material	May increase food supplies Carry organic matter (POC)
5. Drive mobile organisms out of an environment	Temporary effect	Animals adapted to nepheloid layer
6. Affect respiratory surfaces	Can be important	Dilution and dispersion reduces potential effect
7. Sorption of toxic materials	Can be important to filter-feeders	Widely dispersed, reduced number of filter-feeders
Bottom Sediment Buildup:		
1. Smother benthic organisms	Can be important because biomass high	Less important because biomass low

(Continued)

Table 14 (Concluded)

Effect	Shallow Water	Deep Ocean
	High proportion of epibenthic species	Also higher proportion of infaunal species
2. Destroy spawning areas	May be important	Relative effects unknown
3. Reduce phytobenthos cover	Locally important to sea grass beds	No sea grass beds
4. Effect on bottom habitat diversity (change in grain-size distribution)	May reduce diversity	Probably will increase habitat diversity by introduction of coarse material
Depletion of Dissolved Oxygen:		
1. Suffocate organisms	Important, but species specific	Anoxia not as severe a problem in deep sediments
2. Can cause release of materials	Important locally	Lower concentrations will occur in deep waters

erosive action on whatever mounding of dredged material does occur, thus providing a structuring of the bottom that will serve as an attractant to many species.

DIRECT VS. INDIRECT IMPACTS

These categories of impacts are generally more applicable to the effects of dredging than of disposal. However, as noted above, disposal can have a direct anatomical or physiological effect on the organism and/or on the physical environment, which in turn will affect the organism's food supply, say by modifying a micro-current, and thus affecting the organism. In general it is felt that these effects are negligible in the deep ocean, primarily because of the depauparate nature of the fauna and because any possible deleterious effects of mounding through modification of the slow bottom flow could be outweighed by the value of environmental structuring.

B. PHYSICAL IMPACTS

TURBIDITY INCREASES

Turbidity of an aqueous suspension results from the presence of insoluble material that renders the water phase cloudy or less transparent and that reduces the intensity of a beam of light passing through it. It is the cloudiness that causes considerable unfavorable public response to some dredging projects, whereas it is the attenuation of light and to a lesser extent direct contacts between particles and organisms that produce the principal biological responses. In general, at least where hopper dredges are involved, it is the dredging process, not the disposal process, that produces the greater amount of turbidity. It is not anticipated that deep ocean disposal will produce significant turbidity, although it may add to the nepheloid layer. Nevertheless, it is worthy of further consideration.

The degree of turbidity is determined by both the concentration and particle size of the insoluble materials and in turn the degree determines the magnitude of light scattering. Ordinarily turbidity is measured by a nephelometer, which compares by means of photocell electronics the translucence of a test solution against a standard. Several commercial instruments based on this technique are now on the market. The most popular of these, called a transmissometer, is towed through the water during which time it measures the percent transmission of light through a 5- or 10-cm light pathway and relates this to underwater visibility.

LIGHT ATTENUATION

In the ocean, turbidity tends to decrease with increasing distance offshore, but even the clearest of deep ocean waters contain suspended matter and thus are turbid to some degree. Since the oceans contain an enormous number of particles of all sizes, the final attenuation of light results from the additive actions of absorption and diffusion on the light beam.

Jerlov (1951) determined that the transparency of ocean water is quite constant and found that in deep-sea water, which contains little particulate matter, transparency approaching 97 percent transmission is common. Some of his results are shown in Table 15.

Table 15

Percent Transmission of Normal Sunlight Through a Meter of Ocean Water

	Wavelength ($m\mu$) of Normal Sunlight				
Source of ocean water	310	425	550	600	650
Very clear ocean water	86	97.8	97.2	85	70
Relatively turbid ocean water	69	93.5	93.5	80	67

(Modified From Jerlov, 1951).

It is apparent from the above that wavelength is a parameter in light attenuation. It would be expected that oceanic waters and especially deep waters would have high proportions of fine particles. Thus, it can be seen that the shorter wavelengths are more readily scattered by small suspended particles than are the longer wavelengths. Later, the implications of this in the nepheloid layer will be discussed.

RELATION TO THE THERMOCLINE

Turbidity is one of the most important factors controlling horizontal and vertical distributions of bacteria and fungi in the oceans. A significant increase of turbidity in the open oceans and in most coastal waters is very often accompanied by increasing bacteria counts, while a decrease of turbidity generally causes decreasing numbers of bacteria. This interrelation is very striking in waters with either a halocline or thermocline, where turbidity and bacteria counts often attain maximum values.

ROLE OF RESUSPENSION PROCESSES

It is well known that shallow water may suffer from a condition perhaps best called chronic turbidity when fine dredged materials are resuspended by high wind and swell conditions. This will not be a problem of any significance.

AESTHETIC IMPLICATIONS

If the disposal operations connected with deep ocean disposal are carried out properly, there should be little visible evidence of the release. Hence there should be no aesthetic implications. It appears, however, that efforts should be made to reduce the turbid flow from hopper dredges in those places where brown water may become a chronic event under unusual weather conditions.

INPUTS TO THE NEPHELOID LAYER

Over wide areas of the oceans, including some of the deepest trenches, a layer of turbid water is found that varies in thickness from a few hundred metres to more than a kilometre. Its position is often misleadingly defined as being "near bottom", but in truth the nepheloid layer as first described by Jerlov (1953) extends from the water/sediment interface upwards. It is to be noted, however, that other turbid zones may exist within the water column and they too can be called nepheloid layers. They are, however, of lesser distribution and significance than the original Jerlov layer. There is no doubt that deep ocean disposal may contribute to the nepheloid, but the impact would certainly be negligible.

Pierce (1976) reports that concentrations of material in the near-bottom nepheloid layer are much higher than those of overlying waters but still considerably less than those found in nearshore waters. Betzer et al., (1974) report finding levels of suspended matter of 0.003 mg/l for clear ocean water off Cape Hatteras with the nepheloid layer having concentrations of 0.025 to 0.030 mg/l. As Pierce (1976) points out transport of material in the nepheloid layer is considerable even though the concentrations and movements are both low. The important factor is the thickness of a kilometre or more over thousands of km^2. Based on data provided by Ewing et al., (1971), it is estimated that between 30 and 300 million metric tons of material occur in the Argentine Basin alone. Thus, it is unlikely that deep ocean disposal will have much input to the nepheloid layer of the world ocean.

Recent data suggest that much of the suspended sediment occurs in aggregates that contain large amounts of organic material, both soft and mineral (Folger, 1970). This is compatible with the assertion by Bright and Pequegnat (unpublished data) that burrowing organisms make substantial inputs to the nepheloid layer by resuspending aggregates during burrowing, feeding, and cleaning activities. Observations were made on the outer continental shelf and upper slope off Texas during summer of 1976 that led to this opinion.

There are many possible sources for materials in the nepheloid layer: volcanic dust (Ewing and Connary, 1970), outward diffusion of river discharge (Ewing and Connary, 1970; Plank et al., 1973), low-density flows down canyons (Bennett et al., 1970), turbidity currents (Ewing et al., 1971; Eittreim and Ewing, 1972), resuspension of bottom sediments (Hollister and Heezen, 1972), and pelagic contributions. Clearly, the activities of benthic organisms in contributing to the near-bottom nepheloid layer should be added here.

IMPLICATIONS FOR BENTHIC LIFE

If, as believed, benthic organisms in shallower (upper slope) areas contribute at least to the formation and maintenance of the near-bottom nepheloid layer, it is difficult to believe that it will have any deleterious effect as such on their welfare. In addition to the observations above, W. E. Pequegnat (Personal Communication, TerEco Corporation, College Station, Texas, 1977) has bottom motion pictures taken at depths of 900-1000 m in the northern Gulf of Mexico showing fish (Gadidae) throwing up relatively dense clouds of fine materials during feeding activities. These fish remained voluntarily in the sediment clouds for several minutes at a time.

There are, however, certain types of sessile organisms, in particular hermatypic corals, that may be damaged or killed by siltation. These, however, are not distributed in areas that are likely to be affected by the deep ocean disposal of dredged material under consideration here. Only solitary corals are known to exist at depths being considered in the framework of this report.

RELATIONSHIP BETWEEN NEPHELOID LAYER AND CERTAIN TOXIC WASTES

There are obvious advantages to using the heads of submarine canyons as conveyor troughs for the transport of dredged material and perhaps other wastes to the continental rise and beyond. However, considerable concern has been expressed from time to time that some nondegradable materials, metals and organics, including chlorinated hydrocarbons that have a tendency to adsorb onto sediment particles, might build up to a point where repopulation would not occur if indeed there were an initial kill. The chlorinated hydrocarbons present the problem of greatest importance but perhaps unnecessarily so. If sediments are presently being charged with organo-chlorines, the situation probably stems from an accident or past lack of proper discharge control. Such sediments are far better discharged into the deep ocean, no matter what the cost, especially if the buildup has taken place in sediments likely to affect human marine food supplies. Most of the metal inputs into marine sediments have come from municipal and industrial discharges. Except as noted below, these sediments can be deposited in special areas of the deep ocean with only inconsequential effects.

LANDWARD RETURN OF MATERIAL TO SHOAL WATER

STORM SURGE INFLUENCES

There is no observational evidence for the lifting of deposited material on the outer shelf and continental slopes by hurricane-generated waves. A simple appeal to the tables available from Airy Wave Theory indicates that the potential for creating a pressure deviation by such waves at depths of 200 m or greater is quite small. On the other hand, if material is still in suspension above 200 m when such waves occur vertical mixing due to the orbital paths could occur and a net, but extremely small, horizontal translation in the wave propagation direction is possible. Thus storm surge influence becomes important when the shelf width is small and disposal has been initiated shortly before the advent of a major storm.

BREAKING OF INTERNAL WAVES

The influence of internal wave breaking is in the realm of an effective vertical mixing enhancement. As in the case of storm surge influence, there is no direct observational evidence in the literature for this mechanism operating on disposed material in the open ocean. Plumes of material and their vertical distribution have been observed acoustically on the inner shelf in the vicinity of a major current regime. If internal waves were breaking in this region the tendency would be to keep fine material in suspension. Internal waves are suspected to be present on the continental slopes and shelves that are generated in the tidal frequency range as a response to tidal forcing. There is no definite evidence of their existence (or breaking) in the open ocean literature reviewed for this report.

TOPOGRAPHIC MODIFICATIONS

TRIGGERING OF MASSIVE DOWNSLOPE MOVEMENTS

Slumping

It is not beyond the realm of possibility that the disposal of dredged material on the shelf-slope junction or upon the continental slope itself could trigger a large or small slump of the sediment cover. Although rapid deposition is often advanced as the basic cause of slumping, Uchupi (1967a) speculates that the slumping that occurred in the New York Bight in the Pleistocene may have been triggered by an earthquake. Lewis (1971) also believes that earthquake vibration can cause sediment bed failure. Kelling and Stanley (1976) describe slumping as "a gravity-controlled process in which cohesive materials yield and move under gravity in a more or less coherent manner." The failure occurs along discrete shear planes. Morgenstern (1967) points out that the degree of consolidation of the sediment largely controls the shear strength, but internal pressure induced by high rates of sedimentation can reduce the undrained strength to the point where failure may occur in clay on slopes as low as 3°. Thus, both the vibrations and internal pressures induced by discharging large quantities of dredged materials (especially consolidated types) on the continental slope, where the gradient is generally from 3-6° but may range as high as 15° or more (Emery and Uchupi, 1972), are capable of triggering a slump.

Sliding

Sliding is very similar to slumping, differing primarily in the fact that true slides exhibit little internal deformation as a result of their translation downslope (Kelling and Stanley, 1976).

Creep

This is a variant of slumping and sliding which is slow and which probably occurs along a large number of shear planes.

All of the above phenomena are known to have occurred in very recent times. For instance, the best known slump is one that occurred west of the Grand Banks in 1929 (Heezen and Ewing, 1952; Heezen and Drake, 1964). The movement involved both slumping and sliding on the slope and continued seaward down the rise as a turbidity current that successively broke about a dozen telegraph cables. Similar slides and cable breaks have been reported in this area for a long time (Milne, 1897; Stanley and Silverberg, 1969). Numerous authors have presented data on recent slumps, slides, and creep occurring on the slope, rise, and in canyons. Among these are Pequegnat et al. (1972), showing results of a slump in De Soto Canyon and creep on the slope, and James (1972) who marked various recent slumps in the Gulf of Mexico by displaced bivalve shells. In general, slumping or turbidity flows, triggered as a result of dumping in carefully selected areas, can be considered as an efficient way to distribute the dredged material into the deep ocean. It is not envisaged, however, that this would occur on a one to one basis for each disposal event. If the disposal introduced coarse sediments into an area otherwise dominated by muds, environmental enhancement might well result.

MODERATE MODIFICATION OF BOTTOM CURRENTS

Discharged material can be expected to modify bottom currents to a greater or lesser degree wherever they occur. Very likely such modifications would be more important in shallow water where much more mounding would be expected to occur than in deep water. Moreover, the deleterious effects of such modifications might be more significant in shallow water than in deep insofar as there are in the former, higher percentages of suspension-feeding organisms and those that produce pelagic larvae (which are distributed by currents - often on the microscale).

In deep water whatever mounding does occur could be taken as a biological plus factor since structuring is known to enhance the biological environment (Pequegnat, 1974).

C. CHEMICAL IMPACTS

The presence of large quantities of dredged material in shallow water can interfere with the use of the water for recreational or commercial purposes in a simple mechanical way; however, such mechanical or engineering problems can usually be anticipated and avoided by using proper disposal sites and practices. The chemical impacts that the dredged material has on the disposal environment are, on the other hand, difficult to predict and even more difficult to control. Concern for the chemical impact from an environmental quality standpoint has to be the overall effect on the marine biosphere, but such effects can be so subtle as to defy detection prior to irreparable damage, thus other evidences of environmental change must be considered. The usual rationale applied is that dredging and disposal are adversely affecting the environment if certain changes in water-quality parameters such as oxygen, nutrients, trace metals, and pesticides can be detected, because these are known to affect marine life. In order to predict the likely water-quality effect of removing and re-depositing material from a given site the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers have developed the elutriate test (Keeley and Engler, 1974). The test is designed to simulate dredging and disposal by mixing sediment to be dredged with water from the dredged material or disposal site, separating the two, then analyzing the water, especially for nutrients and known contaminants. The considerable work with the elutriate test, much of which is summarized by Lee et al. (1975), has added greatly to the understanding of the interactions between re-suspended bottom sediments and components in the water column. The results of laboratory studies, primarily with the elutriate test, and field investigations of water quality at disposal sites can be discussed under the following headings:

1) changes in oxygen concentration
2) uptake and release of nutrients
3) uptake and release of toxins
    a) trace metals
    b) halogenated hydrocarbons
    c) petroleum hydrocarbons
    d) unknown toxins and synergisms as detected by bioassay.

DISSOLVED OXYGEN

All nearshore sediments, whether clean or contaminated, will contain substances susceptible to oxidation by the dissolved oxygen in normal seawater. The amount of such substances, and hence the oxygen demand they exert will, however, vary greatly. Clean sands from which most clay and organic matter has been winnowed by wave and current action will have little oxygen demand, whereas organic rich muds and sludges will have very high oxygen demands. It is generally recognized that some oxygen loss will occur when any sediment is exposed to oxygenated water, but the magnitude of the loss will depend on the particular sediment and the chemical and physical factors in the disposal environment. One measure of the potential loss is the chemical oxygen demand (COD) of the material; the original Federal Water Quality Administration (FWQA) criteria for the suitability of sediment for dredging and disposal gave a maximum value of 5 percent (dry weight basis) for COD.

It has been found, however, that bulk chemical analyses of material does not give a reliable guide to the actual behavior of the material during dredging and disposal. Thus, the elutriate test was developed so as to measure the actual behavior of the material under laboratory conditions designed to simulate dredging and disposal. Work with the elutriate test has shown widely varying oxygen uptake rates depending on the sediment used (Lee et al., 1975). Furthermore, it is not a simple matter to convert these laboratory measurements to estimates of behavior in the field, because the oxygen uptake rates vary with time, temperature, and the aqueous-to-solid ratio in the settling mass, as well as with the amount of oxygen in the disposal water and its renewal rate by advection and diffusion. It is also important to note that in the elutriate test only the relatively short-term effects likely to occur during water column passage are being considered, whereas in nature the sediments will continue to exert an oxygen demand long after settling to the bottom.

Most of the environmental parameters needed to predict the overall impact of dredged material on oxygen concentrations at the disposal site can be obtained through a baseline data gathering program at the site. In such a program it is extremely important to consider seasonal effects, especially those that influence the stability of the water column, such as the development of a strong thermocline, which inhibits mixing and thus renewal of oxygen below the thermocline. Certain areas of the open continental shelf, for example, the U.S. mid-Atlantic area, develop anoxic or very nearly anoxic conditions in the bottom water when strong seasonal thermoclines develop and inputs of oxidizable matter from shore and from surface ocean productivity are high. Adding high BOD-COD dredged materials to these areas could have very serious deleterious consequences, even though the dredged material is almost certain to represent only a very small percentage of the total oxygen demand. It could figuratively become the straw that broke the camel's back.

The situation described above is certainly not typical of most of the U.S. continental shelf and slope at most times. Rather, a rapid renewal of oxygen in the bottom waters by advection and mixing is the rule. The unlikelihood of a significant lowering of oxygen concentrations in the open ocean under normal conditions can be implied from a consideration of natural sediment transport and deposition processes. These processes result in much larger and more persistent additions of oxygen-demanding substances to natural waters than those resulting from dredging. Nevertheless, serious oxygen depletion is caused by natural sedimentation processes in only rare times (e.g., large floods) or rare environments (e.g., certain highly stratified closed basins). One reason for this is the rapid flocculation and precipitation of even fine-grained suspended material, particularly in high ionic strength solutions such as seawater. Trefry and Presley (1976b), for example, point out that over 90 percent of the suspended load of the Mississippi River is deposited within hours of entering the saline waters of the Gulf of Mexico. The similarly rapid transfer of dredged material through the water column has been considered in Part 1 of Section B of this report, and it is this factor that will largely control oxygen uptake during water column passage. It should also be noted that nutrient release from dredged material to the water will stimulate photosynthetic oxygen production thus counteracting some or all of the oxygen uptake. The net result of all reactions involving oxygen will have to be determined on a case by case basis, and in fact whereas several studies rather clearly show oxygen depletion in bottom waters due to disposal of dredged materials (Brown and Clark, 1968, May, 1973), other studies show no effect (Windom, 1972). The observed oxygen depletion almost certainly results not from reactions in the water column, but from reaction in the bottom sediments, of the type discussed in an earlier section of this report.

Another viewpoint on the probable effect on water column oxygen levels can be obtained by a consideration of the relative amounts of available dissolved oxygen and oxygen demanding material, as has been stated above. An appreciation for the quantities involved can be obtained by considering that an absolute maximum suspended material load of a few hundred milligrams per liter can be expected, for short periods, in the immediate vicinity of the disposal site, whereas oxygen concentrations are typically 5 mg/l or so. Lee et al. (1975), in an extensive laboratory study of oxygen uptake by bottom sediment, found that between 0.15 and 0.6 mg of oxygen were used per gram of sediment during the first hour of exposure (much of this was within the first 10 minutes) after which the rate generally decreased. Thus, if there is no exchange or renewal of a parcel of water (an unlikely situation), which contains a high suspended load (500 mg/l) of material like the most oxygen demanding used by Lee et al. (1975), then 0.3 mg or 6 percent of the 5 mg of original oxygen could be used in one hour. Less material, a lower oxygen demand, and oxygen renewal by photosynthesis, diffusion, and advection would lessen the effect, whereas if the material were reacted with low-oxygen water, for example, from the oceanic oxygen minimum layer, or in the unlikely event of an even higher oxygen demand by the material, then a more serious depletion of oxygen could occur. As with many aspects of environmental behavior, prediction is difficult, and to a large extent must be made on a case by case basis.

UPTAKE AND RELEASE OF NUTRIENTS

Marine phytoplankton, like land plants, require certain chemical elements in addition to carbon dioxide and water in order to photosynthesize and grow. These elements are called nutrients, and the most important of them seem to be nitrogen and phosphorus, although many other elements may be required, but in such low concentrations as to seldom limit growth by their absence. Nitrogen and phosphorus, on the other hand, clearly limit phytoplankton growth and can be completely depleted in surface water during intense biological activity. The nutrients are released or regenerated when the organisms that took them up die and decay. Regeneration takes place in the water column as dead organisms and their metabolic products sink, and it continues after the material arrives at the sea floor. It has been shown, by Broecker (1974) among others, that the regeneration process in the water column is quite effective; that is, only a small percentage of the nitrogen and phosphorus that becomes fixed in biogenic particulates survives to reach the sea bottom, especially in water more that 50-100 metres deep. Furthermore, only a small percentage of the material making it to the bottom survives destruction at the seafloor-seawater boundary. Nevertheless, the bottom sediments represent a very large reservoir of nutrients because they have accumulated over a long time period compared to the residence time of the overlying water, and their nutrient content is more concentrated since it is in a solid form.

The release of nutrients from bottom sediments to the overlying water under various naturally occurring conditions has been studied for a number of years and is discussed in detail in a later section of this report. The release (or uptake) from sediments that have been mechanically disturbed, such as in dredging, has been less intensely studied, but several investigators have considered the problem in recent years due to its obvious relationship to water quality and biological activity. Biggs (1968), for example, reported nitrogen and phosphorus levels 50 to 100 times above ambient in the immediate vicinity of dredged material disposal sites. Windom (1975, 1976) has reported large increases in ammonia at disposal sites, but little change in nitrate and phosphate. In another study Windom (1972) found ammonia to be the only constituent of the many monitored that was consistently released in large quantities during initial dispersion of dredged sediments into water. In some cases, phosphate was released but in others it was not, a behavior Windom (1972, 1975) could not explain. Recent work with the EPA-COE elutriate test, especially by Lee et al. (1975), has done much to clarify the behavior of phosphate and other constituents of dredged material during disposal and has shown the overriding importance of the oxygen concentration as a controlling factor.

Windom (1972), May (1973), Keeley and Engler et al. (1974), Lee et al. (1975), and others have pointed out that changes in water-quality parameters, including nutrient levels, can not be simply related to the bulk chemistry of dredged materials. The elutriate test, however, which attempts to simulate dredged material disposal, offers promise as a predictive tool. Nevertheless, the elutriate test as originally proposed, wherein sediment and water are mixed in a 1-to-4 ratio and mechanically agitated, has given ambiguous data on the behavior of certain components of the dredged material, especially phosphate. Lee et al. (1975) reported that the seemingly anomalous behavior of phosphate during the elutriate test was related to variations in the redox nature of the sediment-water mixture, since no provision is made for maintenance of the redox level during the test. They obtained much more consistent results if the mixture was stirred and agitated by a stream of nitrogen or air, so as to maintain reducing (nitrogen) or oxidizing (air) conditions.

When the elutriate test is performed under oxidizing conditions, phosphate is almost always removed from the solution, presumably due to adsorption onto iron oxide particles that result from oxidation of reduced iron from the sediment. This result could have been anticipated because $iron^{+++}$ oxide addition has been a common method of phosphate removal from wastewater for a number of years (Recht and Ghassemi, 1970), and natural processes, which add iron oxide particles to water, have been shown to strongly affect phosphate concentrations (Berner, 1974). Figure 37 from Lee et al. (1975) very clearly shows the strong effect of redox levels on phosphate concentrations, and whereas the actual behavior will depend on a number of factors, it can be predicted by doing an elutriate test on the material to be dredged, using the water it will mix with during disposal and main-

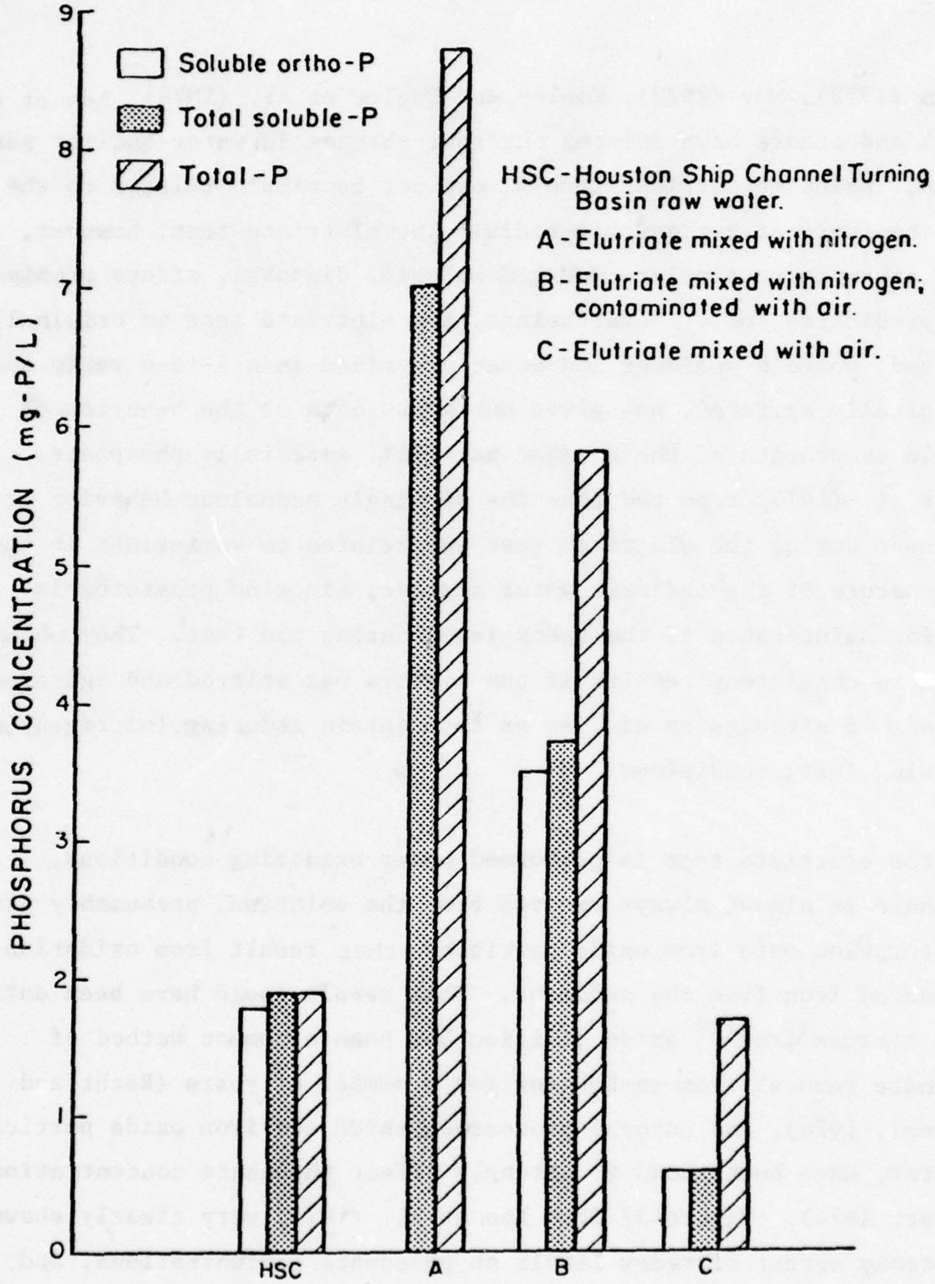


Figure 37. Phosphorus release under oxic and anoxic conditions: Houston Ship Channel Turning Basin sediments (from Lee et al., 1975)

taining the redox level to be expected. In the case of deepwater disposal the redox would almost always be positive due to an abundant supply of dissolved oxygen, thus an uptake rather than a release of phosphate is to be expected and little or no biological impact is likely. Ammonia levels in the open ocean are extremely low because it is thermodynamically unstable with respect to nitrate in the presence of oxygen. However, early workers found high levels in anoxic waters and pore waters, a fact well documented by Rittenburg et al. (1955) and later by Nissenbaum et al. (1972). Apparently, few reactions take up ammonia in the absence of oxygen, such that it builds up to levels in excess of those of the carbon, phosphorus, and sulfur species, which would be released with it during the decomposition of organic matter. It is not surprising, therefore, that most experiments with re-suspension of anoxic bottom sediments (e.g. elutriate tests) show large-scale ammonia release. Lee et al. (1975) emphasize this observation very strongly, and Chen et al. (1976b) and others have commented on it. Windom (1975) gives some dramatic examples of ammonia release in the field during actual discharge from dredge pipelines (Figure 38).

Concern over ammonia release stems from two opposing effects such release might have. It can stimulate biological activity, leading in the extreme to rapid growth to undesirable organisms and eutrophication, or it can act as a powerful toxin. Whether either effect is realized depends on environmental factors, especially oxygen levels, and the rapidity of mixing and dilution. It seems unlikely that a problem would develop in open ocean disposal, but due to the extremely low levels, which can cause measurable biological effects, each disposal operation should be evaluated individually, including monitoring of actual discharge. Little data are available on short-term toxic effects of ammonia; nevertheless, it is important to know what levels result from disposal and for what time, so as to guide future effects studies.

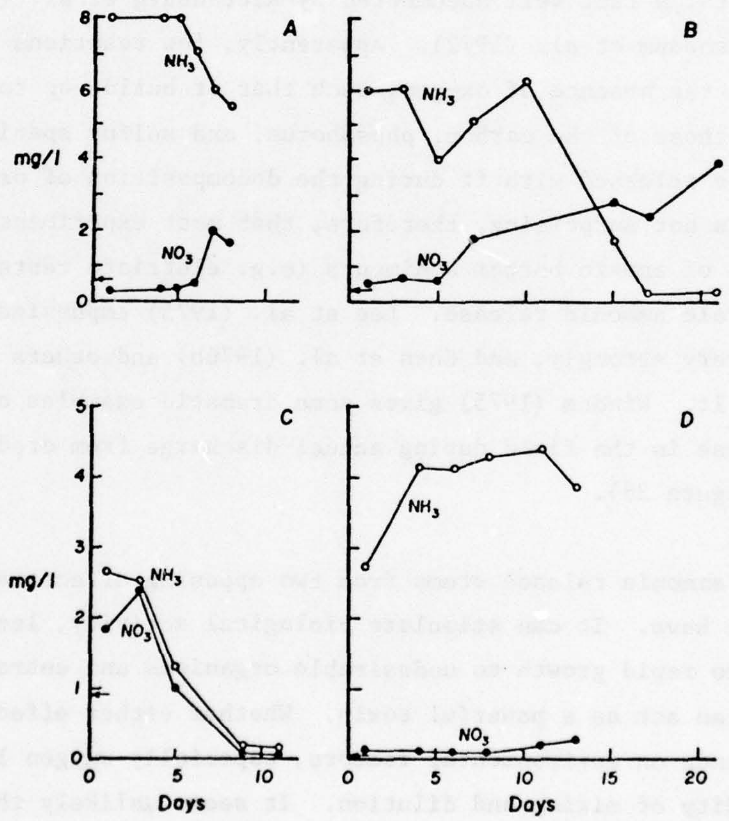


Figure 38. Changes in nitrate and ammonia with time after discharge in the water of the sediment-water slurry discharged from dredge pipeline. Arrow indicates nitrate concentration in ambient water. Ambient ammonia levels were always less than nitrate. (A) Upper Charleston Harbor. (B) Lower Charleston Harbor. (C) Cape Fear River. (D) Terry Creek, Ga. (From Windom, 1975).

If surface phytoplankton productivity is greatly stimulated as a result of ammonia and other nutrient release during disposal, the possible consequences of this activity must be considered. Even though it seems unlikely that adverse effects would result from increased productivity in the open ocean, the fact remains that oxygen uptake will result as the surface organisms die and sink, and under conditions of poor renewal of deeper water, significant oxygen depletion could occur. Furthermore, increased surface productivity could conceivably add to the organic carbon loading on the sea floor, which will occur as dredged material deposits. This organic carbon addition can have very pronounced, although probably very local, effects on benthic organisms, because, in the extreme, completely anoxic and hydrogen sulfide-containing sediments will develop that are devoid of almost all but microscopic forms of life. A more likely situation, however, is that the dredged material will slowly oxidize as it sits on the sea floor, with the depth of the oxidized layer of sediment being a complex function of the nature of the material, the oxygen renewal rate of the bottom water, and the mixing of the sediment. While an oxidized zone of sufficient thickness to prevent diffusion of reduced species from sediment to water is developing, such diffusion will occur. Thus, some additions of ammonia, phosphate, etc. will come from the bottom, but their effect on bottom water quality should be minimal except under extremely slow renewal rates of the water.

In summary, nutrients in measurable amounts are likely to be released to, or in the case of phosphate sometimes taken up from, the disposal site water, both during settling of dredged material and from the sedimented mass. This activity can have potentially significant effects on both pelagic and benthic organisms. However, the extent of the biological effects is largely dependent on the rate of dilution of added nutrients and the rate of renewal of water. In the case of typical open ocean areas, and considering the limited exposure of the settling material to the water column during disposal, it seems unlikely that pelagic organisms would be significantly affected. Benthic organisms may, however, be affected over a small area if the dredged material is richer in nutrients and organic carbon than the sediments on which it is depositing.

UPTAKE AND RELEASE OF TOXINS

Ammonia can act as a stimulant or as a toxin depending on its concentration, as was discussed in the previous section. Many other compounds and elements show similar behavior and some of these will be considered in this section. The most important classes of toxic substances, as determined on the basis of amount of production, toxicity, and persistence in the environment (National Academy of Sciences, 1971), are heavy metals, chlorinated hydrocarbons, and petroleum hydrocarbons. However, other toxins, especially other synthetic organics, may be of equal or greater importance in a given dredged material, even though they have not been extensively studied or discussed.

HEAVY METALS

The toxic levels for metallic compounds to marine organisms have not been clearly established, partially due to the extreme variability in sensitivity exhibited by different organisms and different life stages. There is little argument with the proposition, however, that such metals as mercury, cadmium, arsenic, chromium, copper, and lead can act as powerful toxins, not only to marine organisms but to man if he consumes seafood contaminated with them. The tragedy of Minimata Bay (Irukayoma, 1967) brought this fact dramatically home. Nor is there any argument with the fact that man's activities are drastically increasing the input of many metals to the ocean, as can be seen from Table 16, which was compiled from various sources by Ketchum (1972).

Table 16

Heavy Metal Production and

Potential Ocean Inputs

(in 10^6 metric tons/yr)

Substances		Mining Production	Transport by Rivers to Oceans	Atmospheric Washout
Lead,	Pb	3	0.1	0.3
Copper,	Cu	6	0.25	0.2
Vanadium,	V	0.02	0.03	0.02
Nickel,	Ni	0.5	0.01	0.03
Chromium,	Cr	2	0.04	0.02
Tin,	Sn	0.2	0.002	0.03
Cadmium,	Cd	0.01	0.0005	0.01
Arsenic,	As	0.06	0.07	-
Mercury,	Hg	0.009	0.003	0.08
Zinc,	Zn	5	0.7	-
Selenium,	Se	0.002	0.007	-
Silver,	Ag	0.01	0.01	-
Molybdenum,	Mo	-	0.03	-
Antimony,	Sb	0.07	0.01	-

From Ketchum, 1972.

The percentage of metal mined, and, therefore, presumably used, which escapes to the environment is difficult to estimate, but Table 16 emphasizes the potential of the problem. That the potential is realized, at least in some instances, is shown by Table 17 from Trefry and Presley (1976a) where data from San Antonio Bay, Texas, an area shown to be largely free of anthropogenic metals, are compared to Galveston Bay and the Houston Ship Channel. Iron and manganese concentrations are similar in the three data sets, but cadmium, copper, lead, and zinc are 10-20 times higher in the Houston Ship Channel samples.

Few sediments are likely to be as polluted by heavy metals as those from the Houston Ship Channel, yet enriched nearshore sediments must be common near population and industrial centers. Trefry and Presley (1976a) present a simple technique for demonstrating subtle contamination. They found that many metals give strong linear correlations with iron on scatter plots. Figure 39 for example shows zinc and iron data for a number of Gulf of Mexico sediments. A similar plot of zinc and iron using data from Hann and Slowey (1972) shows many samples falling near a straight line, but several samples well off the line. These latter samples from the Houston Ship Channel, are greatly enriched in zinc relative to iron, probably due to man's activities. Trefry and Presley (1976a) show, using much additional data, how this plotting technique allows one to recognize rather subtle evidence of contamination, without the necessity of considering complicating factors such as grain size, calcium carbonate percentage, organic carbon content, etc.

It is generally recognized that heavy metals, whether natural or anthropogenic, are largely transported to the ocean by streams and largely in particulate rather than dissolved form. Trefry and Presley (1976b), for example, show that 90 percent of the total flux by the Mississippi River for several metals is in the particulate form.

Table 17

Leachable Heavy Metal Concentrations for Sediments from San Antonio Bay, Galveston Bay, and the Houston Ship Channel

Location		Heavy Metal						
		Fe (%)	Mn (ppm)	Pb (ppm)	Zn (ppm)	Cd (ppm)	Cu (ppm)	Ni (ppm)
San Antonio Bay								
Mean (N = 51)	:	1.04	210	9.5	32.7	0.2	4.0	9.9
Range	:	1.65 to 0.19	423 to 60	14.4 to 3.3	51.7 to 5.6	0.44 to 0.22	8.3 to 1.6	10.3 to 2.6
Galveston Bay*								
Mean (N = 44)	:	0.71	408	24	51	0.6	19	22.1
Range	:	1.27 to 0.08	1060 to 53	50 to 5	141 to 9.8	4.9 to 0.2	96 to 4	58 to 0.6
Houston Ship Channel*								
Mean (N = 24)	:	0.98	392	113	240	2.9	46	34
Range	:	1.31 to 0.23	931 to 83	268 to 30	622 to 74	10.7 to 0.1	157 to 17	63 to 15

*Data from Hann and Slowey (1972) obtained with nitric acid (HNO_3) leach.

From: Trefry and Presley, 1976a.

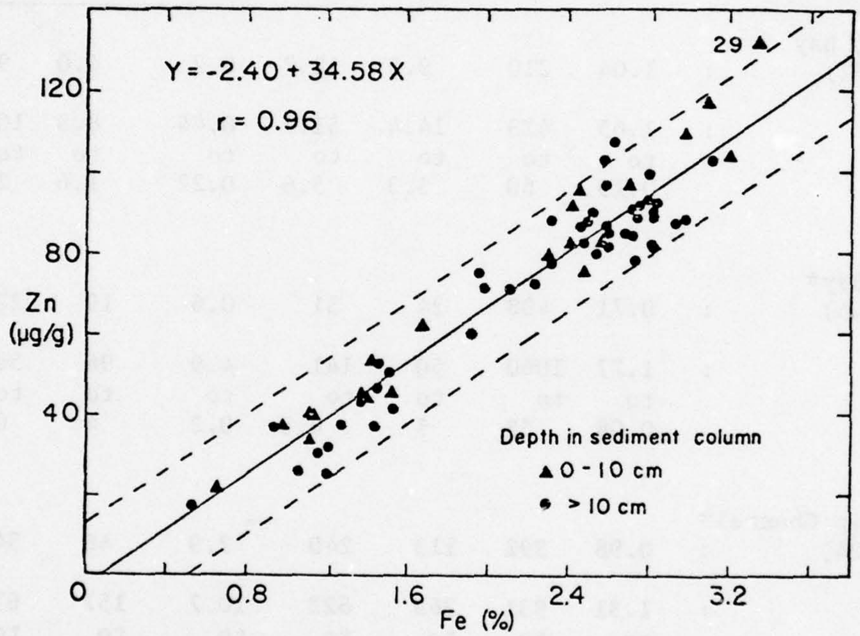


Figure 39. Zinc/Iron scatter plot for NW Gulf of Mexico sediments (from Trefry and Presley, 1976a).

Furthermore, these particulates deposit quickly upon entering the sea. This can be appreciated by noting that deep-sea sediment accumulation rates are typically 1000 or more times slower than rates in estuaries and near river mouths. Thus, the great bulk of sediment reaching the ocean settles where it may well have to be disturbed by dredging, and as has been suggested, this sediment can contain higher than natural levels of toxic heavy metals. In fact, studies of actual dredged material deposits have shown high heavy metal levels. For example, Gross (1972) found high silver, chromium, copper, tin, zinc, and lead in sediments composed of material dredged from the New York area and Horne et al. (1971) report similar findings on New York and other metropolitan area dredged material.

The discussion above concerns only the bulk composition of sediments and says nothing about the biological availability of metals or the effects on organisms. It is not surprising that grossly contaminated sediments seem to cause adverse effects. The Sandy Hook Laboratory (1972), for example, found that areas of the New York Bight, which were covered with "sewage sludge and dredging spoils were devoid of normal, or are characterized by greatly reduced, benthic macrofaunal populations." The Houston Ship Channel and other highly contaminated water bodies are almost devoid of benthic organisms. However, many studies of actual dredged material disposal areas, including a variety of sediment types, have either failed to find any evidence of biological effects, or have found the area returning to normal within months after disposal stops. Stickney and Perlmutter (1975) found the benthic infauna along the Atlantic Intracoastal Waterway returned to normal two months after being completely displaced by dredging. Harrison (1970) found only a few animals had colonized dredged material deposits one month after deposition in Chesapeake Bay, but in 15 months there was complete recovery of the normal population. Brehmer (1967) found greater species diversity and numbers of organisms in dredged (material disposal) areas of Chesapeake Bay than on natural substrate nearby. Saila et al. (1971) found effects of disposal of dredged material into Rhode Island Sound to be limited to small areas, which were quickly recolonized.

The studies referred to above argue against any extensive biological effect of heavy metals in most dredged material, and few if any studies have been able to show increased concentrations of metals in organisms collected on or near dredged material. Several authors, especially Windom (1972) and Lee et al. (1975) have strongly argued that bulk chemical analysis of sediments is relatively uninformative as to the biological availability of the toxins in the sediment. Gross (1972) found that only small percentages of the metals in the New York Bight dredged material could be leached out with hydrochloric acid and concluded that most of the metal was not available to organisms. The elutriate test, as has been discussed earlier in this report, was developed to give a better indication of biological availability than does simple bulk chemistry.

Lee et al. (1975) have done extensive work with heavy metal release during the elutriate test. They concluded that manganese is released in greater quantities than any other metal, under both oxidizing and reducing conditions. Under reducing conditions substantial amounts of iron and possibly lead were also released. Zinc, on the other hand, was taken up from the water under oxidizing and perhaps under reducing conditions, while copper, lead, and cadmium were not released or taken up under oxidizing conditions. Lee et al. (1975) found that a 30-minute agitation period allowed maximum release of metals, and that there was no additional release if 24-hour settling periods were used instead of 1 hour. Thus, the metal release seems to occur rapidly upon mixing sediment and water.

Chen et al. (1976b) conducted numerous experiments by resuspending sediments in seawater, allowing them to settle for 48 hours, and analyzing the overlying water. They found no change in the concentrations of silver, cadmium, and mercury under any experimental condition. Chromium, copper, and lead were released 3 to 10 times above background levels, and iron, manganese, and zinc were released in even larger amounts. The results of Chen et al. (1976b) are thus similar but not identical to those of Lee et al. (1975). In both cases, however, the actual concentrations of metals in the equilibrated water was very low, in the parts per billion range or less, and the large increases noted simply result from the extremely low metal levels in the starting water (normal seawater). In fact, the equilibrated concentrations were so low that considerable analytical difficulties were encountered in determining them, and there is little evidence to indicate that such low levels would have adverse effects on marine organisms in the short time before they would be diluted or precipitated in open ocean disposal operations.

It seems unlikely, based on the above discussion, that metal release in the water column during open ocean disposal would have significant biological effects, but because subtle sublethal effects are so poorly understood, more study of this situation seems warranted, especially using manganese, the metal released in greatest amounts. In addition to release to the water while settling, metals will be released from the sedimented mass of dredged material on the bottom under some conditions. One indication of this phenomenon is high heavy metal concentrations in the pore water (interstitial water) of normal marine sediments. In general, interstitial water trace metal concentrations are 5-1000 times greater than those in the overlying seawater (Brooks et al., 1967; Presley et al., 1972; Manheim, 1976). This difference establishes a concentration gradient, which allows significant diffusion and also potentially puts benthic organisms in contact with dissolved concentrations far above those of normal seawater. Despite analytical problems in obtaining interstitial metal concentrations, available values still appear to be below toxic levels and thus pore water solutions in dredged material would not appear to be an environmental problem. Nevertheless, the paucity of such data suggests that close-spaced vertical sections of pore water be analyzed for some of the toxic metals (e.g. mercury, lead, cadmium) in some dredged materials. Then, when more data are available on actual toxic levels of various metals, a judgement can be made as to the likely biological effects.

Interstitial water metal data tell about dissolved species, which are readily accessible to the benthos but very little about metal species bound to sediment particles, which may be released in the gut of an organism. The standard elutriate test is of little use for deposited dredged material because, except in unusual circumstances, no significant fraction of this material will be resuspended in the overlying water, and in any case it is the benthic organisms that may be most affected. Therefore, chemical leaching of sediments has been used to help identify the physico-chemical forms of solid-phase metals and predict biological availability. Sediment leaching techniques have closely followed those developed by soil chemists and have primarily been concerned with separating surface-held and authigenic metals from lattice-held mineral phase metals (Goldberg and Arrhenius, 1958; Hirst and Nicholls, 1958; Chester and Hughes, 1967, 1969; Presley et al., 1972; Gibbs, 1973).

Recent studies of metal partitioning applicable to dredged material (Brannon et al., 1976: Chen et al., 1976b) have incorporated many of these earlier techniques. A sequential partitioning scheme is outlined in Figure 40, and a sample data set for nickel is given in Figure 41. Chen et al. (1976b) and Brannon et al. (1976) have shown that metals are primarily found in reducible and residual phases. The large residual fraction observed in most sediment would most likely be unavailable to marine organisms whereas the reducible phases may be released in anoxic sediments or dissolved in an acidic digestive

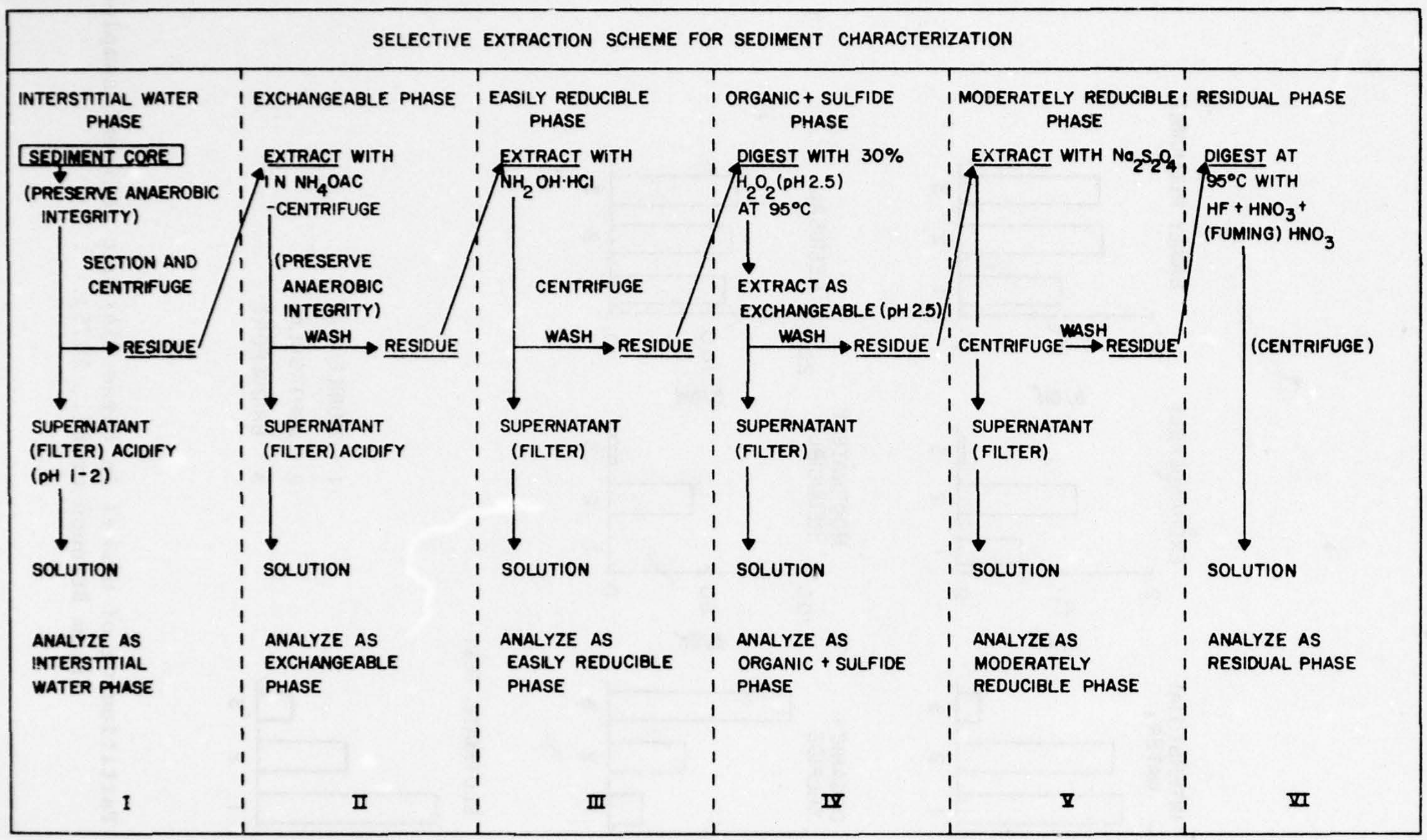


Figure 40. Selective extraction scheme for sediment metal partitioning studies (from Brannon et al., 1976).

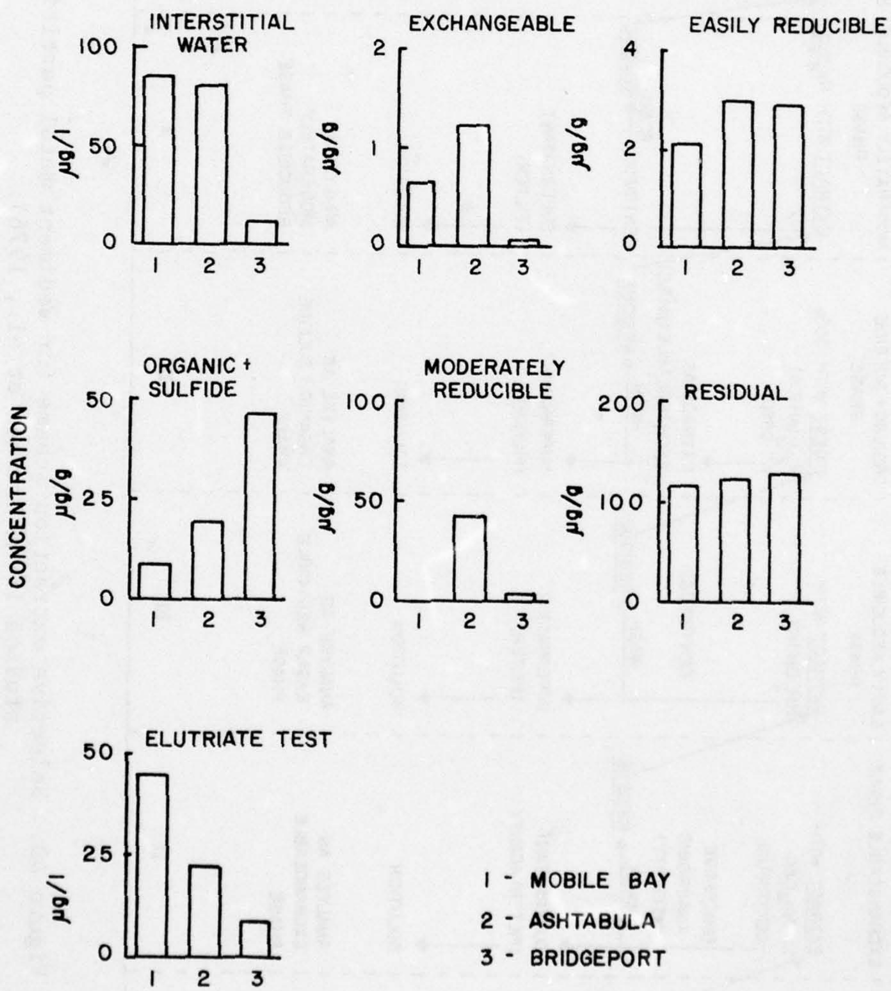


Figure 41. Partitioning of nickel in three distinct sediment samples (from Brannon et al., 1976).

medium. However, it is still not possible to make a straightforward assessment of the biological availability of sediment metals strictly from the partitioning data of the above schemes.

Khalid et al. (1975) present what is perhaps a more useful approach for environmental assessment as they measured the sorptive behavior of mercury as a function of pH and redox potential (Eh). It is, in effect, the Eh that is altered during diagenesis and the pH that is lowered during digestion. Trefry (unpublished data) leached sediments with phthalate buffers (ph 2.2 - 5.8) to assess biological availability (Figure 42). Results show that the amounts of iron and zinc removed from a surface sediment sample from the Mississippi Delta increase dramatically with decreasing pH. Within the range of known internal pH for benthic invertebrates (pH 4, Gates and Travis, 1969) only a small amount of metal would be released. On the other hand, vertebrate digestive systems are commonly at a pH of 3 or even less and would be able to mobilize much greater amounts of heavy metals, according to the data presented in Figure 42. More work is needed on the release of metals from various types of sediments due to leaching with solutions of different pH; however, no amount of leaching work can do more than imply biological availability of heavy metals. What is even more critically needed is simple uptake experiments to see if various sediment ingesting organisms do become enriched in heavy metals when cultured on a metal rich substrate. Dr. Frank Slowey (Personal communication, Texas A&M University, 1977) in ongoing unpublished work is finding little uptake by clams, worms, and other organisms, but Young and Jon (1976) find metal enrichments in scallops from areas off Los Angeles, California where sediments are metal rich and Kielor (Personal communication, University of Wisconsin, 1976) finds metal uptake from sediments by amphipods in a laboratory study. It is obviously difficult to judge the possible effect of heavy metal rich bottom sediment on benthic organisms. Nevertheless, because effects have generally been minimal in laboratory and field studies using

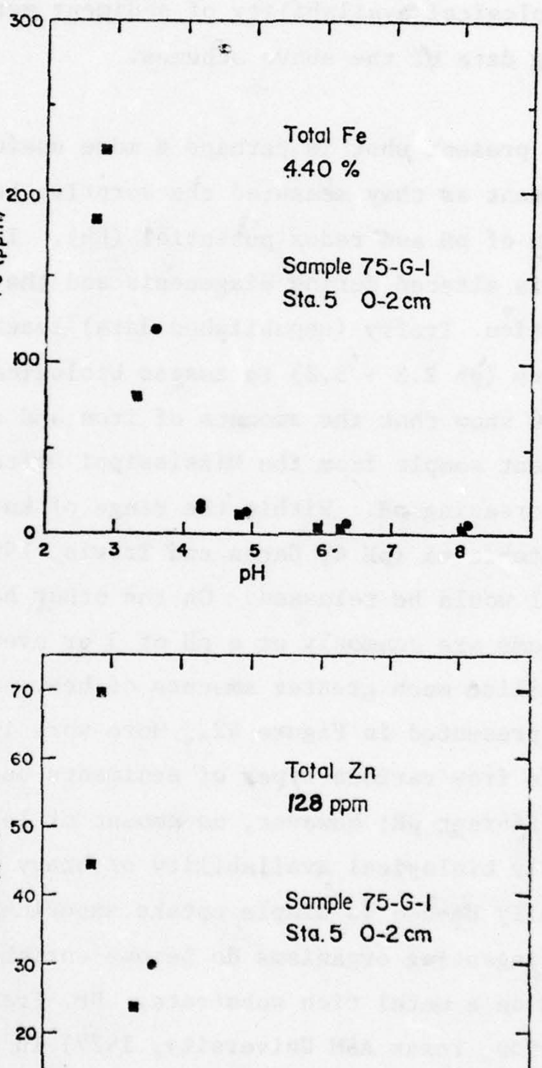


Figure 42. Iron and zinc concentrations in sediment leached by various buffer solutions after 6 and 24 hours equilibration (from Trefry, Unpublished Data).

undiluted contaminated sediment, it seems likely that no effect would occur in a typical deep ocean disposal operation where the sediment to be discharged is unlikely to be highly contaminated to start with and will be diluted by physical and biological mixing with the underlying sediment in any case.

SYNTHETIC ORGANICS

Over the past 20 to 30 years the chemical industry has developed literally thousands of new synthetic organic products and more thousands of applications for existing synthetic materials. Consumers are nevertheless demanding more plastics, solvents, synthetic fibers, pesticides, cleaning products and the like, so there is little doubt that production and use of such materials will continue to expand. A feeling for the magnitude of the potential problem can be obtained from Table 18, compiled by National Academy of Sciences (1971), which lists only a few of the compounds thought to be toxic to organisms that are produced in large volumes. The sheer mass and chemical complexity of synthetic organics makes the study of their environmental impact difficult indeed, but much research is under way and better assessments should be forthcoming soon. Meanwhile, it is essential to at least establish their distribution in the marine environment.

The two groups of synthetic organics that have received the most attention due to concerns over their environmental impact are halogenated hydrocarbon pesticides (e.g., DDT) and polychlorinated biphenyl compounds (PCB). These groups are produced in very large amounts (Table 18), are persistent, and are known to be toxic. Like other products of man they get into rivers from sewage outfalls and land runoff and ultimately enter the ocean where they are strongly concentrated in nearshore sediments (McDermott et al., 1974) (a large percentage of the continental supply of these compounds may also enter the ocean from the atmosphere, but this rate is of less

AD-A053 183 TERECO CORP COLLEGE STATION TX F/G 13/2

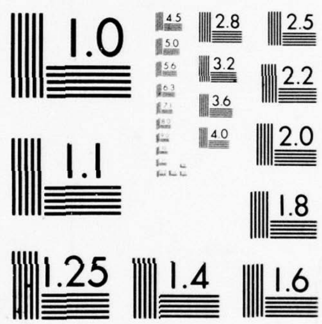
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)

JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL DACW39-76-C-0125

UNCLASSIFIED WES-TR-D-78-2 NL

4 OF 7

AD A053183



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

Table 18

Estimated Production and Environmental Leakages of Some Synthetic Organic Chemicals

Chemical	Global Production		Estimated Leakage to Environment	
	Annual Million Tons	Total Million Tons	Annual Million Tons	Total Million Tons
DDT	0.1	2	0.25	-
Aldrin-toxaphene	0.1	1	0.25	0.5
BHC	0.1	0.5	0.05	0.25
PCB	0.1	0.5	0.025	0.25
1, 2 dichloroethane	5	-	0.5	-
Freons	0.4-0.6	-	0.4-0.6	-
Dry Cleaning solvents	2	-	1-2	-
Total synthetic light organic	20-30	-	2-3	-
Total synthetic organic	100		?	-

From: National Academy of Sciences, 1971.

importance in a dredging study). As with other toxic substances, then, one must question the effect that dredging might have on the availability of pesticides and PCBs to marine organisms. To most people the real question is a simple "are pesticides and PCBs released to solution during mixing and dredged material disposal?" As noted below this may not be the proper question, but it must be answered in any case.

Pesticides, PCBs, and similar compounds can associate with a number of phases in the sediments (various clays, natural organic substances, organoclay complexes, petroleum hydrocarbons, etc.). Furthermore, there is considerable evidence showing that different synthetic organics associate with different phases of sediments and have different susceptibilities to leaching (Bader, 1962; Pfister et al., 1969; Huang and Liao, 1970; Boucher and Lee, 1972, and others). It is not surprising, therefore, to find a poor correlation between the amount of pesticide and PCB released to solution and that in the bulk sediment. An elutriate test is the best available tool for evaluating release and has been used by Lee et al. (1975).

Lee et al. (1975) worked with four different sediments from various locations in the U.S., one of which was highly contaminated with pesticides and two others of which contained detectable amounts. They also used, in the elutriate test, water contaminated with pesticides, as well as pesticide-free water. They found little or no release of pesticides in the elutriate test and, in fact, found some uptake from contaminated water. On the other hand, PCBs were released from some of the sediments but retained by particulate oil and grease.

There seems to be no consistent correlation between the initial concentration of PCBs in the test water and extent of release or sorption in the elutriate test. The PCB concentrations detected in all samples of water and elutriate, did not excced the aqueous solubility of

56 μg/ℓ for Aroclor 1254 at room temperature (Haque et al., 1974). However, whether the PCBs detected were soluble or associated with suspended solids that could not be removed by the centrifugation used was not determined.

Fulk et al. (1975) collected water and sediment from five different areas around the United States and from a variety of environments. PCBs were found in 59 of the 64 sediment samples analyzed, and dieldrin and DDT compounds were also common. Other pesticides were found in only a few samples. Water column samples also contained PCBs and dieldrin, but associated with particles, not as dissolved species. In desorption tests, desorption occurred only when sediment-water ratios were 1 to 5 or higher, with no measurable release to water with 1-to-10 ratios. The amount of pesticide in the sediment was more important to release than TOC or grain size, but oil and grease was also important. The amount of PCB remaining in the water column after settling of sediment was directly related to the oil and grease and suspended sediment in the water.

The above studies indicate that little of the PCB and pesticide content of sediments will be released to solution upon mixing with water as in dredged material disposal. However, the suspended sediment particles, especially if they have oil and grease associated with them, contain measurable PCBs and pesticides and probably even scavenge these compounds from solution. Unfortunately, from an environmental quality standpoint, contaminated particulates may be at least as harmful as dissolved compounds. For example, Nimmo et al. (1971) found crabs and shrimp could take up PCBs from sediment, and Odum (1969) made similar observations. Boothe (Unpublished Data) found that copepod larvae took up DDT almost exclusively from particles in the water, not from solution. This much of the elutriate test work may be relatively meaningless because only release to solution was considered, whereas the fine particulates may be more important, as might association with oil and grease, which could form a surface slick.

PETROLEUM HYDROCARBONS

From television news coverage, the general public is well aware of the impact of petroleum hydrocarbons (PHC) on the marine environment from the several spectacular oil spills, which have occurred in recent years. However, large episodic discharges from tanker and oil well accidents account for only 1 percent or so of the total PHC entering the marine environment. Table 19, reproduced from a National Academy of Sciences (1975) study, shows that most of the PHC enter by river and urban runoff and from other sources that constantly add these compounds to the coastal ocean.

Most of the PHC added to the ocean either dissolves in seawater or floats to the surface. In either case physical, chemical, and biochemical processes then start to degrade the petroleum, ultimately reducing it to carbon dioxide and water. However, in the processes of degradation a more dense residue is produced, and agglutination forms semisolid lumps called "tar balls." At the same time, the petroleum tends to adsorb or otherwise be taken up by suspended particulate material (L. M. Jeffrey, Personal Communication, Texas A&M University, 1977). Tar balls and oil-containing particles settle to the bottom, thus enriching the sediments in oil residues, especially near areas of major inputs such as harbors of industrial cities. Investigators of the Sandy Hook Laboratory found petroleum in the dredged material discharged in the New York Bight (Sandy Hook Laboratory, 1972) and Pearce (1969) reported 0.5 to 5.0 percent hexane extractable material in the New York dredged material disposal site. Blumer and Sass (1972) found petroleum in the sediments two years after an oil spill, which occurred near Woods Hole, Massachusetts. Farrington (Unpublished Data) (Figure 43) found high concentrations of

Table 19

Budget of Petroleum Hydrocarbons Introduced Into the Oceans

Source	Input Rate (million metric tons) Best Estimate	Probable Range	Reference
Natural seeps	0.6	0.2-1.0	Wilson et al. (1973)
Offshore production	0.08	0.08-0.15	Wilson et al. (1973)
Transportation			
LOT tankers	0.31	0.15-0.4	Results of workshop panel deliberations
Non-LOT tankers	0.77	0.65-1.0	
Dry docking	0.25	0.2-0.3	
Terminal operations	0.003	0.0015-0.0005	
Bilges bunkering	0.5	0.4-0.7	
Tanker accidents	0.2	0.12-0.25	
Nontanker accidents	0.1	0.02-0.15	
Coastal refineries	0.2	0.2-0.3	Brummage (1973a)
Atmosphere	0.6	0.4-0.8	Feuerstein (1973)
Coastal municipal wastes	0.3	-	Storrs (1973)
Coastal, Nonrefining, industrial wastes	0.3	-	Storrs (1973),
Urban runoff	0.3	0.1-0.5	Storrs (1973), Hallhagen (1973)
River runoff	1.6	-	Storrs (1973), Hallhagen (1973)
TOTAL	6.113		

From: National Academy of Sciences, 1975.

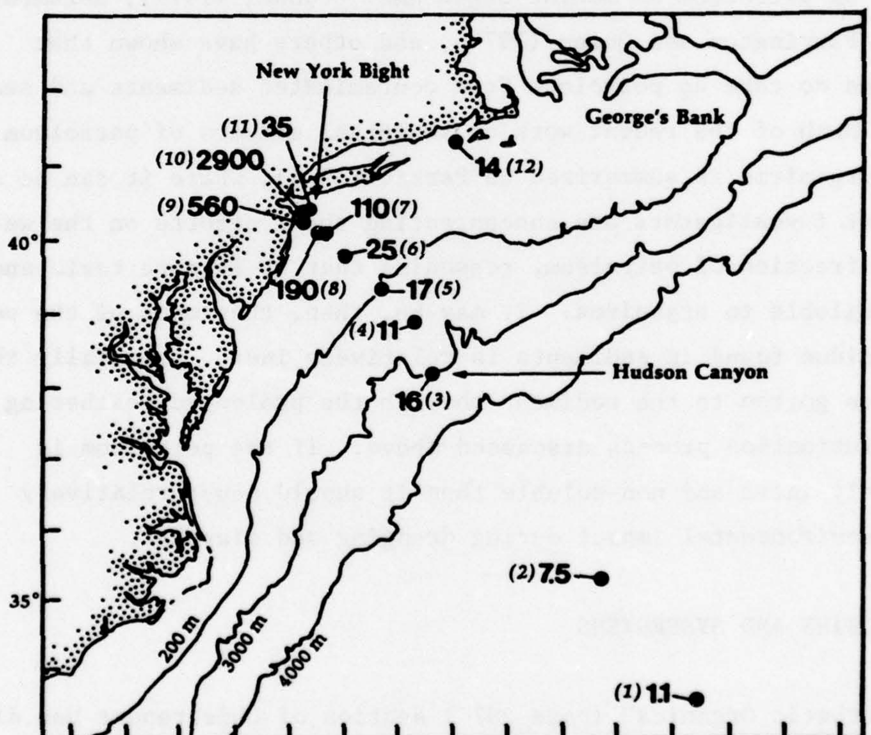


Figure 43. Hydrocarbon concentrations in sediments (micrograms per gram dry weight), including alkanes, alkenes, and two- to six-ring aromatic hydrocarbons. Station numbers are in parentheses. (Farrington, Unpublished Data).

petroleum in many nearshore sediments. There is thus no doubt that petroleum hydrocarbons exist in nearshore sediments and in material that has been or will be dredged. As with other toxins, however, the question is, "will dredging make the material more available to organisms?"

The National Academy of Sciences study referred to above (National Academy of Sciences, 1975) adequately documents the potential adverse effects of petroleum on marine organisms. Connel (1971), Ehrhardt (1972), Farrington and Quinn (1973), and others have shown that organisms do take up petroleum from contaminated sediments and seawater. Much of the recent work on sublethal effects of petroleum on marine organisms is summarized in Parker (1974), where it can be seen that most investigators are concentrating their efforts on the water soluble fraction of petroleum, reasoning that it is more toxic and more available to organisms. It may be, then, that much of the petroleum residue found in sediments is relatively inert, especially that which has gotten to the sediment through the prolonged weathering and agglutination process discussed above. If the petroleum is relatively inert and non-soluble then it should cause relatively little environmental impact during dredging and disposal.

OTHER TOXINS AND SYNERGISMS

The "Synthetic Organics" (page 287) section of this report has discussed the organic compounds produced in large qualtities that are thought to be most toxic and most persistent in the environment. A very large number of other organic compounds are produced that may be toxic to marine organisms and may be released to the marine environment in significant quantities near their source of manufacture or transport, thus creating local problems. An example of a local, but important problem is the kepone contaminated sediments in the James River, Virginia (U.S. Environmental Protection Agency, 1976). These sediments are probably more toxic than anything that has yet been dredged from any river or harbor, and unusual precautions will have to be taken during their removal and disposal. If such an unpredictable occurrence can happen once, it can happen again, thus one should be prepared, insofar as it is possible to prepare, for unusual local concentrations of little known synthetic organic toxins.

Among other groups of compounds that can be locally important are antibiotics, vitamins, and other medicinal wastes. While hospitals and clinics are the obvious sources of such materials, they are not the most important in many cases. Tetracyclines and other antibiotics, for example, are used in large quantities in animal feeds to promote more rapid growth. This latter use probably accounts for a large part of the increased production of tetracycline in recent years (Figure 44). It is known that animals release tetracyclines in active form. Elmund et al. (1971) found that 75 percent of the amount administered in feed could be found in fresh manure, thus there is the potential for introduction into rivers and the ocean. In the particular case of tetracycline, release to the environment may not be very significant, because it seems not to remain active very long. Nevertheless, tetracycline provides a good example of a class of compounds that are produced in large quantities and for which the environmental impacts are not well known. These compounds should be considered in dredging and disposal operations, and research as to their impact should be encouraged.

Pulp mill wastes and effluents are significant pollutants in many coastal waters. Wood chips, fibers, and wastes from the particular process used are common in nearshore sediments, where they not only produce a large oxygen demand but release toxins associated with the sulfate or sulfide liquors and cations involved. Few of these toxins have been studied, but they definitely affect marine organisms and must be considered if sediments rich in pulp mill wastes are to be

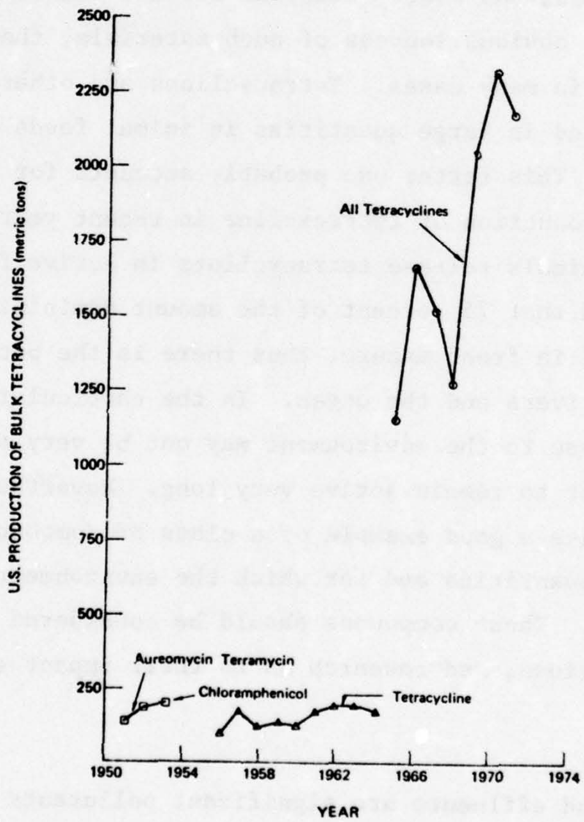


Figure 44. U.S. Production of Bulk Tetracyclines (Source: U.S. Tariff Commission 1962-1973).

dredged.

As has been mentioned above, many chemicals can cause local pollution problems. Waste organic sludges and solvents, chemicals that strongly taint seafood (e.g. chlorophenols), chlorine, cyanide, radioactive wastes, and others may be locally released in large quantities. Furthermore, it is essentially impossible to predict how a mixture of heavy metals, pesticides, petroleum, and other toxins will behave, even if accurate information were available on the behavior and environmental impact of each acting individually. In some cases toxicity is greater than the sum of the individual components (Gray and Ventilla, 1971) whereas in others it is less. In many cases the causative agent or combination can not even be identified. For example Young and Jon (1976) have noted fin erosion of Dover Sole due to the sediment from the Palos Verdes, California area, but have eliminated most common toxins as a cause. It may well be, then, that bioassays will have to be conducted using the actual material to be dredged and organisms from the disposal site in order to make a judgment as to likely environmental impacts. In the context of dredged material disposal, it is suggested on page 9 of the implementation manual for Section 103 of Public Law 92-532 (Engler and Wilkes, 1977) that "liquid phase bioassays can aid in evaluating the importance and the total net impact of dissolved chemical constituents released from the sediment during disposal operations." The methodology for conducting such bioassays is provided in the manual.

D. BIOLOGICAL IMPACTS

WATER COLUMN EFFECTS

IMPACTS ON PHYTOPLANKTON

Turbidity

Increased turbidity as a consequence of dredged material disposal will certainly reduce the penetration of light through the water column. It follows that a reduction in the amount of light available for photosynthesis would result in diminished primary production in the affected area. However, laboratory experiments have not consistently corroborated this relationship. The effects of kaolinite suspensions on the primary productivity of *Skeletonema costatum* were found to be contrary to expectation (New England Aquarium Corporation, 1974). Over a wide range of concentrations, the addition of kaolinite suspensions brought about increased values in a number of parameters used to measure primary productivity. Cell counts, C^{14} uptake, and the ratio of chlorophyll per cell number increased over the range of kaolin concentrations of 0 to 1000 ppm.

Utilizing laboratory cultures of four phytoplankton species, Sherk et al. (1974) demonstrated a 50-90 percent reduction in carbon assimilation as light was attenuated using suspensions of fine silicon dioxide. While these reductions may seem significant, similar drastic reductions under *in situ* conditions are seldom observed. Ingle (1952) reported limited reductions in primary productivity in close proximity to dredged channels. Others have found no significant changes in primary productivity in areas of increased turbidity associated with dredging (Odum and Wilson, 1962; Taylor and Saloman, 1968). Moreover, considering the nature of phytoplankton populations and productivity variability, these slight reductions induced by light attenuation are likely to be only short-term effects. Indeed, investigators of the Chesapeake Biological Laboratory (1970) demonstrated that reduction in light penetration from overboard disposal had only short-term effects on the phytoplankton, and that no long-term impact on primary productivity had occurred.

Nutrient Enrichment

In explanation of the lack of observed reductions in primary productivity associated with dredged material disposal, it has been suggested that reduced photosynthetic activity resulting from light attenuation is offset by the stimulation from nutrient enrichment. Significant enrichment of ammonia was found during estuarine dredging and disposal operations in the southeastern United States (Windom, 1973). Elevations in the concentrations of total phosphate (1000 times greater than normal ambient concentrations) and total nitrogen (50 times above ambient) were observed shortly following disposal in the Chesapeake Bay (Chesapeake Biological Laboratory, 1970). The remobilization of nutrients during dredging operations was thought to account for the observed 3- to 13-fold increases in primary production in a tropical coastal embayment (Subba Rao, 1973). Dredging activities in a small shallow bay at Gooseneck, New York, brought about significant increases in particulate phosphorus, silicates, and chlorophyll a (as indicative of phytoplankton biomass). When dredging was completed the concentrations of dissolved phosphorus and nitrates continued to increase; however, concomitant increases in the phytoplankton were not observed (Kaplan et al., 1974).

Stimulation of photosynthesis through nutrient enrichment, hence an enhancement of primary productivity, may be considered a beneficial impact. However, overenrichment can result in an algal bloom with adverse consequences. Although algal blooms in coastal waters have been attributed to nutrient enrichment occasioned by municipal sewage discharges and agricultural and feedlot runoff, such drastic responses are not typical side effects of dredging or disposal activities. Over enrichment would be more likely to occur in the shallow restricted environment of estuaries and coastal embayments than in the open ocean. Considering the low levels of phytoplankton standing crop, low nutrient concentrations, and the great capacity for dilution that characterize the open ocean, it appears that the nutrient enrichment from disposed dredged material, as it quickly transits the euphotic zone and disperses in the open ocean, would have only minor localized effects on phytoplankton production. As with any decreases in production due to turbidity, these localized increases would quickly disappear as nutrients are utilized and the resultant phytoplankton population and nutrient supplies are diluted through lateral mixing and sinking out of the euphotic zone.

Flocculation

The settling of sediments, especially the flocculation of the very fine fractions, can mechanically trap phytoplankters (Brehmer, 1965). As these particles sink, the adhering phytoplankters are physically removed from the euphotic zone, resulting in a relatively rapid, though short-term, decrease in phytoplankton standing crop for the limited area affected.

Contaminant Effects: Bioaccumulation

Chemical contaminants introduced with contaminated dredged material also present a potential for affecting the food chain at the first trophic level. It is apparent that no simple direct relationship exists between bulk chemical properties of dredged sediments and the changes in water quality that occur during dredging and disposal operations (Boyd et al., 1972; Windom, 1973; Keeley and Engler, 1974; Lee and Plumb, 1974). The effect of a particular contaminant on any organism is a function of both the nature of the contaminant and its mobility and biological availability within the sediment. Mobility and biological availability in turn are a function of where and how the contaminants occur within the sediments as well as their chemical form.

These variables preclude a precise assessment of the physiological effects of a milieu of contaminants. However, the nature of phytoplankton populations would suggest that, for the most part, impacts on phytoplankton populations would be insignificant. Acute toxicity, resulting in death of the individual phytoplankters, would be a short-term impact. As the source of contaminants rapidly sank below the euphotic zone and the infinite dilution capacity of the open ocean rendered the contaminants innocuous, the high reproductive rates of phytoplankton would quickly return the population to previous levels.

The sublethal effects of contaminants present greater potential for long-term adverse impact. The uptake of contaminants and their incorporation into the phytoplankters may have no apparent effect on the organisms or on primary production. However, as the plankters are consumed the contaminants are transferred to and concentrated in the consumers at the next trophic level. This transfer and concentration of contaminants continues throughout the food chain to higher trophic levels where the effects may become more manifest.

IMPACTS ON ZOOPLANKTON

Availability of Food Supplies

As zooplankton are the primary consumers of phytoplankton, any changes in phytoplankton abundance will affect the zooplankton through a reduction in their food supply. Whereas it was shown that, in the worst case, reductions in phytoplankton abundance and production would be short term and very localized in extent, the potential for adversely affecting zooplankton by diminishing their food supply would seem remote.

Introduction of Suspended Solids

Fine sediment fractions slowly sinking through the water column may adversely affect the zooplankton through an impairment of the feeding process and an interference with their capacity to control buoyancy and thereby to maintain themselves in the more productive parts of the ocean.

During exposure of two species of calanoid copepods to suspensions of natural silt, Fuller's earth, and sand, Sherk et al. (1974) observed significant reductions in the ingestion of food cells, i.e. phytoplankton. In addition to physical dilution of food particles in the suspension, it has been suggested that suspended sediments could reduce the effectiveness of, and even damage, feeding appendages (Sullivan and Hancock, 1973).

Similar to the flocculation and entrapment of phytoplankton, the resuspended sediments can remove the zooplankton from the water column. The specific gravity of individuals can be increased to the point of sinking by ingestion of solids in the feeding process and by entrapment or adhesion of particles to the projections on the zooplankters.

Oxidation of Dredged Material

Numerous investigators have reported that dredging and disposal activities cause at least temporary reductions in the dissolved oxygen (DO) concentrations in the water column overlying dredging or disposal sites (Brown and Clark, 1968; U.S. Army Corps of Engineers, 1969; Servizi et al., 1969; Pearce, 1972; Hopkins, 1972; Slotta et al., 1973; Maurer et al., 1974). On several occasions no changes in the DO concentration were observed in the vicinity of dredging and disposal operations (Chesapeake Biological Laboratory, 1970; Shelton, 1971; May, 1973). Rarely, DO concentrations were found to increase in the vicinity of the disposal site (Windom, 1973; Wakeman, 1974). Obviously the effect on dissolved oxygen concentrations in the water column varies with the nature of the dredged material.

The physiological stress of a diminished oxygen supply is not limited to adversely affecting the zooplankton. The benthos and nekton are affected as well. However, unlike the nekton, the zooplankters are not capable of moving out of and avoiding low oxygen areas. In addition to their inability to escape affected areas, the zooplankton represents an especially vulnerable stage in the life cycle of many organisms in the sea. Thus, any diminution of zooplankton standing stocks is likely to affect recruitment to the nekton and benthos.

Meroplankton, being eggs, larvae, and developmental stages of nektonic and benthonic organisms, are only temporary constituents of the zooplankton. These sensitive stages are more abundant in neritic waters where conditions favorable to their development prevail. Potential impacts resulting from oxygen deficiencies will vary seasonally with respect to the zooplankton. Impacts would be more severe at those times corresponding with an abundance of meroplankton. However, the potential impacts are of less significance in areas of low meroplankton abundance, i.e. the open ocean beyond the neritic zone. Moreover, as a significant depletion of dissolved oxygen in the water column of the open ocean appears implausible (see Part 3C), it is anticipated that zooplankton will not be adversely affected through an oxygen deficiency.

Contaminant Effects: Bioaccumulation

As was the case with phytoplankton, the effect of contaminants and toxicants on the zooplankton is regulated primarily by the nature of the material and its availability to the organisms. The effects may assume greater significance with the zooplankton due to several factors. The availability of contaminants is greater when incorporated into the food organisms of the zooplankton. Through the process of bioaccumulation, the zooplankton may concentrate the contaminants at levels far exceeding those found in the phytoplankton or in the surrounding water column. The sensitivity of larval stages also makes the meroplanktonic component of the zooplankton especially vulnerable to ambient concentrations of contaminants and more so to the effects of ingested pollutants. Relative to similar impacts on the phytoplankton, these impacts may be long lasting and widespread as meroplankton losses or disabilities will affect recruitment to the benthos and nekton. Because of the longer regeneration times required for both the holoplankton and the meroplankton, the impacts on zooplankton tend to be longer lasting than similar effects on the phytoplankton.

IMPACTS ON NEUSTON

Because neuston is largely composed of the same species that constitute the underlying zooplankton populations, except that the relative species abundances may vary, the impacts of disposal of dredged material will be similar to those discussed for zooplankton. The main difference, however, is the fact that neuston occupies the top 10-15 cm surface layer of water, an area that is particularly susceptible to certain environmental stresses such as the inflow and accumulation of dead organic matter, biological activity of the foam, presence of ultraviolet and infra-red rays from solar radiation, temperature extremes, wave action, currents, and man's contaminants (e.g. pelagic tar, plastic, DDT, and PCBs).

During ocean disposal of dredged materials, the greatest potential impact will be the fine materials, which do not settle out as readily as the heavier materials. These fines might be retained in the surface layer for some time, float back up, or be carried back up to the surface by currents or turbulence. MacIntyre (1974), in discussing the top millimetre of the ocean, states that this microlayer concentrates heavy metals such as lead, mercury, copper, etc. and also retains slow-degrading chlorinated hydrocarbons such as DDT and PCBs. Therefore, depending upon the composition of the dredged material, there will be a greater or lesser potential impact on the surface layer and its fauna.

Because of the greater abundance of larval forms in continental shelf neuston versus oceanic neuston, and because many of these larvae are important links in the life cycles of the commercially important fish and shellfish species on the continental shelf, there would appear to be less deleterious impacts if the disposal of dredged materials occurred in oceanic areas, i.e., beyond the continental shelf zone. Neuston concentrations have been shown to be relatively impoverished in off-shelf areas compared to those above the shelf and compared to the zooplankton concentrations beneath them (Morris, 1975; Berkowitz, 1976).

IMPACTS ON NEKTON

It is difficult to discern the effects of dredging or disposal on motile organisms since the composition of the population and the concentration of organisms vary considerably with time and space. As a result, few <u>in situ</u> studies have been conducted to determine the impact of dredging or disposal activities on the nekton. Of these, most have been limited to the effects in coastal or estuarine areas where organisms encounter significant amounts of natural turbidity on a regular basis.

In offshore areas, naturally turbid conditions are uncommon and consequently the nekton found therein would be expected to exhibit a lesser tolerance for the high turbidities associated with dredged material disposal than would their estuarine counterparts. Thus, it is not possible, with a great deal of certainty, to extrapolate from estuarine studies to offshore areas where naturally turbid conditions are uncommon.

It is anticipated that organisms capable of relatively high mobility would be least affected by dredging and aquatic disposal activities since they can avoid the areas of disturbance. A possible exception to this would be conditions in which a nektonic population is restricted to or obliged to inhabit a small geographic area that is totally affected by the disturbance. As an example, dredged material disposal activities in a river may effect a significant increase in suspended solids throughout an entire cross section of the river. Anadromous fish, unable to find alternate passage and thus obliged to enter the affected area, may be impaired in their migration to freshwater spawning areas. The widespread impact on the population is obvious. Similar conditions can be envisaged for coastal embayments or passes whereby species dependent on estuaries to complete their life cycles are adversely affected in their passage to or occupancy of vital habitats.

However, such exclusionary conditions in the open ocean exist rarely, if they exist at all. Unique habitats or migratory pathways in the open ocean lack the confining boundaries common to riverine or estuarine habitats. Moreover, they tend to be of a much greater size than their coastal counterparts. Due to the great disparity between the size of unique habitats in the open ocean and the areal extent of areas affected by dredged material disposal, it seems implausible that such an exclusionary effect would result from open ocean disposal. Given that proper site selection procedures are employed in the designation of a site, such exclusionary effects on any areas unique to the maintenance of the nekton can be eliminated.

Availability of Food Sources

A reduction or elimination of food supply in an area affected by open ocean disposal probably would not result in death of the nekton, but rather it would cause displacement of the individuals into other unaffected areas in search of food. Pelagic fish feeding on the phytoplankton or zooplankton would not be affected significantly as their food sources would not suffer permanent or long-term reduction. Short regeneration times and lateral mixing would ensure rapid replenishment of planktonic food organisms to the affected water column following disposal.

Demersal fish, feeding on the benthos, are likely to be affected over a longer term. The destruction and loss of benthic communities eliminates a food source for many fin fish and invertebrates. In areas where reestablishment of the benthic community is rapid, the effect is transient. Where sediments are altered sufficiently to prevent recolonization by the benthic communities, fish populations, which feed thereon probably, will not return.

Introduction of Suspended Solids

Chronic exposure to relatively high turbidity may adversely affect fish. However, short-period exposure in open areas where fish are free to vacate affected waters will likely result in insignificant impact on the nekton.

Fish were observed to avoid areas of high turbidity occasioned by dredging or disposal operations (Ingle, 1952; Ingle et al., 1955; Stickney, 1973). Although no mortalities occurred during field observations, mortality attributed to suspended solids is common in laboratory studies. Gill clogging and subsequent suffocation were observed where fish were exposed to high concentrations of suspended solids (Ingle et al., 1955). Rogers (1969), investigating the effects of varying concentrations of suspended solids, found sensitivity to be species specific with lethal concentrations varying approximately six fold. Damage to gill epithelium also was reported to be a function of the presence of large angular particles in suspension rather than the optical turbidity of the suspension.

Ritchie (Chesapeake Biological Laboratory, 1970) attempted to monitor gross impacts of dredging and disposal on 44 fish species. No gross adverse effects nor any damage to gill epithelium was observed in 11 species sampled from the disposal site. Of the fish species held in cages at the disposal site, effects ranged from near total mortality on striped bass to near complete survival for the channel catfish. A comparative assessment of mortality due to disposal was not possible as control data for the study were lacking. Unfortunately, the field approach used was insensitive to the more subtle impacts, which may have occurred.

Sherk et al. (1974) conducted extensive laboratory studies of lethal and sublethal effects of suspended solids on estuarine organisms, including fish. Utilizing varying concentrations of minerals of known composition they were able to elucidate the effects of particle size distribution and concentration without interference from complicating factors inherent to natural sediment, e.g. sorbed toxic metals, high BOD, and organic material. Lethal effects of suspended solids were most acute on fish of the lower tropic levels. Different tolerances were evident for various life stages of the same species as well as for different life habits and habitat preferences of the organisms. "Tolerant" species exhibited a habitat preference for the mud-water interface, where the concentration of suspended solids tends to be higher than elsewhere in the water column. Common features of the "sensitive" species were not readily apparent. Although "sensitive" species were not restricted to filter feeders, menhaden and anchovy (both deriving their sustenance by filtering plankton from the water) were found to be sensitive to the effects of suspended solids. A high potential sensitivity of filter feeders to suspended solids is inferred by their feeding habit (O'Connor and Sherk, 1975).

Fine particles were found to coat the gill epithelium thereby effecting a reduction in respiratory exchange with the water. Larger particles were entrapped in gill lamellae, and water passage across the secondary lamellae was blocked. Eventually, asphyxiation results from the creation of these dead spaces at the sites of gas exchange (Sherk et al., 1974).

Among the sublethal effects of suspended solids on fish observed by

Sherk et al. (1974) were a hematological compensation for the reduced gas exchange at the gills, abrasion of the body epithelium, accumulation of large quantities of ingested solids in the gut, disruption of gill tissues, and reduction of stored metabolic reserves. Behavioral changes attributed to the suspended solids were also noted. Exposure to highly turbid waters usually induced violent displays of escape behavior in the fish.

Field and laboratory studies at San Francisco and San Pablo Bays, California, in addition to delimiting tolerance levels of various species to turbidity, also revealed that as turbidity increased, fish exhibited an increasing tendency to concentrate DDT and its metabolites in fat tissues (U. S. Department of the Interior, 1970a).

Effect on Demersal Eggs

An indirect effect of dredged material disposal on the nekton is through the destruction of demersal eggs. Significant reductions in the reproductive capacity of a species due to spawning bed damage could have greater adverse effect on species survival than the effect of a loss of part of the existing population (Ricker, 1945). A change in sediment composition and particle distribution at the disposal site could interfere with or prevent fish reproduction by destroying demersal eggs (Huet, 1965). In laboratory experiments Bayliss (1968) reported hatching variability of striped bass eggs to be a function of sediment composition.

The potential for adversely impacting the nekton through egg loss or spawning bed damage is much less offshore than it is for inshore or estuarine waters. Most of the marine teleost fishes spawn eggs that float freely in the surface waters. A few such as the herring, e.g. Cyclopterus lumpus, Liparis sp., Blennius pholis, and other inshore species stick their eggs to objects on the substratum (Newell and

Newell, 1963). Deeper water species, whose spawning is related to type of bottom, are primarily demersal species such as the hakes, cod, cusk, and haddock (Walford, 1938). Elasmobranchs lay eggs in a horny capsule bearing coiled filaments for attachment to the substratum (Newell and Newell, 1963).

Oxidation of Dredged Material

The high motility of the nekton will mitigate to a large degree the temporary reductions of dissolved oxygen concentration as dredged material transits the water column. In contrast to inshore disposal sites the vast openness and depth offshore would allow for rapid dispersion of the oxygen depressed waters. Compared to the size of the area affected, the open ocean provides essentially unlimited space into which the nekton may move in avoiding areas thus affected. Moreover, the range of the oceanic populations of fish is so great that the same individuals are unlikely to be exposed repeatedly, much less continually, to the same stress, as is often the case at estuarine and nearshore disposal sites.

It should be emphasized at this point that depressed oxygen concentrations are very unlikely to result from the disposal of dredged material in the deep ocean (see Part 3, Section C). In short, the degree of oxygen depression in the water column and resultant impacts on the nekton are likely to be far less in offshore areas than if disposal were to occur in estuarine or shallow nearshore environments.

Contaminant Effects: Bioaccumulation

As low levels of contaminants are incorporated into organisms of the lower trophic levels the concentrations increase through each step in the food chain. The end result of this accumulation through the food chain is that higher trophic levels may exhibit concentrations of contaminants far in excess of the ambient levels at which they are introduced into the environment. The effects of these contaminants are of immediate concern to man as fish of various trophic levels are consumed directly as well as used for food production in agriculture. Contamination of a fishery constitutes an economic loss as well as a potential health hazard through the human consumption of contaminated fish.

Although it is impossible to specifically predict the effect of a milieu of contaminants on the nekton, several characteristics of the nekton suggest that offshore disposal would tend to mitigate the effects of contaminants on this group of organisms. The initial dilution of contaminants is great, both in the physical sense in the water column and biologically through the higher trophic levels. Unlike many nearshore and estuarine species with stocks and spawning populations confined to relatively small geographical areas, the dispersed distribution and wide ranging horizontal migrations of the epipelagic nekton tend to retard the accumulation of contaminants in the nektonic populations through a spatial and temporal separation of the consumers and their "contaminated" food sources.

The great majority of contaminants introduced with contaminated dredged material will remain tied up with the sediments and will rather quickly settle out to the sea floor. In the open ocean where depths are in excess of 1000 metres the pelagic fishery is limited to planktophages and predators, which feed almost exclusively in the epipelagic zone with few ranging into the mesopelagic. Also, there is essentially no existing or potential exploitation of demersal fish in depths greater than 1000 metres (see Part 6). Thus, the fish harvested from the open ocean do not feed on the substratum where the greater concentration of contaminants are found. Moreover, the trophic links from the benthic to the epipelagial are quite far removed both spatially and temporally.

Relative to the fisheries of the continental shelf, the open ocean provides little in the way of fishery resources. The pelagic fishery of the open ocean contributes only approximately 3 percent to the total marine harvest (see Part 6, Table 6-3). In view of the enormity of the open ocean and the effect that past disposal practices have had on the fisheries of the continental shelf, widespread contamination of the pelagic fishes of the open ocean seems inconceivable. Yet assuming such an unrealistic effect would occur, the direct impact to man in loss of fishery resource would be far less than from contamination of the shelf fisheries.

Finally, it should be noted that disposal of dredged material in nearshore waters, as has been practiced for decades, does not preclude contamination of the nektonic species of the open ocean. Physical mixing of the waters, as well as migrations of epipelagic species into shelf waters and the trophic links between the epipelagial and neritic species will insure eventual exposure of oceanic species to the contaminants as trace amounts in the water column and as passed through the food chain.

BENTHIC EFFECTS

GENERAL CONSIDERATIONS

The benthic environment includes the bottom surface and the subsurface to a depth of about a metre and also the water column above the bottom to a height of a few metres. Organisms that live in association with the bottom or in the near-bottom waters are all dependent, one way or another, upon the integrity of the bottom environment. The effects of disposed dredged material upon such organisms will depend upon several factors.

The physical nature of the material will be important. Particle size is known to play an important role in determining the habitability of benthic environments by organisms. The angularity of suspended particles has been cited as causing gill damage and digestive tract damage to some aquatic species.

The quantity and rate of disposal will determine the degree to which many species can handle the material and survive in the affected environments. Also involved is the extent of the bottom area affected.

The chemical nature of the disposal material may be a factor in species survival. Materials rich in organic matter, as they decompose on the bottom, may create high oxygen demands, and they may release toxic products such as hydrogen sulfide. If the disposal materials have high concentrations of heavy metals, organochlorides, or other toxic substances, they may also be expected to have deleterious biological effects.

The nature of the pre-impact environment is another factor to be considered. If the benthic area receiving the disposal material is characterized by low flushing and mixing rates, then noxious materials may accumulate and create greater biological damage than would result in areas of greater circulation and higher dilution capacity.

Finally, the nature of the benthic species themselves will be an important factor. Almost nothing is known about the tolerances of deeper water benthic species to the various factors listed above. However, studies on shallow water species, both in the laboratory and in the field, demonstrate great variability among species in their susceptability to damage from suspended and sedimented materials.

EFFECTS IN THE SUPRA-BENTHIC WATERS

Respiration

Most aquatic animals require free oxygen for respiration, and they are very sensitive tc oxygen reduction below critical minimum levels. Gradual reduction of oxygen levels would be expected to selectively eliminate species in sequence, based upon minimum levels of oxygen tolerance. It would be anticipated that deepwater benthic species have little tolerance for reduced oxygen tensions. Complete removal of oxygen would, of course, eliminate all but the anaerobic species (primarily bacteria and small infaunal invertebrates).

Wallen (1951) and others have shown that extremely high levels of suspended materials can suffocate fishes by clogging the gill filaments and filling the opercular cavity. Sharp and angular stony materials are abrasive to soft tissues and can directly damage the delicate gill filaments (Kemp, 1949), reducing the effective respiratory surface, lowering respiratory efficiency, and leading to microbial infection (Ellis, 1944). Gill clogging and tissue damage may affect mollusks and other invertebrates, as well, but little information is available on this topic.

Feeding and Nutrition

Suspended sediments have been shown to interfere with feeding and nutrition of aquatic animals. Many benthic marine invertebrates feed by straining and filtering food particles from the water. High levels of suspended sediments can clog such mechanisms and lead to starvation (Darnell et al., 1976). Studies by the New England Aquarium Corporation (1974) on two bivalve mollusks subjected to high levels of turbidity showed evidence of starvation (loss of body weight) and feeding impairment associated with modifications of the digestive tracts.

Behavior

High levels of suspended sediments would reduce visibility and could decrease an animal's efficiency in locating food. Silt particles are known to be very effective in removing organic compounds from solution, and they could play a role in reducing feeding efficiency by removing the chemical odors important in guiding aquatic animals to the appropriate food sources.

Other Metabolic Effects

It is clear that suspended solids may tax an animal's metabolism and energy resources, even though they do not directly induce mortality. Loosanoff and Tommers (1948) found that pumping rates of adult oysters were reduced by 57 percent when they were subjected to silt loads of 100 ppm and by 94 percent when exposed to loads of 3-4,000 ppm. Pumping provides for respiration and nutrition, and prolonged reduction of pumping could be expected to induce metabolic stress. Decreased oyster growth in areas of high suspended solids has been reported by Wilson (1950). Sublethal effects of suspended solids on two additional bivalves (*Placopecten magellanicus* and *Arctica islandica*) have been reported by the New England Aquarium Corporation (1974). Exposure to high levels of suspended solids was found to induce increased mucus cell proliferation, increased mucus secretion, high rates of pseudofecal production, and an apparent decline in feeding activity. Filtering rates also declined dramatically. They concluded that these factors resulted in increased energy demands and eventual metabolic stress.

Indirect Effects Through Modification of the Chemical Environment

In shallow water areas suspended solids, especially if they contain significant quantities of organic matter, tend to increase the levels of bacterial activity greatly (Darnell et al., 1976). This may result in oxygen depletion, carbon dioxide buildup, and lowered pH. As the environment becomes anaerobic, quantities of hydrogen sulfide and other toxic products may be released. The more acid conditions also favor solubility and release of heavy metals, often as sulfides. If the dredged material contains other toxic chemical materials, these may also be released into the suprabenthic waters.

EFFECTS ON BOTTOM-DWELLING ANIMALS

To the extent that the bottom animals feed by filtration or respire in the suprabenthic waters, they may be affected by the factors discussed above. However, the bottom-dwellers are also subjected to any additional effects due to modifications in the substratum. These additional effects are discussed below.

Smothering

Any organism in the direct path of the disposal material will be subject to burial, and the effect of this burial will relate to the nature of the disposal material, its rate of accumulation, and the burrowing capabilities of the individual species. The subject of response to burial has been reviewed by Morton (1976) and by Saila et al. (1971, 1972). Sessile or attached organisms are killed outright by direct burial. Small animals tend to be more vulnerable, when sediments are anoxic, because of their inability to reach the surface before they suffocate. Crustaceans respond to oxygen deficiency by increased ventilation, and if the pressure of the sediments interferes with this activity, they will quickly die. Some bivalve mollusks can incur an oxygen debt, and certain polychaetes can reduce their metabolic activity when oxygen levels are low, thus increasing the time available for escape.

Great variability among species in the ability to withstand and to escape from burial conditions have been noted. Large active polychaetes such as *Nephthys incisa* may burrow rapidly to the surface. Other polychaetes such as *Streblospio benedicti* form tubes that can be extended to the surface fairly rapidly if the overlying sediment is not too deep. Some of the larger more active bivalves such as Macoma, Yoldia, and Nucula can move laterally out of the area, whereas others, which are smaller and less mobile, may succumb.

Change in Sediment Particle Composition

Numerous studies have demonstrated that grain size of bottom sediments is of utmost importance in determining the distribution of microscopic bottom animals (Sanders, 1958; Wieser, 1959; Rogers, 1976; and others), mollusks (Harman, 1972), and other invertebrates (Pennak and Van Gerpen, 1947). Smith and Moyle (1944) have pointed out the importance of bottom type in the production of aquatic invertebrates of importance as fish food. In general, a change in the bottom composition may be expected to be followed by a shift in species composition and likely a change in the standing crop. The nature of such changes, however, will depend upon the composition of the original bottom and the nature of the new sedimenting material.

Toxic Effects Resulting From Decomposition

Organisms that are trapped and die beneath the sediments will undergo decomposition. In the process they will release acids and other toxic decomposition products that may reduce the habitability of the area for some months. Stagnating sediment-water samples have been shown to release heavy metals (iron, manganese, zinc, and others) as soluble organo-metallic complexes (Schindler et al., 1972). McNeil et al. (1964) have shown that riffles contaminated by decomposing salmon eggs may remain toxic for over a year.

CONCLUSIONS

The above analysis, based upon shallow water species, indicates in some detail the types of biological effects likely to occur in the suprabenthic water and on the bottom itself within the areas most heavily impacted by disposal materials. To the extent that the impacted bottom area is small, the effects will be local. To the extent that the area is subject to flushing and dilution, the severity of the impacts will be lessened. To the extent that the disposal material is low in organic matter and chemical contaminants, the biological damage will be minimal and short-lived. Within the disposal site area changes may be expected in the composition and abundance of the benthic community. Whether such changes will be locally advantageous cannot be predicted on a priori grounds. Smaller and less mobile species may be immediately killed, but these are widely distributed in the benthic environment and many should be able to recolonize the area within a period of a few months. Larger, more mobile species should be able to tolerate the changed conditions or to move out. For example, Saila, et al. (1968) demonstrated that the lobster Homarus americanus was able to withstand prolonged exposure to heavy suspensions of silt and dredged material sediment. From these considerations it is concluded that, although some temporary and local damage may occur to the benthic species, disposal of dredged material in deeper waters of the oceans will not cause significant or long-lasting damage to the benthic species of marine ecosystems.

PART 4. HYDROBIOLOGICAL ZONES AS DISPOSAL ENVIRONMENTS

A. NEARSHORE - OFFSHORE TRENDS

Being bathed by a single body of water, all the marine environments are in potential continuity with one another. Yet the sea is not homogeneous. Nearshore waters are influenced by the continental climate, they are modified by the proximity of estuaries and coastal lagoons, they are freshened and nourished by runoff from streams, and their bottoms are not far removed from the sea surface. Proceeding away from shore the continental climate gives way to the maritime climate; the influence of estuaries, lagoons, and streams becomes less pronounced; and the depths become progressively greater until the abyssal plain is reached. These basic factors are reflected in the nature of the water columns and the benthic environments, each zone being characterized by its own suite of temperature, salinity, turbidity, nutrient, current pattern, and sediment conditions. Some of the changes occur gradually, while others are more abrupt.

As the environments change with depth and distance from shore, so do the living systems that inhabit the environments. Dramatic shifts are observed in species composition, abundance, diversity, and production. Such changes in the environments and the biological systems they support must be taken into account in any consideration of the effects of disposal in the marine environment, because the effects will vary depending upon which systems receive the materials. In the present section some of the more important ecological trends will be examined to provide a basis for the zonal analysis that follows.

TRENDS IN ENVIRONMENTAL FACTORS

The environment of the continental shelf is highly variable on a seasonal and shorter term basis. Proceeding seaward and deeper, the environment tends to exhibit less extreme variation and a greater regularity in the occurrence of this variation. Water masses of the continental shelf are driven by winds, tides, and some influence of the oceanic water. Offshelf the oceanic currents prevail, and although tidal and other influences are felt, they are less extreme in their effects. Water temperature of the shelf follows that of the atmosphere, whereas at sea, less extreme annual variation is noted. Temperature of the deeper water tends to be more or less constant. Due to the influence of rivers, estuaries, and coastal lagoons, the shelf waters tend to be fresher, and this grades to the full marine salinity as one proceeds offshelf. Salinity of the deeper water tends to remain rather constant. Turbidity of the shelf waters is variable, and on the average, much higher than that of the oceanic water.

Surface sediments of the continental shelf vary from one region to another. In some instances there may be rather smooth transitions from the sandy nearshore bottoms to the fine clays and silts of the outer shelf. In other cases the outer shelf may be predominately sand or shell. Near the mouths of large rivers the entire shelf may be blanketed with fine sediments for some distance downstream. In other regions where there are active currents, the shelf sediments may display wide local variation in grain size and texture. Proceeding offshelf to the slope, the sediment tends toward uniformity with fine particles prevailing, and from the shelf break to the abyssal plain there tends to be a rather smooth trend in the very fine particle sizes.

TRENDS IN BIOLOGICAL FACTORS

The distribution of the living resources of the sea is far from uniform, and both horizontal and vertical trends are present.

PHYTOPLANKTON

Geographically, high phytoplankton production is limited to three types of areas:

a. upwelling regions and divergences off the western subtropical continental coasts (e.g., California, Peru, northwestern and southwestern Africa, and along the equator);

b. temperate and subarctic waters of the Southern Ocean, North Atlantic, and North Pacific;

c. shallow waters over parts of the continental shelves.

These areas of high production are shown in Figure 45, which also exhibits the horizontal variation in this parameter. On the average, nearshore areas support far larger standing crops of phytoplankton than do the oceanic waters. As seen in Table 20, phytoplankton biomass of the continental shelf (of the Pacific Ocean) averages around 1,000 mg/m^3, whereas for most of the vast oceanic areas the standing crop averages less than 10 mg/m^3. The geographic distribution of zooplankton, nekton, and benthic biomass closely parallels the distribution of the phytoplankton.

ZOOPLANKTON

The world distribution of zooplankton biomass is shown in Figure 46. The parallel with that shown earlier for phytoplankton is obvious. This relationship is further demonstrated by reference to Table 20. Here it is shown that the zooplankton standing crop of the continental shelf averages over 500 mg/m^3, while over most of the open sea it is less than 50 mg/m^3.

Another interesting relationship exists in the patterns of depth distribution. Because of its immediate dependence upon sunlight, the phytoplankton is restricted to the surface layers of the sea. The euphotic zone rarely exceeds 100-140 metres, and the bulk of the phytoplankton is found in the upper 50 metres. Zooplankton organisms subsist mainly on the phytoplankton, and they also are largely confined to the upper layers of the water column. This is well illustrated by

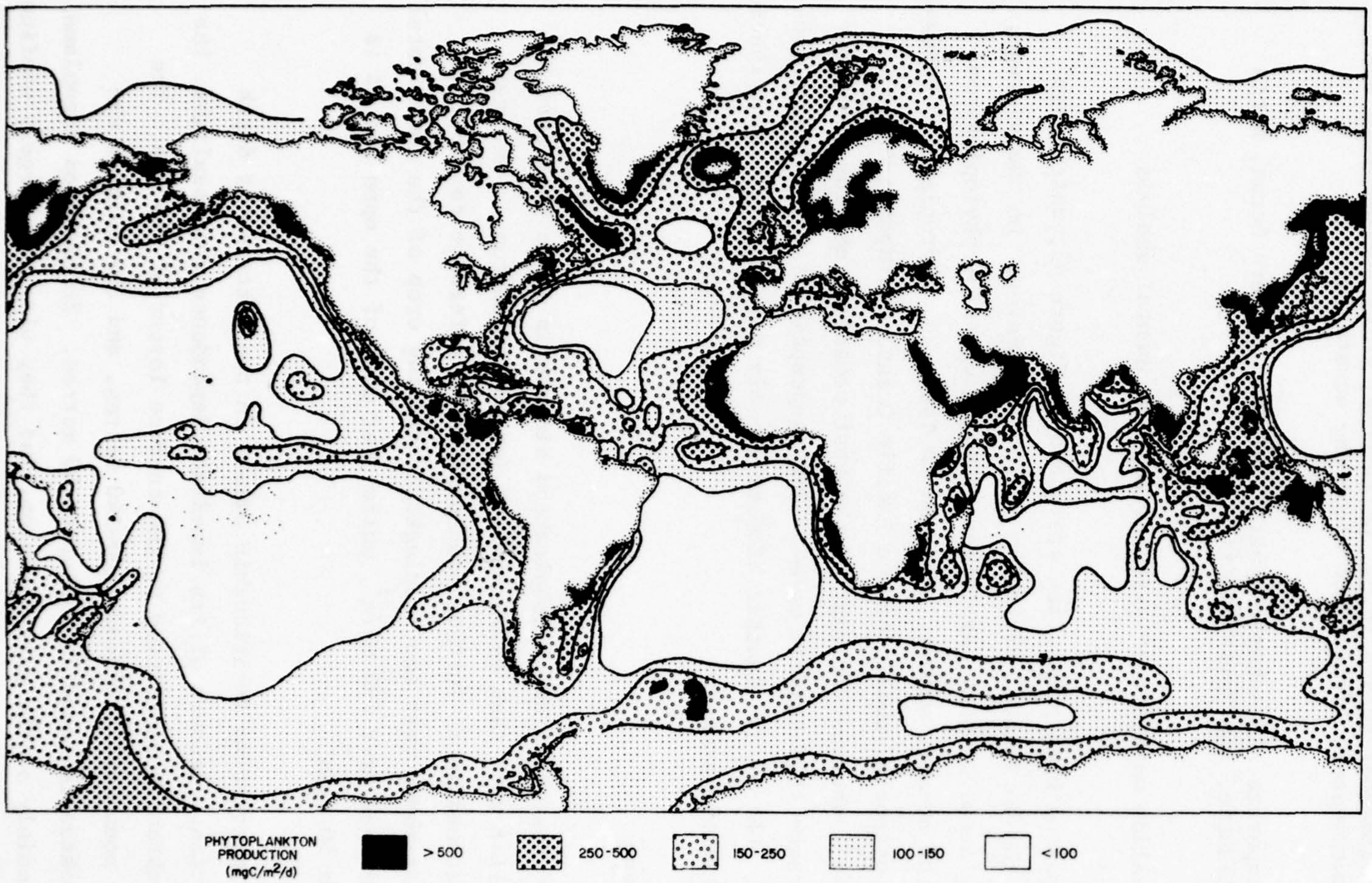


Figure 45. Geographic distribution of phytoplankton production in the world oceans. (After Food and Agriculture Organization, 1971).

Table 20

Areas of the Pacific Ocean with Different Zoo- and Phytoplanktonic Biomass in the 0-100-m Layer

		Area	
Zooplankton, mg/m^3	Phytoplankton, mg/m^3	10^6 km^2	Percent
>500	1,000	3	2
500-200	100	6	4
200-100	25	19	11
100- 50	10	35	20
50- 25	2	48	29
<25	0.6	58	34

Source: Bogorov (1966)

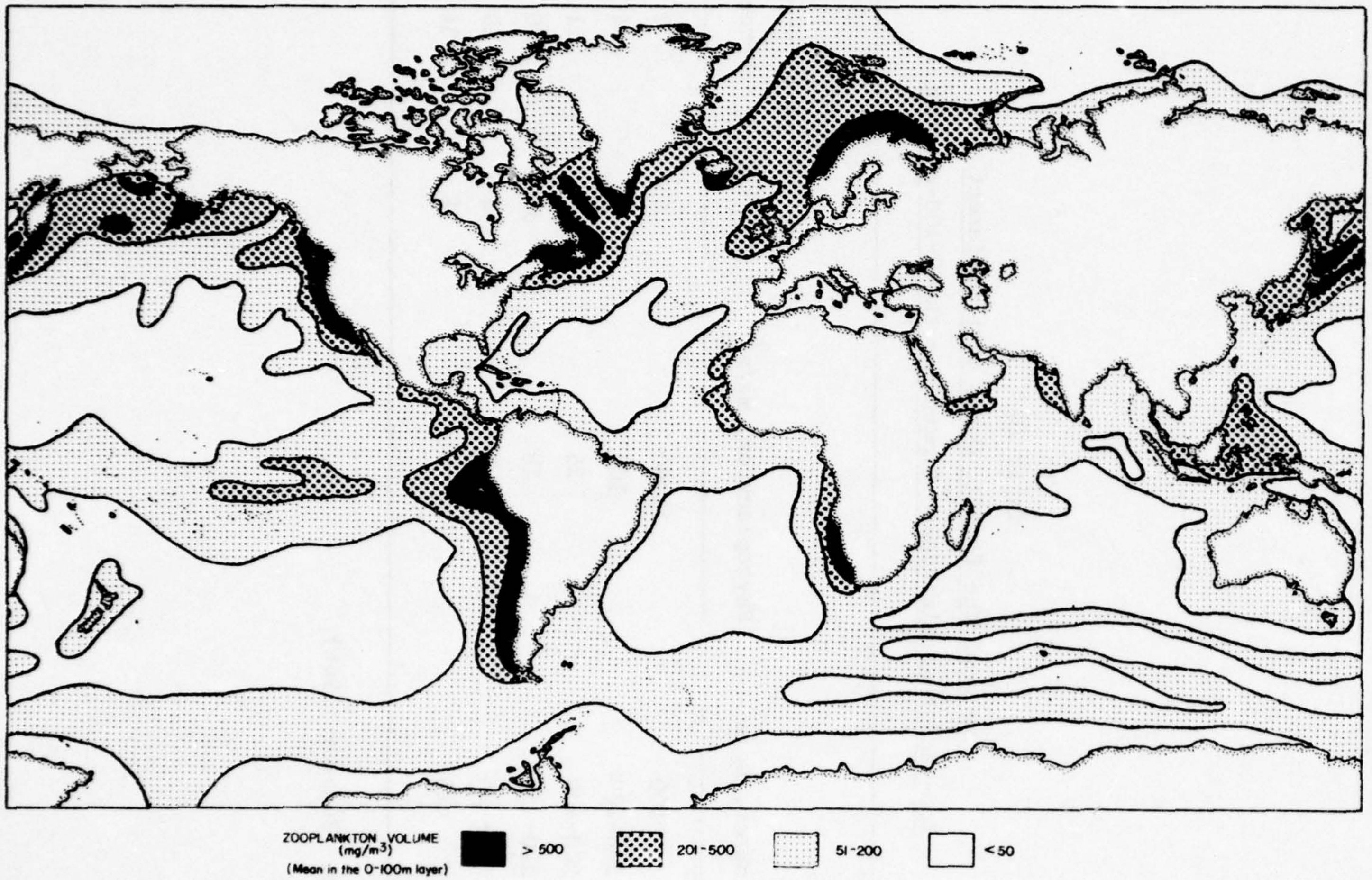


Figure 46. Geographic distribution of zooplankton biomass in the world ocean. (After Food and Agriculture Organization, 1972).

the data of Brodskii (1952) that show the vertical distribution of copepods, the most abundant and important component of the zooplankton (Table 21). Copepod density in the top 150 m of water varies from 5,000 - 15,000 per cubic metre, but below that depth it ranges from about 300 to less than 1 per cubic metre. Vinogradov (1955) has calculated the zooplankton biomass for the different layers in the world oceans. It was estimated that 65 percent (by weight) of the meso-plankton (zooplankters less than 30 mm in length) is contained in the upper 500 metres of the ocean, and that approximately 35 percent of the biomass is found in the layer between 500 and 4000 metres. The planktonic biomass below 4000 metres is only 1/150-1/800 of that found in the upper 500 metres. Although the zooplankton concentration is subject to diurnal and seasonal migrations extending through hundreds of metres, but especially vigorous in the upper 50-100 m, the vertical distribution of zooplankton is approximately the same in all oceans.

Bogorov (1966) computed areas of the Pacific Ocean with different planktonic biomasses (Table 20). Relatively productive regions (biomass >100 mg/m^3) constituted only 17 percent of the total area, while regions of very high production (>7500 mg/m^3) accounted for only 2 percent of the area. By contrast, 63 percent of the total area was considered to be depleted (<50 mg/m^3), and over half of this area was depauperate (<25 mg/m^3).

From Bogorov's (1966) estimates of zooplankton biomass in the Pacific Ocean, zooplankton rich areas (>100 mg/m^3) were shown to contain 705 x 10^6 tons of zooplankton, i.e. 17 percent of the area contained 56 percent of the total plankton biomass. The remaining 44 percent of the total plankton biomass (540 x 10^6 tons) was dispersed over 83 percent of the total area. Within these low biomass areas, regions were found to exist wherein zooplankton biomass was very low (<50 mg/m^3). These depleted areas occupied 63 percent of the total area, yet contained only 22 percent (270 x 10^6 tons) of the total zooplankton biomass. Moiseev (1971) contends that "such dispersion renders the

Table 21
Vertical Distribution of Copepods in the Northwestern Pacific

Layer, m	Number of species	Number of specimens per m^3
25- 0	7	15,240
50- 25	7	8,160
100- 50	9	5,040
200- 100	10	320
500- 200	28	84
1,000- 500	30	65
4,000-1,000	87	----

Source: Brodskii (1952)

zooplankton practically unavailable as food for other animals and is evidently hardly exploited at higher trophic levels." Reference to Figures 45 and 46 suggests that approximately the same distributions apply in the other oceans as well.

NEKTON

Marine nekton is far more abundant on the continental shelf than it is in the open sea, and at sea it is far more abundant near the surface than it is in deeper water. Whereas there are no available figures on the total nektonic biomass, useful information can be obtained from the distribution of the world harvest of pelagic fishery resources (excluding whales). Such data have been provided by Moiseev (1971) (Table 22). The total catch of pelagic resources from the shelf zone is an order of magnitude greater than from the open sea, and the catch per unit area is almost 150 times as great on the shelf as it is at sea. This difference is more striking when one realizes that the oceanic catch (primarily tunas and sharks) is limited almost entirely to the upper 150 metres--in a region where the average water column depths exceed 3,000 metres. Most of the open ocean and all the water below the euphotic zone is devoid of pelagic fish harvest potential.

BENTHOS

In 1843 Edward Forbes, a pioneer in marine biology, observing the diminution of the number of animals with increasing depth of water beyond the littoral zone, established an "azoic" zone covering the ocean floors from depths below 300 m (Sverdrup et al., 1942).

It was not until the Challenger Expedition of 1873-76 that samples were taken from greater depths to disprove the notion of an abiotic sea floor. Since that time, with increasingly sophisticated research techniques such as giant cameras mounted on submersible research vessels, much has been learned about benthic life in the deep sea.

Table 22

Distribution of the Production of Aquatic Items (Not Including Whales) Over Different Depths in 1966

Animals	Oceanic region	Depth, m	Area: 10^6 km²	Area: %	Area: suitable for habitation by commercial fishes 10^6 km²	Catch: 10^6 tons	Catch: %	Catch, kg/km²: total area	Catch, kg/km²: in area suitable for habitation by fishes
Demersal	Shelf	0—200	26.66	7.4	21.6	16.14	32.6	602	746
	Slope (bathyal)	200—3,000	57.42	15.9	14.1	2.42	4.9	35	170
		including 200—1,000	15.14	4.2	12.1	2.42	–	159	200
		1,000—3,000	42.28	11.7	2.0	–	–	–	–
	Ocean floor (abyssal)	more than 3,000	276.14	76.7	–	–	–	–	–
Pelagic	Neritic zone	–	26.7	7.4	21.6	15.52	31.3	579	720
	Outer neritic zone	–	60.2	16.6	35.0	14.11	28.6	245	400
	Pelagic zone	–	273.3	76.0	253.0	1.32	2.6	5	5.2
	Total	–	360.22	100	318.0	49.51	100	138	156

Source: Moiseev (1971)

As the quality and amount of research on the benthos has increased, certain general trends have become evident. It may now be said with certainty that with increasing depth or distance from shore, the numbers of larger animals (the invertebrate macrofauna and the benthic and demersal fishes) decrease steadily. The weight of animals per unit area is as much as 10,000 times greater in inshore waters as it is in the abyssal plains of the deep ocean (Thiel, 1975).

Even with the great decrease in numbers of animals, the diversity, or numbers of kinds of animals tends to remain fairly constant with changes in depth (Hessler and Sanders, 1967). However, there are changes in the kinds of animals found at different depths that tend to fall into regular patterns of zonation. In all areas of the world ocean a distinct change in the faunal composition is found between the continental shelf and the continental slope. This break occurs between depths of 100 to 200 m depending on the region. Another distinct transition occurs at about 1000 m between upper continental slope faunal assemblages and those of the lower continental slope. The transition from continental rise to abyssal zones at depths greater than 3300-3400 m is reflected in another change in faunal composition.

The fauna of the continental shelf is separable into distinctive assemblages or biotic units, which correspond to the zoogeographic provinces of the terrestrial ecologist. The slope assemblages are less distinctly regional, and the fauna of the abyssal zones are truly cosmopolitan, certain species occurring at great depths in all oceans.

Distribution of Biomass

The general trend of a decrease in the numbers of animals with increasing depth and distance from land is emphasized when the distribution of biomass is examined. The smallest component of the benthic ecosystem, the bacteria in the sediment, ranges from 1 g/m^2 on the outer continental shelf to 0.003 g/m^2 on the Mid-Atlantic Ridge (Table 23).

The distribution in biomass of the meiofauna is less clearly related to increasing depth and shows greater variability between regions than between different depths in the same region.

More data have been published on the biomass of macrofauna from both shallow and deep-sea regions than on the microbial populations or the meiofauna. The macrofauna can be conveniently separated into two groups: the infauna that live in the sediments and the epifauna that live on the sediments. The biomass of the larger, motile epifauna is much lower than that of the infauna. Estimates of the difference would be 8:1 (Wigley and McIntyre, 1964) in the outer continental shelf, to approximately 3:1 or 2:1 on the upper slope, diminishing with depth to the same levels as the meiofauna in the abyssal zones. Since both the density and the average size of the macrofauna diminishes with increasing depth, the biomass decreases over several orders of magnitude (Table 23). Thiel (1975) points out that this is a consequence of decreased food supply with increasing distance from continental influences. The only exceptions are areas under highly productive waters, such as the Peru upwelling (Rowe, 1971) or in areas where submarine canyons or trenches serve to channel or trap the organic matter that is the basis of the food chains.

Regional differences are important. The macrofauna of the outer continental shelf of the East Pacific (off California) is incredibly rich with higher biomass values, 240 g/m^2 (Barnard et al., 1959), for natural aquatic communities than is usually found at these depths. This is probably related to the upwelling that occurs off the California coast resulting in high productivity generally throughout the water column.

Table 23

Distribution of Benthic Biomass by Faunal Groupings According to Hydrobiological Zones

Zone	Biomass g/m^2				
	Microbial	Meiofaunal	Infaunal	Epifaunal	Benthic and Demersal Fish
Outer continental shelf 50–200 m	0.97	5.9–3.2	58.12	7.96	2
Slope 200–3400 m	0.29	3.6–0.1	26.5	5.9	0.2
Rise and Abyss >3400 m	0.003–0.01	1.0–0.01	0.5–0.01	0.5–0.01	–

Sources: Ernst, 1970; Haedrich et al., 1975; Hodson et al., 1976; Karl et al., 1976; Rowe et al., 1974; Thiel, 1975; Wigley and McIntyre, 1964.

The Atlantic shelf averages four times the biomass of the Gulf shelf, and the continental slope average differs by a factor of ten.

Biomass of benthic and demersal fishes shows the same trends toward a decrease with increasing depths. Struhsaker (1969), reporting on the demersal fish resources of the continental shelf off the southeastern United States, found that shelf-edge fisheries yielded only one percent of the total catch. However, these commercially valuable catches of black sea bass, snappers, and groupers represented 3 percent of the total monetary value of the landings.

Diversity of the Benthos

Measures of species diversity are influenced by the species richness (the actual number of species present in an area), the species abundance (the number of individuals in each species), and the sample size. Comparisons of diversity made between samples of shallow water benthos and deep-sea benthos have led to some seemingly contradictory statements concerning the apparent diversity present.

Little is known of the diversity of the microbial components of the benthos. The principal differences appear to be related not to the species present, but rather to the numbers present, and to their relative productivity.

Similarly, diversity of the meiofaunal components of the benthos cannot be discussed with any degree of confidence since nematodes are the dominant organism of this category, and measures of their diversity are rarely made.

Diversity of the macrofauna has been well studied. Although species diversity of the benthic macrofauna appears to remain fairly constant along the gradient of depths being considered (Hessler and Sanders, 1967), the fact remains that the number of species present decreases with increasing depth similarly to the decrease in absolute numbers and in biomass. Ecological measures of species diversity remain high because the few animals present in the abyssal zones are quite evenly distributed among the few species present. Greater than 99 percent of the benthic and demersal species (excluding fish) are confined to shallow regions. Of the more than 181,000 benthic species, approximately 180,000 live in the shelf zone. Approximately 1,080 species are found at depths greater than 2000 metres, and only about 189 species live in excess of 4000 metres (Moiseev, 1971).

Fish are the most diverse of the benthic megafaunal taxa (Grassle et al., 1975), however, the megafauna, or larger epifauna, are consistently less diverse (and less numerous) than the infauna.

Benthic Production

New production in animal populations includes both the growth of individuals in the population and the reproduction of new individuals.

Microbial production in the benthos at all depths is considerably greater than any other size class of organisms, although the standing stock is much lower, except in abyssal depths.

Standing stock of the meiofaunal populations is 10 times that of the microbial populations. However, since generation times are so much shorter in the bacteria, their turnover rate is much higher and their total production in $g/m^2/yr$ would exceed that of the meiofauna by an order of magnitude. This relationship holds at all depths considered.

Continental shelf macrofaunal populations have a standing stock from 20 to 50 times that of the meiofauna. The meiofauna, however, have very diversified reproductive patterns with anywhere from 2 to 40 generations per year. Gerlach (1971) uses an average turnover rate of 9 to show that macrofauna production exceeds meiofauna by only a factor of 5. Macrofaunal production decreases with depth far more than meiofaunal production does. In the abyssal zone production is limited by the scarcity of food, and microbial production exceeds that of the meiofauna and macrofauna by an order of magnitude.

Production of benthic and demersal fishes is relatively high on the outer continental shelf. The total annual catch of benthic and demersal fishes on the continental shelf is at least equal to that of pelagic fishes, and if commercial catches of invertebrates (shrimp, crabs, mollusks) are included, it exceeds the pelagic catch in some regions. The fisheries of the upper slope are not as well developed for benthic species in all areas. Northern regions produce large catches of cod and halibut. Struhsaker (1969) points out that large unexploited stocks of commercially important fish such as sea bass, snappers, groupers, and porgy exist on the outer shelf of the southeastern United States, which could be harvested with the use of roller-rigged, New England-type fish trawls or the more conventional handlining methods.

Fishes of the lower slopes make up a much smaller percentage of the epifauna. Haedrich et al. (1975) found fish comprising only 27 percent of the epifauna of the lower slopes, with a standing stock less than that of the infauna or meiofauna. Production rates of benthic and demersal fishes of the lower slope, continental rise, and abyssal depths are negligible compared to other groups, amounting to one percent of that of the microbiota, or to ten percent of that of the meiofauna or macrofauna.

B. ZONAL ANALYSIS

OUTER CONTINENTAL SHELF ZONE

GENERAL CHARACTERISTICS

Definition

The continental shelf is the submerged margin of a continent, and, by extension, it is also considered to include the shallow margins of oceanic islands. Officially, United States laws define the continental shelves as the seaward extension of the coast to a depth of 600 feet (100 fm, 183 m). From a geological or an ecological standpoint the outer edge of the continental shelf is more difficult to delineate, and the landward edge of the outer continental shelf zone must be defined in somewhat arbitrary terms.

By and large, the continental shelf slopes gently from shore at an average drop of 12 feet per mile (0.23 percent), although the actual slope varies somewhat with locality. From an ecological standpoint, three shelf zones are generally recognized: the inner, middle, and outer continental shelf zones. Although no precise definitions of these three zones have achieved universal acceptance, they may be roughly defined in terms of hydrographic conditions and biological compositions. The inner continental shelf, being closest to the shore is greatly influenced by rivers and estuaries. Hence, the salinity tends to be lowest in this zone. The area is shallow, and the water temperature closely parallels that of the atmosphere at all seasons. Most of the migratory fishes and invertebrates that spend parts of their lives in estuaries spend the remainder of their lives in the inner shelf zone. In the northern Gulf of Mexico this zone extends to a depth of about 22 m (Chittenden and McEachran, 1976).

The middle continental shelf zone, being farther from shore and deeper than the inner zone, is less influenced by the estuarine waters, and far fewer estuarine-related species occur here. Water temperature tends to parallel that of the atmosphere to a reduced degree, and this zone is subject to some influence from water masses and species of the outer shelf. In the northern Gulf of Mexico this zone extends to a depth of about 70 m.

The outer continental shelf is only lightly influenced by coastal phenomena. Salinities more nearly approximate those of the open ocean, and bottom temperatures are nearly uniform the year around. For example, Pequegnat et al. (1976) provide seasonal data on the depth distribution of temperature in the northern Gulf of Mexico, and at about 70 m the annual temperature tends to be relatively uniform (near 20° C). The outer edge of the shelf is marked by a "shelf break" where the slope increases greatly. This break may occur anywhere from 110 m to 146 m. On the northern continental shelf there is a faunal break at 118 m (Pequegnat et al., 1976), and for practical purposes in the present report the 118-m contour will be considered to be the outer limit of the continental shelf.

The outer continental shelf in most areas of the United States is a relatively flat plain with some low relief features, which vary regionally. Off New England ridges and valleys characteristics of glacial moraine topography are observed. Off the southern and western coasts of Florida drowned reefs are seen. In the northern Gulf diapiric hills punctuate the otherwise flat plain. Off the west coast thrust fault blocks are not uncommon. Off the Hawaiian and Caribbean islands drowned reefs and some submarine volcanic features are observed. The outer continental shelves of nearly all coasts are incised by the upper reaches of submarine canyons.

Geologic Nature

Emery (1968) has noted that most of the continental shelves of the world were exposed during the last major period of continental glaciation and that as late as 19,000 years ago the sea level stood as much as 90 m below the present datum (maximum sea level lowering to -134 m took place during the past 25,000 years). Therefore, most of the continental shelves are covered by sediments, which were subject to subaerial weathering. Such materials (coarse sands, etc.) are referred to as "relict sediments." Off the entire Atlantic coast these relict sediments represent the predominant exposed sediment type, although landward and locally on the outer shelf this may be overlain by finer materials of more recent origin. The southern and western shelves of Florida are composed largely of calcareous reefal detritus, which grades into the sands and finer silts and clays of the northern Gulf. Off the west coast the finer materials are locally mixed with rocks and rock fragments arising from tectonic activity. These sediments grade into ice-influenced sediments of the northwest where glaciers and icebergs have deposited many rocks. Hawaiian and West Indies shelves contain mixtures of calcareous sediments intergraded with finer volcanic materials and some terrigenous sand. The outer shelves of the Atlantic and, to some extent, the Gulf of Mexico contain occasional deposits of peat, estuarine shells, river-borne rocks, and terrestrial fossils, indicative of the lower stand of the sea during the past several thousand years.

Currents, Tides, and Circulation

Irrespective of specific geographic locations on the continental shelves of the United States, the outer continental shelf contains a wide spectrum of structural and dynamic features that interact often with complex results. Directly off the shelf major current regimes are present, some seasonal in nature, which provide intrusions of clearly oceanic conditions on the shelves. The meso-scale turbulence generated by instabilities in these currents can provide relatively long-lived structural changes and eddy currents at the shelf. Patterns of mean and transient circulation are definitely impressed by meteorological forcing as well. The shallow depths of the shelves enhance this effect and bring to the shelf break region considerable influence from the coastal direction. As a result, the prospective disposal sites are found to lie in the most active boundary of what is normally acknowledged to be a transition zone of the ocean.

The wave-like phenomena propagating within this boundary have a spectrum similar in terms of diversity. The astronomical tides present contribute to the energetics of the region directly as well as serving as a forcing function that excites modes of motion linked to the density structure. In addition, long-shore wave components are present that are generated by traveling meteorological disturbances. Theoretical evidence has been advanced for the propagation of topographic Rossby waves that move up the continental rise in the boundary region. At long periods, in the vicinity of 30 days, the waters over the shelf break will be found to respond to macro-scale movements of the major boundary currents in the sense of mass conservation. In essence, this is a heaving or sloshing of the entire shelf-slope water body. At shorter periods, inertial oscillations, most probably wind induced, will be present in surface waters. The generation of transient Ekman responses by the wind will develop under sustained forcing and produce the well-known upwelling conditions that bring water through the deeper portions of the boundary region and move water shoreward while surface waters are transported seaward.

Other Characteristics

For practical purposes the outer continental shelf has been defined and described, but in a real sense it is a zone of transition between the shelf proper and the deep sea. It is influenced, on the one hand, by the hydrography and organisms of the shelf and by the hydrography and life of the open ocean. Although faunal breaks may be defined on the basis of the benthic organisms, there is considerable mixing of the faunas on a local or seasonal basis. As efforts are made to exploit the resources of the outer shelf and to consider the area in terms of a disposal environment for the wastes of civilization, it should be kept in mind that the outer shelf is in physical and biological continuity with the zones on either side.

BIOTA OF THE OUTER CONTINENTAL SHELF ZONE

Pelagic Life

Phytoplankton. The most obvious, and often the most numerous of the phytoplankton forms, are the diatoms. Although phytoplankton organisms as a group are microscopic, some diatoms such as species of Coscinodiscus and Rhizosolenia can be relatively large, approaching 1 mm. Others can be quite small, approaching a few microns. Diatoms tend to predominate in the neritic phytoplankton with Skeletonema costatum being ubiquitous in most coastal waters. In some regions however, dinoflagellates, which are present in all seasons, will become dominant during the summer.

Dinoflagellates constitute the next major component of the phytoplankton. Unlike the diatoms, many dinoflagellates are capable of movement and some species undergo diurnal migrations to the sea surface in response to light. Dinoflagellates and diatoms account for 80-95 percent of the more than 2000 phytoplankton species. Other groups which make up the phytoplankton include coccolithophorids, silicoflagellates, euglenids, blue-green algae, and many micro-flagellates.

Differences in species composition and abundance occur regionally and seasonally. Differences in the parameters also occur between the neritic and oceanic environments. Geographically, phytoplankton species may be classified as arctic, antarctic, temperate, and tropical

(Raymont, 1963). Within each of these regions some species are more typical of coastal conditions and are classed as neritic, e.g., Astrionella, Skeletonema, and Thalassionema nitzschioides, although they may occur in reduced numbers at considerable distance from shore. Neritic species are usually more euryhaline and eurythermal than their oceanic counterparts.

Diatoms are overwhelmingly important in high latitudes, and especially so in polar waters. Diatoms also dominate the neritic phytoplankton during most of the year, with dinoflagellates increasing in importance in the summer. In the tropics some blue-green algae, for example Trichodesmium, may be important, however, the Cyanophyceae are usually rare outside of tropical regions.

As light is the limiting factor controlling the vertical distribution of reproducing phytoplankton populations in the sea, phytoplankters are by necessity restricted to the surface layers of the ocean. In neritic waters light is attenuated rapidly in the water column due to the greater preponderance of suspended particles of detrital and terrigenous origin as well as a higher plankton biomass. Thus, in neritic waters the euphotic zone may range from 1 m or less in turbid estuaries to 10-20 m in waters over the outer shelf. By contrast the euphotic zone of the open ocean often exceeds 100 m. Generally speaking the depth of the euphotic zone increases with distance from the coastline. As a corollary to this the depth at which the phytoplankton maximum occurs varies with depth of the euphotic zone. In coastal waters, the phytoplankton maximum is likely to be near the surface. Because of vertical mixing above the thermocline, the vertical distribution of phytoplankton is irregular with significant numbers of phytoplankters occupying a transient position below the euphotic zone. By contrast, the open ocean plankton usually exhibits a subsurface abundance maximum, which may be as deep as 50-100 m, and then tapers off toward the bottom of the euphotic zone.

The greatest difference between neritic and oceanic phytoplankton is in the abundance and productivity of their two zones. Except in regions of upwelling or divergences and at high latitudes, great abundance of phytoplankton and consequently high primary productivity are limited to waters over the continental shelves (Figure 45). The number of phytoplankters declines in a seaward direction. Cell concentrations of 10^4 to 10^6 per liter are common in coastal waters, while concentrations of 10^4 to 10^3 per liter and lower are characteristic of the open ocean. Primary productivity parallels the trends in phytoplankton biomass. Neritic waters are approximately an order of magnitude higher than offshore waters in primary production.

Zooplankton. The neritic zooplankton community, as opposed to the oceanic zooplankton community, is that floating animal population in the relatively shallow zone over the continental shelf. Although these plankton communities are not sharply separated, differences in the neritic and oceanic groups are apparent. The most obvious of these differences is the greater abundance of zooplankton in waters over the continental shelves (Figure 46). The distribution and abundance of zooplankton biomass closely follows that of the phytoplankton, as the latter is the primary food source of the former. It has been estimated that zooplankton-rich areas contain 56 percent of the zooplankton biomass (Bogorov, 1966). These areas constitute approximately 17 percent of the oceanic area and are made up in large part by waters overlying the continental shelves and slope. If the distribution of zooplankton biomass is considered on an areal basis, one finds from these estimates that the ratio of biomass to area in productive waters, i.e., over the shelf, is about 3.2, whereas in the vastness of the open ocean the ratio is only 0.5. Thus, as an estimate, neritic zooplankton biomass tends to be slightly less than an order of magnitude greater per unit area than the oceanic biomass. The differences are even greater if the concentration of biomass is considered on a volume basis.

In addition to horizontal differences in abundance distributions, neritic and oceanic zooplankton exhibit differences in their vertical distribution in the water column. This also reflects the distribution of their food items, the phytoplankton, but is modified somewhat by the restrictive depths of the neritic zone. In the open ocean, vertical segregation of species with depth occurs throughout the water column to great depths. Zooplankton biomass and the number of species show general trends of decreasing with depth. Such gradients are attenuated in the neritic plankton, as the biotic and abiotic factors controlling their distribution are more uniform and conducive to life in the shallow waters over the continental shelf. Patchiness in the distribution of zooplankton both horizontally and vertically is more evident in neritic waters. Over the shelf, species composition of the holoplankton may vary as much as 100 percent in 1-2 metres, and variation in the species composition of the meroplankton may exceed 1000 percent over the range of just a few metres.

Vertical migration is less pronounced among the neritic plankton. However, seasonal changes in the composition are very great especially in neritic waters due to the high contribution of the meroplankton. Where seasonal changes are marked by great variation in abiotic factors such as light and temperature, the zooplankton also shows seasonal variability in composition and abundance. At high and mid-latitudes, seasonal changes in the zooplankton are very great in contrast to the seasonal monotony of the tropics.

Because of the high contribution of meroplankton forms, almost every animal phylum is represented in the neritic zooplankton. The meroplankton does not always form a conspicuous part of neritic zooplankton communities. In high latitudes of the Arctic and Antarctic, benthic animals tend to develop directly or to have only brief larval stages (Thorson, 1950). Even in more temperate latitudes the neritic plankton is not always dominated by meroplanktonic forms. Several species of copepods, which as a group are the most abundant zooplankters, occur only in neritic waters and do not extend far into oceanic waters, e.g., Acartia tonsa, A. discaudata, Temora longicornis, Labidocera wollastoni, Anomalocera patersoni, and several species of Eurytemora (Raymont, 1963).

Although different communities of zooplankton exist in neritic and open ocean waters, it is difficult to make a sharp distinction between the communities. The distance to which neritic plankton extends seaward is highly variable and depends on the topography of the coast, the depth of water, and local water currents. Neritic plankton tends to be more eurythermal with tendencies toward warmer water than the oceanic species. Neritic plankters also are more euryhaline. Thus oceanic plankton, to some degree, is prevented from colonizing neritic waters, due to the more variable temperature and salinity conditions found over the shelf (Raymont, 1963).

The reasons why neritic forms do not spread over the open ocean are even less clear. Meroplankters are obviously restricted to the favorable waters over the shelf in order to complete their life cycles. However, holoplanktonic species appear able to withstand considerable changes in temperature and salinity and it is not readily apparent what precludes their invasion of oceanic waters (Raymont, 1963). Some species such as the ctenophore Pleurobrachia occur both in neritic and oceanic waters.

Neuston. Neuston organisms are frequently indistinguishable from the underlying plankton organisms, except for some of the larger epineuston, i.e., those organisms living in or above the air-water interface, partially in air and partially in water, often possessing some type of gas flotation device, and mainly distributed by the direct action of the wind. Examples of larger epineuston organisms are the coelenterates, Physalia ("Portuguese-man-of-war"), Velella ("by-the-wind-sailor"), and the sea-snail, Janthina ("purple storm snail").

The remaining neuston category, the hyponeuston (i.e., organisms living in the surface layer, but below the interface) is often composed of the same species that are found in the underlying plankton, but in different relative abundances.

Particularly distinctive of the continental shelf neuston are the larval forms of benthic animals, especially the decapod crustacean larvae, which have strong diurnal and seasonal fluctuations in numerical abundance and biomass in the surface waters. L. Pequegnat et al. (1976b, 1977a, 1977b) report consistently higher numbers of decapod larvae in night samples versus day samples at stations in the Gulf of Mexico on the South Texas outer continental shelf and higher numbers in the Spring (especially April) than in any of the other monthly samples during a 1976 study. The dominant decapod larvae were portunid crab zoeas and megalopas. Larvae of other invertebrates, i.e., mollusks, echinoderms, barnacles, etc., as well as fish eggs and larvae are present in varying amounts in continental shelf neuston. The latter are especially important constituents of continental shelf neuston, particularly in view of the fact that most of the commercially important species of fish on the continental shelf pass the egg and larval stages of their development in the continental shelf plankton and/or neuston.

Copepods are generally the dominant organisms in continental shelf neuston. In the studies of L. Pequegnat et al. (1976a, b, 1977a, b) off South Texas, pontellid copepod genera such as Pontellopsis, Pontella, Anomalocera, and Labidocera are dominant as are other calanoid species such as Centropages furcatus and Temora stylifera. Hyperiid amphipods are extremely abundant at certain times, i.e., 100-350/m^3 at night during the spring and fall periods. The sergestid shrimp, Lucifer faxoni, is also abundant at certain times in spring and August in continental shelf neuston off Texas (up to 185/m^3), whereas it is rare in oceanic neuston, where Lucifer typus takes over.

Neuston biomass varies greatly diurnally, seasonally, and geographically on the outer continental shelf area. In the South Texas outer continental shelf study mentioned above (L. Pequegnat et al., 1976a, b, 1977a, b), dry weight biomass ranged from 0.6 g/1000 m^3 in a fall and a winter sample to 121 g/1000 m^3 in a spring sample. The spring dry weight average for 24 neuston samples was 29.8 g/1000 m^3 compared to the November average of 7.7 g/1000 m^3.

Shelf areas seem to have a greater abundance of neuston than oceanic areas, and the night neuston of shelf areas is enhanced by migration of the benthic species (Morris, 1975).

<u>Nekton</u>. The fauna comprising the nekton may be grouped into three major categories:

1. neritic or shelf nekton
2. pelagic or open ocean nekton
3. nekton of the deep sea.

Within each group are various subdivisions based upon vertical zonation, habitat, mode of feeding, etc. By far the major contributor to the nekton is the fishes. Cephalopods (primarily squids) are second in importance, yet make only a diminutive contribution relative to that of the fishes. Thousands of species are represented in the neritic fishes. By contrast, Lipka (1975) reported only 66 pelagic species of cephalopods for the entire Gulf of Mexico, and of these only 5 were typical of neritic waters.

The neritic zone is characterized as being well lighted but with marked seasonal variations in the abiotic factors, i.e. light, temperature, salinity, dissolved oxygen, nutrients, turbulence, and currents. The most important factor governing the distribution of the neritic nekton is temperature. Other limitations are: (Lagler et al., 1962)

- broad expanses of deep ocean water
- nature of coastline configuration and submarine contours
- salinity variations
- currents, both direction of flow and the temperature of their waters.

The neritic zone is richest in variety of biotopes and its nekton is of the greatest abundance and variety. The shelf fish include well over half of the known fish species. Within the limits set by temperature, the range of neritic fish is largely limited by the extent of available coastline and archipelagos.

Neritic habitats include shorewaters, kelp beds, estuaries, coral reefs, submarine plateaus, banks, and varying widths of the continental shelves. The most characteristic of the fish of the neritic zone are the herrings (Clupeidae) (Lagler et al., 1962). Among many others are the barracudas (Sphyraenidae), mackerels (Scombridae), bluefish (Pomatomus), needlefish (Belonidae), tarpon (Megalops), eels (Anguilla), butterfish (Stromateidae), porgies (Sparidae), grunts (Pomadasyidae), snappers (Lutjanidae), and sea trout (Cynoscion).

The number of neritic fish species increases in moving from polar to temperate waters. The increase continues into warm temperate waters. The greatest diversity of nekton is found in tropical neritic waters (Marshall, 1966). The greater part of this diversity is found in areas where coral reefs flourish. Coral communities, among the most productive natural communities, are restricted to waters where the water temperature does not fall below 18° C. Because of this special need for warm water the fish of the tropics hardly penetrate the sub-tropics to the north and south. Consequently, there exists a high degree of endemism among the tropical neritic fishes.

Those tropical species occurring throughout the tropics in both the Pacific and Atlantic are termed circumpolar. Tropical neritic faunas exist in four major regions: Indo-Pacific, West African, West Indian, and Pacific American or Pan American (Lagler et al., 1962). All are relatively distinct in species composition and have some distinctive genera. However, the similarities between the four are greater than the links to their respective neritic faunas to the north and south.

The subtropical faunas are considered diluted tropical faunas, whose distributions are limited by yearly minimum temperatures of 16-18° C. They more closely resemble the tropical fauna than the neighboring fauna of the temperate region.

Temperate and boreal neritic nekton is characterized by much less diversity and fewer species. However, in this region neritic fishes are often present in tremendous numbers. The most important commercial fisheries, e.g. cods (Gadidae), herrings (Clupeidae), and flatfish (Pleuronectiformes) center in temperate to boreal waters. Warmer water fisheries include the sardine (Sardinella) and the anchovy (Anchoa).

In temperate waters the great yearly range of temperatures profoundly affects the neritic fishes. The available food is subject to drastic fluctuations. High peaks of primary production and phytoplankton abundance are followed by periods of low production and sparse phytoplankton populations. The abundance of zooplankton, though lagging behind in time, follows the same pattern as the phytoplankton. Zooplankton abundance also fluctuates with the seasonal influx of meroplankton. Temperature also affects temperate neritic fish directly. Species such as mackerel, silver hake, scup, and weakfish migrate to the coastal spawning grounds in spring and summer. When inshore waters cool, they migrate seaward again to warmer, deeper water. Other cold-loving species, e.g. haddock and pollock, migrate from warm inshore waters in the summer to colder deeper waters offshore. Because of the rigorous fluctuations in the physical environment, neritic fishes of temperate regions are the most adaptable fish in the sea (Marshall, 1966).

Benthic Life

The benthic communities of the continental shelf may be characterized as being as rich and varied as the pelagic communities in the water column above them. The microbial populations in the sediment may equal the production rates of the phytoplankton, which drift above them. The flow of detritus and dissolved organic matter from the off-shore water masses enriched by continental sources, and the drift of particulate and dissolved organic matter from the surface waters serve as a substrate for the rapidly multiplying microbiota, which, in turn, serve as a food source for the "grazers" among the meiofauna. Reid (1970) reports meiofaunal numbers equal to zooplankton numbers in the water column above them. The meiofauna serve, in the same fashion as the zooplankton of the surface waters, as food for the smaller carnivores. Large predacious polychaetes, small shrimp, cumaceans, tanaids, and other crustaceans, and small fish feed on the meiofauna, and are in turn fed on by larger carnivores, including fish (Bright, 1970). Fish production as measured by commercial fish catches annually show as high a catch of benthic fishes from the shelf as pelagic fishes. Commercial catches of invertebrates (shrimp, etc.) are important economically in many areas of the continental shelf.

The biomass of the benthos varies not only with depth but exhibits a geographic variation also. On the Atlantic coast the Georges Bank area has the highest biomass (1300 g/m^2; Bureau of Land Management, 1977). A direct correlation is found between populations of commercially important ground fish and the invertebrate macrofauna of this region.

Animal densities and biomass also vary markedly with ecological conditions. Rowe (1971) points out that although depth exerts the most stringent effects, surface productivity ranks second in controlling benthic biomass. Just as high phytoplankton productivity (Figure 45) is reflected by the high zooplankton densities of the same regions (Figure 6-2) so would benthic productivity reflect this geographic trend were sufficient data available to construct a map. A recent review of all published studies (Thiel, 1975) of benthic productivity documents those trend.

The kinds of animals, or the species distribution, also varies with depth and with geographic location. A third factor, the type of substratum, is strongly related to the distribution of species in shelf communities. Although there is a range of substratum types, a few broad classes are sufficient to define the habitat of most species: silt-clay (mud), sand, gravel or shell, and rock. For instance, Ampelisca (a tube-dwelling amphipod) communities have been described in similar sediments at similar depths on both the east coast and the west coast of the United States. Wigley (1968) describes communities of A. vadorum numbering thousands per square metre in silty sand off South Georges Bank, and Barnard et al., (1959) describe a similar community with A. cristata on the shelf off San Diego.

CONTINENTAL SLOPE ZONE

GENERAL CHARACTERISTICS

Definitions

The continental slope zone may be characterized as a transitional zone between the shallow, highly productive waters of the shelf, and the less productive waters of the deep oceans. The gently sloping shelf, with grades seldom exceeding 2-3°, is succeeded by the more rapidly descending slope zone with grades over 3° and sometimes as high as 25°. This characteristic, rapid increase in depth, from 200 m to 3000 m, is then replaced by the gentler grade of the continental rise at its base (see Part 5, Figure 50, of this section)

The area of the continental slope, worldwide basis, is nearly twice that of the continental shelf, occupying 15.3 percent of the total area of the oceans (Sverdrup et al., 1942). The more productive upper slope (200-1000 m), comprises an area of only 4.3 percent as compared to the shelf's 7.6 percent of the total area. The difference in the areas of the continental shelf and continental slope may be noted in the figures of the continental margins in Part 5.

Geomorphology and Geologic Nature

The continental slope is the most significant topographic discontinuity of the earth's crust because it marks the general position of the contact between low-density rocks of the continents and the high-density rocks of the ocean floor (Emery and Uchupi, 1972). However, the contact itself has largely been obscured by extensive prograding of the continental slope and by deep burial of its base by detrital sediments from the land and pelagic sediments from the ocean. The contact is further blurred by topographic irregularities such as submarine canyons, growth of organic reef dams, diapiric intrusions, and fault blocks. Instability of the environment also adds to the quite varied configuration of the edge of the continental crust.

In general, continental slopes range in overall elevation from about 1 to 10 km and are normally considered to have a declivity of 3 to 6°; however, extremes of more than 15° exist (e.g. Campeche, Florida, and Blake Escarpments) as do those of less than 1° (e.g. portions east and west of Florida). Most profiles across the continental slope generally show two types of bottom: a steep, irregular upper slope and a smooth lower slope. Such are the cases for the northwestern Gulf of Mexico continental slope with its upper "hummocky zone" (aptly named by Gealy, 1955) of diapiric structure origin and those of the Atlantic seaboard that possibly reflect a change from an erosional slope to a slumped and debris-covered slope (Pratt, 1968). Directly off southern California and within the continental borderland the slope is a dip slope (Moore, 1960) while off Oregon and Washington, the slope is broken by normal faulting parallel to the shoreline

(Menard, 1964). These descriptions attest to the complexity of continental slopes that form the topographic boundary between the continent and the ocean basin.

Sediments from the continental slope have probably been studied less than those collected from the continental shelf, continental rise, or abyssal plain. In general, these sediments are of a smaller grain size than those collected from the shelf but contain a higher percentage of organic matter than those on the shelf or on the deep-sea floor. Mass movement of these sediments may be common because the steepness of the slope is probably near the angle of repose of the sediment.

Currents and Circulation

The waters overlying the continental slope represent a transition zone in both a dynamical and a structural sense. This region is subject to changes that can be generated by shelf water movement or temperature/ salinity changes as well as the intrusion of oceanic boundary currents or eddy structures associated with their instabilities. While there appears to be a cyclic behavior in thermohaline modification and circulation on the shelf keyed to the progression of seasons, the effects of the boundary currents are known only by isolated, documented observation; predictability is beyond present means.

In the surface waters of the slope zone the currents react quickly, relative to oceanic currents, to changes in driving mechanisms. Atmospheric generation of motion may result in overall Ekman seaward transport with attendant deeper motion landward or an alongshore transport due to the maintainence of a quasi-geostrophic balance depending on initial creation of an across-the-shelf pressure gradient established by Ekman transport. On a smaller scale, the subsidence of a rapidly established pressure gradient may permit the generation of inertial motion, which will be superimposed on a background drift.

Mixing and cooling also take place in the surface region during autumn with an associated and widespread vertical motion. The effects of this mechanism operating on the shelf are reflected in the thermohaline structure over the continental slope.

The waters of the slope region respond not only to the shelf region but, dynamically, to the offshore oceanic current and, structurally, to mixing processes related to their turbulent behavior. Undoubtedly, a certain amount of surging and movement takes place in concert with lateral adjustments of the boundary current path. Shoreward movement of this current could enhance entrainment of the water over the continental slope, and its removal tends to import a different water mass to a given geographical location. Conversely, considerable offshore movement of the path would delay export of the slope water. Genuine intrusions of the boundary current can occur, possibly on a regular basis since stream instabilities are exhibited in terms of lateral meanders from the mean stream path. Some geographical locations, and, in fact, whole segments of the United States coastline, exhibit strong topographic control on the lateral movement of the boundary current, and semi-permanent eddy structures driven by the main flow can result.

In recent years attention has focused on the meso-scale eddies that are either driven by the current or are introduced over the slope region by an instability growing to the point of its turbulent release by the current. In the latter case direct exchange of boundary current, shelf, and slope waters is achieved over significant portions of the slope region as the eddy vortex drifts along in the background motion. In this case the circular motion associated with the vortex continuously exchanges waters around its periphery, which could extend over the slope and onto the shelf.

The slope region is slightly stirred horizontally by the periodic barotropic movement of the astronomical tide. However, the nominal motion for this feature would be a closed orbit in the vertical plane. The tide has further implications in association with motion at depth and the thermohaline structure.

At depth and over the slope, water motion takes place primarily in response to sustained and generally longer and possibly periodic mechanisms. A general delineation of the spectrum of phenomena can be given at present, however, the interaction of these middepth features is largely unknown. Evidence is present that indicates that motion in this portion of the water column is primarily in terms of a spectrum of internal wave modes. The orbital paths in this case are ellipses with the major axis in the horizontal direction. The periods range between the local inertial and Vaisala periods although the diurnal tide period could form an upper bound. In the latter case, internal wave motion would be present and initiated by an interaction of the tidal motion with a strong pycnocline representing a definite layering of the water mass.

Below the major thermocline in the slope region the presence of a counter-current that interacts with the oceanic boundary current must be considered. This semi-permanent feature over the slope can extend down to the abyssal depths and can often achieve speeds that match those of the surface boundary current. In some instances, the counter-current is generated, in a direct sense, by the same forces that produce the boundary current and is closely associated with the surface flow both temporally and spatially. However, the counter-current can conversely be a response to driving mechanisms that are linked to the boundary current in a macroscale (or whole ocean) circulation picture. In this case the counter-current is more independent of the surface boundary current although it does interact in an only vaguely understood manner. This type of counter-current often extends from middepths on the slope downwards to the foot of the continental rise and spreads laterally into the abyss. In most cases, the counter-currents essentially flow along isobaths on the slope. Although this is so, evidence has been found that prompts the suggestion that interaction with the lower limits of the surface boundary condition can steer the deep counter-current.

Other Characteristics

The major portion of the continental shelf waters lie within the euphotic zone. The consequent productivity of an area of the shelf will be influenced by the insolation regime of the latitude of the area. In addition, coastal influences such as the presence or absence of nutrient export from terrestrial sources via rivers or marshes, or upwellings can be identified. The abyssal depths must depend on whatever particulate organic matter drifts down through the water column to the cold, dark unproductive bottom waters. The factors affecting productivity of the slope zone, however, are not so clearly defined.

Down-slope currents from the outer edge of the shelf may bring some organic matter with them. Recent research (Karl et al., 1976; Devol et al., 1976) has identified a microbial population between 650 and 1040 m at the level of the oxygen minimum. This population has been identified as bacteria (Sorokin, 1971) and as small, biflagellated, pigmented cells (Fournier, 1971). This layer impinges on the slope providing a distinctly increased food supply to the benthos at those depths.

The slope zone is not only physically a transition between shelf and abyss, but also dynamically a transition zone. The upper slope receives some organic matter from the shelf and shares some species with the shelf; the middepth slope, with its own faunal assemblages, receives its organic matter from mesopelagic sources, and the lower slope, below 1000 m, is influenced by deeper currents and has yet another faunal assemblage.

The characteristics that might serve to distinguish the continental slope from the contiguous shelf and rise, other than geomorphological features, would include the presence of the oxygen minimum layer and an associated increase in certain other parameters (ATP and total phosphorus, Karl et al., 1976; ATP, ETS activity, and nitrite, Devol et al., 1976), distinct faunal zonation along isobaths (Haedrich et al., 1975; Grassle et al., 1975; and Pequegnat et al., 1976) and the unpredictable, weakly defined interactions of the seasonal influences from the shelf on the one hand and the steady-state abyssal system on the other hand.

BIOTA OF THE CONTINENTAL SLOPE ZONE

Pelagic Life

Phytoplankton. The microflora of the slope zone is not distinct from the vaguely distinguishable neritic and oceanic phytoplankton communities. Except where upwelling occurs over the slope thereby stimulating primary production, the slope phytoplankton may be considered transitional between neritic and oceanic with respect to composition, abundance, and productivity.

Zooplankton. Whereas neritic and oceanic zooplankton are distinguishable as communities, no separate and distinct community exists for the zooplankton over the continental slope. The slope zooplankton is made of a mixture of both neritic and oceanic forms and possess some characteristics of both the neritic and open ocean biotopes.

Prevailing currents are likely to be the single most important factor regulating the relative composition of the slope zooplankton. Because of its proximity to the more productive neritic waters, zooplankton biomass over the slope would be expected to be somewhere between that of the adjacent neritic and oceanic zones.

Because of the greater depths involved, more vertical structuring of the zooplankton community would be expected. Similarly, the distribution of species and biomass would become more regular, tending to decrease with depth following subsurface maxima. With the introduction of many oceanic species such as euphausiids, vertical migration becomes more predominant and extends over much greater depth ranges, although remaining especially vigorous in the upper 50-100 m.

The composition of the slope zooplankton is a mixture of oceanic and neritic species and varies with local conditions. Offshore zooplankters, e.g., euphausiids, chaetognaths other than Sagitta elegans and S. setosa, and siphonophores, will be mixed with holoplanktonic organisms from the nearshore zone such as decapods (planktonic shrimps), mysids, isopods, amphipods, and other crustaceans (Newell and Newell, 1963). Depending on the season, larval stages of oceanic and neritic organisms will be present, though not in abundance.

Neuston. Like the zooplankton beneath it, the neuston of the continental slope zone is made up of a mixture of both shelf and oceanic forms. Larval forms are generally not as abundant as in shelf neuston.

The neuston, however, is much less abundant over the continental slope area than the plankton beneath. Berkowitz (1976) in a comparison of neuston tows taken in the upper 9-19 cm and plankton tows at a depth of one metre found that the neustonic zone of the continental slope of the northwestern Gulf of Mexico is a relatively impoverished area. The large majority of the animals identified and counted were between two and six times more abundant at one metre than they were in the neuston at an average of 14 cm depth. This difference occurred in both daytime and nighttime samples. Certain species, however, were found in higher concentrations in the neuston than in the plankton of one metre depth: the pteropods Cavolinia longirostris and *Diacria quadridentata*, brachyuran megalops larvae, and copepods of the genera *Pontella* and *Pontellopsis*.

Neuston of the continental slope zone appears to show a more pronounced increase in concentration at night as compared to day, than in the shelf zone. Berkowitz (1976) reports a greater than tenfold increase in concentrations of a majority of the animals at night and attributes this to diurnal vertical migrations. Thus, any studies of neuston over continental slope and deep ocean zones must be conducted with an awareness that the time of day is a major factor influencing the nature of the samples taken.

Nekton. The slope zone has been characterized as a zone of transition between continental influences and oceanic influences with respect to such aspects as currents, nutrients in the water, and temperature regimes. The fauna of the water column overlying the slope strongly reflect this transitional quality.

The uppermost layer, the epipelagic zone, is really a relatively thin, offshore extension of the neritic zone, but it is bottomed by water, not solid substrate. This zone is well lighted at the surface, dimming toward its downward limit of about 200 m. Seasonal variations are shown in temperature, light, salinity, oxygen, nutrients, and plant and animal populations, quite similar to the variations in the waters of the outer continental shelf. Fish inhabitants include oceanward utilizers from the neritic zone as well as some mackerels, bonitos, albacores, and tunas (Scombridae), some sharks, dolphins (*Coryphaena*), flying fishes (Exocoetidae), mantas (Mobulidae), eels (*Anguilla*), marlin (*Makaira*), sailfish (*Istiophorus*), bluefish (*Pomatomus*), molas (*Mola*), lanternfishes (Myctophidae), the mouthfishes (*Stomias*), and the mouthfish relative *Cyclothone* (Lagler et al., 1962).

In addition to fishes, other vertebrate groups occur in the epipelagic zone of the slope. Sighting of whales off Pacific coasts and dolphins off all American coasts are frequent. The cosmopolitan Tursiops truncatus does not venture as far, perhaps, as the widely distributed oceanic Delphinus delphis, but both are frequent over slope zone waters (Marcuzzi and Pilleri, 1971). Large sea turtles are not infrequently found in southern and Gulf waters, since they must return to land to lay their eggs (Rebel, 1974).

Invertebrate nekton over the continental slopes include only mollusks and crustaceans. The crustacean fauna of the epipelagic zone is, as with the fishes, an extension of the neritic or shelf assemblage. Epipelagic mollusks are the cephalopods. Squids of the species Loligo peali and Doryteuthis plei appear to be ubiquitous in slope zones of the Atlantic, Pacific, and Gulf coasts and are mentioned as food sources for many epipelagic fish (Leim and Scott, 1966; Hart, 1973).

The mesopelagic of the slope zone is more closely allied to the oceanic than to the neritic zonation. The water is always cold, usually around 10° C, the pressure is high and the light extremely dim or absent. This division is inhabited by dark-adapted fishes, which either bear light organs or are reddish or dark colored. The small lanternfishes (Myctophidae) are so numerous that sound reflected from their gasbladders is responsible for the "deep scattering layer" (Lagler et al., 1962). These small fish and their predators, the viperfish (Chauliodon) and the deep-sea swallower (Chiasmodus), undertake lengthy vertical migrations nightly as the lanternfish rise to the epipelagic to feed on plankton. The dark fishes, such as the anglemouths (Gonostomatidae) and the large red fishes, such as the rockfish or ocean perch (Scorpaenidae) are accompanied by many red crustaceans, such as the red prawn Acanthephyra. Many of the squid at these depths have reddish coloration (Voss et al., 1973).

The mesopelagic nekton are difficult to sample directly. More is known about the species and numbers of the smaller fishes and invertebrates from the examination of the gut contents of commercially important fishes. The mackerels and tunas (Scombridae) although epipelagic, feed heavily on the small fish and squid of the mesopelagic at night when they rise toward the surface. Swordfish are found to consume quantities of hake (Gadidae) and rat-tails (Macrouridae) from the mesopelagic. Other commercially important fishes, such as the halibut and the witch flounder (Pleuronectidae) of the upper slope feed both on these mesopelagic species and on the benthos.

In the bathypelagic division of the slope zone there are essentially no seasonal variations in physical factors of the environment; the water is very cold (between 2° and 4° F at 2000 m), pressures are very great, and darkness prevails except for the bioluminescence arising from the light organs of many of the inhabitants. Fishes are greatly reduced in numbers and kinds below those of the mesopelagic or upper slope areas but include most ceratioid deep-sea anglers, dories (Zeidae), some rockfish (Scorpaenidae), the deep-sea swallower (Chiasmodus), the gulpers (Eurypharynx), and deep water eels such as Cyema (Lagler et al., 1962). The bathypelagic squids, the chiroteuthids and cranchiids are much smaller than the giant architeuthid squids of the mesopelagic regions of the slope.

In addition to the changes in coloration and development of light producing organs noted in the mesopelagic nekton as adaptations to dim or absent light, many of the bathypelagic fauna have tactile structures. Many of the fish have elongate, threadlike structures on the head, tail, or fins. The prawns at these depths also possess extremely long tactile antennae, which in the penaeid Aristaeus aristaeopsis are twelve times the length of the body.

The nekton of the lower slope is sparse, probably a reflection of the quite limited food resources at these depths.

Benthic Life

Whereas continental shelf biomass values averaged for all areas under consideration, and for all faunal groups, would be approximately 200 g/m^2 wet weight, the less productive slope regions would be nearer 10 to 20 g/m^2. Rowe et al. (1974) investigating the macrofauna, found 11 g/m^2 for the upper slope of the northwestern Atlantic Ocean, and 5.9 g/m^2 for the lower slope. For the Gulf of Mexico they found 0.5 g/m^2 for the western slope and 0.15 g/m^2 for the eastern slope. These are values equaled by the meiofaunal values.

The epifauna of the slope is also characterized by its similarity in all the world ocean. A brittle star Ophiomusium lymani and the polychaete Hyalinoecia artifex are truly cosmopolitan species found in continental slope communities the world over. Grassle et al. (1975) found that five species overwhelmingly dominated the slope epifauna, forming 97 percent of the animals counted. Two sea urchin species and a cerianthid anemone were the three other ubiquitous species.

Frequently found on slopes in the Atlantic Ocean (including the Gulf of Mexico) is the red crab Geryon quinquedens. Although fish constitute only 30 percent of the slope epifauna (Haedrich et al., 1975), they are the most diverse of the larger organisms present, with no single species showing a high numerical dominance (Grassle et al., 1975) such as Geryon quinquedens does among the crustaceans, or Ophiomusium lymani among the echinoderms.

Coull et al. (1977) found twice the amount of meiofauna at 800 m as they did at 400 m. Thiel (1975) found similar increases at this depth on METEOR Cruise 26. Rowe et al. (1974) show an increase in biomass of macrobenthos between 500-1000 m. Faunal assemblages of the continental slope show zonation along gradients that correspond to depth, to sediment type, and to food availability (Haedrich et al., 1975;

Grassle et al., 1975; Pequegnat et al., 1976). Most of the demersal fish, which are commercially important in shelf fisheries, also feed in the upper slope zones down to 700-800 m (Moiseev, 1971).

CONTINENTAL RISE-ABYSSAL ZONE

GENERAL CHARACTERISTICS

Definition

The continental terrace is constituted of the shelf and contiguous slope. The continental rise is a smooth apron that rises gently from the true ocean floor or abyss to the base of the continental slope. Ordinarily the rise is grouped with the shelf and slope forming with these two the continental margin. However, its rather unique mode of formation and its current regime seem to be more allied to the abyss than to the shelf-slope complex.

Morphologic and Geologic Aspects

As a region of transition between continents and ocean basins, the continental rise is characterized by low, elongate hills and shallow channels. The hills may well be formed by input of sediments from slumps on the slope; the channels are often connected to submarine canyons.

The continental rise appears to have been formed by the coalescence of adjacent fans at the bases of submarine canyons (Menard, 1955), although geostrophic currents may play some role in their definitive shape (Schneider et al., 1967).

The hills may prove to be giant ripples that are migrating down-current (Ichiye, 1968; Ewing et al., 1971). In fact, Ichiye believes the ripples are formed by fallout from the nepheloid layer as a result of stationary waves generated in bottom waters. The matter is still debatable as to whether these features are depositional or erosional, but there is no doubt that slumping has played an important role in formation of the rise.

The abyssal plains are in the aggregate immense areas of very flat ocean bottom lying near the continents. There is generally a gradual merging of the continental rise sediments and those of the abyssal plain. The plain may in places have such features as low hills and shallow channels, but their formation probably differs very much from the processes involved on the rise.

Currents and Circulation

Knowledge of currents in the deep ocean is expanding but it is still scanty. Pequegnat (1972) gave a history of the development of knowledge of deep currents up to 1970. Data gathered since that time verify the belief that near-bottom currents are a normal feature of the rise and abyssal plain. It is not known in all cases what their speeds may be, but photographic evidence indicates that many are of sufficient magnitude to resuspend and transport some sediment components. It is doubtful, however, that most actual bottom currents are sufficient to erode clays in many areas. Lonsdale and Southard (1974) found that the lowest speed necessary to erode red clay varied with water content but the lowest velocity was 18.7 cm/sec at the bed surface. Several investigators have reported velocities of 20 cm/sec along the contours of the rise off New England (as part of the North Atlantic Western Boundary Undercurrent).

BIOTA OF THE CONTINENTAL RISE AND ABYSS

Pelagic Life

Phytoplankton. Comparative features of the oceanic phytoplankton are discussed in the phytoplankton section of the outer continental shelf zone. Only a brief summary will be reiterated here.

The composition of the oceanic phytoplankton differs from that of the neritic zone. Dinoflagellates and coccolithophoids are of increasing importance offshore. The number of phytoplankton species present in the open ocean is greater than in shelf waters. The distribution of individuals among these species is more even, i.e., diversity is greater in the open ocean.

The depth of the euphotic zone is deeper in the open ocean, extending as deep as 150 metres. Because of the decreased turbidity, photosynthesis occurs at greater depths in the open ocean. However, production of the phytoplankton is still limited to the surface layers (upper 100-150 metres). Phytoplankton are distributed more regularly in the water column of the open ocean. A maximum in phytoplankton abundance and productivity occurs below the surface. Below this point both parameters decrease as the bottom of the euphotic zone is approached.

Oceanic phytoplankton is less abundant by 1-2 orders of magnitude than phytoplankton of the shelf. Primary production is also less by about 1 order of magnitude in oceanic waters.

Zooplankton. The oceanic zooplankton has an extraordinarily wide distribution and species are apparently present throughout all depths in the oceans. The zooplankton is comprised almost entirely of holoplanktonic forms. There are few meroplanktonic exceptions such as the leptocephalus larvae of eels and phyllosoma larvae of lobsters.

Expatriate species from the neritic zone occasionally are swept by currents into the open ocean; however, their chances for survival and thereby completing their life cycle are low. Some species of the oceanic zooplankton occur in all of the world's oceans. Such cosmopolitan species include the ctenophores, Beroe cucumis and Pleurobrachia pileus; the copepods, Oithona similis and Scolecithricella minor; the polychaete worm, Tomopteris ligulata; and the siphonophore, Lensia conoidea (Raymont, 1963). On the other hand, many species are restricted to and indicative of certain water masses, the main factor controlling their distribution being temperature.

The variety of species of oceanic zooplankton is highest in tropical regions with relatively few species present in cold waters. Over 90 percent of all zooplankton species occur in warm tropical and subtropical waters. Of the greater than 2000 zooplankton species, copepods account for approximately 750 species. Amphipods are the next most abundant group with over 300 species, while the euphausiids, second only to copepods as a basic animal food source in marine food webs, number approximately 85 species.

The vertical and horizontal distribution of zooplankton is irregular and closely follows that of the phytoplankton, which serves as the primary food source. The distribution is subject to diurnal and seasonal vertical migrations extending over several hundred metres for some species (primarily euphausiids). Migrations are especially vigorous in the upper 50-100 metres of the ocean (Moiseev, 1971). At mid and high latitudes the zooplankton exhibits marked seasonal changes that correspond to variations in temperature, illumination, and the abundance of food organisms, i.e., phytoplankton.

While tropical and subtropical regions are rich in the variety of zooplankton, their zooplankton biomass is low, usually not exceeding 10-20 mg/m^3 (Moiseev, 1971). By contrast, surface zooplankton concentrations in boreal (north of 40°N) and notalian (south of 40°S) waters often exceed 100 mg/m^3. Bogorov (1959) contends that wherever zooplankton is scant in surface layers of the ocean, the deeper zones are also considerably depleted. Most of the deep oceanic area (63 percent of the oceans surface) is zooplankton poor. Containing only about 22 percent of the total zooplankton biomass, average zooplankton concentrations are less than 50 mg/m^3 (Figure 46). Moiseev (1971) contends that "such dispersion renders the zooplankton practically unavailable as food for other animals, and is evidently hardly exploited in higher trophic levels."

Vertical distribution of the zooplankton in the open ocean is more predictable than in neritic waters and extends over a much greater depth. The number of zooplankton species increases with depth to a subsurface maximum perhaps as deep as 500 metres, then the number of species drops off rapidly with increasing depth. Zooplankton biomass decreases with depth; the maximum occurring usually in the near surface layers. For example, the predominance of copepods (primarily Calanus) occurs in the euphotic zone, less than 100 metres. The concentration of copepods is 15-50 times greater than in the 100- to 200-metre layer and tens to hundreds times greater than in deeper layers (Moiseev, 1971). Vinogradov (1955) has computed that 65 percent of the zooplanktonic biomass is contained in the upper 500-metre layer. The 500- to 4000-metre layer contains most of the remaining 35 percent of the zooplankton biomass. Below 4000 metres the zooplankton biomass is only 1/150 to 1/800 of that found in the 0- to 500-metre layer.

Neuston. Oceanic neuston differs from continental shelf and slope neuston in that it is generally less seasonal, contains fewer meroplankters, and contains more oceanic forms such as euphausiaceans and certain characteristically oceanic species of sergestid shrimps, e.g., in the western Atlantic, *Lucifer typus* in place of the continental shelf *Lucifer faxoni*, *Sergestes* spp., etc.

W. Pequegnat et al. (1976) summarized information on previous neuston studies from such widely separated regions as the Sea of Azov, the Indian Ocean, the Gulf of Mexico, the North Sea, Norwegian Sea, and subtropical Northeast Atlantic (Zaitsev, 1970; Hempel and Weikert, 1972; TerEco Corporation, 1974; and Jeffrey et al., 1974) and compiled a table of common genera from neuston samples throughout the world oceans (Table 24).

Very few detailed studies with complete faunal analyses of oceanic neuston have been reported. Weikert (1972) presented a faunal survey of the zooplankton in the neuston of the subtropical Northeast Atlantic. Morris (1975), in a study of the neuston of the Northwest Atlantic, including the Caribbean Sea and southeastern portion of the Gulf of Mexico, asserts that oceanic neuston shows very little difference in species composition from the plankton of deeper layers. Neuston does, however, differ from the underlying plankton primarily in the proportional abundances of the individual species. Fewer species and individuals inhabit the surface neuston layer than the subsurface plankton layers, and there is no correlation between neuston abundance and the abundance of zooplankton at 5-m depth in the same area.

Morris (1975) also found that the only species to show consistently greater abundances at the surface than below the surface was the calanoid copepod, Pontella atlantica. All other species in the neuston were of equal or greater abundance beneath the surface. Table 25 lists species encountered by Morris in North Atlantic samples, which he reports as "day-positive" species (i.e., characteristic of daytime neuston as opposed to nighttime migrators into the surface areas), along with reports of day-positive notations for each species by other investigators from other ocean regions.

As in the continental shelf and slope neuston, oceanic neuston is greater at night. Examples of wet weight biomasses of day and night

Table 24

Common Genera Collected From World Oceans in Neuston Samples

Siphonophora

Physalia, *Porpita*, *Velella*

Chaetognatha

Krohnitta, *Pterosagitta*, *Sagitta*

Polychaeta

Nereis, *Nephthys*, *Phyllodoce*, *Platynereis*, *Tomopterus*

Gastropod Mollusca

Atlanta, *Cavolinia*, *Creseis*, *Glaucus*, *Hydrobia*, *Janthina*, *Styliola*

Crustacea

Amphipoda

Caprella, *Corophium*, *Gammarus*, *Nototropis*

Copepoda

Anomalocera, *Calanus*, *Candacea*, *Copilia*, *Eucalanus*, *Euchaeta*, *Labidocera*, *Parathemisto*, *Pontella*, *Pontellopsis*

Cumacea

Bodotria, *Cumella*, *Cumopsis*, *Pterocuma*

Decapoda

Crangon, *Latreutes*, *Leander*, *Lucifer*, *Palaemon*, *Parapeneus*, *Planes*, *Portunus*, *Sergestes*

Euphausiacea

Euphausia, *Nyctiphanes*, *Stylocheiron*, *Thysanoessa*

Isopoda

Eurydice, *Idotea*, *Sphaeroma*

Mysidacea

Gastrosaccus, *Mysis*, *Pseudoparamysis*, *Siriella*

Insecta

Halobates

Pisces

Balistidae, Blenniidae, Carangidae, Engraulidae, Exocoetidae, Gonostomatidae, Mugilidae, Mullidae, Myctophidae, Sternoptychidae

From: W. Pequegnat et al., 1976.

neuston from various regions are presented in Table 26. Hempel and Weikert (1972) conclude that the magnitude of the nocturnal increase depends on several factors such as the abundance and composition of the subsurface zooplankton, hydrographic features of the water column, and depth to bottom.

It is generally concluded that, compared to subsurface zooplankton populations, the neuston is a depauperate fauna (Morris, 1975).

Nekton. Nekton of the open ocean exists in three relatively distinct biotopes: epipelagic, mesopelagic, and the deep ocean including the bathypelagic and abyssopelagic. Although separable by depth and biotic compositions, considerable overlap exists between biotopes not only at the boundaries but also through the biotope owing to diurnal and ontogenetic vertical migrations.

In general the nekton of the open ocean is less abundant and more dispersed than that found in shelf or slope regions. Within the open ocean proper, nekton of the epipelagic is more abundant than mesopelagic nekton. Mesopelagic nekton, in turn, is more abundant than the deep ocean (bathypelagic and abyssopelagic) nekton. Vertical gradients in abundance follow distributional patterns of food items, which are highest near the productive euphotic zone. The number of species comprising the open ocean nekton is low. Deep-sea species are about an order of magnitude less in number and epipelagic species about two orders of magnitude less than nektonic species of the neritic zone.

Despite the practical importance of some fish species of the epipelagic ichthyocene, information is scant on the total epipelagic nekton. Even less is available on the total nekton of the mesopelagic and deep ocean biotopes. An excellent review by Parin (1968) on the ecology of the epipelagic provides the greatest insight into the nekton of the open ocean and accordingly forms the basis for the following

Table 25

Comparison of Daytime Classification of Species Reported from North Atlantic Neuston with Reports of Day-Positive Occurrence of some Species in Literature

Species	Region
	I. Day-positive species
Lepas cypris larvae	Meditteranean Sea Black Sea N. E. Atlantic
Pontella atlantica	Central Pacific N. E. Atlantic Indian Ocean
Idotea metallica	Mediterranean Sea N. E. Atlantic N. Atlantic
Creseis virgula	Mediterranean Sea
Exocoetid juveniles	North Pacific
Colonial Radiolaria	Gulf of Mexico
	II. Day-neutral species
Fish eggs	Black Sea
Spionid larvae	Black Sea
Bivalve larvae	Black Sea
Gastropod larvae	Black Sea
Myctophidae larvae	North Pacific

From Morris, 1975.

Table 26

A Summary Comparison of Regional and Diel Differences in Neuston Biomasses, as Wet Weights (mg/m^3)

Region	Day	Night
Sargasso Sea (year)	23	16- 188
Sargasso Sea (winter)	22	16
Sargasso Sea (spring)	32	?
Sargasso Sea (summer)	23	88
Sargasso Sea (autumn)	17	?
Gulf Stream (summer)	50	99
Caribbean Sea (winter)	18	75
Scotian Shelf and Slope (autumn)	64	?
North Sea (autumn)	53-98	218- 263
Norwegian Sea (summer)	41	388
Black Sea, NW (summer)	610	?
Black Sea (summer)	14	54
Tyrrhenian Sea (summer)	9	60
Ligurian Sea (summer)	25	120
Ionian Sea (spring-summer)	12	208
Mediterranean Sea, central (summer)	14	92
Black Sea (summer-autumn)	0.4-20	8-1479
Black Sea (summer)	320	?

From Morris, 1975.

discussion, which will concentrate on the fish component of the nekton. The invertebrate component will be discussed separately at the end of this section.

Epipelagic Nekton. The biotope of the epipelagic fish and large invertebrates is the upper mixed layer of the ocean having the thermocline as the lower boundary. Characterized by high illumination it is essentially the productive euphotic layer. The lower boundary is not a plane of division but rather a zone of overlap wherein the mesopelagic and epipelagic biotopes are linked by distinct trophic relationships. The limits of vertical distribution of the epipelagic and mesopelagic biotopes are determined by temperature conditions and as such vary regionally. In high and temperate latitudes the epipelagic biotope develops only in the summer and is restricted to the upper 10-20 metres. Where development of the thermocline is vague or weak, mixing of the mesopelagic and epipelagic is facilitated. In tropical regions the epipelagic may extend to 200-250 metres.

Epipelagic fish constitute the last levels of the productive process taking place in the open ocean. Their numbers are directly dependent on a supply of forage items. This in turn depends on the magnitude of primary production of organic matter in the region. However, the role of epipelagic fish in present day fishing is relatively unimportant when compared to pelagic fish production over the shelf or slope (Table 27). This meager contribution of the epipelagial total fish production (< 3 percent) is due to the low productivity of the open ocean and the lack of dense concentrations of fish in the zone.

Distribution of the epipelagic nektonic biomass is heterogeneous in the oceans, corresponding to the distribution of biogenic elements, primary production, and the production of zooplankton. Areas richest in ichthyofauna generally coincide with the biologically productive areas (Figures 45 and 46), although the abundance maxima of the nekton and zooplankton are shifted down current from zones of upwelling

Table 27

Distribution of World Catch in 1966 by Oceanic Zones (10^3 Tons)

Group	Total Catch	Demersal Habitat		Pelagic Habitat		
		Shelf	Slope	Neritic Zone	Outer Neritic Zone	Epipelagic Zone
Salmons	1,180	–	–	980	200	–
Flatfishes	1,090	900	190	–	–	–
Cods	7,270	6,000	1,270	–	–	–
Ocean perches, greenlings, gobies, etc.	3,190	2,390	800	–	–	–
Jacks, sauries, etc.	2,020	–	–	500	1,500	20
Herring and sardines, anchovies	19,150	–	–	8,490	10,660	–
Tunas	1,320	–	–	120	200	1,000
Mackerels	2,000	–	–	1,300	600	100
Sharks and rays	430	100	–	30	100	200
Unsorted fish	7,950	3,200	100	4,000	450	–
Total fishes	45,600	12,490	2,360	15,420	13,710	1,320
Crustaceans	1,260	1,200	60	–	–	–
Molluscs	2,910	2,410	–	100	400	–
Echinoderms	44	44	–	–	–	–
Total invertebrates	4,214	3,654	60	100	400	–
Grand total	49,814	16,144	2,420	15,520	14,110	1,320

From: Moiseev, 1971.

and high primary production. Of great importance to the epipelagic ichthyofauna are regions of upwelling and the productive waters of the temperate zone. The extensive oligotrophic waters of the major subtropical circulations have very sparse fish stocks and are of little value as far as commercial exploitation is concerned.

Nektonic communities of the epipelagial are characterized by well balanced trophic cycles. The trophic links of the epipelagic fishes, especially in tropical regions, are highly complex. This results in a very dispersed distribution of fish in the epipelagial. In the less well-balanced communities of high and temperate latitudes, epipelagic fish form dense feeding aggregations, although much smaller than the concentrations of pelagic fish over the shelf.

The epipelagic ichthyofauna is not as varied as that of shelf waters or even that of the deep ocean. Epipelagic species are present in 12 out of 37 elasmobranch families (sharks and rays) and in only 59 out of over 400 teleost (bony fish) families. Of the approximately 400 fish species found in the epipelagic only about 150 are endemic to the biotope. By contrast the neritic zone contains thousands of teleost species and approximately 500 elasmobranch species. The relative variety of the nekton in the neritic, deep ocean, and epipelagic biotopes is approximated in Table 28.

The epipelagial is characterized by a predominance of phylogenetically young fish and the virtual absence of ancient groups. This suggests a rather recent origin of the epipelagic ichthyofauna, being younger than either the neritic or deep ocean groups. The principal source for formation of the epipelagic ichthyofauna is the neritic ichthyofauna; however, a few have originated from deep ocean ancestry.

True epipelagic species, e.g., sauries, tunas, and marlins, have pelagic (or floating) eggs and spawn in the open ocean hundreds to thousands of miles from shore. Fecundity and mortality in early developmental

Table 28

Relative Abundance of Nektonic Groups in Different Biotopes

Group	Biotope		
	Neritic	Deep Ocean	Epipelagic
Families	200	100	20
Species	Thousands	Hundreds	Tens

From: Moiseev, 1971.

stages are extremely high among epipelagic fishes. Embryonic development is completed in a short time. The number of species spawning in the open ocean is small in comparison to those species depending on or spawning in the shelf waters or neritic zone. Only a very few commercially exploited fish species spend their entire life in the open ocean, e.g., several tunas, sailfish, swordfish, flying fish, sauries, and some squid.

Epipelagic nekton may be classified according to their time of occurrence in the epipelagial:

- Holoepipelagic - nekton inhabiting the epipelagic throughout an entire life cycle.
- Meroepipelagic - nekton spending only a portion of time in the epipelagial, and which can be further subdivided into:
  - Epheboepipelagic - only adult stages inhabiting the epipelagic.
  - Brephoepipelagic - early development occurring in the epipelagic.
  - Nyctoepipelagic - occupying the epipelagic zone during nocturnal migrations from depths to the surface.
- Xenoepipelagic - a special group of nekton that normally do not constitute part of the epipelagial but rather form isolated pseudopopulations whose individuals are incapable of completing their life cycles in the epipelagic zone.

Most fish of the neritic zone never pass into the waters of the epipelagic. Similarly most epipelagic fish do not enter neritic waters. However, mutual invasions between the epipelagic and neritic nekton do occur. Either on a regular or fortuitous basis the migrations are always carried out by specific species of the interfacing ichthyocenes.

Fish typical of the epipelagic, but which also frequent neritic waters especially near islands include the skipjack tuna (Euthynnus pelamis) (Waldron, 1963). Many epipelagic sharks are also common in neritic waters. Other tuna, especially Thunnus albacares, go through a period of their life cycle in the pelagial over the shelf. In the tropical Atlantic, small individuals of this species aggregate in considerable concentrations off the coasts of Africa and America in the region of the 200-metre isobath (Zharov and Torin, 1964).

Larvae and fingerlings of neritic fish, including some demersal fish with pelagic stages of development are transported passively into the epipelagic zone of the open ocean. The capacity of these young for existing in the conditions of the epipelagial varies greatly among species. However, Parin (1968) believes these larvae and fingerlings die off in large numbers, thus removed from the specific conditions of the neritic and unable to withstand a prolonged stay in the open ocean.

Also passively transported into the epipelagial during early development and at later stages are the poorly swimming fish of the tropical shallows such as: porcupine fish (Diodontidae), trunk fish (Ostraciidae), and trigger fish (Balistidae). Usually foragers among the reefs, these species apparently change their diet while part of the epipelagial and thus become primarily planktophages. Similarly epipelagics that enter coastal waters also switch to food uncharacteristic to the epipelagic zone. In shallow water, tuna and swordfish often feed on bottom and demersal fishes, sometimes even consuming the benthos.

Trophically the epipelagic nekton are planktophages and predators. Selectivity of feeding does not predominate as most fish have a broad range of food, consuming any accessible food items of convenient size. Very few species (e.g., flying fish and sauries) feed on plankton alone, predation being more prevalent. Fish populating deeper layers of the pelagial play an essential role in the feeding of many epipelagic predators. Active migration allows the nekton to change location at will, thereby finding optimum conditions for reproduction and feeding and somehow guaranteeing energy gains for the migrants. Thus the vertical and horizontal migrations of the nekton are significant influences on the process of redistributing organic matter in the ocean.

Migrations to lower horizons of the epipelagic (i.e., lower portion of the isothermic surface layer and into the upper part of the thermocline) are regularly performed by many predatory fish of the epipelagic, e.g., tunas, swordfish, marlins. During these migrations they come into contact with populations of the mesopelagic, feeding directly on species of the families Chiasmodontidae, Paralepididae, Caulolepidae, and others.

Due to the complex relationships between meso- and epipelagic ichthyocenes at the lower boundary of the upper mixed layer, it is difficult to assign some species to either group. Lancetfishes (Alepisauridae), oarfishes (Regalecidae), and ribbonfishes (Trachipteridae) are neither true epipelagic nor true mesopelagic groups. While lancetfish are usually considered a deepwater group. i.e., mesopelagic, they are a common catch in the oceanic setline fishery (Rass, 1959).

Nocturnal migrations into the upper layer by subsurface lantern fishes (Myctophum, Symbolophorus, and Centrobranchus) occur regularly, thus precluding their classification into either epipelagic or mesopelagic proper, as they occur in both to an equal degree.

True mesopelagic and even bathypelagic species sometimes penetrate the epipelagic, however these migrations are not regular. As an example, the early developmental stages of some deepwater fish, e.g., the anglerfish (Ceratioidei) occur in the epipelagic as the species alters their depth of habitat in the course of ontogenetic vertical migrations.

Mesopelagic Nekton. Mesopelagic nekton is distributed during daylight hours between the depths of 200 and 1000 m. Accordingly this biotope begins over the continental slope and extends throughout the open ocean.

However, depth limitations usually preclude the appearance of mesopelagic forms in neritic waters in spite of the fact that many mesopelagic fish make diurnal migrations to the near surface waters at night.

Lower mesopelagic fish include the families Gonostomatidae (lightfishes), Chauliodontidae (viperfishes), Bathylagidae (deepsea smelts), and some Myctophidae (lanternfishes). These fish rarely penetrate the halocline and thus do not migrate into the epipelagic at night. Upper mesopelagic fish occur regularly above 200 metres at night and are comprised primarily of myctophids (Pearcy, 1964). Lanternfish ascend regularly through the halocline and thermocline and are an important food source for some epipelagic fish. Vertical migration is largely confined to mesopelagic (and epipelagic) species as the deep scattering layer is rarely observed below 700 metres (Marshall, 1971).

Species composition of the mesopelagic nekton apparently does not change seasonally. Yet seasonal changes in relative abundance of the dominant fish are indicated by large catches during the summer and smaller catches at other times (Pearcy, 1964).

There is no direct exploitation of mesopelagic fishes by man nor is exploitation likely to increase in the future. The ecological importance of this group lies in their utilization as a food source by epipelagic species and the maintenance or enhancement of energy flow in the surface layers of the ocean.

<u>Nekton of the Deep Ocean</u>. Fishes of the deep sea show a greater variety of species than is found in the epipelagic or mesopelagic zones (Table 28). Rass (1959) considers 72 families to have representatives in the deep sea, e.g., Macrouridae (grenadiers), Myctophidae (lanternfishes), Stomiatidae, and Alepocephalidae. Secondary deep-sea fishes are represented in 30 additional families; e.g., Liparidae, Zoarcidae (eelpouts), and Brotulidae (=Ophidiidae: cusk-eels and brotulas).

The deep-sea fauna is rich in tropical latitudes, but the number of species is reduced in high latitudes where the secondary deep-sea fauna predominate. Biomass also exhibits some variation with latitude. Increases are noted from tropical to northern temperate waters; however, nektonic biomass is never abundant at depths exceeding 1000-1500 m.

Fish of the deep ocean, as well as mesopelagic fish, tend to be smaller than epipelagic or benthonic representatives. Because of the scarcity of food in the bathypelagic and abyssopelagic zones, the principle of large predator-small prey does not hold. As good example, the viperfish, Chauliodus sloanei, can engulf prey larger than itself by opening its mouth and distending its stomach. Various other degrees of specialization make these fishes well adapted to the rigors of deep ocean life. Besides luminescent organs along the body, which are common to many species, some have luminescent organs on their barbels, which may act as lures for attracting prey.

Most common of the bottom living fishes in the deep ocean are the rat-tails (family Macrouridae) (Idyll, 1964). Macrourids usually live in close association with the bottom, plowing through the ooze to feed on crabs, shrimps, many other crustaceans, sea squirts, sponges, and foraminiferans. They also have been recovered from midwater where their food includes pelagic organisms such as euphausiids, prawns, copepods, lanternfish, and even other macrourids.

Young macrourids live in shallower water than adults. Seeking great depths as they mature, they retain the ability to swim upward at will. They have well-developed swim bladders to assist in the vertical migrations.

Next to the macrourids, fishes of the family Brotulidae (=Ophidiidae) are the most numerous in the deep sea. Brotulids are among the most successful of all fishes in adapting to a variety of habitats. Most species inhabit the deep ocean although a considerable number of species are found in shallow waters up into the intertidal zone. There are even a few freshwater cave-dwelling species in the West Indies (Idyll, 1964).

Unlike many other deep ocean animals, young brotulids apparently develop at approximately the same depth as where the adults live instead of higher in the water column. With the exception of eye development, brotulids are morphologically similar to the macrourids, yet the two families are not closely related. Macrourids are relatives of the cods. Brotulids are closer relatives to the live-bearing blennies of shallow water, and as a result many species bear their young alive. Some brotulids, however, lay eggs like most fish.

Other fish of less numerical significance in the deep ocean include the ray fins (subfamily Sudidae), chimaeras, and some eels.

Like nekton of the mesopelagial, no deep ocean species are utilized in any existing fishery. Moreover, Moiseev (1971) contends that the ocean depths show virtually no promise whatsoever for contributing to the future marine harvest because of the low concentration and dispersed nature of the deep ocean biomass.

Invertebrate Nekton. Two main invertebrate groups, the cephalopod mollusks (squid and octopi) and crustaceans (decapod and mysidacean shrimps) are strong enough swimmers in the adult stages to move independently of currents and thus form a part of the nekton at various depth levels above the continental rise and abyss. Many of the nektonic invertebrates, pass through planktonic developmental stages. In some cases, long-distance migrations occur for reproductive or feeding purposes. In the case of midwater or bathypelagic species, these migrations are vertical toward shallower water at night.

The distribution of open-ocean invertebrate nekton is mainly limited by barriers of temperature and food, although these barriers are not as apparent and have not been as completely investigated as in the case of the benthos and the plankton, especially for deep-sea species. As in the case of the benthos, the numbers of species and the quantity of pelagic organisms are inversely proportional to depth. All nekton living in the deeper zones below the epipelagic are ultimately dependent on production in the waters above.

Most of the invertebrate nekton species over the deep ocean areas are relatively sparse in abundance, especially in the bathypelagic areas. The bright red shrimps of the bathypelagic zone, primarily caridean and mysidacean shrimps, although large in size, are not abundant enough or live too deep to be economically feasible for commercial harvest, and thus are not fished commercially and probably will not be in the future.

Benthic Life

An exponential decrease in the density and biomass of benthic organisms occurs between the shallower continental shelf environments and the deeper continental rise and abyssal zones. The patterns of abundance, however, found on the continental shelf, remain consistent in the abyssal zones. Biomass is higher in the Pacific than in the Atlantic and lowest in the Gulf.

Griggs et al. (1969) give values of 5.57 g/m^2 for the continental rise, 0.98 g/m^2 for the abyssal zones, and 2.2 g/m^2 for the Cascadia Channel off the coast of Washington and Oregon. The Cascadia Channel traps organic rich sediment from the mainland and, despite the fact that it lies deeper than the abyssal plains to either side of it, has a benthic animal population four times that of the abyssal zones.

Thiel (1975) lists abyssal zone (4350 m depth) values off the California coast of 3.5 g/m^2. These are all consistently higher than data given for the Atlantic. Rowe et al. (1974) give values of 0.2 to 1.5 g/m^2

for the continental rise off the Massachusetts coast, and 0.2 g/m^2 for the abyssal zone. Thiel (1975) cites a value of 1.8 g/m^2 for rise and 0.7 g/m^2 for the abyss off North Carolina.

Rowe et al. (1974) give values for the Eastern Gulf of Mexico continental rise of 0.06 g/m^2 and 0.03 g/m^2 for the abyssal zone. For the Western Gulf abyssal zone, 0.08 to 0.15 g/m^2 would indicate slightly higher benthic productivity than in the Eastern Gulf, while still less than in the Atlantic or Pacific.

Thiel quotes a figure of 0.2 g/m^2 as an average value for abyssal zones. If all the bacteria, the meiofauna, the macrofauna, and fish in an area the size of six king-size beds were carefully collected, the total biomass would hardly fill a teaspoon. The diversity within this spoonful is quite high, however, because of the necessity for the organisms present to partition the scarce food resources present in the abyssal zones.

C. ECOSYSTEM DYNAMICS

As discussed earlier, marine communities consist of aggregations of living organisms (plankton, neuston, nekton, and benthos) linked together through the exchange of matter and energy in the food chains and food webs of the sea. Such aggregations live and operate within prescribed physicochemical environments, to which they are evolutionarily adapted and with which they also exchange materials and energy. In classical ecology, the organisms together with their environment constitute an ecosystem. This basic notion also holds true for the sea, but the problem in the marine environment is that there are no barriers, and in a very real sense all the world's oceans represent one grand ecosystem. Therefore, for practical purposes, in the present discussion, it is desirable to consider only a single section of the ocean, one which may be thought of as ten to twenty miles wide and extending across the outer continental shelf and into the abyss.

THE WATER SECTION AS AN ECOLOGICAL UNIT

The section under consideration is conceptually divided into three zones, the shelf, slope, and rise/abyss. Vertically, it is also divided into three units, the euphotic, aphotic, and benthic environments. These nine parcels of water form the functional ecological unit, since all the basic processes of any portion of the greater marine ecosystem occur in this ocean section.

EXCHANGE PROCESSES

Within the section, waters of the three zones are in physical continuity with one another, horizontally and vertically. Exchange takes place within the section. However, the section is also in continuity with adjacent sections, and exchange also takes place with these bodies of water. As the water masses move into and out of a section, they transport chemical materials as well as living organisms. These processes are shown diagrammatically in Figure 47.

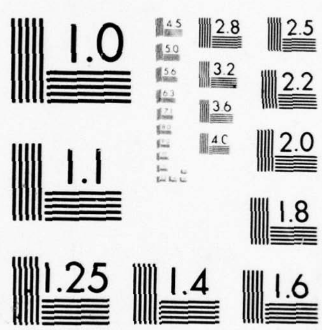
RESIDENCE VS. TRANSIENCE OF SPECIES

Planktonic organisms are carried passively by water currents. Hence, they are swept into and out of the area with the water masses. However, since planktonic species typically exhibit rapid reproductive response to favorable environmental conditions, those species that find a particular zone especially favorable are able to maintain resident populations, even though many individuals do get swept away by the current.

Nektonic species are free-swimming and are capable of maintaining themselves in an area despite the currents or of migrating to more favorable areas. It seems likely that some nektonic species inhabit each of the zones as year-round residents, but little direct information on this point exists. However, a great deal of information points to

AD-A053 183 TERECO CORP COLLEGE STATION TX F/G 13/2
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)
JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL DACW39-76-C-0125
UNCLASSIFIED WES-TR-D-78-2 NL

5 OF 7
AD
A053183



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

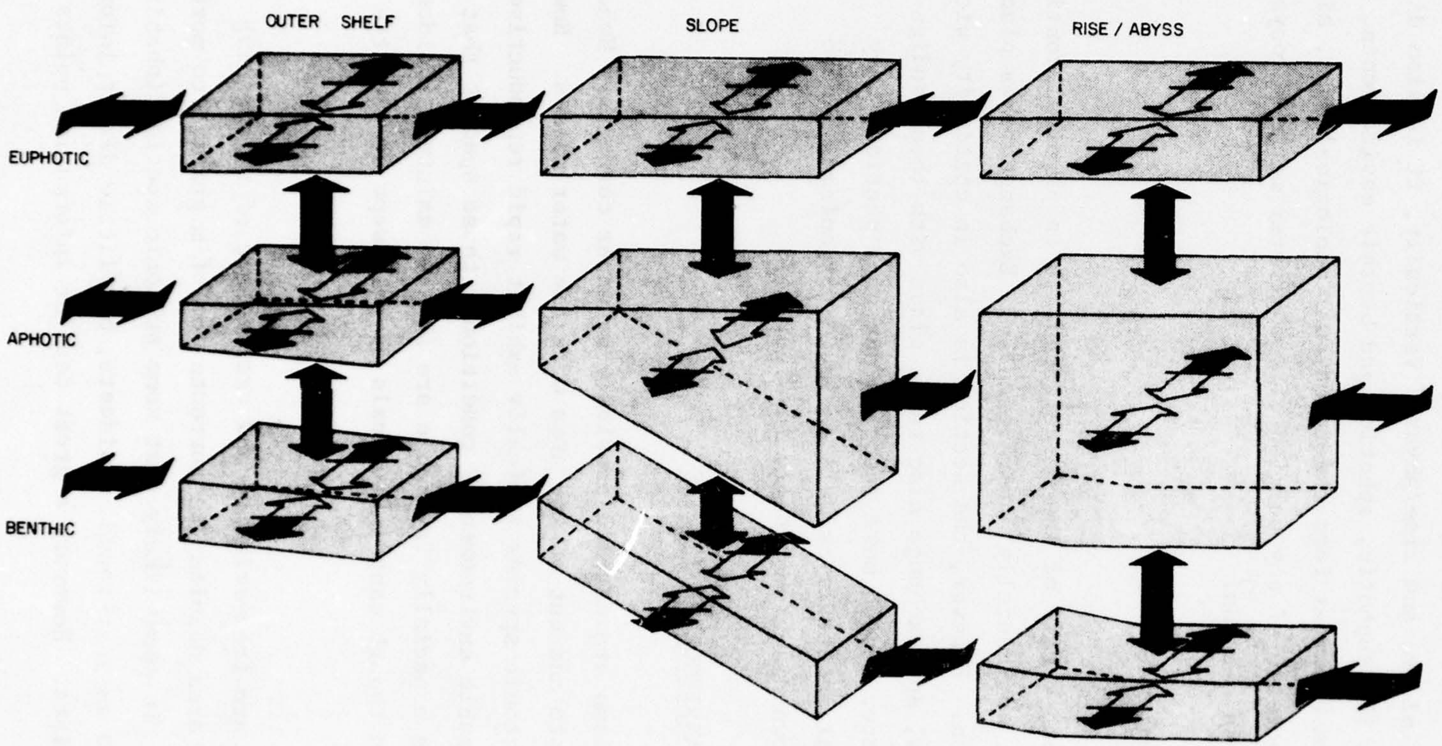


Figure 47. Model of a single section of ocean water to show exchange processes. The model is conceptually divided into component parcels to show that processes may take place within the section as well as between the section and adjacent water masses.

the fact that many of the predatory species are seasonal transients in the area, appearing primarily during the warmer months. These include the billfishes, tunas, dolphins, wahoos, jackfishes, mackerels, and other highly mobile forms.

Benthic and near-bottom species must be primarily, if not exclusively, resident. Their ability to populate other areas rests largely in the production and transport of planktonic larvae.

The open nature of the marine systems is, thus, reflected in the plankton, and to some extent, the benthic species. In all three instances, however, there is apparently a resident group of species that constitutes the true local biota. The percentage of true resident species likely increases with depth, reaching its maximum in the benthic inhabitants.

INTERNAL DYNAMICS: PRODUCTION, CONSUMPTION, AND DECOMPOSITION

Biological production involves the creation of living organic matter through photosynthesis (primary production) or through consumption of pre-existing organic matter (secondary production). In all the zones of the section, as elsewhere in the world oceans, primary production is limited to the euphotic zone. Such material may then be consumed locally, transported out of the area horizontally, or transported to deeper layers of the system. In addition, organic matter produced elsewhere (especially on the nearshore shelf) may be imported into the system.

Consumer species are found at all levels of the water column as well as on the bottom. Those species inhabiting the euphotic zone may utilize locally produced or imported food resources, but those inhabiting the aphotic and benthic areas are dependent entirely upon production that comes from the upper layers or from outside the system.

Decomposition of non-living organic matter (corpses of dead organisms, fecal material, shed exoskeletons, secretions, etc.) takes place primarily through the action of bacteria, fungi, and protozoans. Such microbes themselves become food for larger consumer species that feed upon decomposing organic matter (organic detritus). Although likely of some importance as a food source for consumer species in the euphotic zone, organic detritus assumes a prominent role in aphotic waters, and it must be the chief food resource in the benthic environment. The rate of decomposition is inversely proportional to the temperature. Therefore, microbial action is greatly retarded in the chilly environment of the aphotic zone, and organic matter imported from above must have quite a long residence time, especially in the benthic sediments.

INTERNAL DYNAMICS: VERTICAL AND HORIZONTAL TRANSPORT

Transport of nutrients and organisms involves the displacement of materials from one area to another. It may take place by a variety of means. Horizontal transport may involve the passive movement of dissolved and suspended matter by wind or water currents, or it may entail active swimming by nektonic species.

Vertical water currents may transport dissolved and suspended materials upward (through upwelling) or downward (through water mass sinking). Materials may also be transported upward by gravitational floating (if particles become less dense than water, as through the incorporation of gas bubbles in the carcasses of dead organisms) or by gravitational sinking of dense particles and dead organisms. In addition, vertical migrations of animals in the water column are known to occur on daily and seasonal bases, and large amounts of organic matter may be transported by this means. Finally, it may be noted that some benthic organisms may pass portions of their life cycles in the water column.

SYSTEM COORDINATION AND REGULATION

Ecosystem processes cannot be based upon random events. Environmental signals, however subtle, serve as cues to initiate biological activities, insuring simultaneous response of different members of the same species and coordinating simultaneous and sequential activities of different species in the system. In all ecosystems so far studied, the general signals are provided by the physical environment, and specific recognition cues are provided by individuals in each species. The former often relate to seasonal and daily weather phenomena, and the latter may be based upon visual display, behavior pattern, sound or light production, release of specific chemical cues, and the like.

Very little is known about the signals and communication devices in the life histories of most organisms on the outer shelf, slope, and abyssal environments. On the outer shelf and within the euphotic layer, such factors as light, seasonal storms, and other well-known atmospheric phenomena supply the primary information required. Although such information becomes subdued with depth, at least some of the seasonally induced changes of the surface waters must reach the bottom in "coded" form. Slight modifications of currents, nutrients, or sediments from above may supply the information needed to trigger breeding, spawning, release of larvae, feeding, etc. Individual species recognition may be accomplished through photophores, specific chemicals (taste and odor), sound and other vibrations, and touch. These modifications or adaptations are only hints at what must be a very complex and sensitive communication system in the deeper waters of the slope and abyssal environments.

GEOGRAPHIC VARIATION

On a broad geographic basis, the marine coastal environments change in relation to latitude and longitude. Patterns of solar radiation, climatic conditions, and oceanic circulation impress upon the coastal waters a general regional differentiation. Within each region the submarine topography, river influence, water mass characteristics, and available sedimentary material may play major roles. As a result of the interplay of these factors, the waters bordering each section of the coastline are characterized by their own locally peculiar combination of factors involving temperature, salinity, and circulation patterns, chemical make-up, and bottom types.

In response to these regionally different environments, biological communities vary in composition on a geographic basis. From sector to sector the variation may be slight, but along a large stretch of coastline the changes are of sufficient magnitude to permit the delineation of rather distinct faunal assemblages, especially among the benthic species (Defenbaugh, 1976). Whereas many of the faunal changes are gradual, abrupt community changes are observed in certain areas where the environment shifts sharply. Cape Cod, Cape Hatteras, and the southern tip of Florida, for example, all constitute rather sharp faunal barriers.

Coastwise geographic variability in biological communities is most pronounced on the continental shelf and least evident in the deeper waters, where geographic and seasonal changes in the environment are much less pronounced. Accordingly, on the continental shelf, individual species tend to have more restricted distributional ranges, whereas in the abyss, many of the species are worldwide in distribution. Those of the slope tend to be intermediate in distributional range.

D. CHAPTER SUMMARY

In the present chapter the environments and the biological components of the marine ecosystem have been analyzed in terms of their potential as sites for the disposal of dredged material. Two perspectives have been developed: the examination of onshore-offshore trends and the analysis by zones.

From either perspective the environment of the continental shelf appears highly variable, and the hydrographic regimes, which are influenced by a variety of factors, are relatively unpredictable. Biological diversity and production and the human harvest of fishery resources are all far higher on the continental shelf than elsewhere in the sea. The inner shelf zone, in close proximity to civilization and utilized by society for many purposes including food harvest, is not a preferred candidate for disposal of contaminated dredged material.

The continental slope zone is environmentally less variable and biologically less diverse and productive than the continental shelf. It is further removed from civilization, and it is less utilized in the harvest of food resources. However, water masses of the upper slope may move onto the shelf and influence the shelf environment. Furthermore, some harvest of living resources of the slope does currently take place, and the potential for increased harvest clearly exists.

The environment of the continental rise and abyssal plain is, for all practical purposes, constant. Deep oceanic water generally does not affect the continental shelf environment (with the partial exception of some upwelling areas). The bottom of the sea is extensive, occupying over three-quarters of the surface of the earth, and it is far removed from the surface layers. The dilution capacity of this large volume of water is very great. Due to density stratification of the water column and long residence time of the bottom waters, any materials entering the abyssal environment will be effectively locked away from civilization for hundreds, perhaps thousands of years. Biological diversity and production of surface, intermediate, and bottom water is extremely low. Although benthic diversity may be locally high, the species tend to be of very widespread distribution, and damage to the local populations cannot be considered to be of major import. Although some fishery harvest does take place in the deep oceans, this activity is limited to certain specific geographic areas and all of it takes place in the upper hundred meters of the water column.

For all these reasons, the continental slope, continental rise, and abyssal plain stand out as the logical environment to receive extensive quantities of dredged material, even if such materials contain fairly high levels of toxic constituents.

PART 5. REGIONAL ASSESSMENT OF DEEP OCEAN DISPOSAL RECEIVING ENVIRONMENTS

A. INTRODUCTION

NEED FOR REGIONAL ORGANIZATION

The coastlines of the United States differ markedly in appearance along a circuit of the coastal perimeter from Maine southward around Florida to the Texas-Mexico border and thence from southern California to Puget Sound and on to the Gulf of Alaska. During a flying trip following this route one could easily see certain geomorphic differences from the rocky shores of Maine along the drowned river mouths and broad shelves of the mid-Atlantic, narrowing from Cape Hatteras to a mere strip of a shelf off Miami, broadening again as a wide carbonate shelf off Tampa, to the great Mississippi delta and the expansive muddy shelves off western Louisiana and much of Texas. At times along this flying course one might see differences in coloration of the circulating waters, giving some clues as to their origins and differences. But it is what an observer can not see from the air that both requires and permits this section of the report to be organized on a regional basis. Suffice it to say that above and beyond the geomorphic there are major regional differences (1) in currents and water circulation, both inshore and well offshore, (2) in the nature of the bottom of the receiving environments for dredged material, and (3) in the pelagic and benthic communities, including the fisheries. Moreover, it is soon apparent to anyone delving into the dredging-disposal problem that there are marked regional differences in dredging needs and in the ease with which solutions, at least for now, can be found to the problem of disposing of the dredged material.

In summary, then, it is apparent that the receiving environments have regional characteristics, not only along the shore and in shallow water but also, albeit to a somewhat lesser extent, in the deep ocean. The following sections provide a synthesis of these regional similarities and differences.

APPROACH TO THE SOLUTION

There is a remarkable concurrence among the geographic limits that have been arrived at independently and, indeed, at different times by various authors for the establishment of

1) Geomorphic Regions
2) Circulation Regimes
3) Biological Provinces

Circulation regimes, constituted of water masses and currents, are fundamental determiners of the other two, but circulation is in turn clearly affected by visible and submarine geomorphics. Thus, there are geometric constraints to circulation provided by the topography of the continental margin. As Mooers (1976) has pointed out, all anomalies in bottom and coastline topography have an influence on the circulation. Of interest here is the outer shelf circulation regime and beyond, and the influence this has on the distribution of organisms in the biological provinces. Also, this is generally a region of strong density stratification, implying considerable differences in temperature and salinity, which controls the survivability of adult marine organisms and their larvae. Frequently the outer shelf-upper slope regime is very much influenced by the adjacent general oceanic circulation. If so, a major boundary current (e.g., the Gulf Stream) is generally present. These powerful boundary currents, especially on the eastern continental boundaries, can and usually do induce a steady circulation in the slope and outer shelf regimes.

It is productive to tabulate these three diverse entities (geomorphic, physical oceanographic, and biologic) in a single display (Table 5), which indicates not only fundamental interrelationships but also a certain internal constancy. Mooers (1976) noted that the concept of a regional circulation regime implies some continuity of flow within the regional regime and some separation from "or only partial coupling" with contiguous regional regimes. As is often the case, two adjacent circulation regimes are separated by a prominent geologic feature, such as Cape Hatteras, with which they interact. Essentially the same statement can be made in regard to the biological provinces, viz., there is a considerable regularity of occurrence of marine organisms within a biological province (assuming sampling in similar habitats). However, there should be considerable differences among a given province and the adjacent ones on each side of it. Occasionally two widely separated biological provinces can have very similar faunas. For instance, the Louisianian of the northern Gulf of Mexico shares many species with the Carolinian of the South Atlantic Bight. As a result, Hedgpeth (1953) considered them to be the same, making peninsular Florida fall into the Caribbean Province. There are then unifying factors operating within these geomorphic-oceanographic complexes that once comprehended will permit one to understand the basic workings of the marine system off his coast no matter where he lives. In a word what is being dealt with is that dimensionless term "ecosystem."

All of the units can be considered to be ecosystems whose frameworks are basically the same but whose specific building blocks are different. Stressing differences, however, can be overdone: it is essential to understand that for all of their complexity the oceans surrounding the North American continent have sufficient regularity of components that what deep ocean disposal of dredged material will do in one place, it will tend to do (or not do) in another. There are certainly more common factors than differences, a fact that makes it reasonable to predict the effects from known causes. Accordingly, and this is the essential point to grasp, no matter how different offshore waters may appear to be from one region to another, the important factors controlling the behavior of dredged material dropped in deep water will not differ in kind but only in degree from place to place.

SECTOR SYNTHESIS

A term is needed to pull together all of the above entities (geomorphic, oceanographic, biologic) into a coherent unit and relate all of them to the relevant Corps Districts. The term sector appears to meet this need.

DEFINITION

A sector is a part of the coastal zone, continental shelf, and contiguous slope, in this case of the United States, whose land boundaries are marked primarily by prominent capes or other geomorphic features, whose current regime differs from that of adjacent sectors, and whose biota has the status of a biogeographical province. It is also considered that a sector includes the encompassed Corps District and their dredging activities.

DESCRIPTION

A sector is somewhat wedge-shaped in that its landward boundaries are narrower and more clearly demarcated than its seaward boundaries. This is to be expected since the lines of demarcation between sectors can be more easily drawn in the varying coastal zone than in the more uniform and expansive environment a hundred or more miles to sea. Frequently, also, the oceanography of a sector will be controlled more by phenomena occurring on a line normal to shore than on a line parallel to shore.

RELATIONSHIP TO CORPS DISTRICTS

Most sectors encompass one or more Corps Districts. The relative importance of the sector to the problems at hand is based upon three factors:

1. Volumes of dredged material generated in the sector
2. The probabilities of deep ocean disposal in the sector
3. The number of Corps Districts within the boundaries of the sector.

B. OCEAN DISPOSAL SECTORS OF THE UNITED STATES

The limits and geographic extent can be ascertained from Table 5 and Figure 8 and 48. Also, the Corps Districts in each sector will be found in Figure 49. The sectors are rank ordered below in regard to the volume of dredged material generated. Each is numbered in accordance with its designation in the above figures.

GULF COAST (Sectors 4 and 5)

	Projected average annual volume for 1974-76*
5. Northern Gulf Sector	
New Orleans District	145,610,000 cu yd
Galveston District	70,364,000 cu yd
Mobile District	35,600,000 cu yd
4. Peninsular Florida	
Jacksonville (Gulf of Mexico) District	12,807,000 cu yd

ATLANTIC COAST (Sectors 1, 2, and 3)

*From Arthur D. Little, Inc. 1974 (see also Table 1)

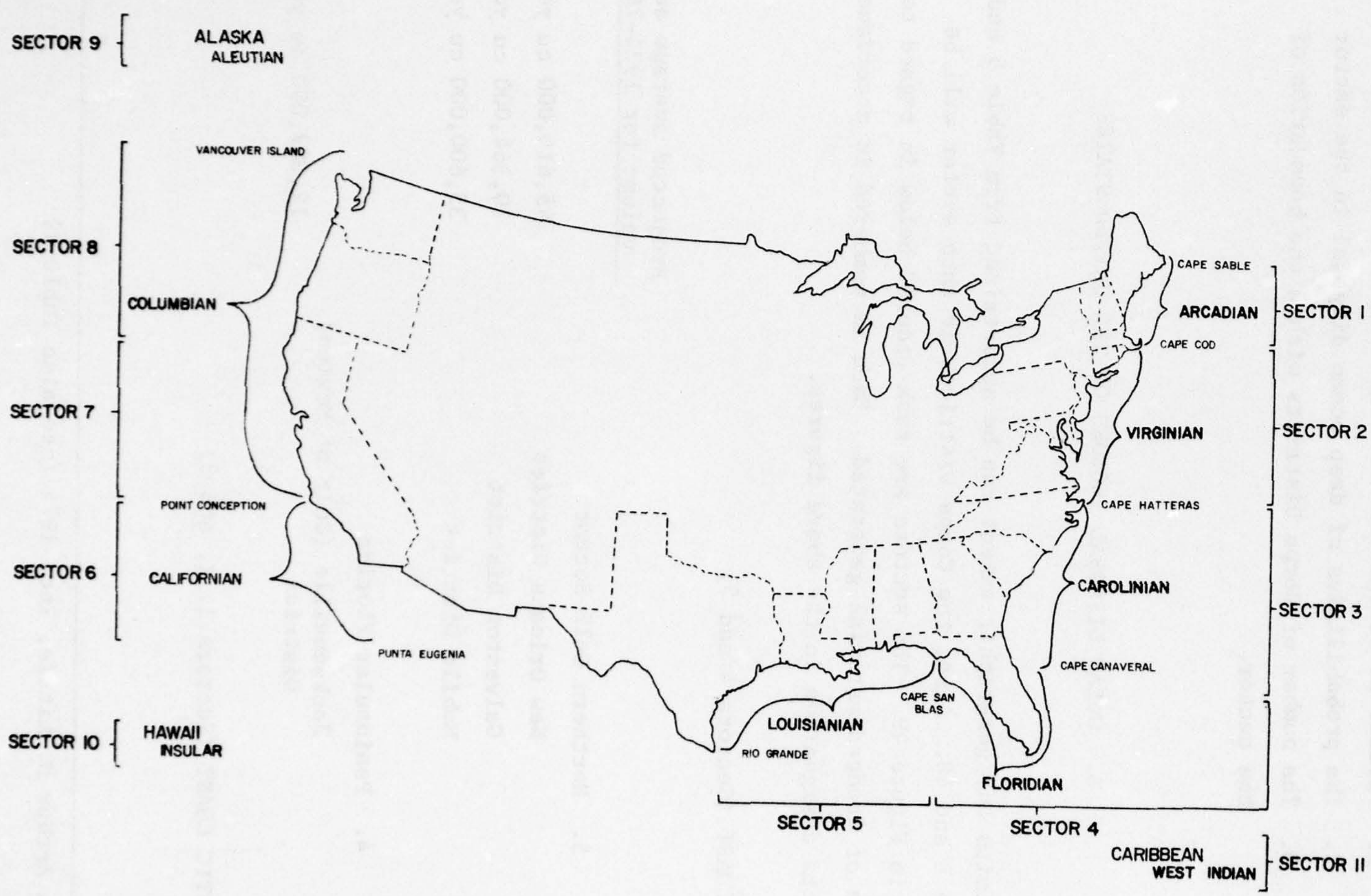


Figure 48. Sectors of the United States in relation to biological provinces.

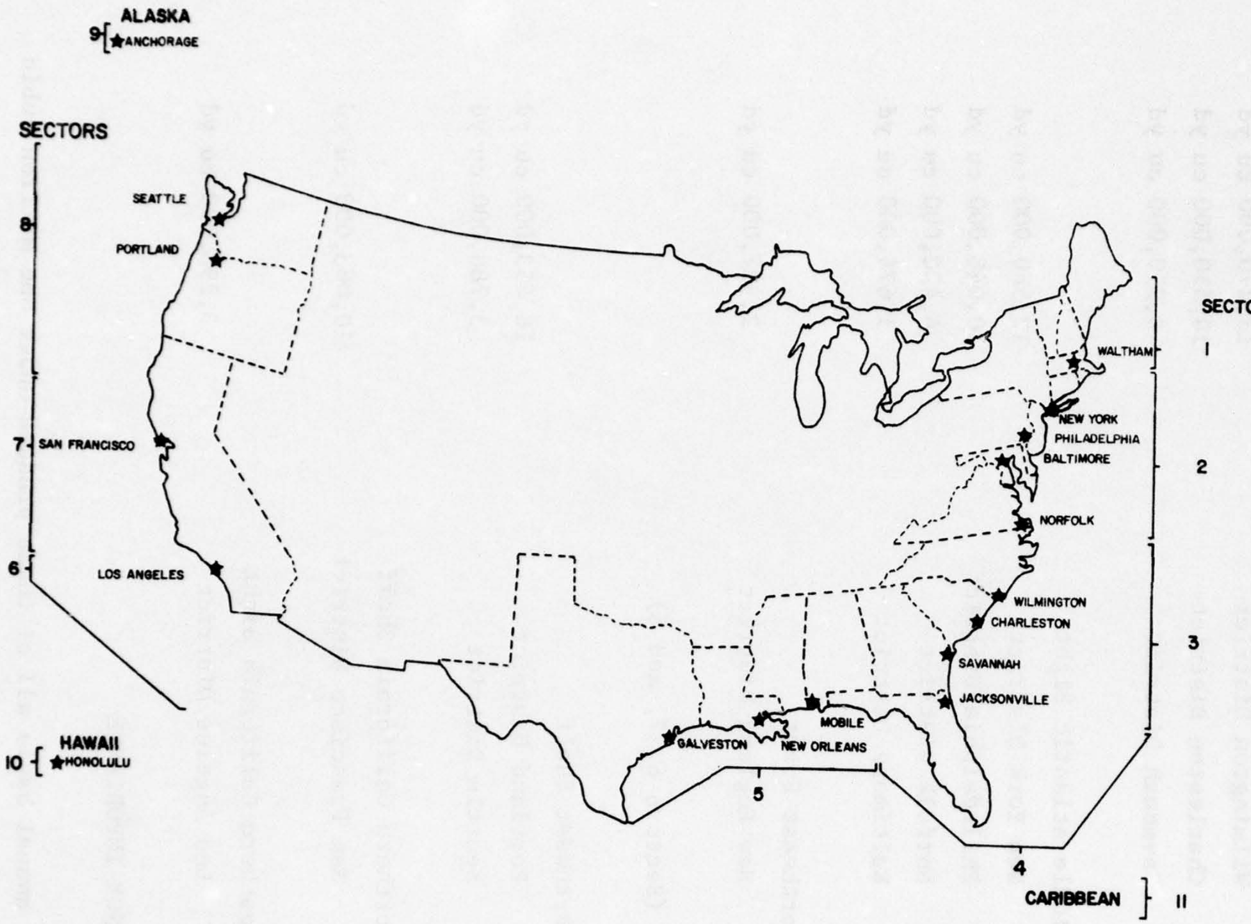


Figure 49. Sectors of the United States in relation to the Corps of Engineers Districts.

3. South Atlantic Bight	
Jacksonville (Atlantic) District)	15,298,000 cu yd
Wilmington District	13,270,000 cu yd
Charleston District	10,510,000 cu yd
Savannah District	8,990,000 cu yd
2. Middle Atlantic Bight	
New York District	12,560,000 cu yd
Philadelphia District	10,048,000 cu yd
Norfolk District	4,420,000 cu yd
Baltimore District	1,674,000 cu yd
1. Northeast Coast	
New England District	2,397,000 cu yd

PACIFIC COAST (Sectors 6, 7, and 8)

8. Northwest Shelf	
Portland District	16,433,000 cu yd
Seattle District	3,786,000 cu yd
7. Northern California Shelf	
San Francisco District	10,063,000 cu yd
6. Southern California Bight	
Los Angeles District	3,298,000 cu yd

SECTORS OF MINOR IMPORTANCE

On an annual basis all of these produce under one million cubic yards:

9. Alaska
10. Hawaii

11. Puerto Rico and the U.S. Virgin Islands

It should be pointed out, however, that in certain years, the Hawaiian Islands will produce well over a million cubic yards. In fact, that is true of 1977. However, some of the harbors involved only require maintenance dredging every fifth year.

C. GULF COAST (SECTORS 4 AND 5)

GEOMORPHOLOGY

GEOLOGIC NATURE OF THE GULF

The Gulf of Mexico basin is one of the world's oldest ocean basins having formed some 160 million years ago (Dietz and Holden, 1970). Those rocks that floor the basin are probably of late Pennsylvanian age (Lehner, 1969) and although the Gulf is classed as an enclosed sea, it appears to have had continuous, although for long periods restricted, connection with the world ocean. Garrison and Martin (1973) state that the Gulf of Mexico basin "... is underlain by oceanic crust... depressed substantially below the levels of equivalent crustal layers in normal ocean basins," and "has gained its present form wholly from a combination of sedimentary and intrabasin tectonic processes." Harding and Nowlin (1966) describe the Gulf of Mexico as a relatively shallow, oceanic-type basin containing no large submarine trenches or ridges.

This semi-enclosed sea is relatively small, having an approximate surface area of over 1.6 million square kilometres and a maximum depth of about 3840 metres. Its opening to the Atlantic Ocean and the Caribbean Sea is confined into two narrow passages, the Straits of Florida (less than 160 km wide and only about 500-800 m deep) and the Yucatan Channel (about 160 km wide and 1500-1900 m deep). Significant characteristics of the Gulf basin are the great width of the shelves, the steepness of the lower part of the continental slope (the scarps), and the flatness of the floor of the main basin with its exceptionally thick sequence of sediments. Those sediments of the Sigsbee Abyssal Plain are reported to be nine or so kilometres thick (W. Pequegnat et al., 1976), and their great influx since the close of the Cretaceous has considerably diminished the size of the old basin proper. During the clastic deposition in the north, the carbonate platforms of Florida and Yucatan continued their upward growth in pace with subsidence and maintained their tops near sea level (Garrison and Martin, 1973). The continental margin of the Gulf thus developed into two major provinces: (1) a southeastern region of shallow carbonate banks and (2) a northwestern region of terrigenous embankments.

Further topographic division of the Gulf of Mexico follows Ewing et al. (1958) and Uchupi (1967a), including the following physiographic provinces: The continental shelf (sub-divided into West Florida Shelf, Texas-Louisiana Shelf, East Mexico Shelf, and Campeche Shelf), the continental slope (including the Sigsbee, Florida, and Campeche escarpments), the Mississippi Fan, the continental rise, and the Sigsbee Abyssal Plain, or floor of the main basin (Figure 50). Antoine (1972) divides the Gulf into seven geologic provinces (Figure 51). For his distinction, shallow seismic reflection methods were utilized to demonstrate unique characteristics of the following provinces: (1) Gulf of Mexico Basin, (2) Northeast Gulf of Mexico, (3) South Florida Continental Shelf and Slope, (4) Campeche Bank, (5) Bay of Campeche, (6) Eastern Mexico Continental Shelf and Slope, and (7) Northern Gulf of Mexico.

CONTINENTAL MARGIN, NORTHWESTERN GULF OF MEXICO

The northern Gulf (Sector #5), at least from a structural point of view, consists of the continental shelf and slope of Texas, Louisiana, Mississippi, and Alabama. According to Ewing et al. (1968), it is

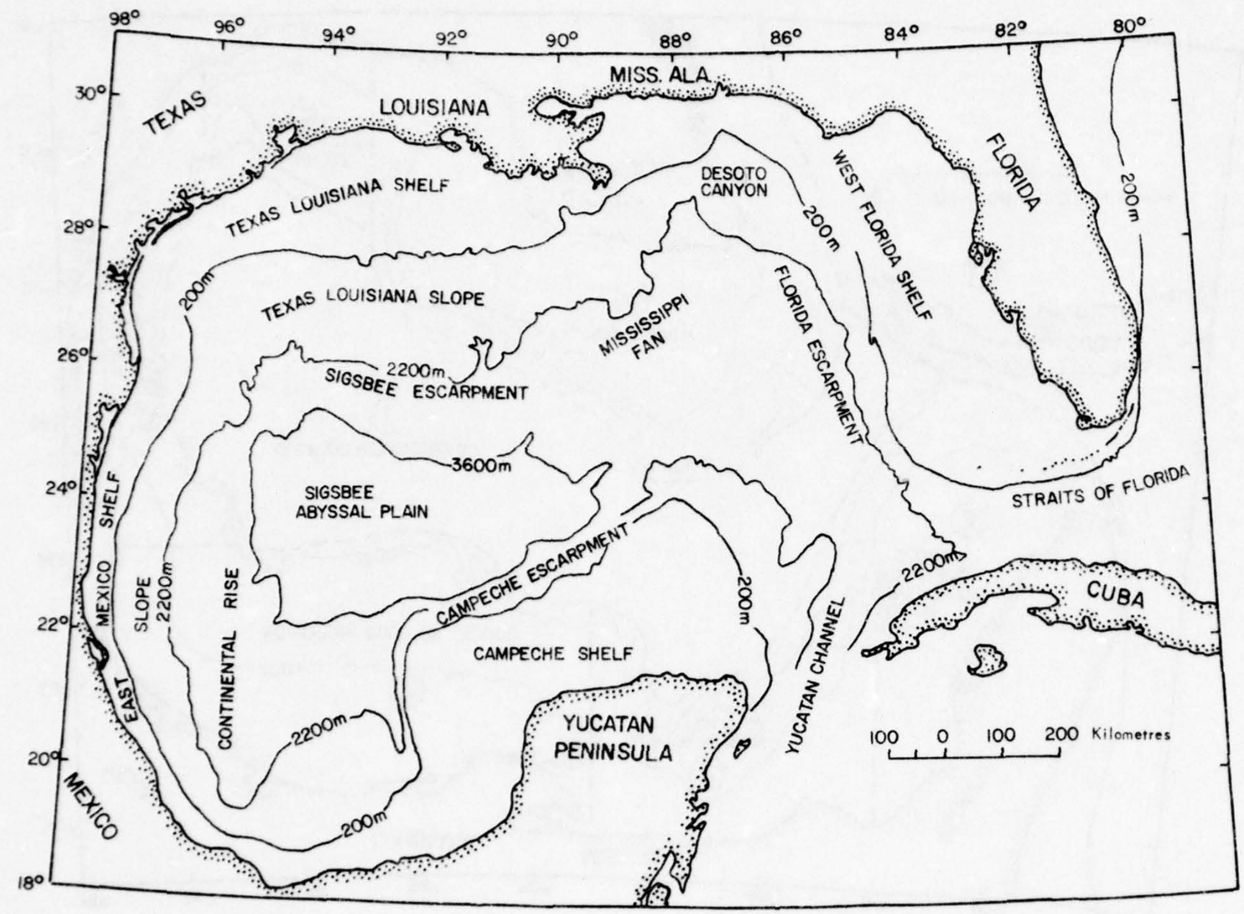


Figure 50. Topographic divisions of the Gulf of Mexico (adapted from Uchupi, 1967a).

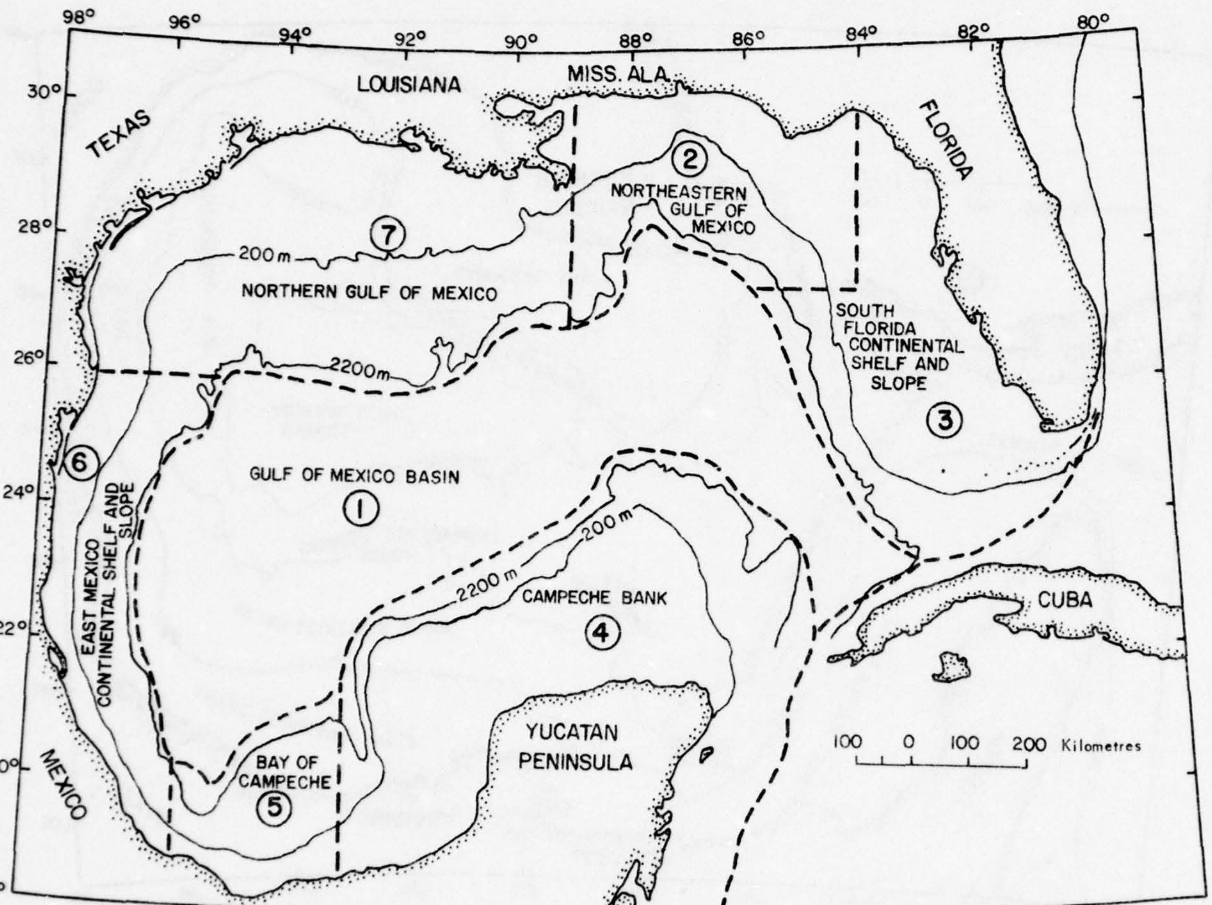


Figure 51. Geologic provinces of the Gulf of Mexico (adapted from Antoine, 1972).

bordered on the east by DeSoto Canyon, on the south and southwest by the bottom of the Sigsbee Scarp, and at the United States-Mexico border by the beginnings of the anticlinal folds that more or less parallel the shoreline. The major structural element of the continental margin is the Gulf Coast Geosyncline. This extends southwestward from Alabama toward northeastern Mexico and contains upward of 20,000 m of sediment. The geosyncline is underlain by varying thicknesses of salt, probably of latest Triassic-Jurassic age (Jux, 1961). Antoine (1972) emphasizes that the widespread salt deposit provides a dynamic sculpturing agent acting throughout the entire northern Gulf region. Deep-seated salt pillows have arched the Tertiary formations, which otherwise have a gentle southward dip; tall slender columns of salt have pierced the Tertiary beds; and evaporitic material has migrated laterally and displaced and rearranged the thick clastic deposits by processes of faulting, slumping, and local thickening or thinning of beds. The offshore area of the northwest Gulf, which includes the major portion of the geosyncline, is characterized by diapiric structures from the coastline to the Sigsbee Scarp. On the continental shelf most of these features are covered by sediments, whereas on the slope they are evident in the varied topography that Gealy (1955) aptly described as "hummocky."

The continental shelf in the northwestern Gulf ranges in width from about 100 km off the Rio Grande in Texas to more than 200 km south of the Texas-Louisiana boundary (Figure 50). Farther east, it is again narrowed by the Mississippi River Delta, whose presently active lobe almost entirely crosses the shelf southeast of New Orleans to empty directly onto the continental slope. The break in slope that marks the outer edge of the shelf is difficult to define throughout much of this region, but on the average it is at a depth of about 120 m (Curray, 1960; W. Pequegnat et al., 1976). This is the point where the bottom begins to dip gradually and then more precipitantly toward the Sigsbee Abyssal Plain. Overall, the continental shelf of the Northwest Gulf can be described as a smooth, gently sloping sediment-covered plain, interrupted by occasional hills or banks. Other subdued topographic features include stream channels and shorelines relict from times of lowered sea level and low fault scarps associated with salt structures (Ballard and Uchupi, 1970).

Curray (1960) describes the sediments on the shelf as products of marine transgression following the Wisconsin glaciation. These recent sediments are divisible primarily into nearshore sands and shelf facies muds (silty clays and clayey silts); however, extensive areas are covered by alternating sands and muds. Basal sands are exposed at the surface near the shoreline, across most of the shelf off the Rio Grande, and much of east Texas and western Louisiana, although here there tends to be more alteration of sands and muds. The shelf facies overlies the basal facies off central Texas, particularly in a band extending from Freeport to Aransas. (The importance of this sedimentary feature to the Texas shrimp fishery is discussed in a later section). Most of the sand-sized particles in the outer shelf silty clays are foraminiferans or echinoid fragments (Curray, 1960; W. Pequegnat et al., 1976) whereas glauconite is locally abundant in the relict basal sands of the outer shelf.

A feature peculiar to the shelf break in the northwest Gulf is a series of prominent banks or topographic highs rising abruptly from the generally smooth, sediment-covered bottom (Parker and Curray, 1956). Several investigators have offered explanations for their origin, dating from Shepard (1937) who suggested that these banks may be related to salt dome structures. One of the more interesting and intensively studied of the banks is the West Flower Garden, a possible element of a discontinuous arc of reefal structures occupying the Gulf's southern and western continental shelves (Edwards, 1971; Bright and Pequegnat, 1974). It and the similar East Flower Garden Bank are capped by what are considered to be the northernmost thriving tropical shallow water coral reefs on the eastern coast of North America. In the near vicinity of these prominences there are many submerged topographic highs that extend 3.5 or more metres above the surrounding bottom and crest at depths less than 180 m. The majority of these banks occur seaward of the 55-m isobath in two linear groupings. The first group forms a broad arc starting southeast of Brownsville and terminates near the Mississippi Delta; the banks are widely spaced and occur between the 45- and 85-m contours. The banks of the second group are closely packed between the 90- and 365-m isobaths and extend from 95°W longitude to the Mississippi Delta. This latter group is only the northern half of a series of banks that continue out to the 1100-m line (Carsey, 1950).

The continental slope of the northern Gulf of Mexico represents the seaward part or the growing margin of the Gulf Coast Geosyncline where geologic processes that helped to shape the basin are active today (Lehner, 1969). The dimensions of the slope off Texas and Louisiana are about the same as those of the adjacent shelf (Figure 50). The greatest slope width is about 240 km at a point south of eastern Louisiana, and its least width of 110 km is seaward of the Rio Grande, off southern Texas. The average gradient of this vast area, according to Shepard (1968), is slightly less than 1°; however, the slope is made up of two segments -- a wide upper hummocky zone with a gentle average seaward slope and the steep lower scarp, the Sigsbee Escarpment, which abuts a well-developed continental rise. Salt structures on the slope occur in a great variety of sizes and shapes, ranging from slender, rodlike forms that have pierced thousands of metres of sediment in reaching the surface, to elongate ridges that arch the overlying sediments into broad anticlines. In general, diapirs in the upper slope seem to consist of ridge-like masses having thick spines thrusting upward a kilometre or more above the main structure. Small depressions on the crests of salt structures and basins between salt spines are usually filled or partially filled with flat-lying beds possibly derived from sediment sheds off the tops of adjacent peaks.

The lower slope, in contrast, is a region about 50-75 km in width that has a smoother topography and separates the upper slope from the Sigsbee Escarpment. Even though smoother, the surface of the lower slope is uneven, consisting of pillows and shallow depressions that reach a common elevation and tend to create a terrace-like topography of broad sedimentary troughs. Such relief is the topographic expression of what appears to be a single large salt mass, the seaward face of its southern wall forming the Sigsbee Escarpment with a height in excess of 900 m.

The continental rise is a broad sedimentary apron onlapping the base of the Sigsbee Escarpment and sloping gently (about 6 m/km) to merge with the flat floor of the Sigsbee Abyssal Plain generally around the 3500-m contour. It stretches westward from the Mississippi Fan to southeast of the Rio Grande Delta where its topographic definition gradually diminishes.

The Sigsbee Plain occupies the deepest part of the Gulf basin where the abyssal floor is essentially flat, having a slope of less than 1:8000 (Uchupi, 1967a). Except for the prominence of the Sigsbee Knolls, it is featureless. The knolls stand 100-200 m above the level of the plain and are primarily clustered near its center.

Toward the Mississippi Delta, the upper slope, lower slope, and Sigsbee Escarpment merge into a relatively smooth incline known as the Mississippi Fan (or Cone). The fan laps across continental slope and continental rise and joins with the abyssal plain, thereby masking all topographic discontinuities, and covers a 160,000 km^2 area of the Gulf floor (Garrison and Martin, 1973). Its apex is the Mississippi Trough southwest of the delta front, from which point the fan trends southeast for more than 600 km to near the southwestern limits of the Florida platform. It can be subdivided into upper and lower fan regions on the basis of a change in slope near the 2700-m isobath, and on a corresponding change in bottom topography (Huang and Goodell, 1970). The gradient of the upper fan is about 40 m/km, but it gradually diminishes to less than 1 m/km on the outer margins of the lower fan. The upper fan is described by Huang and Goodell (1970) as being indented by digitate leveed valleys and canyons cut by transverse ridges, whereas the lower section is characteristically smooth -- a reflection of the underlying structure. The lower fan is composed of relatively flat-lying beds while, in contrast, the upper cone has many internal irregularities, probably caused by gravity sliding, folding, slumping, and possibly by diapiric salt intrusion. The Mississippi Fan has been built from voluminous quantities of sediment delivered to the Gulf by the Mississippi River since early Pleistocene times. Holeman (1968) estimates that quantity to average 310 million metric tons annually. Such quantities of deposition have caused the fan's depocenter to continuously shift basinward as the Delta has prograded gulfward.

The slope is broken in many places by ridges, knobs, canyons, troughs, and basins. In the northeastern section of the Gulf it is interrupted by DeSoto Canyon, a trough that heads near the 440-m contour and terminates near the 950-m isobath. Unlike most submarine canyons (Shepard, 1963), DeSoto Canyon has a comparatively gentle gradient, is S-shaped, and has a closed bathymetric low in its southern extremity. Harbison (1968) describes this topographic feature as being shaped by erosion, deposition, and structural highs associated with at least five domes. Geophysical data of Antoine and Bryant (1968) from the DeSoto Canyon indicate that erosion has played an important part in its development.

CONTINENTAL MARGIN, NORTHEASTERN GULF OF MEXICO

The northeastern Gulf of Mexico is a region of structural and lithologic transition. At the juncture of western clastic deposition and the eastern carbonate embankmant, it has been included in Sector #4 for the purpose of this study. The continental margin in this part of the Gulf attained its present form when outbuilding of terrigenous sediments from the northwest buried the old Cretaceous reef off northern Florida and intertongued with the later Cenozoic carbonate deposits of the west Florida platform.

On the lower continental slope, the change in lithology is marked by a broad structural valley. The northwest wall of the valley is the face of the gulfward-prograding clastic embankment and is composed of great thicknesses of unconsolidated Tertiary sediments. Martin (1972) describes the slope as relatively narrow (< 70 km), having an inclination of 2°-3° and merging imperceptibly westward into the Mississippi Fan. The southeast wall of the valley is formed by the West Florida Escarpment, which eventually is buried beneath the spreading clastic deposits to the northeast. In this region, the scarp is a smooth, steep declivity at the base of an upper slope having a width of more than 100 kilometres. The only significant feature that mars the smooth topography of the upper slope is the S-shaped DeSoto Canyon previously mentioned.

CONTINENTAL MARGIN, EASTERN GULF OF MEXICO

A profound lithologic change occurs in the continental margins of the Gulf across a line extending from DeSoto Canyon on the northeast to Campeche Canyon in the southwest. While land-derived Tertiary sediment filled the subsiding Gulf Coast Geosyncline in the northwest, carbonate sediments were accumulating on shallow shelves southeast of the line. Therefore, the principal direction of growth for the continental margin in the eastern Gulf was vertical. The resulting carbonate bank of West Florida is characterized by a steep, seaward-facing escarpment and great thicknesses of limestone and evaporites. The vast thicknesses developed as the upper surface remained essentially at sea level while the base subsided.

The surface of the West Florida Shelf is one of low relief broken only by reef structures or shoreline features associated with former periods of lower sea level. Drowned barrier spits, lagoon complexes, and small reefs are shown by Ballard and Uchupi (1970) to be grouped around the 60- and 160-m depth contours. The West Florida Escarpment forms the western boundary of the continental margin off Florida and separates the slope from the abyssal floor. The northern portion of the scarp has a smooth, steeply sloping face whereas south of 27°N latitude the face is gullied and has lesser gradient. Cores and dredged material samples recovered from the face indicate that its lower slope originated as a Lower Cretaceous reef that has subsided approximately 2.5 km since time of its origin (Antoine et al., 1967). The Florida Middle Ground, a living reef having an area of more than 750 km^2, is prominent on the shelf northwest of Tampa. Except for this evident feature, the western shelf is practically devoid of prominent relief.

The unconsolidated sediments over the west Florida Shelf are thin and discontinuous. The vast majority of this sediment veneer is biogeneous (i.e., coral debris, mollusk shells, foraminifera tests) in origin and represents various stages of decomposition or disintegration. Scattered low outcrops of limestone and chert provide a substratum for coral and sponge growth.

OCEANOGRAPHY/METEOROLOGY

CIRCULATION AND THERMAL STRUCTURE

Loop Current

The circulation in the eastern Gulf of Mexico is dominated by the Loop Current whose relative northward penetration tends to vary seasonally. An example of a well developed spring intrusion of the Loop Current is shown in Figure 52 (Austin, 1955), which depicts the surface current streamlines based upon a composite of three cruises. The major portion of the water entering through Yucatan Channel from the Caribbean Sea (at a rate of about 30 x 10^6 m^3/sec) is contained in the Loop Current, which ultimately exits through the Florida Straits (whose sill depth is about 500 m). Since the sill depth is much deeper (about 1500 m) at Yucatan Channel, some return flow of the deeper waters can occur there, but the bulk of the flow and the major current speeds occur in the upper 500 m. In the core of the current, surface speeds as high as 150 cm/sec (about 3 knots) are not uncommon, particularly for the entering Yucatan current and the exiting Florida current. Moreover, the core of the entering current tends to flow close to the western side of the straits while the exiting current tends to run close to the Cuban side of the Florida Straits, at least during times when the Loop Current has penetrated well into the Gulf as shown in Figure 52.

Typical vertical profiles of temperature and salinity on the right hand side and the left hand side of the northward moving portion of the Loop Current are shown in Figure 53 (Leipper, 1970). A typical east-west cross-section of the thermal structure in the Loop Current is shown in Figure 54 (Leipper, 1970). This is based upon bathythermograph observations whose maximum observational depth is limited to about 275 m. The Loop Current encloses a core of relatively warm Caribbean water whose salinity is higher than that of the west Gulf or continental shelf regions. The depth of the thermocline in the Loop Current is close to that of the 22°C isotherm shown as the heavy line in Figure 54. In this cross-section the northward flowing part of the Loop Current occurs in the region of the upward sloping isotherms on the west, while the southward branch of the Loop Current occurs in the region of the upward sloping isotherms on the east side. A typical east-west cross-section showing current speeds in the Loop Current are shown in Figure 55 (Nowlin and Hubertz, 1972), based upon data from a cruise in June 1966 at which time the Loop Current extended far northward into the Gulf.

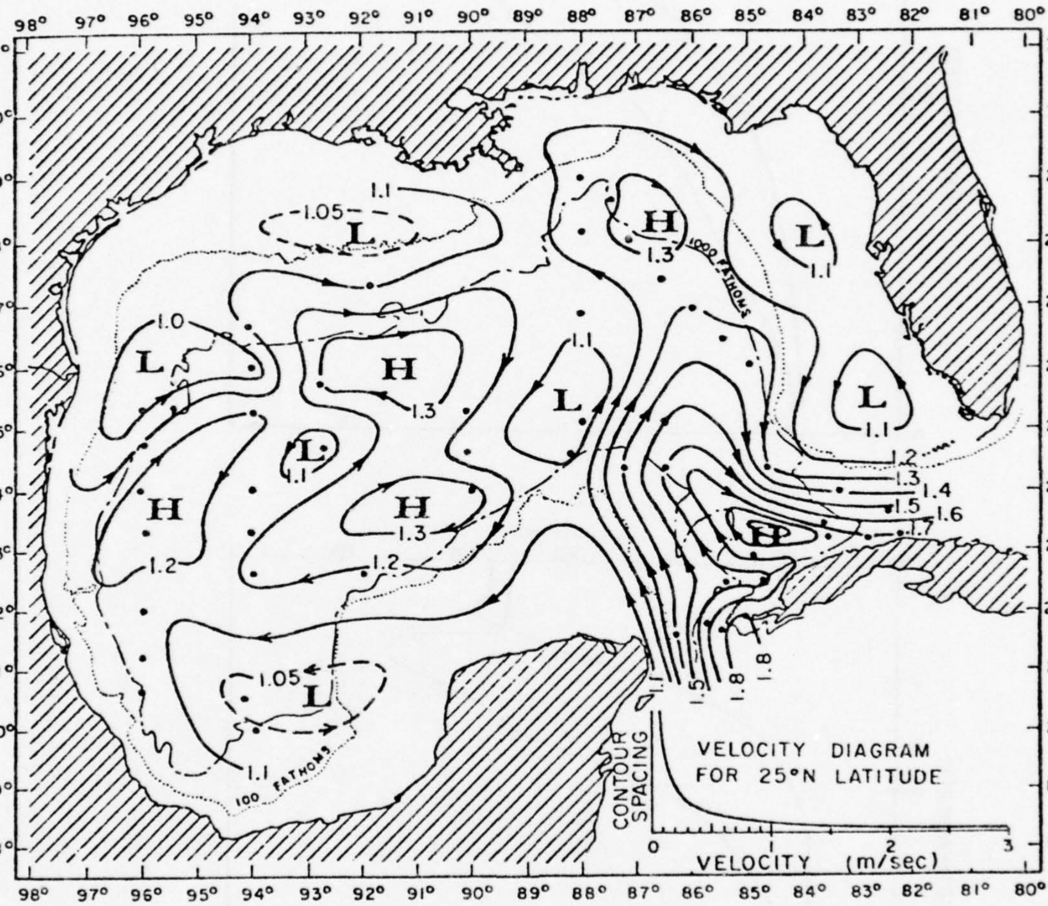


Figure 52. Dynamic topography of surface relative to 100-db surface in the Gulf of Mexico. Alaska Cruises 1-1A, 2-1B and 3-1C, 22 April-21 August, 1951. (After Austin 1955; From Nowlin, 1972). (From Contributions on the Physical Oceanography of the Gulf of Mexico, L.R.A. Capurro and Joseph L. Reid, Editors.)

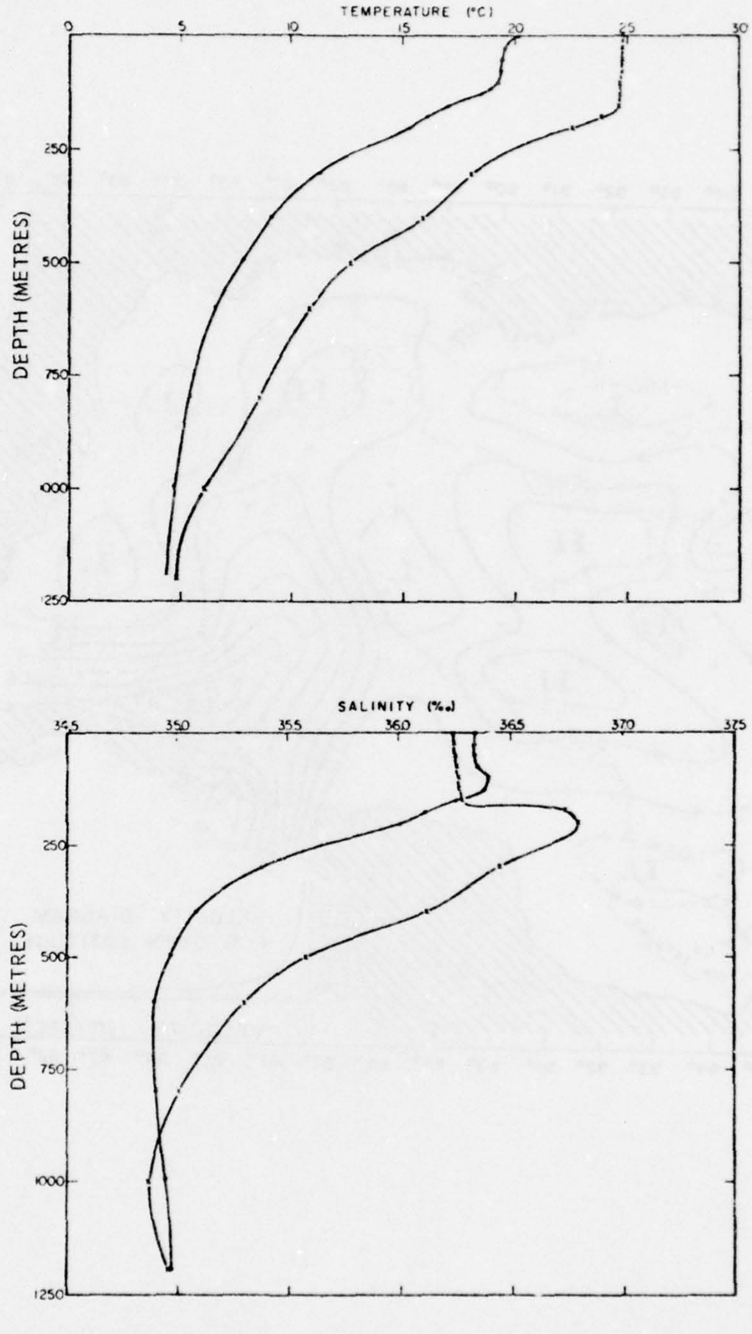


Figure 53. Comparative characteristics of water on the right-hand and the left-hand side of an observer facing downstream in the East Gulf Loop Current. The left-hand water is the colder, lower-salinity water. (Top) Temperature-depth; (Bottom) Salinity-depth. (From Leipper, 1970, Unpublished manuscript).

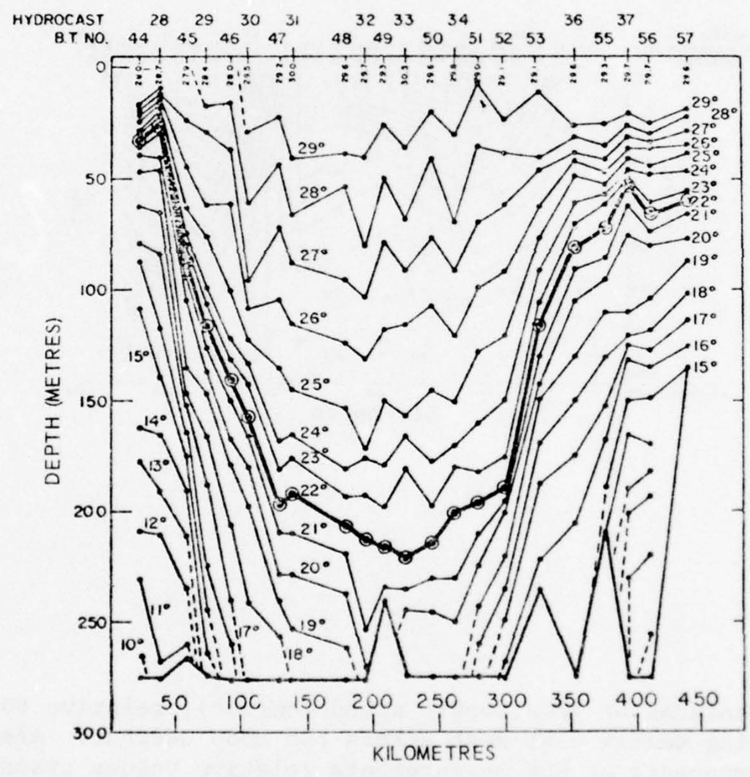


Figure 54. Temperature section across the East Gulf Loop Current based upon Bathythermographic data, August 8 and 9, 1966. Heavy line indicates the 22°C isotherm. (From Leipper, 1970, Unpublished manuscript).

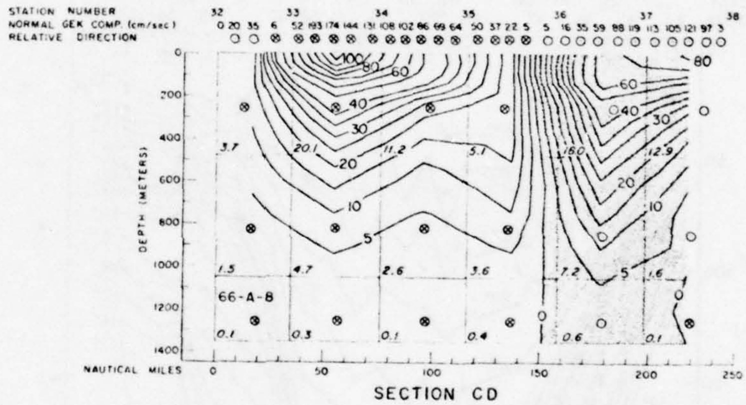


Figure 55. Isotachs of geostrophic speed (cm/sec), relative to 1350-db surface, running nearly east-west across the Loop Current. Also shown are normal components of GEK measurements relative volume transport (10^6 m^3/sec). ⊗ indicates flow into the section. ⊙ indicates flow toward the reader. (From Nowlin and Huberts, 1972. In: Contributions on the Physical Oceanography of the Gulf of Mexico, L.R.A. Capurro and Joseph L. Reid, Editors. Copyright © 1972 by Gulf Publishing Company, Houston, Texas. Used with permission. All rights reserved.)

Intrusion of the Loop and Detachment of Rings

The evolution of the intrusion of the Loop Current, which generally occurs during the spring, has been studied by Leipper (1970) and Cochrane (1972). Figure 56 (from Leipper, 1970) illustrates the intrusion of the core of the current (as depicted by the 150-m contour of the 22°C isothermal surface) based primarily on data for 1966 but supplemented with data from 1964 and 1965. Starting in the fall, the Loop Current is usually in a state of recession in which the inflow takes the least path from Yucatan to the Florida Straits. This is followed by a progressive intrusion of the Loop to the north.

During some years the spring intrusion produces a Loop Current that tends to become distorted into a dumbbell shape (see the curve for August 1966 in Figure 56). Such conditions can lead to the detachment of an isolated anticyclonic (clockwise) eddy. Figure 57 shows the existence of such an eddy near the parent Loop Current as deduced from data taken in June 1967 (Nowlin et al., 1968). Both thermal measurements and direct surface current measurements confirmed the existence of this eddy. Cochrane (1972) documents an exceptional case for May 1969 in which measurements were made before, during, and after the separation process.

Such eddies, or rings as they are more commonly called, contain entrapped Caribbean type water. Their horizontal diameter is generally of the order of 200 to 300 km and their internal thermal structure is comparable to that of the parent Loop Current (Figure 44). These eddies contain considerable energy (both potential and kinetic) and are considered to be one of the dominant sources of energy of circulation to the western Gulf where they tend to drift and ultimately decay.

Western Gulf Circulation

Much less can be stated conclusively about the circulation in the western

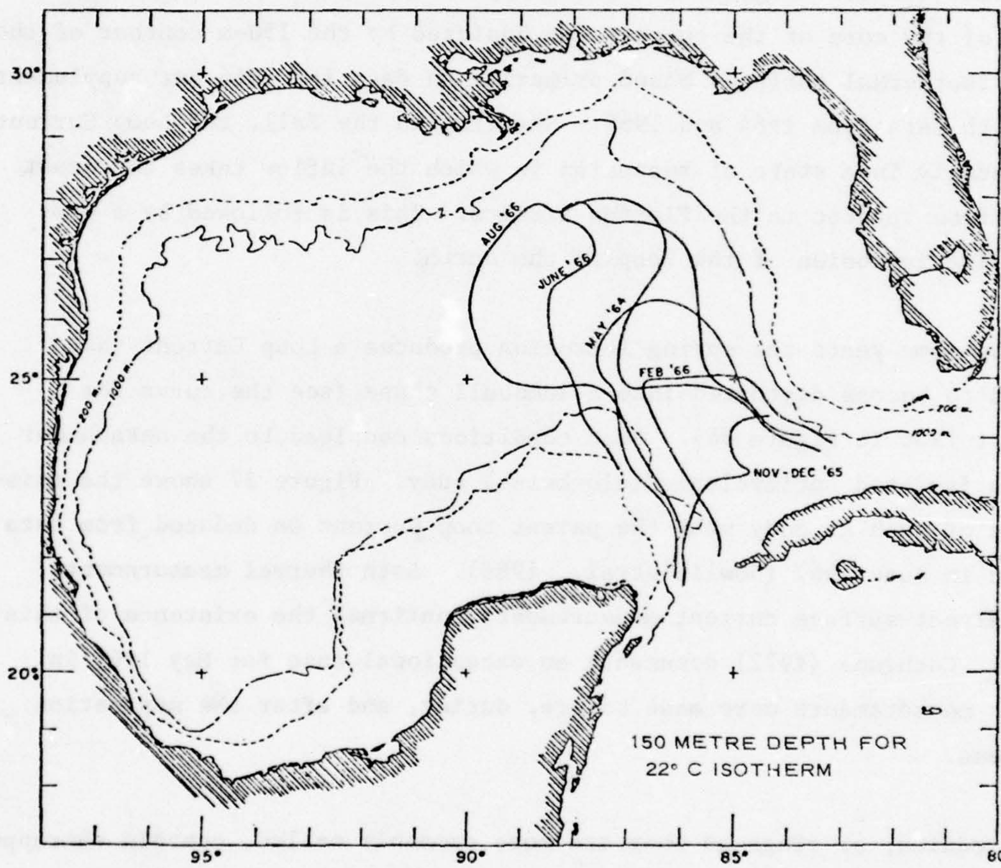


Figure 56. The spring intrusion of 1966 as indicated by overlays of the 150-metre contour lines from the 22°C topographies of all spring cruises of 1966. May 1964 and November and December 1965 are included for supplemental information. (From Leipper, 1970, Unpublished Manuscript).

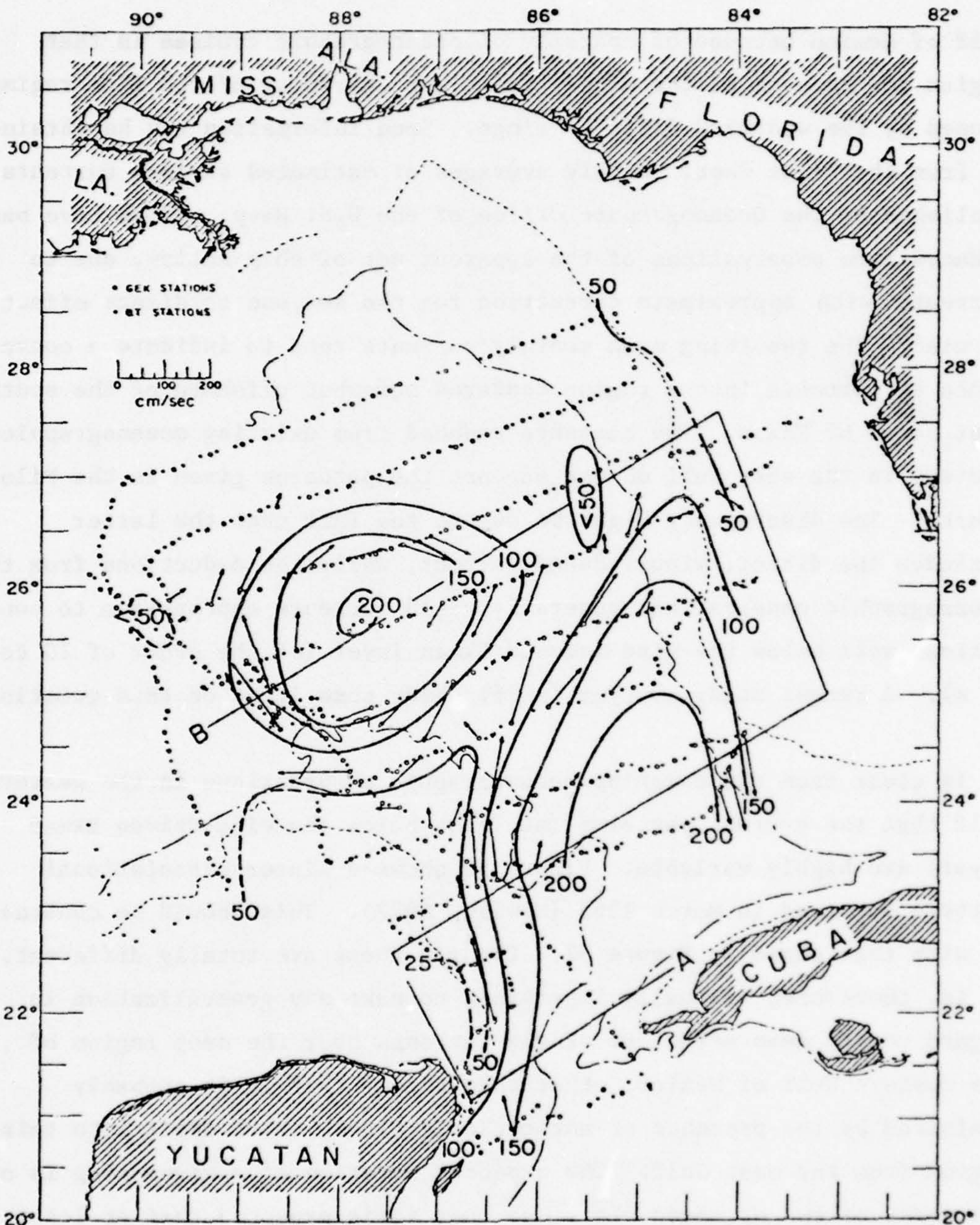


Figure 57. Depth (50-m intervals) of the 22°C isothermal surface from BT observations, and selected GEK surface-current measurements in the eastern Gulf of Mexico. Alaminos 67-A-4, June, 1967. (From Nowlin, 1972. In: Contributions on the Physical Oceanography of the Gulf of Mexico, L.R.A. Capurro and Joseph L. Reid, Editors. Copyright © 1972 by Gulf Publishing Company, Houston, Texas. Used with permission. All rights reserved.)

Gulf of Mexico because of sparsity of oceanographic cruises in that region and because of the highly transient character of the flow regime caused by the westward drift of rings. Some information can be obtained from the Pilot Chart monthly averages of estimated surface currents published by the Oceanographic Office of the U.S. Navy. These have been deduced from observations of the apparent set of ship motion, due to current, with approximate correction for the set due to direct effect of wind. The resulting mean monthly currents tend to indicate a convergence of currents into a region centered somewhat offshore of the southwest coast of Texas. The currents deduced from existing oceanographic cruises in the west Gulf do not support the patterns given in the Pilot Charts. The discrepancy might be due to the fact that the latter includes the direct, wind-induced current, while the deductions from the oceanographic observations generally yield currents appropriate to conditions well below the wind-induced Ekman layer (of the order of 10 to 30 m). A recent study by Lynn (1975) sheds some light on this question.

It is clear from the existing oceanographic observations in the western Gulf that the current patterns (at least below the wind-driven Ekman layer) are highly variable. Figure 58 shows a winter circulational pattern observed in March 1962 (Nowlin, 1972). This should be contrasted with that shown in Figure 52. Clearly these are totally different. It is, therefore, virtually impossible to make any generalization in regard to the mean structure of the currents over the deep region of the western Gulf of Mexico, other than to say that it is probably dominated by the presence of anticyclonic rings, which drift into this region from the east Gulf. The expected duration of a given ring is of the order of two or three years, so that it is expected that at least two or three such rings will be found in this region as indicated in Figure 52. The situation depicted in Figure 58 might represent two young rings reinforcing each other in the central region plus an older weak ring present off the Texas coast.

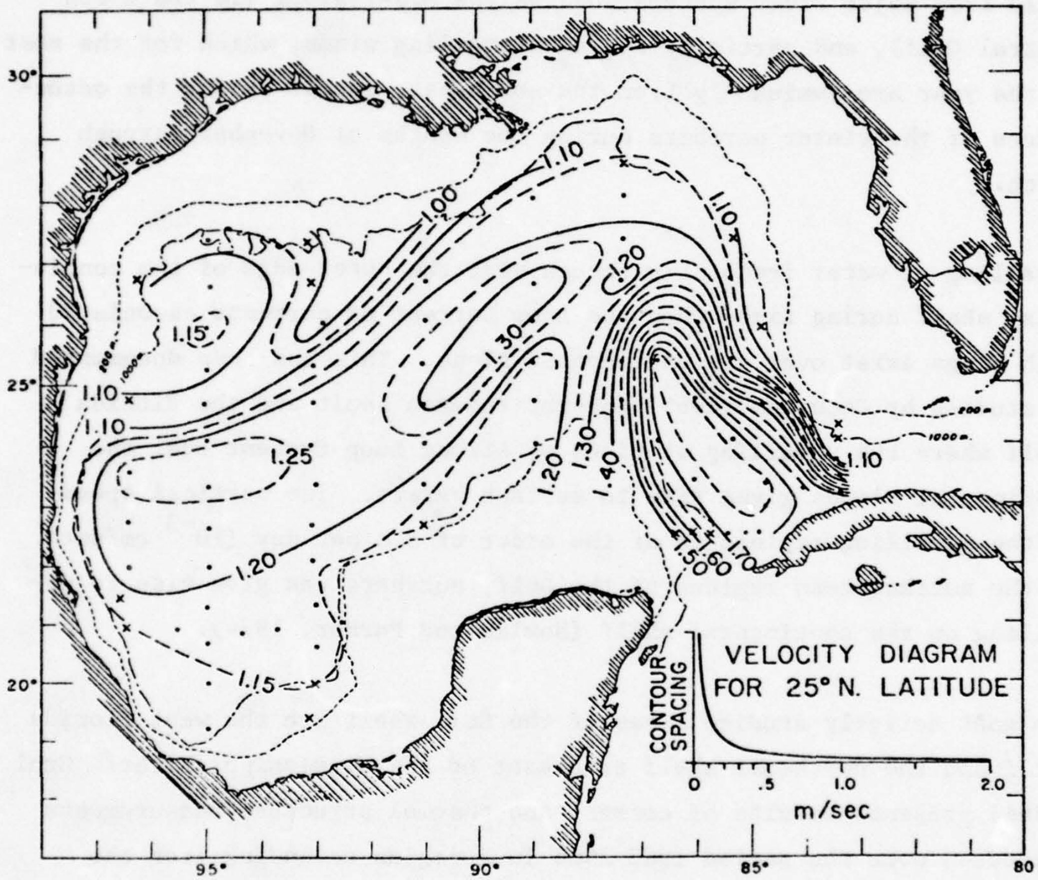


Figure 58. Dynamic topography of sea surface relative to the 1000-db surface in the Gulf of Mexico in March 1962. Hidalgo 62-H-3; x's indicate some extrapolation. Contour interval, 0.05 dynamic metres. (From Nowlin, 1972. In: Contributions on the Physical Oceaongraphy of the Gulf of Mexico, L.R.A. Capurro and Joseph L. Reid, Editors. Copyright © 1972 by Gulf Publishing Company, Houston, Texas. Used with permission. All rights reserved.)

Currents in the Shelf Regions

The currents in the shelf regions are partially controlled by the deep-water circulation (particularly in the eastern Gulf), partially by outfalls from major river systems such as the Mississippi (in the north central Gulf), and partially by the prevailing winds, which for the most of the year are dominantly from the southeast, except during the occurrences of the winter northers during the months of November through March.

Upwelling of water frequently occurs near the outer edge of the continental shelf during times when the Loop Current or currents associated with rings exist over the continental slope. This has been documented in studies by Cochrane (1965) for the Yucatan shelf and the Florida shelf where the upwelling at times of strong Loop Current over the continental slopes gives rise to surface waters. The vertical speed in the upwelling regions is of the order of 3 m per day (10^{-3} cm/sec). In the northwestern regions of the Gulf, northers can give rise to upwelling on the continental shelf (Nowlin and Parker, 1974).

The most actively studied areas of the Gulf shelf are the west Florida shelf and the northeast shelf area east of the Mississippi River. Gaul (1966) presents results of current and thermal structure measurements conducted over the period 1963-1966 in a region extending from the Mississippi delta to Cape San Blas and offshore to about the 2000-m depth contour. In the region offshore of the 200-m depth contour he found that the Loop Current tended to control the circulation, the dominant flow being eastward, but with occasional reversals during times of the recession of the Loop Current. At such times the prevailing winds out of the southeast induce an eastward component of flow. During 1963 and 1965 Gaul carried out a large scale drift card study with releases confined to the region of DeSoto Canyon at about 29°N latitude and due south of Panama City, Florida. The results of this study are summarized by Ichiye et al. (1973). These show that of a total of 1426 recoveries, about 10 percent occurred along the west coast of Florida, 23 percent along the Florida Keys, 41 percent along the east coast of Florida, and the remaining 26 percent elsewhere along the Gulf coast.

Earlier studies by Chew et al. (1959) employing drifters released at various stations on the West Florida Shelf indicated that out of 336 recoveries about 54 percent occurred on the west Florida coast, 11 percent along the Keys, 28 percent along the east coast of Florida, and the remaining 7 percent elsewhere along the Gulf coast. Thus, there can be little doubt that the Loop Current exerts a major impact on the east regions of the Gulf shelf. More recent intensive studies for the west Florida shelf by Rinkel (1971) tend to support these findings.

In the shelf and slope region to the west of the Mississippi River, the discharge of this major river system together with the Atchafalaya River and the prevailing southeast winds have a major impact. The flow is generally towards the west from the Delta to Galveston, then continuing southwest parallel to shore and ultimately to the south along the western Gulf shelf. However, reversals in direction in the southwest coast of Texas tend to occur in the summer, or during times when anticyclonic rings in the deep water of the western Gulf tend to invade the shelf regions. During the latter episodes, one can also expect to find upwellings of water along the continental slope. Typical speeds of the longshore flow are less than one knot.

WINDS AND STORMS

The climatic conditions of the Gulf region are broadly determined by the huge land mass lying to the north, its subtropical latitude, and the strength or intensity of semi-permanent pressure ridges. At least two pressure ridges dominate weather conditions along the coast. One ridge, the Bermuda high, is centered over the Bermuda-Azores area of the Atlantic and the other is the Mexican heat low centered over Texas during the warm months. Pressure changes associated with these ridges set up winds that prevail from an easterly direction, with southeasterly winds predominating. During the winter months, cold fronts from the northwest move southward to the Gulf of Mexico; these "northers" are on the average the highest winds of the year with speeds ranging up to 60 knots.

Average monthly wind speeds for the Texas coast, Sector 5, range from 8.4-12.8 mph (TerEco Corp., 1972). These southeast winds normally predominate during the spring and summer months at velocities ranging on a daily basis from 4 to 30 knots. Winds in the eastern portion of Sector 5, i.e., central Gulf, are very similar in velocity but tend to have a more easterly component. Winds for this sector are the calmest during July and August with average speeds of 7-10 knots (U.S. Navy Hydrographic Office, 1972). Wind speeds increase somewhat during September-October having average speeds of 10-12 knots. Wind speeds are highest in November-February, averaging 13-15 knots. Winds tend to subside in March-June and by July-August they are back to their lowest average velocity.

Sector 4, consisting of the eastern Gulf and specifically western Florida, is influenced more by the Bermuda high and its position than is Sector 5. Southerly components in the summer and northerly components in the winter are more evident in the wind directions along peninsular Florida. The mean annual wind speeds range from 7.4-11.7 knots with a maximum average of 5.9-8.2 knots. The offshore marine region south of 27°N latitude differs only slightly from that region north of the specified latitude as can be noted in the following wind tabulation:

Wind Speed	North Area Sept.-Apr.	North Area May-Aug.	South Area Sept.-Apr.	South Area May-Aug.
Mean speed (km)	12.6	8.4	12.0	8.5
Less than 7 km	19%	38%	19%	40%
Greater than 16 km	22%	6%	20%	6%

For those offshore regions the wind has a northerly component 52 percent of the time and southerly component 37 percent of the time during the fall-winter interim. For the spring-summer period the northerly component is 28 percent while the southerly component is 42 percent.

Abnormally high speed winds may occur within the Gulf region during winter (as "northers") or late summer (as tropical storms or hurricanes). A norther is a strong cold wind coming from the northeast-northwest and may extend into the Gulf area between November and April. This cold air mass is usually preceded by a warm and cloudy or rainy spell with southerly winds. From one to six northers are likely to be severe over the Gulf during individual years. They generally last about a day and a half, but severe storms may endure for three or four days (Brower et al., 1972).

Tropical storms (winds of 34 to 63 knots) and hurricanes (winds of 64 knots or higher) are more active in the Gulf during the months of August and September. The great majority of the Gulf's tropical storms and hurricanes originate in the Caribbean or lower Gulf and move at a mean speed of approximately 10 knots. Figure 59 shows the number of times that hurricanes have occurred in coast-to-offshore zones within the Gulf of Mexico during the period from 1900 to 1956. The eastern portion of Sector 5 reveals the maximum of offshore occurrences; however, that region is almost equaled in frequency by all of the subzones displayed for Sector 4. Tropical storms and hurricane frequencies for specific areas of the Gulf (U.S. Army Corps of Engineers, 1973) are given in the tabulation below.

	Recurrence Interval in Years	
Area	Storms	Hurricanes
Panama City	1.4	3.8
Mobile - Pascagoula	1.8	4.9
Southwest Pass	1.5	4.1

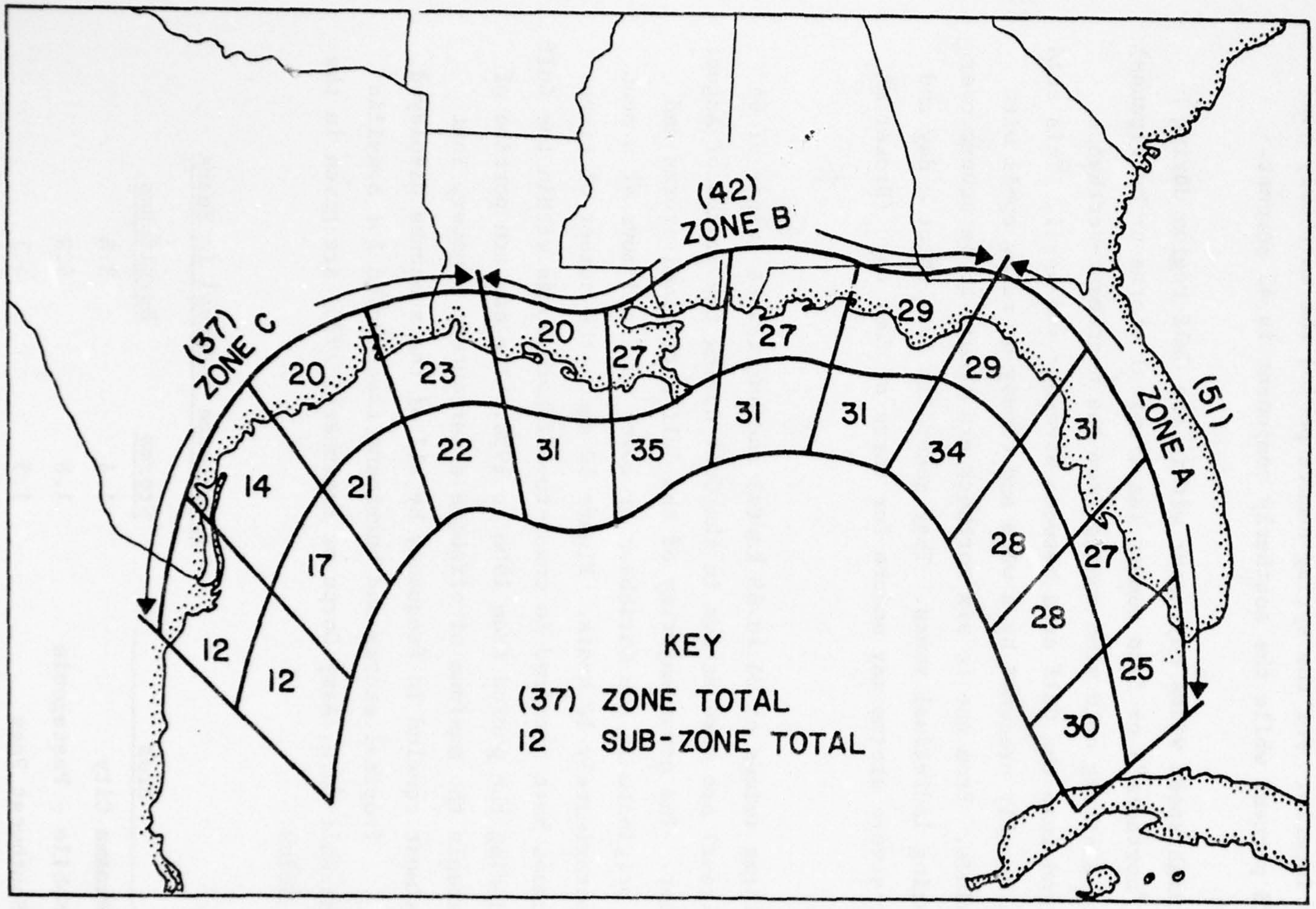


Figure 59. Gulf Coast zone subdivisions showing total hurricane occurrences 1900-1956 (after Carr, 1967).

Bayou Lafourche	1.6	4.1
Sabine Pass	2.3	4.9
Galveston - Freeport	2.1	3.2
Corpus Christi	1.8	2.9

For additional data concerning environmental conditions in the Gulf of Mexico, one can refer to Marcus (1973).

FISHERIES RESOURCES

The Gulf fishery is dominated by shellfish, primarily shrimp, crabs, and oysters with smaller amounts of clams and scallops. The catch of finfish is dominated by the menhaden both in volume and value. Although the volume of the finfish catch greatly exceeds the catch of shellfish, the value of the shellfish catch is 3 to 4 times more valuable. The main shrimp fishery includes the brown shrimp (*Penaeus aztecus*), the white shrimp (*P. setiferus*) and the pink shrimp (*P. duorarum*). Sea bobs (*Xiphopenaeus kroyeri*) and the deepwater royal red shrimp (*Hymenopenaeus robustus*) contribute only approximately 3 percent to the shrimp catch.

The Gulf fishery concentrates around the Mississippi Delta, clearly the most productive region in the Gulf. Approximately 30 to 40 percent of the total fishery production is taken on the eastern side of the Delta (Juhl, 1974).

The dependence of the Gulf fishery on the coastal environment is unparalleled, as Gunter (1967) estimates that 97.5 percent of the total commercial fisheries catch for the Gulf is estuarine dependent, i.e., made up of species spending all or part of their lives in estuaries. Moreover, nearly all of the Gulf coast catch, including most of the menhaden, is made within a few miles of the coast. Of the important commercial fish, only groupers and red snappers are caught primarily beyond the 12-mile limit; combined they constitute only approximately 1 percent of the volume and 2 percent of the value of the total Gulf catch.

The average ranking of the most important commercial finfish for the Gulf coast is shown below (U.S. Dept. of Interior, 1976):

By Volume	By Value
Menhaden	Menhaden
Mullet	Red Snapper
Croaker	Mullet
Red Snapper	Spotted Seatrout
Groupers	Croaker
Spanish Mackerel	Groupers
Spotted Seatrout	Pompano
Red Drum	Spanish Mackerel
Flounders	Red Drum
Black Drum	Flounders
King Whiting	King Mackerel
White Seatrout	Black Drum
Sheepshead	White Seatrout
	Sheepshead

Gulf fisheries currently contribute approximately 25-37 percent to the total U.S. landings. Average landings for the combined (finfish and shellfish) Gulf coast fishery during 1973-74 are estimated to be 1,660 million pounds valued at $254 million.

The almost total dependence of Gulf fisheries on the coastal and estuarine waters would argue in favor of the disposal of dredged material in the deep ocean areas beyond the shelf. At present the only commercial fisheries on the outer shelf and upper slope are the red snapper and royal red shrimp. An open-water fish, the red snapper (*Lutjanus aya*), is usually associated with reefs, banks or other structural features in the environment. The bank dwelling snappers also figure significantly in the coastal sports fishery, which is confined largely to nearshore regions. Commercial snapper fishermen utilize banks out to the edge of the shelf.

The royal red shrimp (*Hymenopenaeus robustus*), a trawlable species of the upper continental slope, is of limited importance to the Gulf shrimp fishery. Bullis (1955) reported on extensive trawling by the OREGON throughout much of the Gulf in the 185 to 550 m depth: "The distributional picture that emerged from this work shows royal red shrimp to be present throughout the Gulf of Mexico on all types of bottom in a depth range of 190 to 270 fms (348-474 m), with a maximum range of 150 to 400 fms (274-732 m)." The species is concentrated on trawlable bottoms southeast of the mouth of the Mississippi River and some commercial fishing for the species has been carried out in this area. Whereas the royal red shrimp is found off the Texas coast, present indications are that its harvest is not economical in this area.

The fishery potential of the Gulf slope has been reviewed in detail by W. Pequegnat et al. (1976). At the present time the commercial fishery potential of the continental slope of the northern Gulf of Mexico is not being exploited in any systematic way.

Results of exploratory bottom longline operations in the western and eastern sections of the continental slope of the northern Gulf were reported by Nelson and Carpenter (1968). The most abundant fish species, by number and weight, was the tilefish, Lopholatilus chamaeleonticeps. This valuable food fish has been removed from the commercial market of the middle Atlantic states since the early 1900's (Bigelow and Schroeder, 1953) where annual landings had reached 12 million pounds. The total depth range of the species in the Gulf was 165 to 410 m with primary concentration between 275 and 365 m. Highest catches of tilefish were made off the Texas coast where catches averaged about 1/2 pound per hook (at 365 m). All six longline sets between 275 and 365 m off Texas caught tilefish. In the eastern Gulf, longline sets caught tilefish with less frequency. The most abundant single catch in this sector consisted of 104 pounds per 300-hook line set at 320 m along the eastern edge of DeSoto Canyon.

Besides the tilefish, the other foodfish taken in abundance was the yellowedge grouper, Epinephelus flavolimbatus. Again, the highest catches were made off the Texas coast. Fishes taken in lesser quantities included the warsaw grouper (Epinephelus nigritus), the red snapper (Lutjanus campechanus), vermilion snapper (Rhomboplites aurorubens), wenchman (Pristopomoides aquilonaris), scamp (Mycteroperca phenax), red grouper (Epinephelus morio), black grouper (Mycteroperca bonaci), porgies (Sparidae), and Gulf hake (Urophycis cirratus). Sharks, which are at present of no commercial value, made up about a third of the total bottom longline catch.

In summary, the most productive longlining area was the Texas coast where peaks of foodfish abundance were noted at about 183 m (several species of grouper, of which the yellowedge grouper predominated) and 365 m (where the tilefish was most abundant). Nelson and Carpenter (1968) concluded that the Texas coast is the only part of the Gulf that appears to offer commercial potential for bottom longlines, especially since such gear can be fished on both rough and smooth bottoms. They suggest that a trawling potential appears likely throughout the depth range of the northern Gulf where the bottom is not excessively rough. Since most of the area appears trawlable by the roller-rigged fish trawls, they conclude that, "certainly a tilefish potential exists."

Hook and line snapper fishing was formerly limited to banks and irregular bottom areas in relatively shallow water of the shelf. However, during the 1950's snapper fishermen equipped with power reels, stainless steel wire lines, and electronic aids for determining position, depth, and likely fishing areas, extended the depth range of their fishing activities to at least 275 m. The catch consists of a variety of excellent food fishes including the red snapper (Lutjanus campechanus), red grouper (Epinephelus morio), and gag (Mycteroperca microlepis). In deeper water the Brazilian snapper (Lutjanus aya) is taken in quantity, especially in 73 to 137 m on Little Campeche Bank south of Freeport, Texas.

Above the outer continental shelf and upper slope in the general region from central Louisiana eastward to about the level of Pensacola, Florida large schools of clupeids and carangids have been reported. One such report (Anonymous, 1969) indicated that the exploratory vessel OREGON II had encountered large schools of round herring (*Etrumeus teres*) and rough scad (*Trachurus lathami*) just off the bottom in 200 m of water off the Louisiana coast. Bogdanov (1969) reported taking two tons of round herring in 1/2 hour of trawling in deep water south of Pensacola. He noted that sonar recordings indicated large dense schools of round herring over a significant area and that during the day these fishes remained somewhat above the bottom at a depth of 80 to 93 m, but that during the night they rose to within 10 to 17 m of the surface. From such reports it would appear that a significant fishery potential exists in the northeastern Gulf for these commercially valuable species if they can be captured.

Iwamoto (1965) reviewed the results of surface school sightings and long-line fishing by the exploratory vessel OREGON in the northern Gulf of Mexico and assessed the fishery potential of the tuna stocks of the area. Commercially exploitable stocks of four species of tuna are found in the northern Gulf area. These include the skipjack tuna (*Euthynnus pelamis*), a yellowfin tuna (*Thunnus albacares*), blackfin tuna (*Thunnus atlanticus*), and bluefin tuna (*Thunnus thynnus*). The area of principal sightings and longline catches lies in the water above the 183 to 1830-m depth contours. Tuna schools were found to be present at all seasons of the year, but they seem to be more abundant in the northern Gulf during the summer and fall months. Tuna schools have been located most frequently east and southeast of the mouth of the Mississippi River, but this may be related to the fact that exploratory operations have been most extensive in this area.

Over the continental slope, both east and west of the mouth of the

Mississippi River, there is clearly a commercially exploitable pelagic fish population consisting primarily of tunas and their relatives, but including other species. American efforts to exploit this resource have not be very successful (Iwamoto, 1965). Antiquated longline gear was tried, and this produced only moderate results. Purse seines, very successful elsewhere, have yet to be tried. Meanwhile, Japanese and possibly Cuban fishermen have been making good catches of the larger pelagic fishes.

Although considerable exploratory work remains to be carried out, the principal features of the commercial fishery potential of the outer shelf and slope waters of the northern Gulf coast may be stated with some precision and assurance. In the eastern sector (essentially, from mid-Louisiana to the vicinity of Pensacola, Florida) three basic fishery types are supportable: these include bottom trawling for royal red shrimp, midwater trawling for clupeids and carangids, and surface long-lining and purse seining for tunas and other large pelagic species. In the western sector (from mid-Louisiana to the south Texas border) the most effective fishing is for bottom and near-bottom species. This includes bottom trawling for snappers and groupers (at about 183 m) and tilefish (at about 366 m), bottom longlining, and hook and line fishing on the snapper banks. At present, none of these fishery potentials is being fully exploited.

D. ATLANTIC COAST (SECTORS 1, 2, AND 3)

GEOMORPHOLOGY

The Atlantic Continental Shelf represents a natural seaward extension of the onshore Atlantic Coastal Plain, which stretches from southern New England to southern Florida. Offshore, the continental shelf, slope, and rise comprise the Atlantic continental margin of North America. In general, the relatively smooth, gently dipping shelf extends seaward to a depth of 100-200 m where the break in slope marks the beginning of the more steeply inclined continental slope as the seaward dip increases to 3°-6° (Uchupi, 1968). The continental slope has been described by Emery and Uchupi (1972) as being the most significant topographic discontinuity of the earth's crust because it marks the general position of contact between continental and oceanic basement rocks. The boundary between the shelf and slope is often cut by submarine canyons of varying dimensions and numbers, thereby adding to the complexity of slope topography. This is characteristic of the slopes of the Atlantic coast of North America, which are discussed in more detail under the following individual sectors. At the foot of the continental slope, around 2000 m, regional declivity decreases onto the continental rise that continues down to abyssal depths exceeding 5000 m. Figure 60 shows the physiographic provinces of the continental margin off the east coast of the United States.

SECTOR 1 (NORTHEAST COAST)

Continental Shelf

The Northeast Coast Sector extends southward from Cape Sable to Cape Cod and is commonly recognized as the Gulf of Maine. This gulf region derives its form from Georges Bank to the south and the Scotian Shelf to the north. Georges Bank, the easternmost part of the United States continental shelf, is separated from the Scotian Shelf by Northeast Channel (Figure 61). The Gulf consists of flat-topped banks, low swells, and numerous basins with varying sill depths. These shallow basins (maximum depth 377 m) occupy 30 percent of the area of the Gulf and most are compound structures enclosing several separate deep areas (Uchupi, 1968). The deep areas are flat plains that contrast with undulating basin floors and the gently sloping basin sides. Between the basins the floor of the Gulf of Maine is irregular due to outcrops of bedrock and concentrations of boulders, the latter being a result of glacial activity. Pleistocene glacial and fluvial action were the primary forces

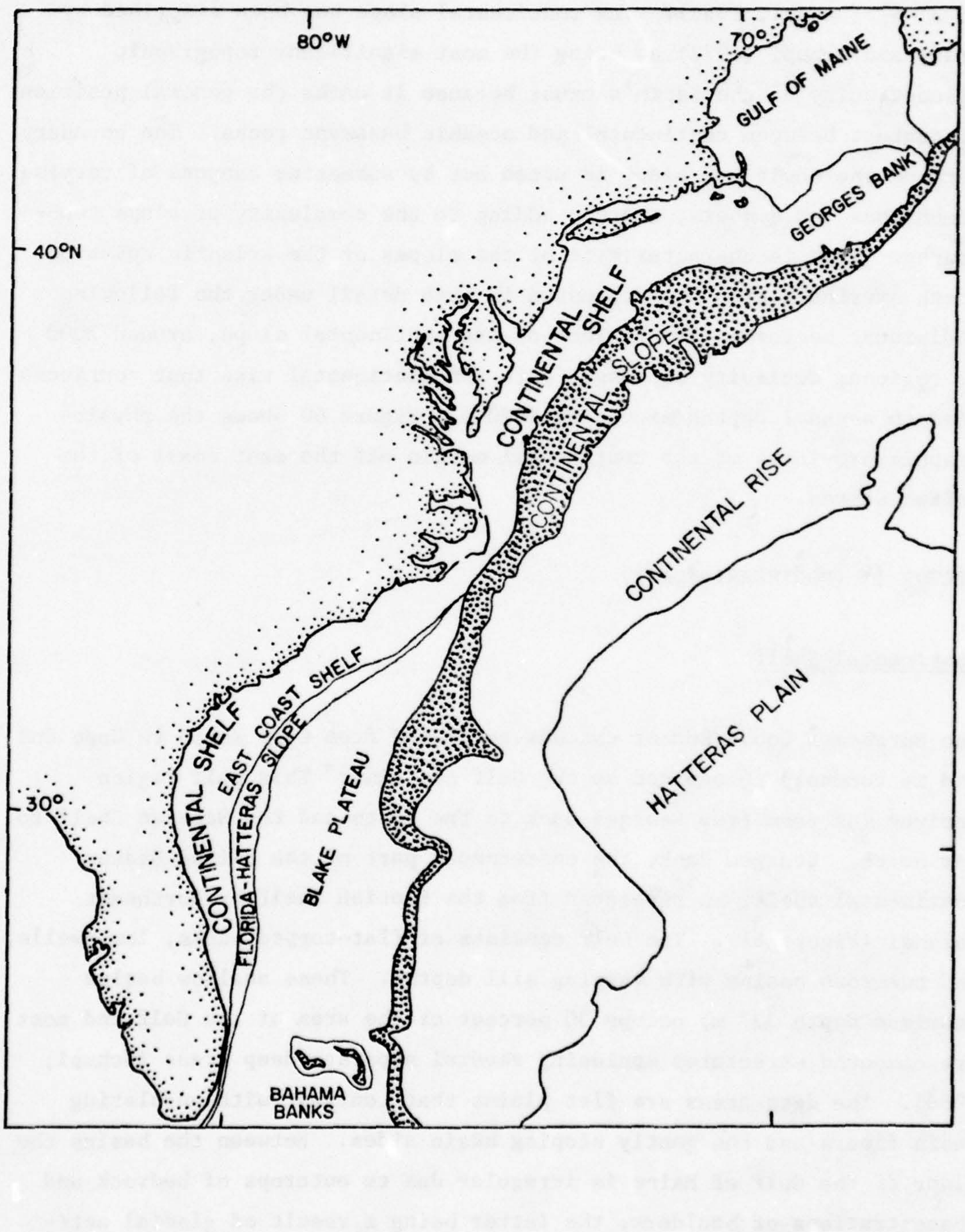


Figure 60. Physiographic provinces of the continental margin off the east coast of the United States (from Uchupi, 1968).

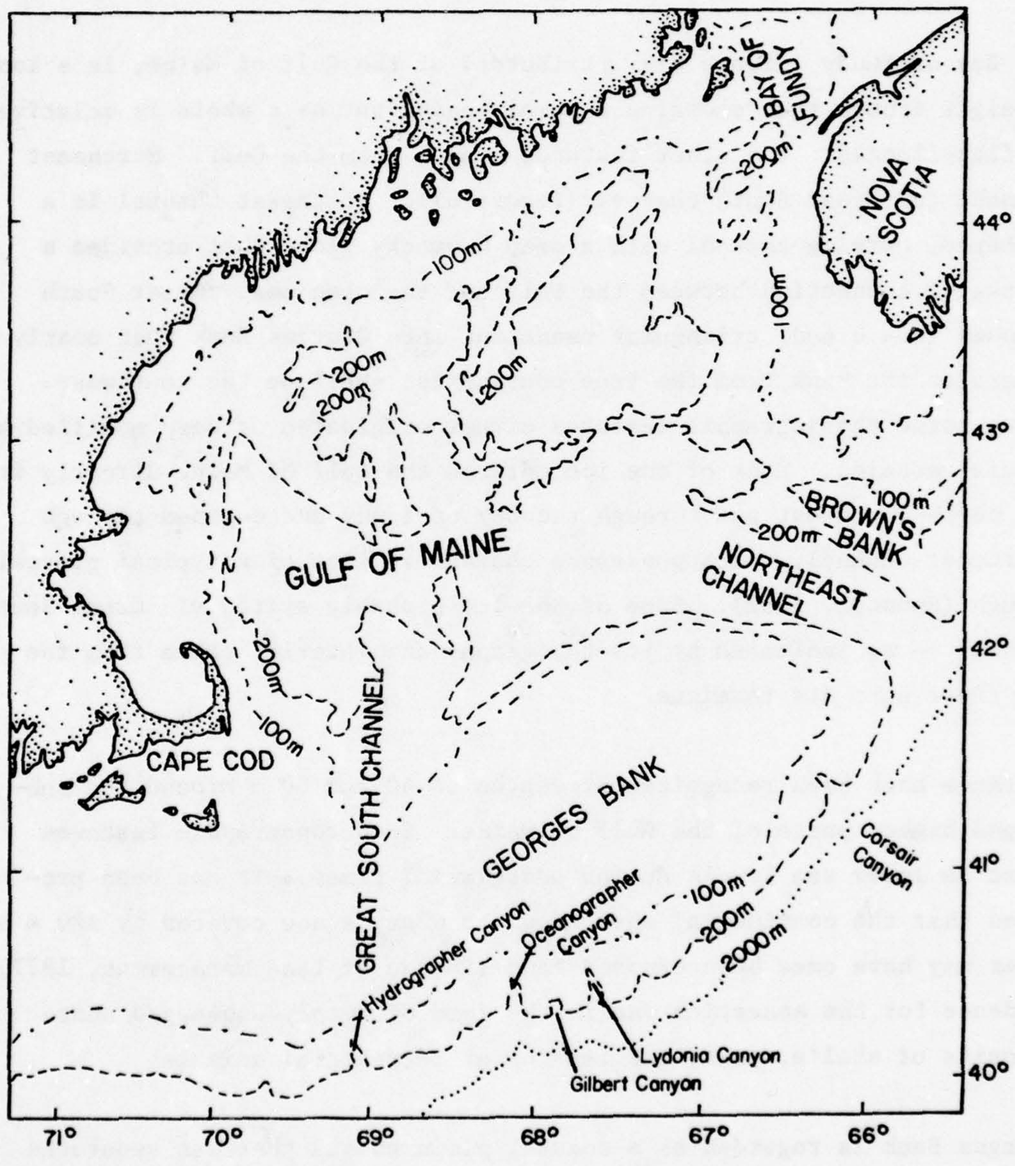


Figure 61. Geomorphology of Sector 1 (Northeast Atlantic Coast).

that shaped the present Gulf (Emery and Uchupi, 1972) and furnished the wide variety of sedimentary types, ranging from clays to boulder tills, found there.

The Bay of Fundy (Figure 61), a tributary of the Gulf of Maine, is a long straight trough that contains several basins but as a whole is relatively flat-floored. Two other features branch from the Gulf: Northeast Channel and Great South Channel (Figure 61). Northeast Channel is a U-shaped, curving channel with a deep hummocky floor that provides a deepwater connection between the Gulf and the open sea. Great South Channel is a broad, triangular reentrant into Georges Bank that nearly separates the bank from the true continental shelf on the southwest. These three physiographic features either originated or were modified by glacial erosion. Most of the ice entered the Gulf of Maine directly from the north-northwest and through the Bay of Fundy and escaped through Northeast Channel, which possesses characteristics of a typical glacial trough (Spencer, 1962). Some of the ice probably exited via Great South Channel -- as indicated by its topography and material taken from the sea floor near its terminus.

Terraces have been recognized at depths of 40 and 60 m around the submerged higher parts of the Gulf of Maine. Such topographic features point to lower sea levels during postglacial times. It has been proposed that the continental shelf down to what is now covered by 120 m of water may have once been exposed land (Bureau of Land Management, 1977). Evidence for the assertion was in the form of deeply submerged shore deposits of shells, peat, and remains of terrestrial animals.

Georges Bank is regarded as a coastal plain cuesta that was separated from the mainland by stream and glacial erosion of the Gulf of Maine and then slightly modified by glacial deposition that was ultimately reworked by tidal currents atop the bank. This topograph high, 150 km wide and 280 km long, is one of a chain of banks extending from

Nantucket Island to the Grand Banks. Two different types of topography are noted across its top. The southern half is essentially smooth sand sloping gently toward the south whereas the northern half is irregular, having very large sand shoals that trend northwesterly and are separated by flat-floored troughs (Uchupi, 1968). The shoals are about 10 km apart and are as long as 75 km. Many are so near the ocean surface that they cause storm waves to break and at all times produce turbulence readily detected from aerial and shipboard observation. Secondary and tertiary sand waves on the tops and side slopes of the shoals exhibit great variety in size, shape, and spacing. The shallower parts of the top of Georges Bank, especially Georges Shoal, is undergoing constant reworking by tidal currents. As a result, sand waves of all but the deepest and largest class are continually being shifted and reworked. Glacial till, with its numerous boulders, is confined to the northern half of the bank while outwash deposits occupy the southern half of the bank top.

Surficial sediments on the shelf region of Sector 1 are primarily well-sorted sands composed largely of quartz and feldspar plus some glauconite, heavy minerals, and rock fragments. Shepard (1963) reports similar deposits for Georges Bank where, in addition, gravel and even boulders have been recovered by fishermen (Schlee and Pratt, 1970). The large basins of the Gulf of Maine have sediments that are high in silt and clay but have also a scattering of gravel and stones of various sizes.

Continental Slope

The continental slope between the Grand Banks and Cape Hatteras is most likely the classical concept of a continental slope where the degree of declivity increases from the outer shelf to that degree marking the continental rise. The most obvious characteristic of the slope in that region is an abundance of submarine canyons. Emery and Uchupi (1972) state that there are at least 190 canyons between Labrador and Cape

Hatteras. Some of the major ones within or near Sector 1 include Corsair, Lydonia, Gilbert, Oceanographer, and Hydrographer Canyons (Figure 61). The base of the slope is found at depths ranging from 1000-3400 m with a median of 2000 m. In Sector 1, Northeast Channel tends to be a site where the slope changes in appearance. North of the channel the base of the slope is at a depth of 1000-1200 m. Its low relief is believed to be due to the deposition of a large volume of sediment removed from the Gulf of Maine and the Scotian Shelf by pro-glacial streams and Pleistocene glaciers. Seaward of Georges Bank the slope increases in declivity and relief. Here the slope can be divided into an upper and a lower shelf break to a depth of 400 m with a declivity of less than 2° and the lower slope extending from 400-2000 m with a declivity of 6° (Uchupi, 1968). Both segments are cut deeply by the aforementioned canyons and innumerable smaller gullies.

Continental Rise and Abyssal Plain

Extending from the base of the continental slope to the western margin of the abyssal plains north of Cape Hatteras is a wide sedimentary apron known as the continental rise. Its greatest width is off New York City where it extends for almost 800 km. Over this distance, local relief is generally less than 40 m whereas its overall depth range is from 1000-2200 m at the base of the slope to about 5000 m at the seaward edge of the rise. Most of the canyons on the adjacent slope have channel-like expressions that cross the rise and disappear on the abyssal plains farther east.

South of Georges Bank a chain of seamounts extends across the continental rise and the Sohm Plain, forming an arc more than 1800 km long (Figure 60). The seamounts seem to be on a fracture zone that possibly was active as late as Eocene time (Uchupi, 1968).

SECTOR 2 (MIDDLE ATLANTIC BIGHT)

Continental Shelf

From Great South Channel to the Florida Keys is a seaward dipping platform extending from the shore to the continental slope in the north, to the Blake Plateau and to the Florida-Hatteras Slope farther south. Uchupi (1968) suggests the name East Coast Shelf for this province (Figure 60). The continental shelf within Sector 2, extending from Cape Cod to Cape Hatteras, may be characterized as a relatively smooth, seaward-dipping platform disrupted by sand swells, channels, coral mounds, and terraces. These surface irregularities generally have less than 10 m of relief and produce moderate changes in the overall declivity. The shelf area is 190 km wide south of New York City and narrows to 23 km wide off Cape Hatteras. Seaward dip of the platform varies from 0°09' off Cape Hatteras to 0°93' off New York. The continental slope flanks the platform to the east of the shelf break where the seaward dip increases to 2°-6° (Uchupi, 1968).

Present features of the continental margin are basically of Pleistocene age although they have undergone modification by post-Pleistocene marine processes (McClelland, 1974). For example, fluctuating sea levels associated with glacial activities during the Pleistocene Epoch resulted in a series of erosional terraces paralleling the present shelf break, each terrace representing a stand-still of sea level. From deepest to shallowest the linear features are termed the "Nicholls," "Franklin," "Fortune," and "Black Island" shores (Emery and Uchupi, 1972). Features such as these terraces in some places have been obscured by reworking and redistribution of the surficial relict sediment. These marine processes coupled with deposition of modern sediments have been sufficient to partially bury or modify old stream channels that aerially developed on the present shelf surface during low sea level stands, which accompanied various glacial stages (McClennen, 1973). Major well-defined channel passes within Sector 2 include Delaware, Hudson, and Black Island Channels, the latter two each having built a delta at its mouth when sea level stood about 70 m below the present level at the Fortune shore (Emery and Uchupi, 1972). In addition, the Hudson Shelf Valley is one of the largest erosional features on the East Coast Shelf. Figure 62 shows the relative position of these physiographic features with respect to the shoreline and shelf break.

Most of the Hatteras-Cape Cod shelf is mantled by fine to medium quartz and feldspar sands that are, in places, interbedded with silt and clay layers. Currents, both tidal and oceanic, have extensively reworked the sand deposits and have formed several kinds of sand waves or ridges on the continental shelf. Some of the ridges extend for tens of kilometers and are up to 10 m high. The shallower features change their shape or their cover of sand ripples with each tide or tidal cycle. A huge area of the features is represented by Nantucket Shoals, an area of sand shoals and smaller sand waves that are closely akin to the ones atop Georges Bank. Sand waves even occur throughout most of the open continental shelf where tidal currents are not particularly fast. Their shoreward movement is at a very slow rate whereas those sand waves in deeper waters of the shelf are remaining essentially static, an indication that the deep ones probably are relict from a post-glacial time of lower sea level. As the sea level rose they became isolated remnants on the shelf surface.

All of the shelf sands are believed to have been extensively reworked by ocean currents as sea level rose to its present position probably accounting for the observed increase in grain size in a seaward direction (McClelland, 1974). Modern sedimentation in Sector 2 is occurring primarily in a narrow nearshore belt area in sediment traps such as those created by lagoons and estuaries (Figure 63). It is of interest that a significant portion of modern nearshore sediment may derive from landward movement of fine-grained sediment from the central and outer shelf (Milliman et al., 1972).

The southwesternmost part of the Hatteras-Cape Cod shelf contains a different type of topographic feature, a submerged irregular calcareous

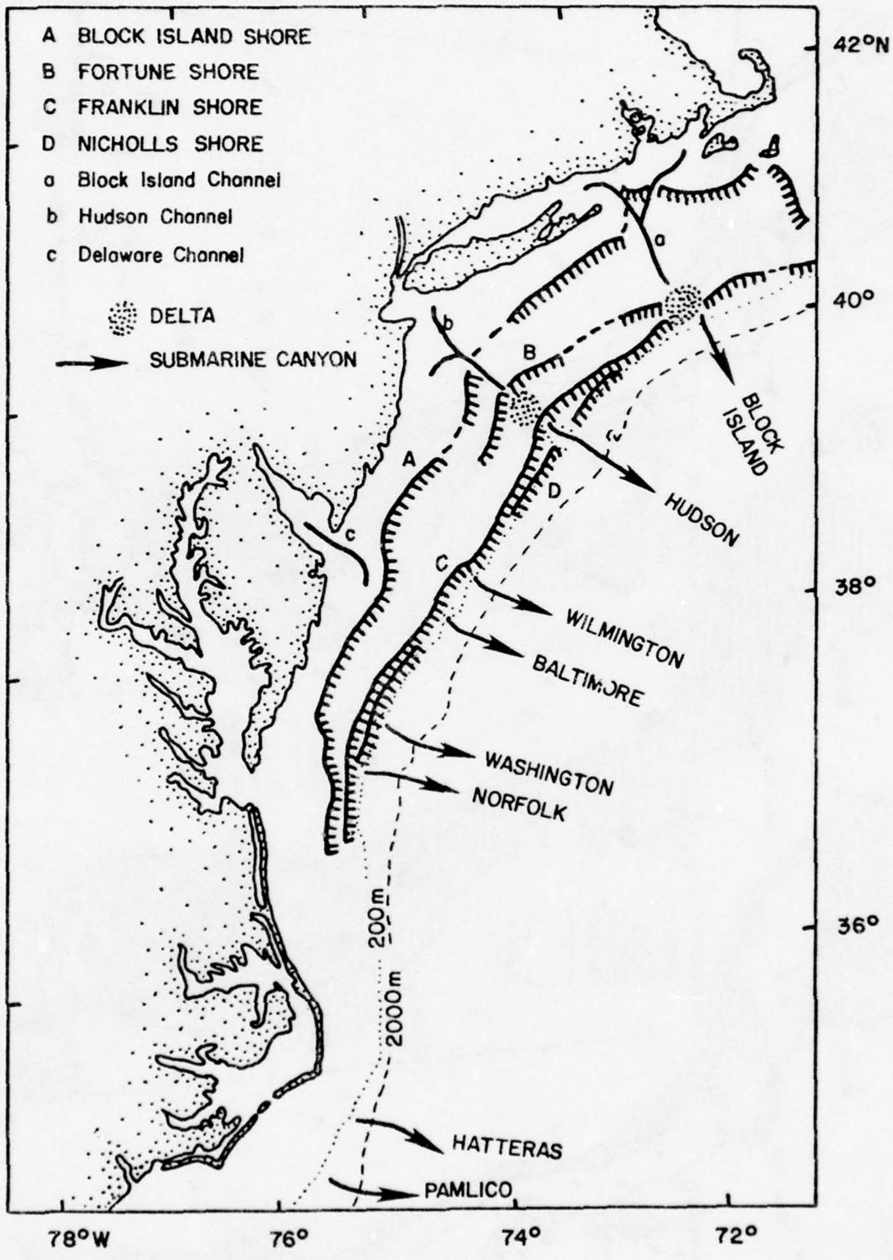


Figure 62. Submerged river channels, shorelines, canyons, and deltas of Hatteras-Cape Cod Shelf region (modified from Emery and Uchupi, 1972).

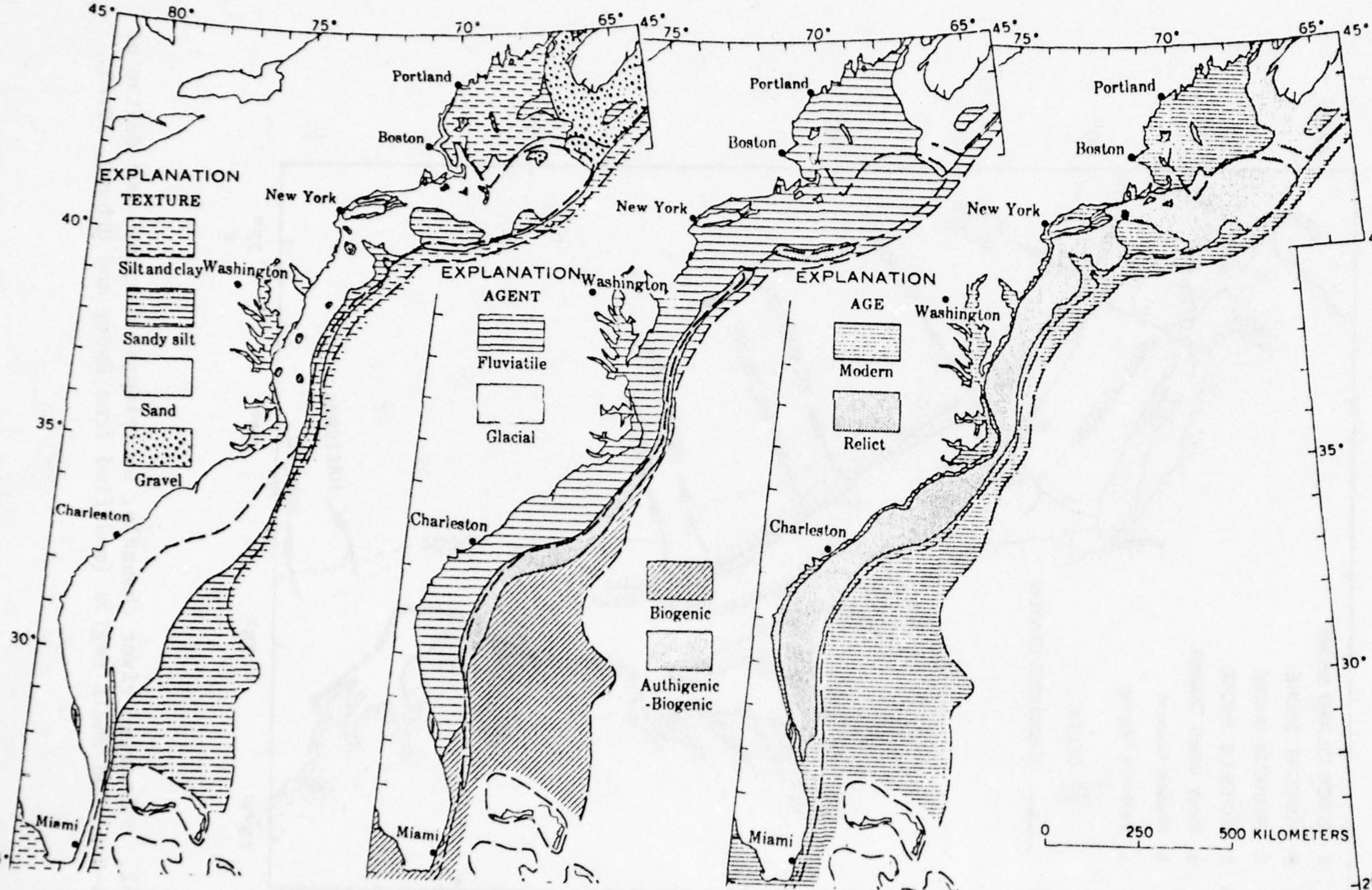


Figure 63. Sediments off the Atlantic coast of the United States classified by texture, contributing agent, and age (from Emery, 1966).

reef made of algal and coral growths. These low banks along the Carolina coast extend from shore to the outer edge of the continental shelf. Such features are more common farther southwest and will be described more fully in the Sector 3 discussion.

Continental Slope

The continental slope between Georges Bank and Hudson Canyon is made up of two segments, as was the southernmost portion of Sector 1. South of Marth's Vineyard the upper slope extends to a depth of 1000 m and has a declivity of about 1°; the lower slope, which extends to a depth of 2200 m, has a gradient of 3° (Uchupi, 1968). Here, as noted in Sector 1, the slope is entrenched by submarine canyons. The upper portion of the continental slope south of Black Island has a larger scar, probably formed by slumping. Hudson Canyon, the largest canyon off the east coast of the United States lies along the western margin of this part of the continental slope and is continuous in a seaward direction across the continental rise. On the slope Hudson Canyon is 100-600 m deep and about 12-15 km wide (Uchupi, 1968).

From Hudson Canyon to Cape Henry the continental slope is very irregular and has an average declivity of 4°. Major submarine canyons that extend partly into the continental shelf in this region include Wilmington, Baltimore, Washington, and Norfolk Canyons. These do not extend onto the adjacent rise. South of Cape Henry to just below Cape Hatteras the continental slope has a declivity between 4° and 5° and a height of 2000-2400 m. No major canyons are present but the scarp is cut by innumerable small gullies (Uchupi, 1968). Off Cape Hatteras the gullies tend to coalesce toward the base of the slope to form Hatteras Canyon that extends across the rise onto the Hatteras Plain.

Continental Rise

The North American Rise begins at the base of the continental slope in depths that average about 2000 m between Cape Hatteras and Labrador (Emery and Uchupi, 1972). On the seaward side it merges with the Sohm Abyssal Plain (previously discussed) and the Hatteras Abyssal Plain at depths between 5000 and 5450 m. Declivities are similar in the rises, decreasing from about 1° near their landward edges to less than 0.1° near their junctions with abyssal plains.

On the North American Rise near its boundary with the Hatteras Plain, a range of asymmetric hills 10-110 m high and 2-12 km apart are recognizable. Some of the hills, particularly those nearest the abyssal plain, appear to be in an inactive stage and to be in the process of being buried by sediments (Emery and Uchupi, 1972). Satisfactory conclusions about their origin have not been reached.

Abyssal Plain

The Hatteras Abyssal Plain is only about a third as large as the Sohm Plain. It is about 700 km long and extends from a depth of 5200 to 5550 m. At the south end it is connected to the Blake-Bahama Abyssal Plain on the west and to the Nares Abyssal Plain on the east by narrow gaps. From west to east, each of the three plains is progressively deeper. The progressive deepening, flat floors, and connection by channels provide topographic support for sedimentary evidence that the abyssal plains are huge turbidite deposits derived from North American land areas.

SECTOR 3 (SOUTH ATLANTIC BIGHT)

Continental Shelf

This sector encompasses that portion of the Atlantic coast extending from Cape Hatteras to Cape Canaveral. In this region the shelf is separated from the true continental slope by the Blake Plateau, the

Florida-Hatteras Slope, and a small portion of the Florida Straits (Figure 60). From Cape Hatteras to Cape Lookout the East Coast Shelf is flanked by the Blake Plateau and south of Cape Lookout by the Florida-Hatteras Slope. Off Cape Hatteras the shelf break is at a depth of 55 m; it increases to 70 m off Jacksonville, Florida. South of Jacksonville the shelf break becomes progressively shallower to a depth of less than 10 m in the vicinity of West Palm Beach. Variation in depth along the shelf break is due to sediment upbuilding off Cape Hatteras and to calcareous deposition off south Florida.

The Florida-Hatteras Shelf is neither traversed by shelf channels nor incised by heads of submarine canyons. If channels or canyons are present, they are inadequately portrayed on the basis of existing soundings (Emery and Uchupi, 1972). Most prominent of the topographic features are long sinuous shoals that reach most of the way across the continental shelf from the major projections of the coast. Diamond Shoals extends southeastward from Cape Hatteras, Cape Lookout Shoals from Cape Lookout, and Frying Pan Shoals from Cape Fear; smaller unnamed shoals are present off Cape Romain and Cape Canaveral. Sand waves are also prominent features on the Florida-Hatteras Shelf especially in embayments formed by the coastal projections. Small negative topographic features are present in the form of spring holes such as the one about 5 km off Crescent Beach, Florida. This spring is approximately 30 m in diameter and has a depth of about 42 m below the general shelf level. Water at a temperature of 22°C rises to the ocean surface from the Eocene Ocala Limestone, carrying with it much sediment and forming a surface boil.

Included with the depositional forms atop the shelf are the low circular algal banks along the Carolina coast that extend from shore to the outer edge of the shelf and the active and dead coral reefs south of West Palm Beach (Uchupi, 1968). Some calcareous reefs are within a few kilometres of the shore, but more of them are the ancient algal reefs that border the shelf break. These reefs are at depths of 80 to 100 m off Cape Lookout and have been shown to extend more or less unbroken from Cape Hatteras to Miami (Emery and Uchupi, 1972). A general southward shoaling of the reef is probably the result of more active growth of calcareous reef-building organisms in warm southern waters rather than the result of tectonic tilting.

The sand cover on the continental shelf of Sector 3 is well sorted and has a symmetrical grain-size distribution curve. These shelf sands south of Cape Hatteras contain an appreciable amount of calcium carbonate but are still texturally similar to those sands consisting mainly of quartz and feldspar north of Cape Hatteras. Thus, it does not appear that composition influences grain-size distribution on the East Coast Shelf. Most calcium carbonate on the shelf is biogenic and of local origin (Pratt, 1968).

Intermediate Provinces

Florida-Hatteras Slope. Adjoining the continental shelf, the Florida-Hatteras slope occupies the usual position of a continental slope (Figure 60), but differs from slopes in its low gradient, low relief, and interruption by a broad flat terrace (Blake Plateau) at depths less than 700 m. The landward edge of this slope appears to be those algal reefs that border the shelf break. Beyond the reefs, the slope has a declivity angle of about 3°. Emery and Uchupi (1972) interpret the Florida-Hatteras Slope to be a sedimentary apron that prograded across Blake Plateau strata eroded by the Gulf Stream rather than a fault scarp.

Blake Plateau. The Blake Plateau is a broad platform extending from the northern tip of the Straits of Florida to Cape Lookout, where it merges with the continental slope. Depths on the plateau range from 60-750 m along its western margin and from 800-1000 m along its outer edge with an average depth of 850 m. Uchupi (1968) describes the area north of latitude 32° as relatively smooth, dipping seaward with a gradient between 0°47' and 0°20' and forming a transitional zone between the continental slope to the north and the broad, flat plateau proper to the south. The plateau is widest south of latitude 30° (Figure 60); this segment of the plateau is relatively smooth, except for a rough zone near the base of the Florida-Hatteras Slope, which extends from the Straits of Florida to Cape Romain.

Between 30° and 32°N latitude the rough topography extends across the plateau. Broad benches are separated by slopes that are 100-200 m high and that have declivities of about 0°15'. The surface of these benches are slightly warped and contain many boxlike depressions with steep side slopes. Around the margin of the lows separating the benches are depressions, some of which are fringed by coral mounds that reach heights upward to 160 m (Uchupi, 1968). Seaward of the benches, the plateau is relatively smooth. Within this smooth zone is a northeast trending projection, the Blake Spur.

From latitude 32° to latitude 28°, contact between the Florida-Hatteras slope and the plateau is very ragged with isolated depressions abutting the base of the slope. The depressions are linear and may have resulted from erosion by the Gulf Stream. Low conical hills are scattered over both the depressions and the separating spurs. These hills are inferred to be coral mounds similar to those near the edge of the Blake Plateau (Emery and Uchupi, 1972).

Continental Slope

From Cape Hatteras to the Blake Spur the top of the slope is at a depth of 1000 m and its base is at depths ranging from 2000 to 2600 m. Here the slope descends directly onto the crest of the Blake Ridge. The continental slope south of the Blake Spur has the steepest declivity of any segment off the east coast. This part of the slope, known as the

Blake Escarpment has a gradient at least as steep as 15° with parts so steep that they cannot be measured with ordinary echo-sounding equipment (Emery and Uchupi, 1972). The Blake Escarpment at the edge of the Blake Plateau extends almost north-south except where it is interrupted at 30°N latitude by the Blake Spur.

The continental slope off the Carolinas is covered by sand and sandy silt. North of this area, the slope is covered by clayey and sandy silt. These deep sands, basically carbonate in content, may be displaced shallow-water sediments from reefs or banks or may be the remains of pelagic organisms in the ocean.

Abyssal Plain

The Hatteras Plain, which constitutes the abyssal plain in this sector, was discussed under Sector 2 (Middle Atlantic Bight).

OCEANOGRAPHY/METEOROLOGY

GENERAL CIRCULATION

The general circulation of the north Atlantic Ocean is shown in Figure 64. The North Atlantic Ocean is dominated by a clockwise gyre. This gyre may be considered to start with the North Equatorial Current, which is driven by the northeast trade winds. This current is joined at about 10°-15°N latitude by part of the South Equatorial Current, which has turned north across the equator into the North Atlantic. Outside the West Indies, these combined currents are known collectively as the Antilles Current. Off the Coast of Florida the Florida Current, which comes from the Gulf of Mexico, is joined by the Antilles Current, and this admixture forms the Gulf Stream. The Gulf Stream breaks away from the coast at Cape Hatteras and flows northeastward to the Grand Banks

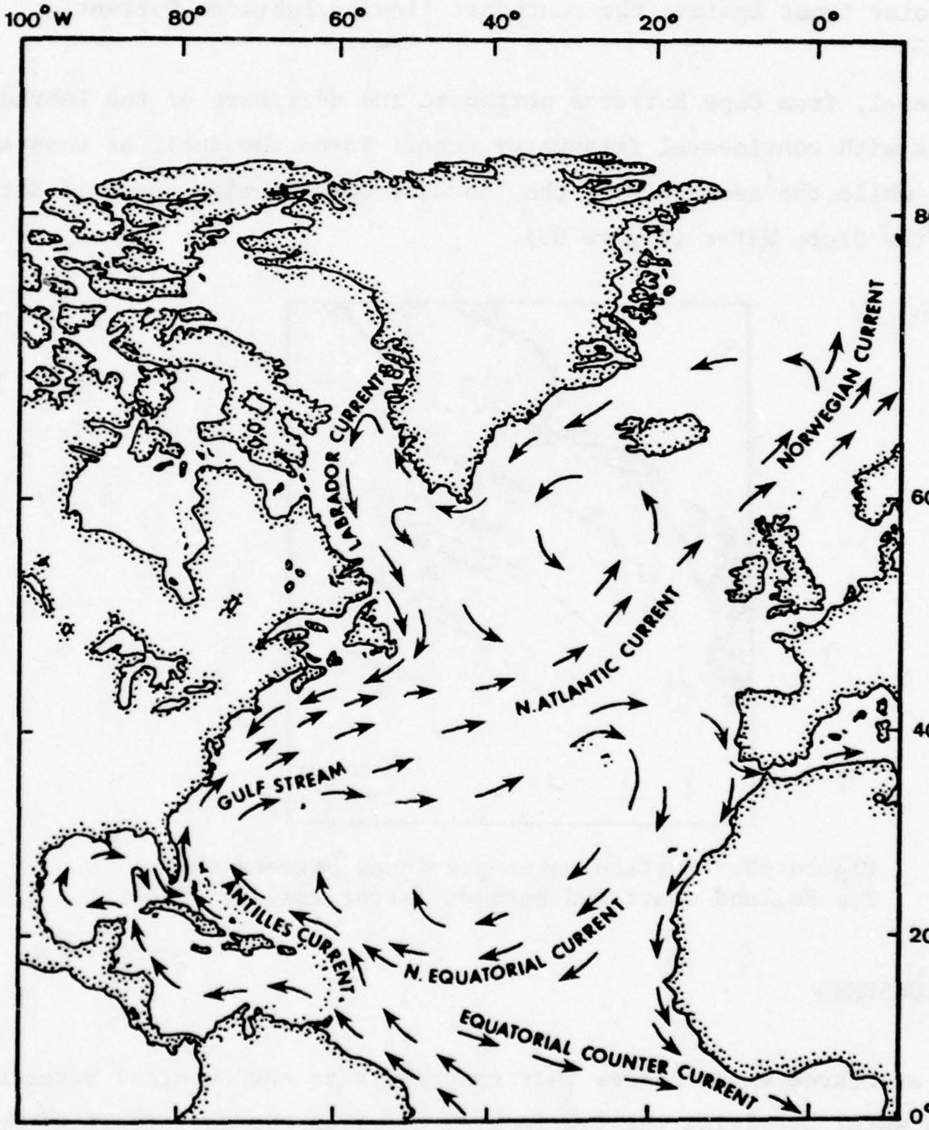


Figure 64. General circulation of the North Atlantic Ocean.

of Newfoundland. From there it becomes diffuse and is known as the North Atlantic Current. The northern edge of the Gulf Stream forms a weak polar front against the southeast flowing Labrador Current.

In general, from Cape Hatteras northward the admixture of the Labrador Current with continental freshwater runoff forms the Shelf or Coastal Water, while the admixture of the Labrador Current with the Gulf Stream forms the Slope Water (Figure 65).

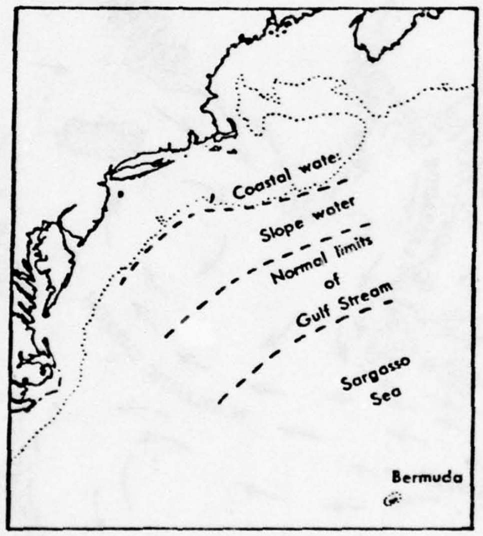


Figure 65. Surface water provinces between the New England coast and Bermuda (after Iselin, 1936).

WATER MASSES

There are three water masses that contribute to the physical structure of the water overlying the continental slope on the east coast of North America. Shelf water (SW) and North American Slope Water (NASW) normally cover this region with somewhat periodic intrusions of the Gulf Stream (GSW), which add to the complexity of the structure.

Shelf Water

Shelf water can be identified in terms of its Temperature/Salinity (T/S) relation by a mode that exists from 3°C, 32.6 ppt to 11°, 35.0 ppt in the volumetric T/S diagram for the mid-Atlantic Bight (Nantucket Shoals to Cape Hatteras).* This mode represents the dominant water mass on the shelf, 31 percent of the total volume during the winter (December, January, February) season (Wright and Parker, 1976). The summer diagram (July, August, September) has more scatter but similar composition. Along this modal line variations in the salinity partial sums are evident with a maximum from 32.6-32.8 ppt, a minimum from 33.6-33.8 ppt and a gradual increase to 35 ppt. The minimum marks the transition between shoreward coastal water (32.6 ppt) and the outlying shelf-edge waters (35 ppt).

A strong correlation exists between the identified subclasses of shelf water and the underwater topography. Water with salinity less than 33.8 ppt constitutes 88 percent of all the water shoreward of the 60-m depth contour. Only 7.5 percent of water in the salinity range 33.5-35 ppt occurs at depths shallower than 60 m and 87 percent of this water occurs in water depths greater than 100 m. From their analysis, Wright and Parker (1976) have determined that the volume of coastal water is remarkably constant, varying from 4945 km^3 in winter to 5147 km^3 in summer.

North American Slope Water

The volumetric T/S diagram for the mid-Atlantic Bight exhibits another modal line that joins the shelf water line at 5°C, 35 ppt and extends to 14°C, 35.2 ppt. These indices mark the main range of NASW in the Bight. The slope water T/S relation closely parallels the North Atlantic basin relation (Wright and Worthington, 1970) but is fresher. Iselin

---

*The volume of this region, inshore of the 200-m isobath, is 7786 km^3 (Wright and Parker, 1976). For comparison, the volume of the North Atlantic Ocean is 137,222,000 km^3.

(1936) considered it 0.02 to 0.04 ppt fresher. The slope water is actually a mixing zone for shelf and Gulf Stream waters. At middepths, the relatively cold waters are quite consistent in character. Slope water was so named by Huntsman (1924) and is indistinguishable in terms of T/S from North Atlantic waters below 900 m. The T/S relation is variable in the surface waters, a fact that reflects the mixing processes that exist in the region. It appears that local climatic conditions affect the structure to a depth of 150-200 m. The mixing mechanisms are then atmospheric and intrusions of shelf and Gulf Stream waters.

Movement of shelf water out over the 200-m contour (over the continental slope) occurs in three ways. Delineated by the 10°C isotherm, the shelf water front actually extends into the slope region above a deeper intrusion of the saltier slope water. During summer the 10°C isotherm is skewed seaward near the surface and shoreward at depth. The offshore movement of the shelf boundary actually represents a 10 percent increase in the shelf water region in a vertical section (Wright, 1976). Complicated temperature and salinity gradients exist in this region. The horizontal exchanges are, therefore, vertically structured and a definite influence is made on the Bight circulation by fluxes along this boundary.* Wright and Parker (1976) state that over half of the shelf-edge water extends over the shelf break in this situation. Shelf water has been found embedded in NASW, and Wright (1976) has broken the occurrence of such "calving" into two classes, which he calls types A and B. The calves are thin lenses of shelf water, approximately 20 to 80 m thick, 10 to 20 km in length, and are defined by temperatures of 10°C or lower and salinities of 34.5 ppt or fresher. Type A has a surface expression of low temperature and is isothermal to 50-80 m. B-type lenses have a minimum temperature at 50 m and may have temperatures of 13°C to 24°C above and 13°C to 15°C below them. (Possibly Type B represents the edge of a Type A lens). These lenses probably form a portion of the

---

*There exists an unpublished T/S analysis of the slope water region by Worthington and Wright.

filamental structures that are often seen on satellite photographs of this region.

A second mechanism for the export of shelf water into the slope water region is entrainment at Cape Hatteras along the northeastern side of the Gulf Stream. Thus, it is not out of the question to have mixing of shelf and slope water on both sides of the slope water region and within the region itself. The mixing process is also augmented by the intrusion of the Gulf Stream into the slope water as it flows along the continental slope and through the means of mesoscale anticyclonic eddies (Figure 66) called rings, which are formed nominally at the longitude of Georges Bank and transit the slope water to Cape Hatteras where they are entrained back into the Gulf Stream (Richardson, 1976). In terms of the physical structure of the mid-Atlantic Bight, these rings can sweep shelf-edge water off the shelf into the slope water region. Further, they are composed essentially of Gulf Stream waters, warmer and more saline than SW and NASW, and reach down to depths of 1000 m with a characteristic "dishpan" lens shape of isotherms and isohalines.

The Gulf Stream

The Gulf Stream, the major boundary current in the western North Atlantic Ocean, represents a band of swiftly flowing waters between NASW and the waters of the North Atlantic central gyre. It forms a continuous movement northward from the Straits of Florida and then northeasterly from Cape Hatteras to Grand Banks (Iselin, 1936). The Stream is approximately 130 n. mile wide and generally no warmer than a corresponding depth in the Sargasso Sea on its eastward and southwestward sides. Occasionally this generalization is broken by the presence of advected waters in its surface layers that have been brought from lower latitudes. There is a considerable gradient in temperature and salinity across the Gulf Stream with, for instance, a cooling of 6° to 7°C in a vertical distance of 400 to 500 m. The Gulf Stream executes small and limited meanders

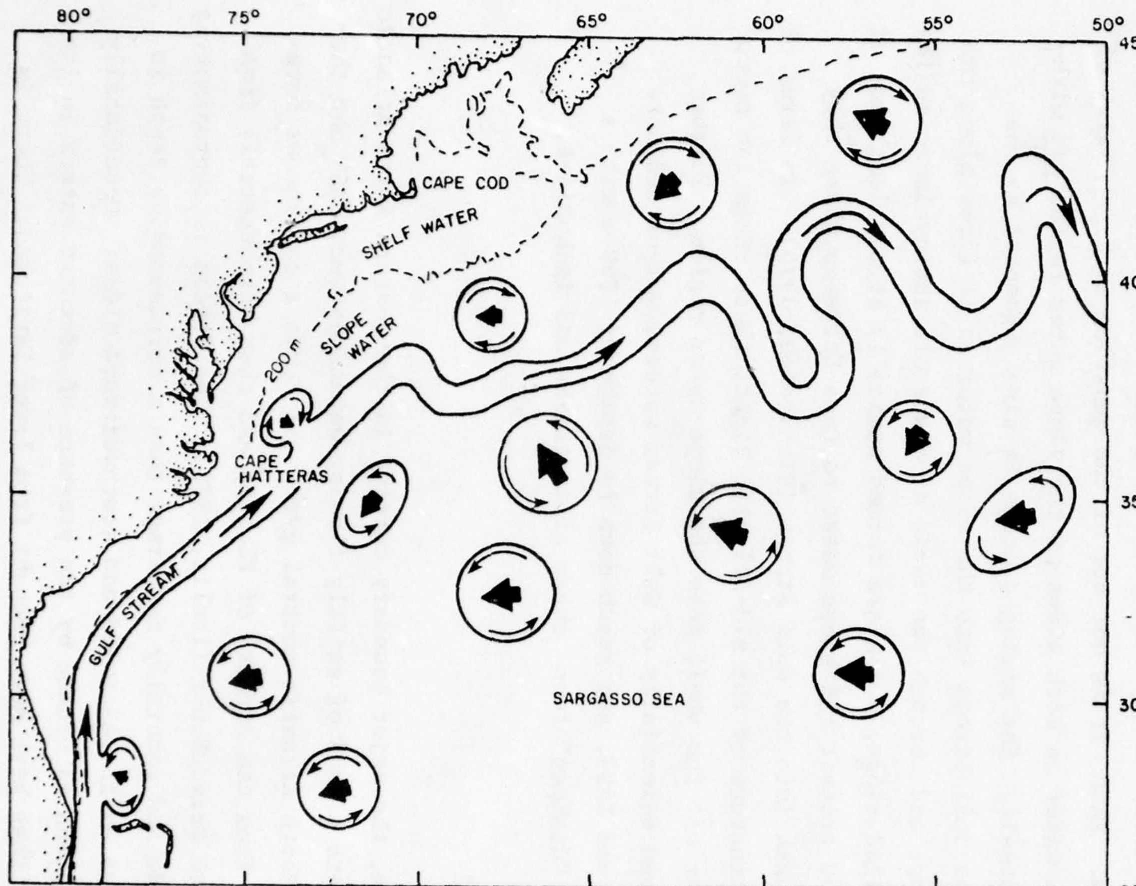


Figure 66. A schematic representation of the path of the Gulf Stream and the distribution and movement of rings (From Richardson, 1976, © Woods Hole Oceanographic Institution)

south of Cape Hatteras and east of 70°W much larger meanders take place (Hansen, 1970) that can eventually progress to complete instability and produce mesoscale rings (both north and south of the main current) (Parker, 1971). The characteristic (or parent wave) T/S index for the Gulf Stream is generally taken as 25°C, 36.3 ppt. The Gulf Stream undergoes zonal transformation as it flows northward by mixing with waters on its shoreward side and from underneath as it proceeds into the North American basin northeast of Cape Hatteras. In addition, cooling and some desalinization occurs due to interactions with the atmosphere.

MESO-SCALE CIRCULATION FEATURES

The dynamic features present at the edge of the continental shelf and over the slope are correspondingly as complex as the physical structure. Movement off, on, and alongshore may be present in addition to advected vortices that circulate water toward and away from the shelf province.

The shelf circulation is certainly responsive to local wind systems and the passage of major winter storms. In the winter, nor'easters can develop a considerable horizontal pressure gradient by setting up water against the coastline. The results are strong south-southwest currents probably in the order of 50 to 75 cm/sec, which would decrease in magnitude toward the shelf break. The period associated with this flow is two or four days (storm passage). This is in contrast with the general drift figure of 5 cm/sec (in a like direction) that is reported by Bumpus (1973) for the background motion from Nantucket Shoals to Diamond Shoals. Winds of this nature endure for up to a week. At Cape Hatteras the slow flow is entrained in the Gulf Stream except in certain instances when meteorological conditions permit the inshore passage of water around the cape to the south. Mixing and convective motions on the inner portions of the shelf are generated with the development of wind systems during the fall and by spring warming and freshwater runoff. These motions are directly correlated to the maintenance of the T/S structure of the region. Superimposed on this possible pattern are the semi-diurnal and diurnal tidal motions that effectively surge the bight rhythmically at 12.4- and 24-hour periods, respectively. These tidal components are linked to the generation of internal wave motions of the same periods. The internal waves propagate shoreward in the slope water essentially following the density structure onto the shelf. Breaking has not been directly observed, but satellite evidence has been cited for their existence on the shelf. At the shelf edge, wind-driven inertial motion should be present and contributes to swirling, mixing motions in the surface layers.

Kroll and Niiler (1976) have discussed the possibility of topographic Rossby waves, which would move upslope onto the shelf and bring longer period motions of the order of one month into play in the region. The motion of the Gulf Stream also plays a part in these longer period motions or surges at the shelf break. Gulf Stream meanders have been observed in satellite photographs to regularly move shoreward and retreat at time intervals of weeks to a month. Given a sufficient departure from its mean path and a sustained growth, these intrusions into the slope water region can break off and become separate dynamic entities known as anticyclonic rings (Saunders, 1971). Trapped in the slope water and bounded by the coastline and the Gulf Stream, these rings transit the mid-Atlantic Bight in two to three months serving as significant mixing mechanisms. Anticyclonic rings rotate in a clockwise manner and bring slope water onto the shelf while transporting cold, fresh water off the shelf in their lee. In addition, by turbulent transfer, their initial Gulf Stream water mass is introduced into the environment at its periphery. The swirl velocity around the ring can amount to 50 to 100 cm/sec.

WINDS AND STORMS

Sector 1 (Northeast Coast)

Winds. The surface winds over the North Atlantic area (both onshore and offshore) generally come from a prevailing westerly direction throughout the year. There is an overall shift to the northwest during winter months and to the southwest during summer (Brower et al., 1972; U.S. Army Corps of Engineers, 1973). Annual average onshore winds in Sector 1 range from a high of 11.5 knots at Boston, Massachusetts to a low of 7.3 knots at Brunswick, Maine (U.S. Department of Commerce, 1976a). Offshore wind conditions for the Boston Sea area show an annual mean of 14.2 knots from the southwest. The offshore winds are, for the most part, higher than those reported for onshore stations; however, directions are basically the same -- northwest component in winter and southwest in summer. The winter months, i.e., December through February, have the greater average velocities whereas the minimum average speeds are noted during July and August. Maximum annual wind speed for Boston is reported for the month of August when velocities reached 56 knots from the north-northwest. Additional data concerning wind conditions within Sector 1 are shown in Table 29.

Storms. Storms passing through the North Atlantic area are of either the tropical or extratropical type. The low pressure center of the extratropical storm enters the region from the west, coming through the St. Lawrence Valley or New England, or the southwest, coming from offshore. The tropical storms form over the warm waters of the Caribbean, Gulf of Mexico, or the Atlantic south of Cape Hatteras and move into the area of Sector 1 along the Atlantic coast or from offshore.

The extratropical cyclones ("Nor'easters"), which move through the area from the southwest (with northeast winds), may be more severe in terms of precipitation and winds than those moving in from the west. These storms can form at any time but are more frequent and intense between October and April (Brower et al., 1972) with maximum severity near New England and Canada. Heavy snow or rain may be extensive before the storm center passes and gales of hurricane force can occasionally occur (U.S.

Table 29

Wind Conditions Within Sector 1, Northeast Atlantic Coast

Month	Mean Speed (Knots) and Direction		
	Brunswick, Maine	Boston, Massachusetts	Gulf of Maine
January	7.3 N	12.4 WNW	18.8 NW
February	7.7 N	12.6 WNW	18.3 NW
March	8.4 N	13.2 NW	16.9 WNW
April	8.9 SSW	13.0 WNW	13.5 W
May	8.5 SSW	11.9 SW	12.0 SW
June	7.6 SSW	10.8 SW	11.4 SSW
July	7.1 SSW	10.2 SW	9.9 SW
August	5.3 SSW	10.0 SW	10.9 SW
September	6.7 SSW	10.3 SW	12.0 SW
October	6.6 S	10.8 SW	14.1 SW
November	6.5 N	11.6 WNW	16.8 NW
December	7.0 N	12.0 WNW	18.3 W
ANNUAL	7.3 SSW	11.5 SW	14.2 SW

From U.S. Department of Commerce, 1975; 1976a

Department of Commerce, 1976a).

Tropical cyclones are most likely to move north into the area during late summer and autumn, though the frequency is low. These storms generally travel through the area in a northeastern direction towards and across Nova Scotia or over adjacent waters and are usually much more severe than extratropical storms that have occurred in the same season. However, many are less intense upon arrival in Sector 1 than they originally were in southern latitudes. Tropical cyclones with winds of 34-63 knots are called tropical storms while those with winds greater than 63 knots are hurricanes.

The northeastern United States has been severely affected by hurricanes five times between 1938 and 1963. Their frequency can, therefore, be estimated to average approximately one per six years, whereas nor'easters with storm surges of two or more feet occur at least once or twice per year. The approximate paths of all hurricanes that passed through the North Atlantic region between 1901 and 1963 can be found in Cry (1965).

Thunderstorms usually occur during the summer months (U.S. Army Corps of Engineers, 1972) but they have occurred in New England during every month of the year. Boston averages 19 days per year with thunderstorm activity while Portland averages 18 days.

Sector 2 (Middle Atlantic Bight)

Winds. Surface winds over the Middle Atlantic region are very similar to those discussed under the Northeast Coast Sector; that is to say, they generally come from a prevailing westerly direction throughout the year, and they experience the same winter and summer shifts to the north and south, respectively. Also, the average wind speeds are generally lower during the warmer months than those during the colder months. The offshore winds, however, do exhibit a tendency to be slightly stronger than onshore winds during winter but exhibit little difference during the summer (U.S. Department of commerce, 1975, 1976b, 1976c).

The position and intensity of the Bermuda-Azores high pressure system primarily controls the Atlantic coast's general surface wind pattern. Its characteristics and location are quite variable through the year. During the winter, the system is centered far to the southeast, which causes major low pressure storm systems to move through the mid-Atlantic states. In the spring, its migration northward begins to affect the southeastern United States. The northernmost position is attained during the summer and at this time the entire eastern seaboard is within its circulation, causing frequent showers and thunderstorms and fairly low wind speeds. Finally, in the fall, the Bermuda-Azores high moves southward and eastward with the weather gradually returning to its winter pattern.

Table 30 presents average wind speeds on both a monthly and annual basis for selected offshore regions. Observations by ocean vessel station "Hotel" is probably most representative of the full range of weather conditions since weather is its primary mission, and the other regions rely on ships in passage for data (Havens et al., 1973). Figure 67 shows locations of the offshore regions under consideration.

Storms. Most storms that occur throughout the mid-Atlantic region are either of the transcontinental or of the tropical type (U.S. Army Corps of Engineers, 1972). In general, the tropical storms occur in the fall or early winter (and are more extensive) while the transcontinental ones occur primarily in the spring. In New Jersey, severe tropical storms causing significant destruction can be expected to occur, on the average, once every five years (EG & G Environmental Consultants, 1973).

According to Cry (1965) the regions of maximum tropical cyclone (hurricane) activity have been Florida, Texas, the middle Gulf coast,

Table 30

Wind Conditions Within Sector 2, mid-Atlantic Bight

Month	Mean Speed (Knots) and Direction			
	New York*	Atlantic City*	Norfolk*	"Hotel"*
January	15.1 W	16.5 NW	16.1 NW	21.0 NW
February	15.3 W	16.1 NW	15.7 NW	22.0 NW
March	17.7 W	15.1 NW	15.4 NW	22.0 NW
April	12.5 W	13.1 S	13.8 S	19.0 SW
May	10.2 S	10.9 S	11.8 S	17.0 SW
June	9.8 S	10.3 S	10.9 S	13.0 SW
July	9.3 S	10.5 S	10.7 S	12.0 SW
August	9.2 S	10.7 S	10.9 S	15.0 SW
September	10.9 S	11.8 S	12.2 S	16.0 E
October	12.1 NW	13.8 N	13.9 N	15.0 E
November	14.5 W	15.2 NW	14.7 NW	18.0 NW
December	15.4 W	15.6 NW	15.2 NW	21.0 NW
ANNUAL	12.2 S	13.2 S	13.4 S	18.0 SW

*Locations of these offshore weather data regions are mapped in Figure 67.

(From Havens et al., 1973; U.S. Department of Commerce, 1975, 1976b).

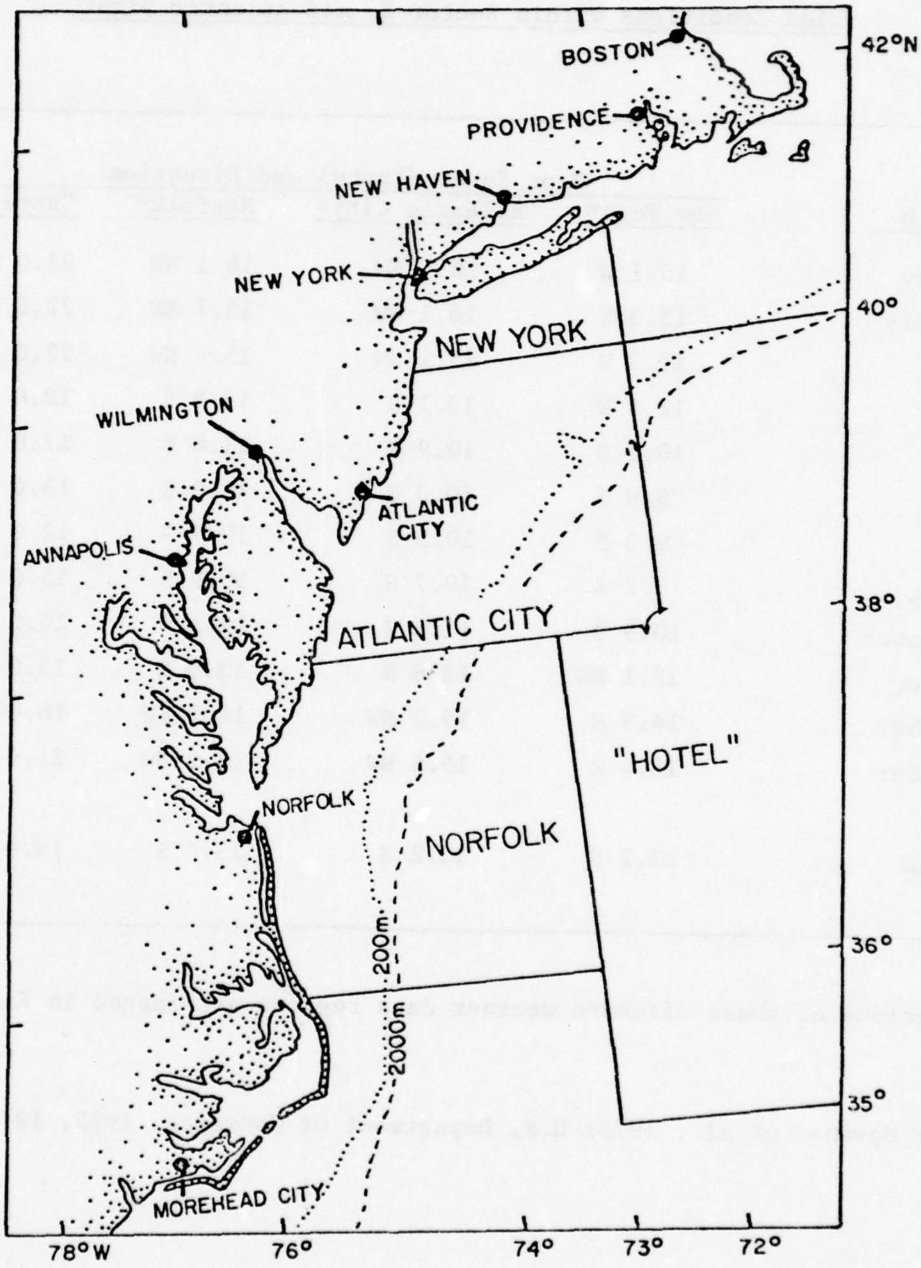


Figure 67. Location of offshore regions providing weather conditions as tabulated in Table 30 (after Havens et al., 1973).

and the Carolinas. Cry (1965) has illustrated the approximate paths of all hurricanes that have passed through the mid-Atlantic region between 1901 and 1963. The period from November 1 to May 31 is the least active in terms of hurricanes, with only two having occurred over the 63-year span. On the other hand, the period from August 21 to September 10 is the most active with a total of 17 hurricanes occurring over the 63 years.

Thunderstorms account for the majority of the precipitation in the mid-Atlantic area from May to September. These are generally localized and tend to be spotty, but they are most frequent over land or near coastal waters in the afternoon, while at night they are more common over the open ocean.

Extratropical storms, north'easters, occur throughout the year but with greater likelihood during the winter. These storms normally enter from the west and pass through the northeastern states and down the St. Lawrence Valley, or they enter from the southwest with their centers offshore.

Sector 3 (South Atlantic Bight)

Winds. In winter over the northern part of the sea area of this sector (north of latitude 30°) predominant winds are from the western quadrant with northwest and southwest winds being quite frequent. Along the Florida coast, south of latitude 30°, easterly winds are predominant throughout the year. Winds from the southwest, south, and northeast are equal in frequency over the northern portion in the spring, whereas along the middle coast of this sector south and southwest winds predominate. In the summer the Bermuda-Azores high causes southwesterly winds over the northern and middle portions of the coast in Sector 3. Recession of the high pressure system in the autumn results in an increase in the frequency of northerly winds from the middle part of the coast northward.

Wind velocities over Sector 3 are generally moderately light, averaging 7-10 knots over the year (Table 31). Monthly averages vary in summer from 6-10 knots and 8-12 knots in winter. North of Cape Hatteras the frequency of calms is less than 1 percent, but over the majority of the South Atlantic Bight Sector it ranges from 15-20 percent during the year. Though winds greater than 34 knots are comparatively infrequent, they have been recorded at the stations listed in Table 31 at almost any time of the year (U.S. Department of Commerce, 1976c).

Storms. Cry (1965) reports that the Florida-Georgia region has been significantly affected by 43 hurricanes between the years of 1901 and 1963. Within that period the two-state area encountered 51 tropical storms. During the same 1901-1963 interim the Carolinas were affected by 27 hurricanes and 15 tropical storms.

The coastal region of Sector 3 has generally experienced tropical cyclones of one type or another as early as May 28 and as late as December 2. That portion of the region near Miami is most likely to experience a hurricane in any one year (16 percent probability). Probability drops to less than 2 percent farther north in the Jacksonville area, rises back up to 8 percent in the Charleston area, and stays uniformly high, peaking again at 11 percent probability at Cape Hatteras.

FISHERIES RESOURCES

SECTOR 1 (NORTHEAST COAST)

Traditionally, the northwestern Atlantic Ocean has been considered one of the more productive fishing grounds in the world. The fishing industry of the northeastern U.S. is large and varied, operating both nearshore and considerable distances offshore, although the bulk of the catch

Table 31

Wind Conditions Within Sector 3, South Atlantic Bight

Month	Mean Speed (Knots) and Direction: Cape Hatteras	Wilmington	Charleston	Savannah	Jacksonville	West Palm Beach
January	11.3 NNE	8.2 N	8.0 SW	7.5 WNW	7.4 NW	8.6 NW
February	11.7 NNE	9.1 NW	8.9 NNE	8.3 NE	8.5 WSW	9.0 SE
March	10.9 SW	9.3 SSW	9.0 SSW	8.3 WNW	8.4 NW	9.3 SE
April	10.8 SW	9.4 SSW	8.7 SSW	9.1 SSE	8.1 SE	9.4 E
May	10.9 SW	8.4 SSW	7.7 S	7.1 SW	7.8 WSW	8.3 ESE
June	9.6 SSW	7.5 SSW	7.4 S	6.7 SW	7.5 SW	7.0 ESE
July	9.1 SW	7.2 SSW	6.9 SW	6.4 SW	6.7 SW	6.5 ESE
August	8.7 SW	6.8 SW	6.5 SW	6.1 SW	6.5 SW	6.4 ESE
September	9.4 NE	7.2 N	7.0 NNE	6.7 NE	7.4 NE	7.5 ENE
October	10.2 NNE	7.4 N	7.1 NNE	6.8 NNE	7.7 NE	8.6 ENE
November	10.2 NNE	7.3 N	7.1 N	6.8 NNE	7.4 NW	8.6 ENE
December	10.5 NNE	7.5 N	7.5 NNE	7.2 NE	7.2 NW	8.5 NNW
ANNUAL	10.2 SW	8.0 SSW	7.6 SW	7.2 SW	7.5 NW	8.1 ESE

From: U.S. Department of Commerce, 1976c.

comes from waters over the continental shelf. Before 1960 the offshore fishing grounds between Nova Scotia and the Hudson Canyon had been exploited almost exclusively by U.S. fishermen. Since that time, foreign vessels have greatly expanded their exploitation of the area to the point where the foreign annual harvest is 2 to 5 times greater than that of U.S. fishermen. During this time of increased exploitation by foreign nations, the total annual catch of fish has increased while U.S. landings over the same period have declined.

The average annual landings of fish and shellfish in the northeastern U.S. is presented in Table 32. Representing mean values over the period 1970-73, the northeast landings includes catches brought to port in New Jersey, New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine. Some contribution from the mid-Atlantic Bight fisheries to these values is inevitable.

Table 32

Annual Average Fish Landings in the Northeastern U.S. for the years 1970-73

(Values = 10^3 pounds and 10^3 dollars.)

	Fish Landings		
Catch Basis	Finfish	Shellfish	Combined
weight	573,681	128,268	701,949
value	\$52,707	\$83,716	\$136,423

Adapted from: U.S. Department of Interior, 1976

The contribution of these northeastern states is approximately 15-20 percent of the total U.S. fish production. However, these percentages do not reflect the true productivity of the region especially Georges Bank, because the landings by foreign vessels are not included.

Most of the major fishing areas of New England are banks or shoals, ranging in size from a few square kilometres to large plateaus, e.g., Browns Bank, Georges Bank. The relative importance of Georges Bank to the northwest Atlantic fishery is evident from records of the International Commission for the Northwest Atlantic fisheries. For the years 1968-72, 57 percent of the total catch was taken on Georges Bank, 22 percent was taken to the west of Georges Bank in the Rhode Island Sound vicinity, 19 percent was taken in the Gulf of Maine, and the remainder was taken from peripheral areas. Also important to the fisheries are the deep basins in the Gulf of Maine and to the north of Georges Bank, which provide refuge for species such as the longfin hake and redfish.

Of nearly 200 species of fish reported to range within the area, less than half contribute to the commercial or sport catch. Less than 30 are of significant commercial value.

Two particularly important aspects of the northwestern Atlantic fishery are the numerical contribution of the demersal finfishes and the economic significance of the shellfish (crustaceans and molluscs). The American Lobster (Homarus americanus) and hard clam (Mercenaria mercenaria) provide the greatest dollar value, together accounting for an average of 41 percent of the northeast U.S. fishery production in 1970-73.

Demersal fishes, which are important to the northeastern U.S. fishery, are primarily the cod, haddock, hakes, and flounders. Ocean perch, scup, and pollock also make a significant contribution. Herring and menhaden dominate the pelagic catch, and although the pounds landed of menhaden and herring are number 1 and 2, respectively, their contribution to the total fishery value of the northeast is quite small.

Because of the preponderance of demersal fishes whose close association with the bottom makes them more susceptible to impacts from dredged material disposal, the New England fisheries constitute a significant biological concern in selecting a dredged material disposal site. It is fortunate in considering deep ocean disposal that these demersal fisheries are largely confined to the waters overlying the continental shelves. The continental shelves in the northeast U.S. are very wide, and fishing efforts extend over their entirety. Although greatest fishing efforts are in depths less than 200 m, the range of many important demersal species extends below 200 m into the upper slope zone. Those species of commercial importance, whose range extends to the edge of the continental shelf and on to the slope and thus would be of primary concern in deep ocean disposal, are presented in Table 33.

SECTOR 2 (MIDDLE ATLANTIC BIGHT)

Of approximately 300 species of marine fishes reported to occur in the mid-Atlantic Bight, less than half consistently occur on a yearly basis (Saila and Pratt, 1973). Although about 80 species are considered commercial species, almost the entire present commercial catch is made up of approximately 30 species.

In the mid-Atlantic states the relative importance of shellfisheries is greater than in the northeast. Hard clams, lobsters, surf clams, and oysters continue to be the top four fisheries providing the greatest dollar value. The contribution of demersal finfish to the mid-Atlantic fishery production is reduced from that in the northeast, and the importance of pelagic fisheries is increased, e.g., bluefish, bluefin tuna, seatrout, striped bass, mackerel, and others.

Owing to the proximity of Georges Bank to some of the northern mid-Atlantic states, a portion of the landings credited to the mid-Atlantic production are inevitably taken in the prolific fishing grounds immediately to the north. This overlap in mid-Atlantic and New England fisheries notwithstanding, the mid-Atlantic states (Rhode Island,

Table 33

Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to the Northeastern U.S. Fishery

Species	Occurrence	Depth Range
Cod Gadus morhua	Abundant off Nantucket, north of Cape Cod, and southeast of Nova Scotia to Newfoundland and Greenland	90-310 m spawns 200 m
Haddock Melanogrammus aeglefinus	North of 41°N, abundant on northern edge of Georges Bank and Browns Bank	30-410 m
White hake Urophycis tenuis	North of 41°N, abundant along northeastern edge of Georges Bank and in Gulf of Maine	30-410 m
Squirrel hake Urophycis chuss	Nova Scotia to Cape May, N.J. abundant south of Cape Cod	30-370 m
Longfin hake Urophycis chesteri	Deep waters of Gulf of Maine at northern edge of Georges Bank	150-410 m
Silver hake Merluccius bilinearis	Nova Scotia to New Jersey, abundant west and southeast of Georges Bank and south of Cape Cod	30-410 m
Redfish Sebastes mentella	Eastern Georges Bank and Gulf of Maine, north to Greenland, abundant in deep basins in Gulf of Maine	50-600 m
Longhorn sculpin Myoxocephalus octodecimspinosus	South of 42°N, abundant on Georges Bank and southeast of Cape Cod	37-370 m
American goosefish Lophius americanus	Nova Scotia to Hudson Canyon abundant on north edge of Georges Bank	30-310 m

(Continued)

Table 33 (Concluded)

Species	Occurrence	Depth Range
Butterfish *Poronotus triacanthus*	South of 41°N, abundant south of Cape Cod to Hudson Canyon	30-270 m
Scup *Stenotomus versicolor*	South of 41°N, abundant south of Cape Cod	30-170 m
American pollock *Pollachius virens*	Gulf of St. Lawrence to New Jersey, occasionally to Chesapeake Bay; abundant near and west of Nova Scotia, and in Gulf of Maine.	30-370 m
Gray sole (Witch flounder) *Hippoglossoides platessoides*	Gulf of St. Lawrence to Cape Hatteras, abundant in Gulf of Maine and southeast of Nova Scotia along outer shelf and slope	35-1500 m
Yellowtail flounder *Limanda ferruginea*	Eastern Georges Bank south to Hudson Canyon, north of Cape Cod	30-190 m
Fourspot flounder *Paralichthys oblongus*	South of 42°N, abundant from eastern Georges Bank to Hudson Canyon	30-130 m
American plaice (dab) *Hippoglossoides platessoides*	North of 41°N, abundant inshore north of Cape Cod and southeast of Nova Scotia	30-330 m
Ocean perch *Sebastes marinus*	Iceland to New Jersey on outer shelf and upper slope	70-330 m
American lobster *Homarus americanus*	From Labrador to North Carolina, at edge of continental shelf south and east of Georges Bank, also common nearshore	Nearshore and at edge of continental shelf
Deep sea prawn *Pandalus borealis*	Deeper parts of Gulf of Maine, at edge of continental shelf north to Greenland	200+ m; most abundant at 100-250 m

Compiled from: Fritz, 1965; Food and Agriculture Organization, 1972; and U.S. Department of Interior, 1976.

Connecticut, New York, New Jersey, Delaware, Maryland, and Virginia) contribute about 7-10 percent of the total U.S. fishery production. The average annual landings of fish and shellfish in the mid-Atlantic states is presented in Table 34.

Table 34

Annual Average Fish Landings in the Mid-Atlantic States (exclusive of Chesapeake Bay) for the years 1970-73 (Values = 10^3 pounds and 10^3 dollars)

Catch Basis	Fish Landings Finfish	Shellfish	Combined
weight	278,892	103,385	382,278
value	\$18,167	\$41,417	\$59,585

Adapted from: U.S. Department of Interior, 1975.

With the exception of the Georges Bank contribution, the mid-Atlantic fishery is more coastal than the New England fishery. With the abundance of shellfish in estuarine and coastal waters, the increased importance of pelagic fisheries, and the diminution and shoreward tendencies of demersal fisheries, deepwater disposal of dredged material presents relatively few problems with regard to mid-Atlantic fisheries. Those commercial species whose range extend over the shelf are presented in Table 35. It should be noted that most of these species occur primarily in the New England area (cf. Table 33) and that the mid-Atlantic area constitutes the margin of their range.

Unique or highly productive biotopes are not common to the offshore mid-Atlantic area. Productive banks and basins, which typify the New England area are lacking in the mid-Atlantic Bight. Canyons, which incise the continental shelf, e.g., Hudson and Baltimore Canyons, are

Table 35

Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to the Mid-Atlantic Fishery

Species	Occurrence	Depth Range
Sea scallops *Placopecten magellanicus*	Labrador to Cape Hatteras most abundant off New Jersey to the Hudson Canyon and south, also off the Virginia capes	3 to 200 m most abundant at 80-100 m
American lobster *Homarus americanus*	Labrador to North Carolina largely on offshore population in mid-Atlantic	80-460 m
Silver hake *Merluccius bilinearis*	Nova Scotia to New Jersey pri- parily an inshore fishery in mid-Atlantic	30-410 m
Yellowtail flounder *Limanda ferruginea*	Southern New England to Hudson Canyon	30-190 m
Fourspot flounder *Paralichthys oblongus*	Southern New England to Hudson Canyon	30-130 m
American goosefish *Lophius americanus*	Nova Scotia to Hudson Canyon abundant north of Georges Bank	30-310 m
Squirrel hake *Urophycis chuss*	Nova Scotia to Cape May, New Jersey, abundant south of Cape Cod	30-370 m
Longhorn sculpin *Myoxocephalus octodecimspinosus*	South of 42°N, abundant south- east of Cape Cod and on Georges Bank	30-370 m
Butterfish *Poronotus triacanthus*	South of 42°N, abundant south of Cape Cod to Hudson Canyon	30-270 m
Scup *Stenotomus versicolor*	South of 41°N, abundant south of Cape Cod	30-170 m

(Continued)

Table 35 (Concluded)

Species	Occurrence	Depth Range
Pollock Pollachinus virens	Primarily north of 41°N, occasionally as far south as Chesapeake Bay	30-370 m
Red crab Geryon quinquedens	Nova Scotia to Cuba shallower off Nova Scotia deeper than 300 m south of New England, tends to congregate near canyons (This species is not presently harvested, but is considered to have good commercial potential.)	100-150 m

Compiled from: Food and Agriculture Organization, 1972; Fritz, 1965; Saila and Pratt, 1973; U.S. Department of Interior, 1975.

thought to have unique faunal assemblages and provide important migration pathways for fish and shellfish.

SECTORS 3 AND 4 (SOUTH ATLANTIC BIGHT AND PENINSULAR FLORIDA)

The fisheries of the south Atlantic states rely heavily on shallow coastal and estuarine areas for the bulk of fishery production. Commercial fisheries are almost totally limited to shoreward of the 100-m isobath north of Cape Hatteras and shoreward of the 80-m isobath to the south. Shrimp constitute the most valuable fishery in the area. The area is second only to the Gulf of Mexico in value of the shrimp fishery. Other shellfish include crabs, oysters, scallops, and spiny lobster. Major finfish species include menhaden, flounder, spot, alewives, mullet, seatrout, mackerel, sea bass, croaker, and bluefish.

The south Atlantic fishery contributes only 6-8 percent to the total value of U.S. landings. The average annual landings of fish and shellfish in the south Atlantic states of North Carolina, South Carolina, Georgia, and the Atlantic coast of Florida, are presented in Table 36.

Table 36

Annual Average Fish Landings in the South Atlantic States for the years 1972-74 (values = 10^3 pounds and 10^3 dollars)

	Fish Landings		
Catch Basis	Finfish	Shellfish	Combined
weight	189,656	70,169	259,825
value	\$14,713	\$33,413	\$48,126

Adapted from: U.S. Department of Interior, 1977

In the southeast Atlantic states there is a pronounced paucity of demersal fisheries, which range to depths of the outer continental shelf and slope. The royal red shrimp (Hymenopenaeus robustus) is a deepwater species found off Florida between Cape Canaveral and St. Augustine. However, their commercial importance at present is very limited due to the great depth at which they occur (350-600 m). The red snapper (Lutjanus aya) is common to the South Atlantic Bight and the Gulf of Mexico. Occurring at depths from 20 to 200 m, 90 percent of the catch comes from rock outcrops, reefs, and banks between North Carolina and Florida. These outcrops are considered to be unique or productive biotopes in the South Atlantic Bight, and as such should be given prime consideration in selecting dredged material disposal sites. Examples of these features include the Lithothamnion reef at the 80- to 110-m isobath between Cape Lookout and Cape Fear (Menzies et al., 1966); Black Rock reefs (Roberts et al., 1975); the hard bottom communities and sports fishing grounds along the 100- to 200-m isobath off Capes Hatteras, Lookout, and Fear (U.S. Department of Interior, 1977).

E. PACIFIC COAST (SECTORS 6, 7, AND 8)

GEOMORPHOLOGY

SECTORS 6 AND 7 (SOUTHERN CALIFORNIA BIGHT AND NORTHERN CALIFORNIA SHELF)

The geographic limits of Sector 6, the Southern California Bight, extend from the California-Mexico border north to Point Conception. Sector 7, the Northern California Shelf, occupies the coastal region on northward to Cape Mendocino. The continental margin of that region of the United States has a complex topography that differs markedly from those of the Gulf of Mexico or Atlantic seaboard.

Continental Shelf

The marginal continental shelf of southern and central California is narrow within the 200-m isobath, ranging from less than 2 km to about 50 km wide (Emery, 1960; Rusnak, 1966). From Point Conception northward (Sector 7), the continental shelf is normal, in the sense of its being somewhat broad and relatively flat. Islands, such as the Farallons of San Francisco, rise above the general level and many submarine canyons incise it below the general level. The continental shelf forms a broad plain in this region ranging from 30 to 40 km in width. Declivity of the shelf is gradually seaward with average inclinations of less than 0.5°. At depths of 125 to 150 m the slope steepens to 4-5° forming the shelf break and the beginning of the continental slope. Erosive forces during periods of glacially lowered sea level contributed measurably to its formation. Sediments on the continental shelf tend to be shallow detrital sands containing various amounts of organic and authigenic sand-sized material (Moore and Shumway, 1959). The outermost portion of the shelf and the adjacent slope reveals sandy silts that grade to fine silts seaward. Many more submarine canyons occur north of 36°N latitude than farther south. Some of the canyons, e.g., Delgado and Monterey, are traceable across the continental shelf and slope into the continental rise. Others, especially in the San Francisco region, are confined to the outer edge of the shelf and slope. Bodega Canyon, unusual in that it changes course from an east-west trend on the slope to north-south near the shelf break, is an example of the confined canyons (Uchupi and Emery, 1963).

South of Point Conception (i.e., Sector 6) the area usually occupied by the continental shelf is so different from typical shelves that it was given a special name, continental borderlands, by Shepard and Emery (1941). In this borderland (Figure 68) are more than 20 basins as deep as 3000 m and separated by submarine ridges, banks, and even islands that rise upward to 500 m above sea level (Uchupi and Emery, 1963). The basins contain thick sediment fills of late Cenozoic age whereas the high areas consist of middle Cenozoic to middle Mesozoic sedimentary,

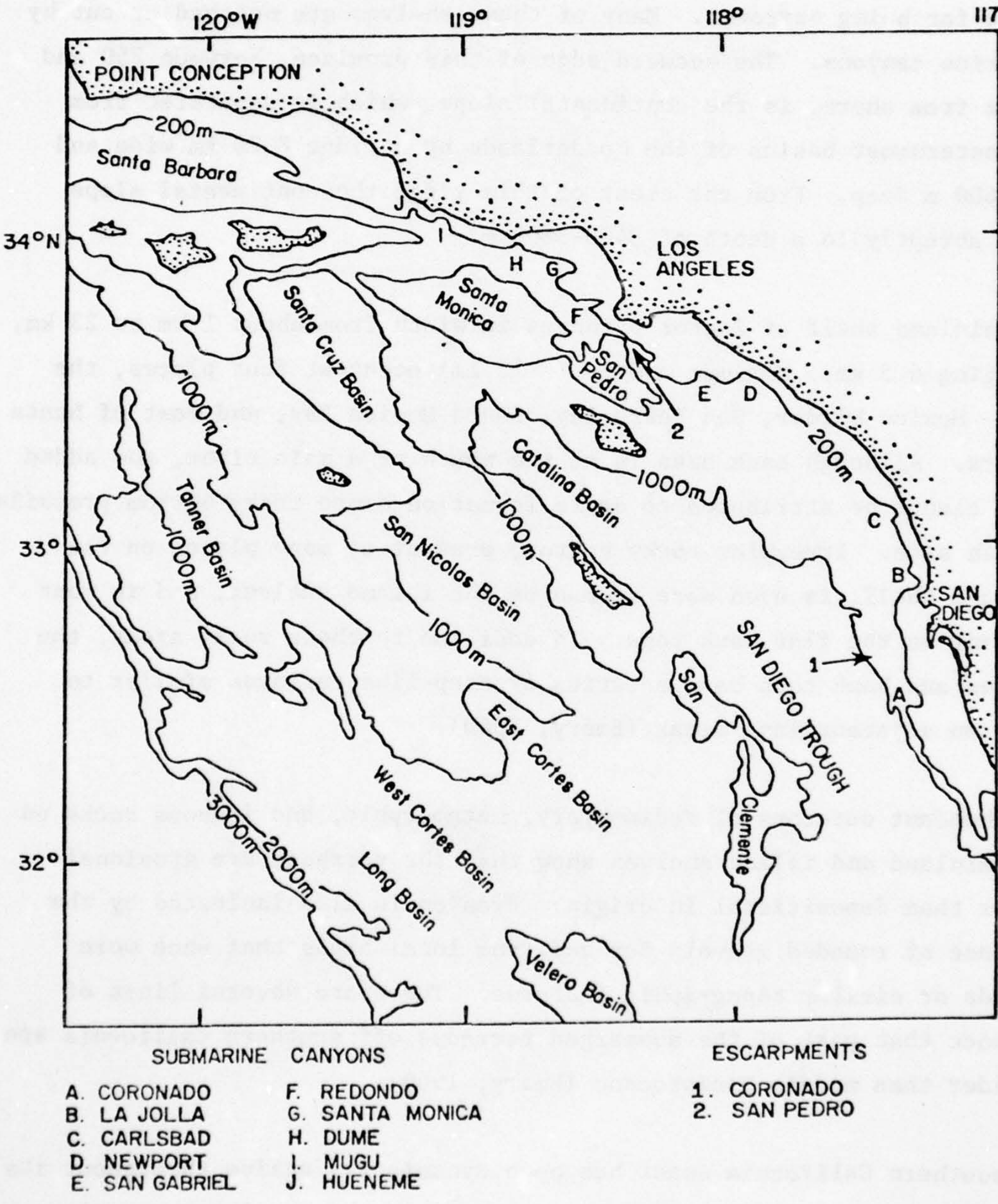


Figure 68. Continental borderlands off southern California showing basins, canyons, and escarpments (modified from Uchupi and Emery, 1963).

igneous, and metamorphic rocks. Shelves around the islands and along the mainland coast are comparable with typical continental shelves, except for being narrower. Many of these shelves are notched or cut by submarine canyons. The seaward edge of this province, between 250 and 300 km from shore, is the continental slope, which is separated from the westernmost basins of the borderlands by a ridge 8-20 km wide and 400-1600 m deep. From the crest of this ridge the continental slope drops abruptly to a depth of 3400-3800 m.

The mainland shelf of Sector 6 ranges in width from about 1 km to 23 km, averaging 6.5 km. Maximum widths ($>$12 km) occur at four places, the U.S. - Mexico border, San Pedro Bay, Santa Monica Bay, and east of Santa Barbara. Although each area is at the mouth of a main river, the added width cannot be attributed to delta formation since rocky bottom prevails at each site. Irregular rocky bottom, present at many places on the mainland shelf, is even more common on the island shelves, and is most abundant on the flat bank tops. In addition to these rocky areas, the shelves and bank tops have a series of step-like terraces similar to those on adjacent land areas (Emery, 1960).

The abundant outcrops of sedimentary, metamorphic, and igneous rocks on the mainland and island shelves show that the terraces are erosional rather than depositional in origin. Erosion is also indicated by the presence of rounded gravels derived from local highs that once were islands or similar topographic features. There are several lines of evidence that part of the submerged terraces off southern California are no older than middle Pleistocene (Emery, 1960).

The southern California coast has been dynamically active throughout its history. Seismic activity, i.e., earth movement, over large as well as small segments of the area have changed the position and shape of the coastal area while variations in sea level played their significant role. Erosion of the rugged hinterland has contributed vast quantities of sediments to the coastal waters with ultimate deposition in the deep basins. This detritus was, in part, afforded passageway to the deeper realm via numerous canyons incising the mainland shelf. Major submarine canyons in Sector 6 include Scripps, La Jolla, San Gabriel, Redondo, Santa Monica, Dume, Mugu, and Hueneme (Figure 69). Of all the sediments of the mainland shelf those composed of detrital fragments are by far the most common. Stevenson et al. (1959) speculate that 80 percent of the shelf surface is covered by these sand-sized sediments. Authigenic (glauconite sand), organic (shelf fragments), and relic (red sand) sediments are minor constituents that vary in abundance along the southern California seaboard. Overall, the southern California shelf sediments have low average carbonate content that tends to increase gradually in an offshore direction. Silts tend to be winnowed from terrestrial detritus by long-shore currents prior to deposition in quiet areas such as north-northwestern portions of bays or on the outer shelf (Allan Hancock Foundation, 1959, 1965).

Continental Slope

Off southern California, Sector 6, the continental slope descends from an outer deep ridge of the borderlands to a depth of about 3400-3800 m (Uchupi and Emery, 1963). Much of the slope is continuous from the crest of the ridge down to the continental rise; however, in some areas it is discontinuous with breaks marked by spur-like ridges 50-100 m high. The continental slope of Sector 6 has an average width of about 10 km and its gradient ranges from 10°-17°, averaging 12°. The slope has a northwest trend and is in line with those to the north and south. Submarine canyons have not been recognized on the slope but several gaps and offsets are present. At each offset the northward continuation lies to the west, thereby increasing the slope width. A gap in the ridge atop the continental slope occurs at each offset. The gaps are oriented northwest-southeast and range from 10-40 km in width. The floor of the gap is relatively featureless and has the appearance of a sedimentary fill.

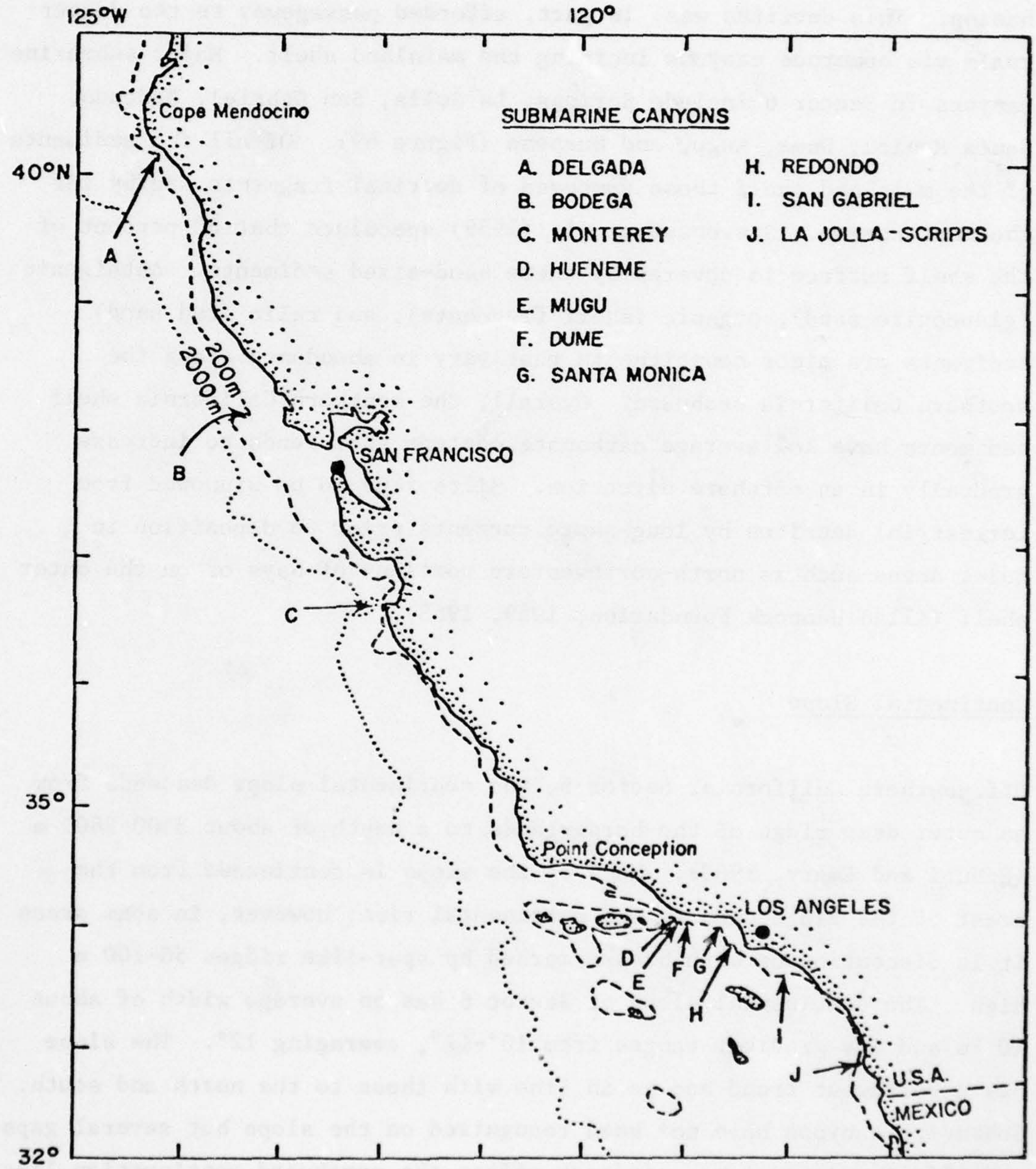


Figure 69. Relative positions of major submarine canyons in Sectors 6 and 7 (Southern and Northern California Bights). (After McManus, 1964).

In Sector 7, beyond the continental shelf off Point Conception, is a plateau about 50 km wide with an outer edge at a depth of about 600 m. This plateau, the Arguello, tends to divide the slope (Figure 70) into a gentle, shallower part and a steep, deeper part that is about 2600 m high with a declivity averaging 8°. This deeper slope trends northwestward for 160 km where it is offset 200 km to the east. Beyond this point the escarpment resumes its northwesterly trend with no added conspicuous breaks. The slope off San Francisco is more irregular than that to the south because of the presence of submarine canyons. Its width ranges from 30-50 km while having an average gradient of 6.5°. Just south of San Francisco the escarpment consists of two segments: 1) an upper one extending from the shelf break at 110 m to 900-1400 m with a gradient of about 1° (possibly an extension of the Arguello Plateau) and 2) an irregular lower slope whose gradient ranges from 4° to 8°.

Three seamounts occur at the base of the slope off San Francisco. Guide and Pioneer have similar dimensions, about 1000 m high and 13 km long, whereas Mulberry is only about half as large while having equivalent relief. Uchupi and Emery (1963) relate the seamounts to the continental slope in view of an unstable area favorable for igneous activity.

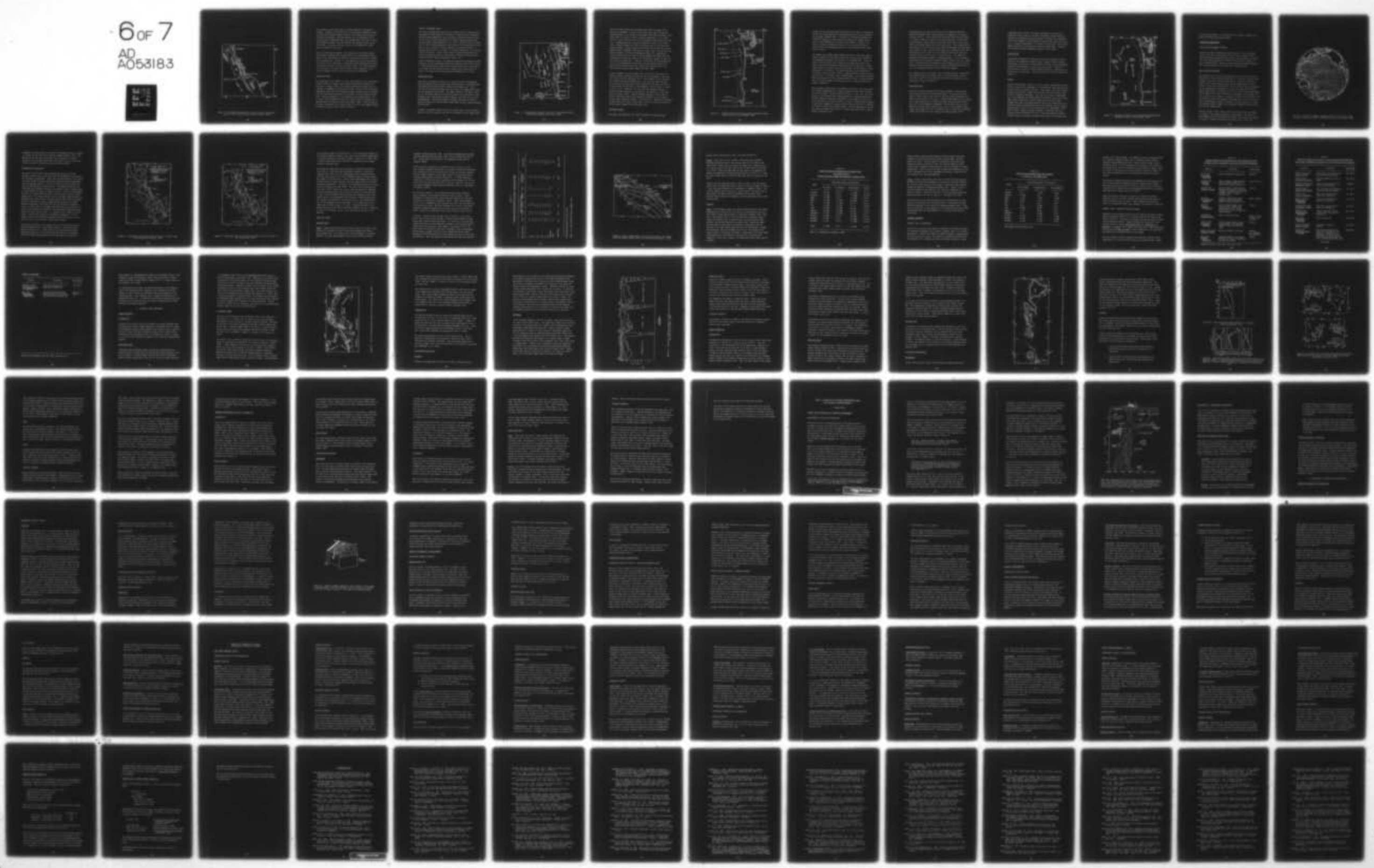
Continental Rise

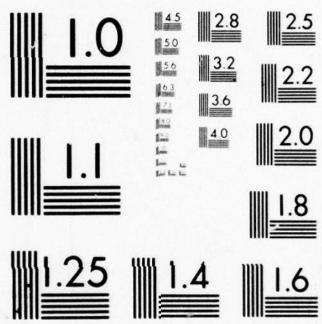
Off southern California the rise is poorly developed or missing, and its position at the slope's base is occupied by a shallow marginal trench. Where present, the rise is only a few tens of kilometres wide and very irregular. In this region the surface of the rise is broken by possibly three seamounts. Only the largest, San Juan, has been surveyed and named. It is 33 km long, 3000 m high and trends northeastward. Deep-sea channels are also present on the continental rise but are not common.

The continental rise is well developed in Sector 7. Giant submarine fans

AD-A053 183 TERECO CORP COLLEGE STATION TX F/G 13/2
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)
JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL DACW39-76-C-0125
UNCLASSIFIED WES-TR-D-78-2 NL

6 OF 7
AD
A053183





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

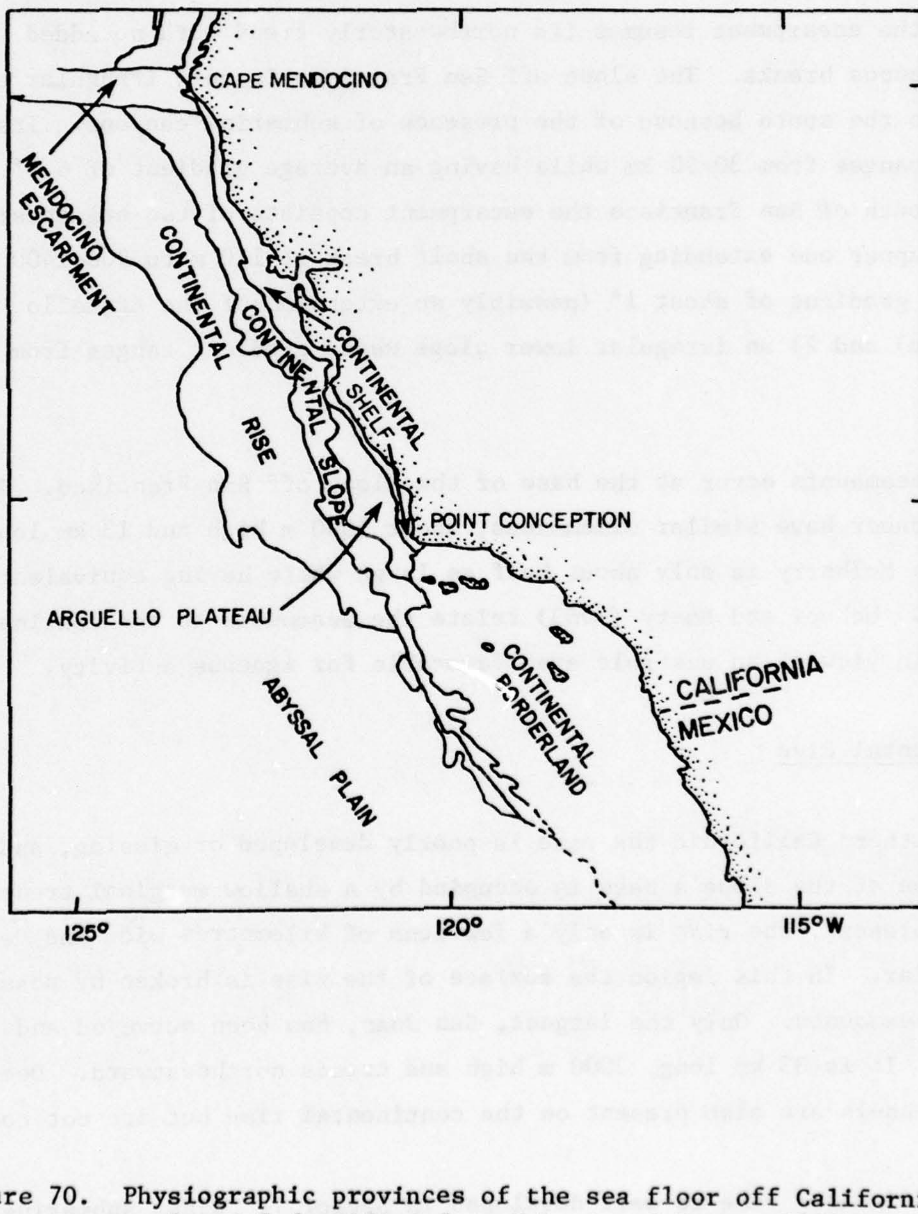


Figure 70. Physiographic provinces of the sea floor off California, Sectors 6 and 7 (modified from Uchupi and Emery, 1963).

have spread out from the mouths of Delgado, Monterey, and Arguello Canyons. Arguello Fan has buried part of the Murray Escarpment, spilling over into the Baja Seamount Province and filling several basins at the base of the slope. Deep-sea channels cut the continental rise; from the mouth of Delgado Canyon, one extends across the rise for about 450 km (Menard, 1960). The main channel from Monterey Canyon trends for 310 km, is 5 km wide and 230 m deep, and is bordered by levees along a portion of its course.

North of the Murray Escarpment, the continental rise extends seaward 165 km where it grades into the Deep Plain of the Northeastern Pacific. Depth of the rise ranges from 3000 m at the base of the slope to 4000 m at its seaward edge. Except for a few seamounts and the many channels, the relief is low, essentially a featureless plain grading seaward with a declivity of about 1° (Uchupi and Emery, 1963). The largest seamount, near the base of the slope where the rise is more irregular, is the Davidson Seamount, which rises 2130 m above its surroundings.

Abyssal Sea Floor

The topography of the abyssal sea floor off California is of diastrophic origin (volcanic, faulting, and folding) except where sediments have blanketed it (Emery, 1960). Off northern California the deep plain is composed of sediments contributed from shore. South of Point Conception smoothness ceases and the topography is highly irregular due to sediment from the land being intercepted by the basins of the continental borderland. Numerous seamounts are also present on the abyssal floor. One of these, San Juan Seamount (near 33°N, 121°W), has the appearance of a volcano; however, others have flat tops (Emery, 1960). Since erosion is virtually nonexistent on the abyssal floor, the flat tops suggest planing off during a lower relative stand of the sea.

SECTOR 8 (NORTHWEST SHELF)

This sector occupies that portion of the Pacific Coast of North America extending from Cape Mendocino, California to Cape Flattery, Washington. Western Oregon, Washington, and the adjacent continental margin occupy the site of a Tertiary geosyncline, its oldest lithology being early Eocene volcanic rocks (Braislin et al., 1971). McManus (1964) concluded that at least three physiographic provinces can be distinguished in that area: 1) the continental terrace (comprised of shelf and slope), 2) Cascadia Basin, and 3) "a province of irregular topography on the western flank of the basin." Gross (1965) further divided Cascadia Basin into eastern and western portions on the basis of Vancouver Valley and the southern trend of Cascadia Seachannel (Figure 71).

A major bathymetric feature, the Mendocino Ridge-Gorda Escarpment strikes east-west into the continental margin and separates Sector 8 from Sector 7. This feature marks a change in the regional depth of the sea floor; to the south the sea floor is several hundred metres deeper than the floor to the north of this fracture zone (Dehlinger et al., 1970).

Continental Shelf

The width of the shelf in Sector 8 is relatively narrow and generally steep in comparison with average shelf characteristics. Northward from Cape Mendocino the shelf tends to become increasingly wider. That portion off California averages less than 30 km, off Oregon about 40 km, and off Washington about 50 km. The widest regions of the shelf, 65-70 km, are the Heceta Bank area off central Oregon and at the mouth of the Columbia River, whereas the narrowest segment, less than 10 km, is off Cape Mendocino. The seaward gradient averages less than 0.5° and is generally uniform to near the shelf break, which occurs at depths ranging from 145-183 m.

A number of submarine canyons incise the seaward edge of the continental shelf in Sector 8; however, none have been surveyed off the Oregon coast

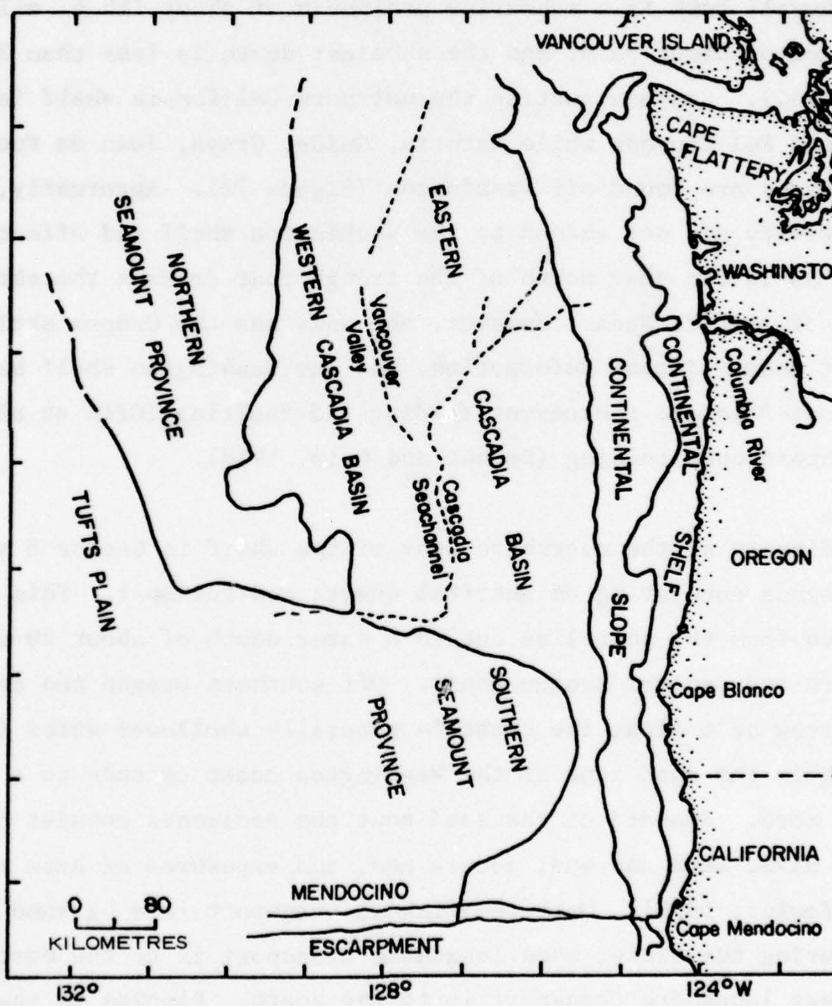


Figure 71. Physiographic provinces of Sector 8 off northwest Pacific coast (after McManus, 1964; Gross, 1965).

except for Rogue Canyon off the Rogue River (Burk and Drake, 1974). The major topographic features of the Oregon outer shelf consist of submerged banks, e.g., Heceta and Stonewall Banks (Burk and Drake, 1974). Heceta Bank is a linear feature occupying approximately 175 n. miles and has a relief of about 145 m with the shoalest depth being less than 45 m. Stonewall Bank is a submarine peninsula of about 115 n. miles with a relief of about 35 m, and the shoalest depth is less than 35 m (McManus, 1964). Canyons cutting the northern California shelf include Mendocino and Eel Canyons while Astoria, Guide, Grays, Juan de Fuca, and Nitinat Canyons are found off Washington (Figure 72). Apparently, glacial activity did not extend to the Washington shelf and affect the topography as it did just north of the trough that crosses the shelf at the Strait of Juan de Fuca. However, not only has the Oregon shelf been the site of post-Pliocene deformation, but the Washington shelf has also had post-Pliocene piercement folding and faulting (Grim et al., 1968) and broad open folding (Bennet and Grim, 1968).

Surface sediments of the nearshore zone of the shelf in Sector 8 are primarily sands consisting of detrital quartz and feldspar. This sand zone extends from the shoreline out to a water depth of about 90 m off the northern and central Oregon coast. Off southern Oregon the sand forms a narrow belt along the coast in generally shallower water (50 m or less) while the sand zone of the Washington coast extends to a depth of 50 m or more. Seaward of the sand zone the sediments consist of patches of mixed sand and mud, modern mud, and exposures of bare rock (Kulm and Fowler, 1970). Onshore-offshore transport rate of sand is greatest during the winter when longshore transport is to the north; in the summer longshore transport is to the south. Ripples in the bottom sediment have been found at water depths of 80 m in the winter and 30 m in the summer (Oregon State University, 1971).

Continental Slope

Off Oregon and Washington, the slope is broken by normal faulting

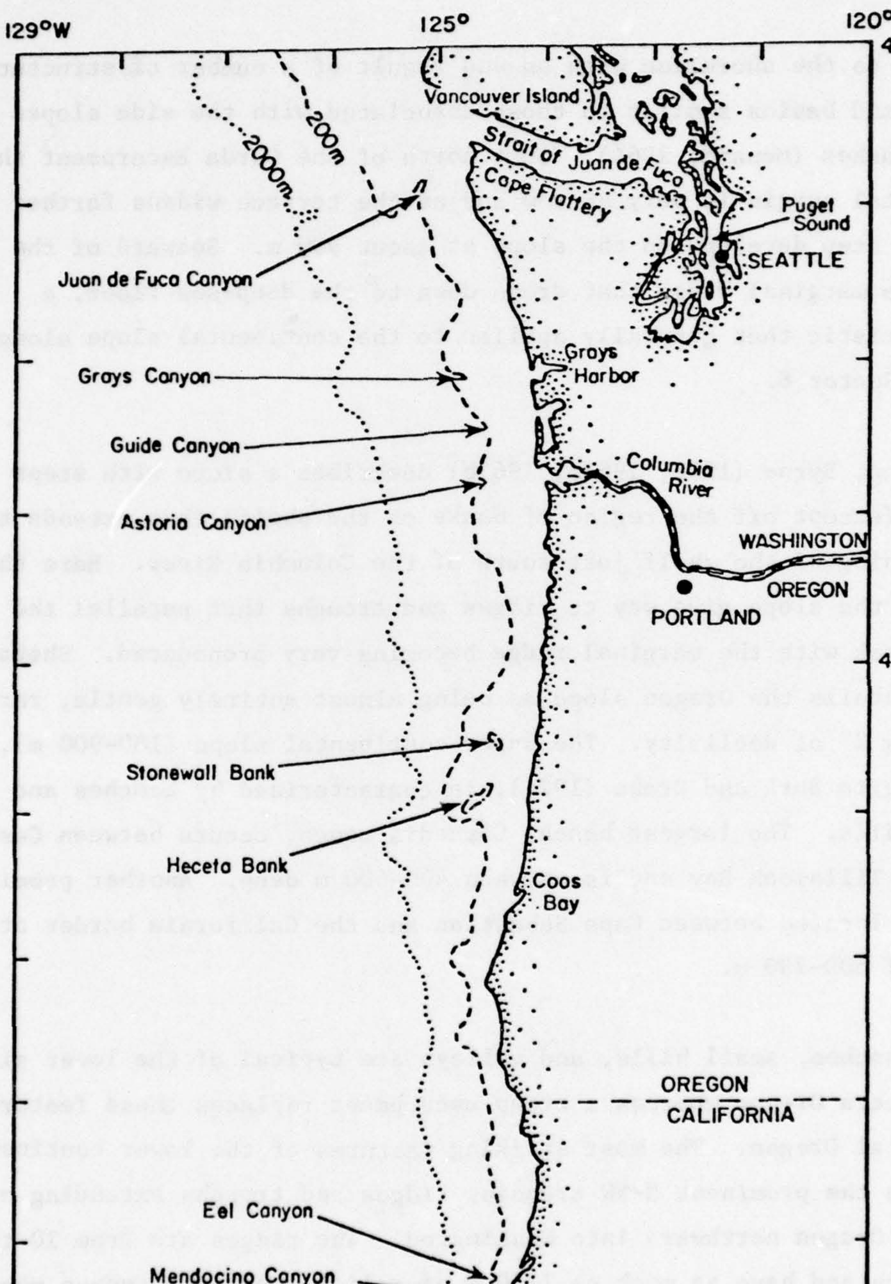


Figure 72. Relative positions of major submarine banks and canyons within Sector 8 (after McManus, 1964).

parallel to the shoreline with an end result of a number of structural benches and basins similar to those associated with the side slopes of deep trenches (Menard, 1964). Just north of the Gorda Escarpment the continental margin is very narrow and as the terrace widens farther north, a step develops on the slope at about 900 m. Seaward of the step is a marginal ridge that drops down to the deep-sea floor, a characteristic that generally applies to the continental slope along most of Sector 8.

Off Oregon, Byrne (1962, 1963a, 1963b) describes a slope with steps or benches (except off the region of banks on the shelf) that extends to the widening of the shelf just south of the Columbia River. Here the steps of the slope give way to ridges and troughs that parallel the shelf break with the marginal ridge becoming very pronounced. Shepard (1963) details the Oregon slope as being almost entirely gentle, rarely exceeding 2° of declivity. The upper continental slope (180-900 m), according to Burk and Drake (1974), is characterized by benches and low relief hills. The largest bench, Cascadia Bench, occurs between Cascade Head and Tillamook Bay and is between 400-600 m deep. Another prominent bench is located between Cape Sebastian and the California border at depths of 500-700 m.

Narrow benches, small hills, and valleys are typical of the lower slope off northern Oregon whereas a steep escarpment replaces these features off central Oregon. The most striking features of the lower continental slope are the prominent N-NW trending ridges and troughs extending off northern Oregon northward into Washington. The ridges are from 10 to 75 km long and have as much as 1150 m of relief. Astoria Canyon meanders through this topography to connect with the Astoria Fan, but it extends to a depth of 3100 m off southern Oregon. With the exception of the fan, the slope and abyssal plain meet at a rather large angle with no intermediate continental rise.

Off Washington, the slope is footed by the continental borderland (McManus and McGary, 1967) whose features are suggestive of relative tensional forces. The continental slope extends from the shelf break to a depth of 1800 or so metres in the south and 1400 m in the north. Large submarine canyons notch the slope and extend down to the borderland at the seaward edge of the continental slope. This borderland is approximately 50 km wide with narrow north and northwest trending ridges and a marginal ridge. Between these ridges are low-gradient areas representing basin fills that are now crossed by valleys that drain the submarine canyons and pass onto the deep-sea fans. The ridges and sediment-filled basins suggest a borderland similar to the continental borderlands off the Southern California Bight, Sector 6, but on a lesser scale. This borderland is developed at the change in trend of the continental terrace from north-south off Oregon and northern California to that of a northwest-southeast trend off British Columbia.

The irregular width of the shelf with its submarine banks, coupled with the abundant benches and linear ridges of the slope suggest strong structural control of the morphology and general configuration of the continental terrace in Sector 8.

Continental Rise

Mendocino and Gorda Escarpments are major bathymetric features that strike east-west into the continental margin. As previously stated, south of these fracture zones the sea floor is several hundred metres deeper than the floor to the north. A 300-km-long segment of the oceanic rise, Gorda Ridge with its crestal mountains and median valley, lies just north of the Mendocino Escarpment. The northern limit of Gorda Ridge is formed by Blanco Fracture Zone, a 20- to 75-km wide system of ridges and troughs that have an average relief of about 900 m, although depths exceed 5100 m in some troughs, and relief exceeds 2750 m

(Dehlinger et al., 1970). The rough topography of the zone that trends for 460 km, acts as a barrier to turbidity current dispersal reflected in the deep-sea fans and plains in Cascadia Gap, therefore, much of the sediment of Tufts Abyssal Plain must have used that corridor. A northern continuation of the Blanco Fracture Zone, Juan de Fuca Ridge, is more of a low rise than a well-developed ridge. Seamounts and furrows are major topographic elements of this ridge.

Abyssal Plain

Depositional topography of deep-sea fans and Tufts Abyssal Plain are seaward of the ridges and fracture zones. Deep-sea channel systems that played a major role in construction of the low, smooth topography (average bottom gradient 1.4 m/km) cross this region. Gorda and Astoria Basins are sites of major deep-sea fans (e.g., Astoria Fan and Nitinat Fan, respectively). These topographic features are depicted in Figure 73.

Fiords

Howell (1957) defines a fiord as "a narrow, deep, steep-walled inlet of the sea, formed by the submergence of a mountainous coast that previously was the site of glacial activity." Puget Sound, a bay with numerous channels and branches, extends 90 miles south from the Strait of Juan de Fuca to Olympia, Washington. The body of the sound is subdivided into four subregions by Friebertshauser and Duxbury (1972) into Whidbey Basin, Puget Sound Basin, southern Puget Sound, and Hood Canal. Somewhat deep water and strong currents characterize these waters; the currents follow the general direction of the channels and have considerable velocity, up to 7 knots in some areas (U.S. Department of Commerce, 1976e). Winds are mainly southeast to southwest from fall through spring and northwest to north in the late spring and summer. Internal storms can generate sustained south winds of 40-50 knots over

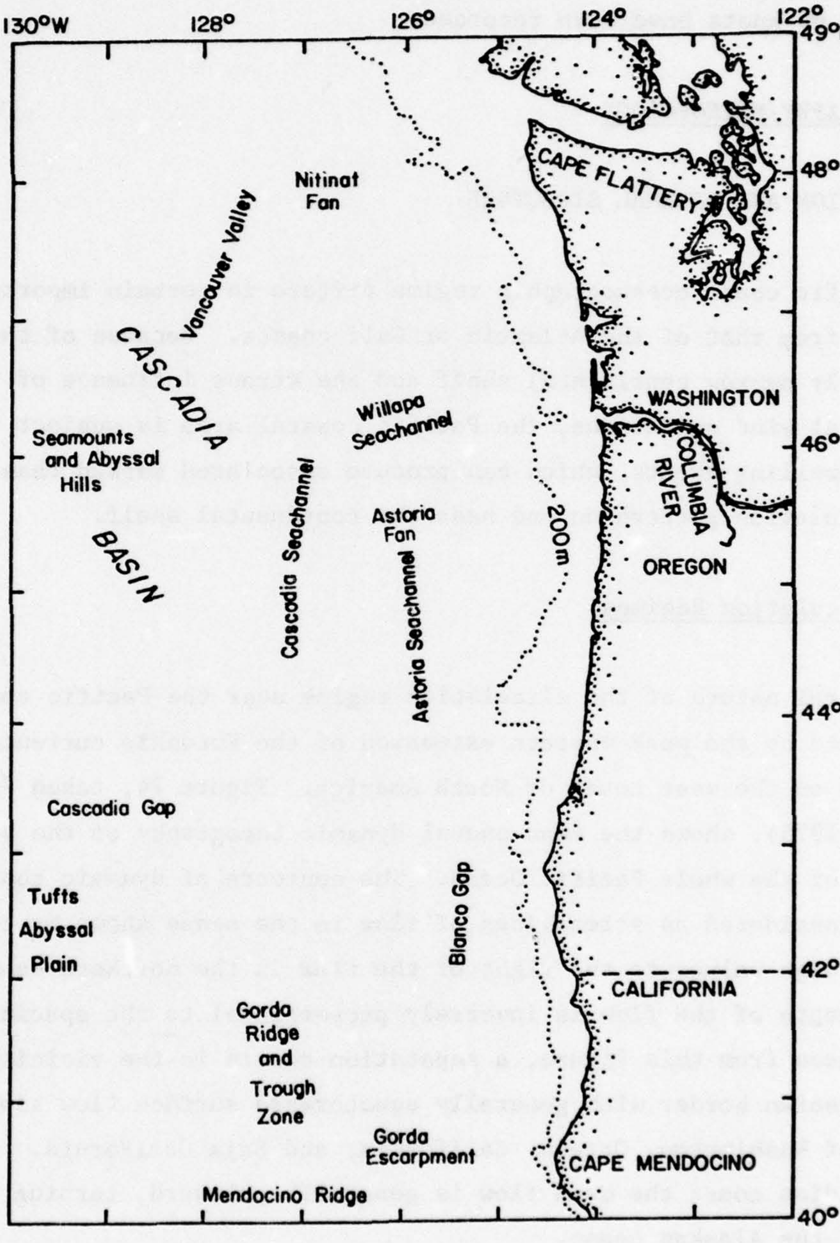


Figure 73. Approximate locations of major submarine physiographic features in Sector 8 (after McManus, 1964).

the area in the winter. In the Seattle area, winds of 56 knots with gusts of 60 knots have been recorded.

OCEANOGRAPHY/METEOROLOGY

CIRCULATION AND THERMAL STRUCTURE

The Pacific coast oceanographic regime differs in certain important aspects from that of the Atlantic or Gulf coasts. Because of the relatively narrow continental shelf and the strong influence of regionally local wind conditions, the Pacific coastal area is subject to major upwelling events, which can produce associated marked changes in the circulation pattern on and near the continental shelf.

Mean Circulation Regimes

The general nature of the circulation regime near the Pacific coast is controlled by the weak eastern extension of the Kuroshio current, which impinges on the west coast of North America. Figure 74, taken from Wyrtki (1975), shows the mean annual dynamic topography of the sea surface of the whole Pacific Ocean. The contours of dynamic topography can be considered as streamlines of flow in the sense shown by the arrows (high values to the right of the flow in the northern hemisphere). The strength of the flow is inversely proportional to the spacing. As can be seen from this figure, a separation occurs in the vicinity of the U.S./Canadian border with generally equatorward surface flow along the coasts of Washington, Oregon, California, and Baja California. Along the Canadian coast the mean flow is generally poleward, turning to the west off the Alaskan coast.

Seasonal changes in the general oceanic circulation occur in response to changes in the general atmospheric wind patterns. The effect of such changes on the currents near the Pacific coast is that the separation point is shifted equatorwards in spring so as to occur off

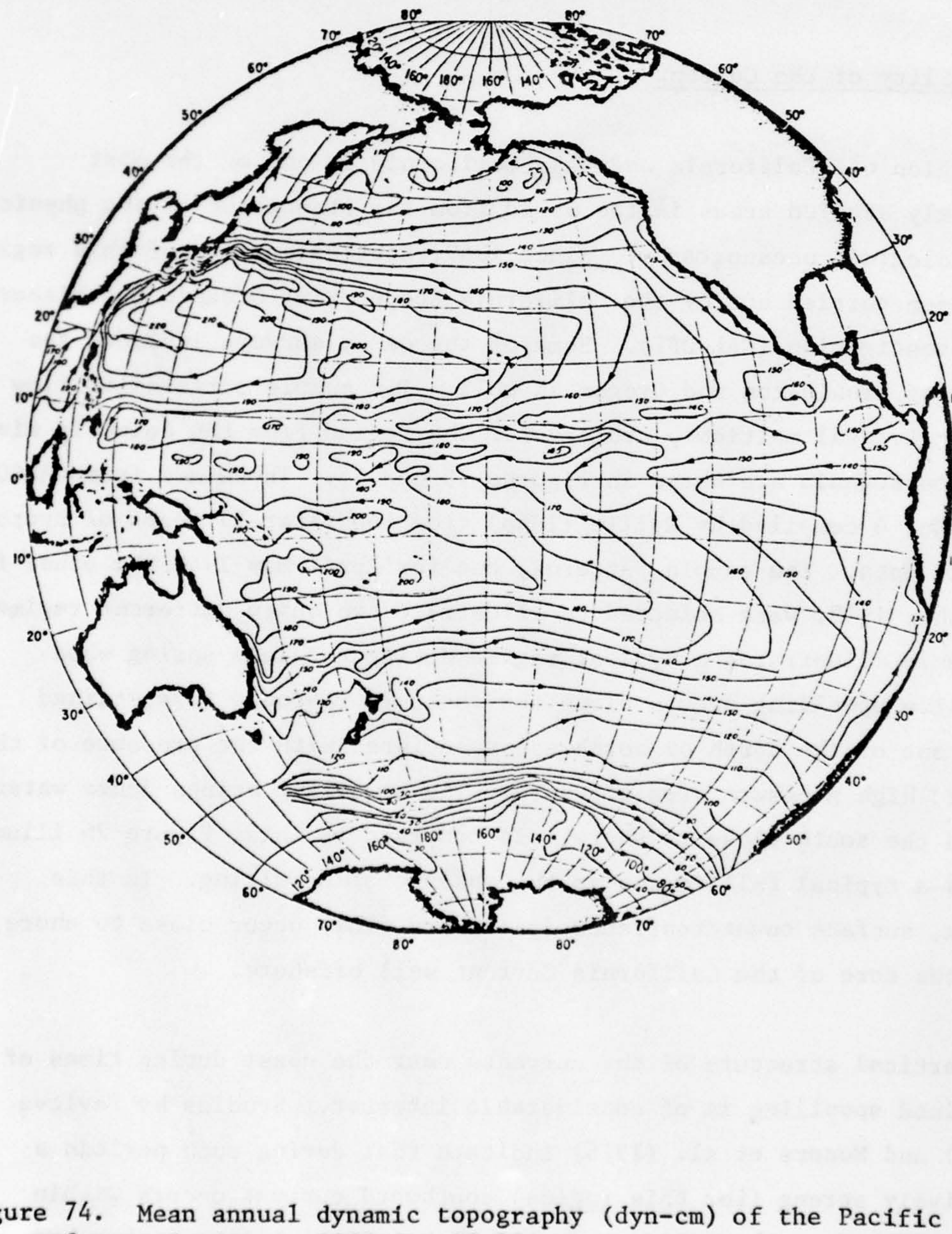


Figure 74. Mean annual dynamic topography (dyn-cm) of the Pacific Ocean sea surface relative to 1000 db: 36,356 observations (from Wyrtki, 1975).

Washington or Oregon, while in late fall the separation point is shifted to a point off the north end of British Columbia (Wyrtki, 1975). The details of the flow near the Pacific coast are subject to strong influence of local winds since unlike the Atlantic coast or east Gulf, the mean currents are generally weak (less than one knot).

Variability of the Current

The region off California and Baja California is one of the most routinely studied areas in the world from the standpoint of the physical and biological oceanography. Since 1949, routine surveys of this region have been carried out by the California Cooperative Oceanic and Fisheries Investigation (CALCOFI). Some of the early surveys included the region of Washington and Oregon as well. Two sample patterns of flow from individual multiship cruises for the region from the Columbia River to Punta Eugenia are shown in Figures 75 and 76. These are from CALCOFI Atlas No. 4 compiled by Wyllie (1966) from the first 17 years of hydrographic data. The sample patterns, one for April-May 1949 the other for September 1949, were selected to illustrate two quite different regimes. Figure 75 illustrates a typical regime during the late spring when extensive upwelling occurs along the coast in response to sustained winds out of the north or northwest associated with the presence of the Pacific high pressure area offshore. The upwelling brings dense water toward the south close to shore. In contrast to this, Figure 76 illustrates a typical fall regime in the absence of upwelling. In this regime, surface countercurrents (polarward flow) occur close to shore, with the core of the California Current well offshore.

The vertical structure of the currents near the coast during times of sustained upwelling is of considerable interest. Studies by Pavlova (1966) and Mooers et al. (1976) indicate that during such periods a relatively strong (for this region) southward current occurs within about 50 km from shore and above 100 m, below which is a weaker but

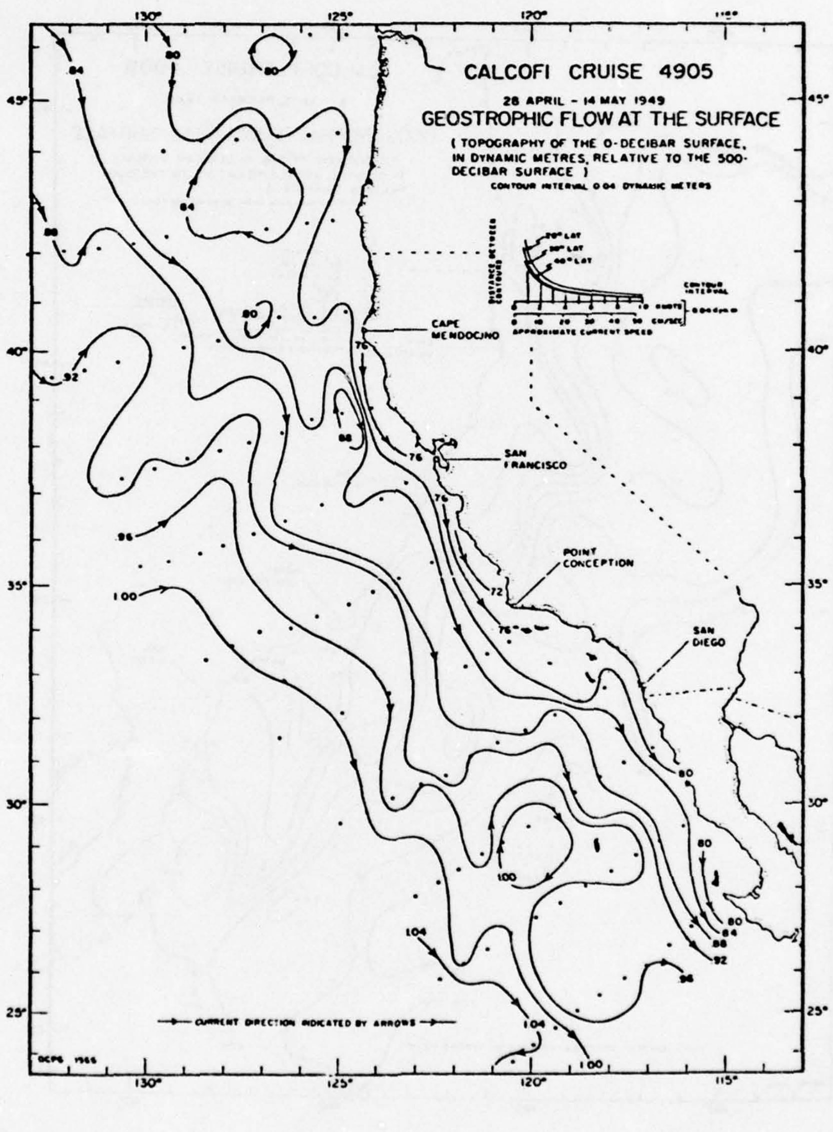


Figure 75. Geostrophic flow at the surface off the U.S. Pacific Coast in late spring (from Wyllie, 1966).

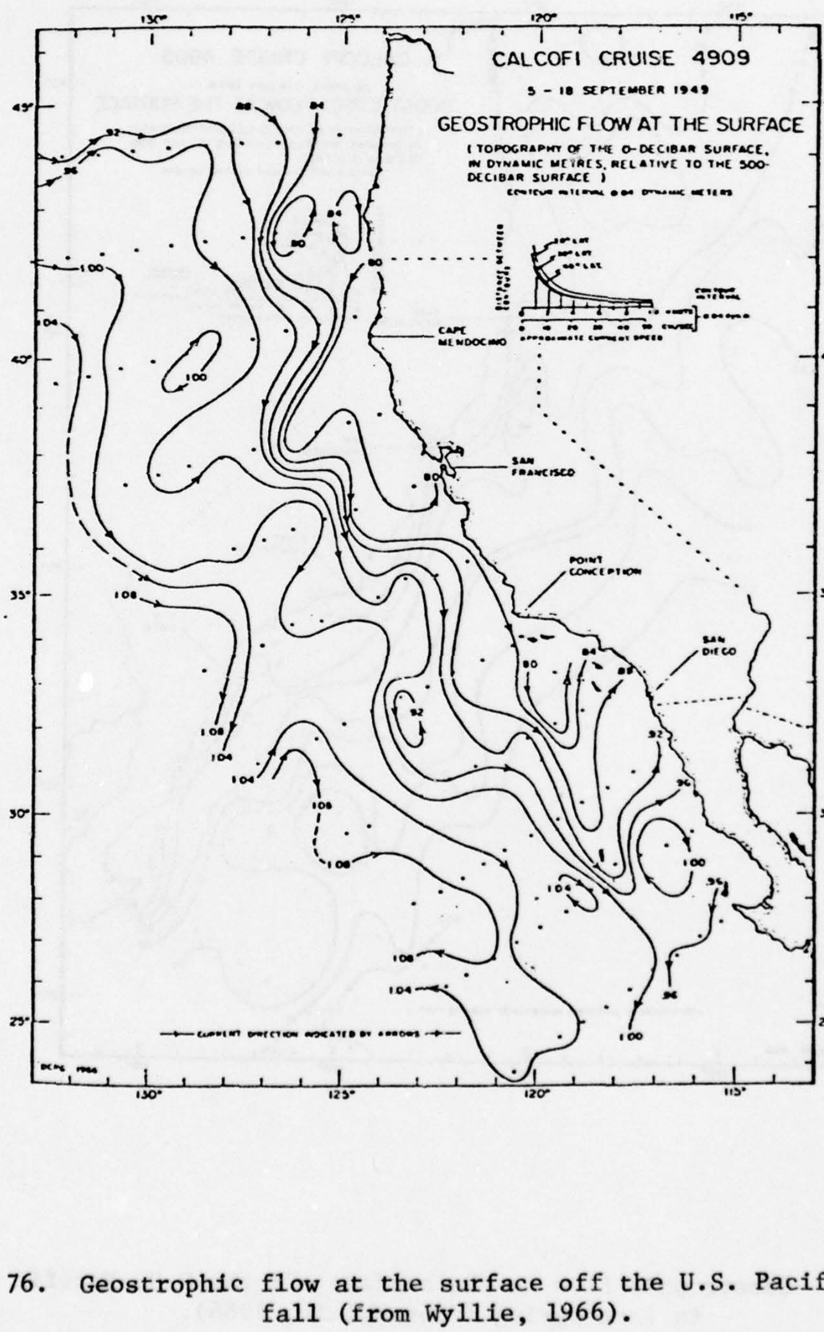


Figure 76. Geostrophic flow at the surface off the U.S. Pacific Coast in fall (from Wyllie, 1966).

more extensive region of poleward flow. In the surface flow speeds up to 25 km/sec (about 0.5 knots) occur, while in the poleward undercurrent the speed is generally less than 10 cm/sec. Mooers et al. (1976) show a vertical cross-section with isolines of longshore flow off Oregon during an upwelling event.

The region off Oregon has been the subject of extensive cooperative field studies of upwelling and associated variations of horizontal currents since 1970. Two very comprehensive field experiments CUE-1 and CUE-2 were carried out on the continental shelf off Oregon during the summers of 1972 and 1973. Direct current measurements were made at multiple levels at eight different stations along and across the shelf during each experiment. The results of a detailed analysis of this data are given by Kundu and Allen (1976). The mean current structure supports the earlier findings for current structure during the upwelling season with maximum mean surface flow to the south of about 20 cm/sec at about 15-20 km offshore and with weaker mean poleward flow in the deeper layers. The measurements also indicate a large variability of the current both along shore and normal to shore. The standard deviation of the longshore flow was generally 8 to 16 cm/sec and for the flow normal to shore about 2 to 7 cm/sec. Spectral analysis of the results by Kundu et al. (1975) indicates a dominant peak at a frequency of about 0.1 cycles/day, which is also indicated in the wind stress spectrum.

WINDS AND STORMS

Sectors 6 and 7

Winds. Along the southern California coast the basic air flow is from the west to northwest; a result of the semi-permanent east Pacific high pressure area. This anti-cyclone is most dominant in the warmer months of the year, May-September, with stronger and more constant northwest winds during that time. From October through April the high pressure diminishes and the center moves and thus reduces the flow of air. During these cooler months an air movement from the land is somewhat common.

Winds near Point Conception, the northern limit of Sector 6, have a more northerly component than those to the south off southern California. Wind velocities are rarely greater than 27 knots and the most frequent velocity ranges between 1 and 16 knots (Table 37); velocities tend to increase with distance from shore (Figure 77). At Point Conception, velocities of 30-35 knots occur occasionally in the summer, but for the rest of the year high velocity winds in any part of Sector 6 occur only with frontal passages (Allan Hancock Foundation, 1959; U.S. Department of Commerce, 1976e).

The Santa Ana condition is an offshore northeast desert wind that occurs primarily in the southern California coastal areas. While infrequent, it may be violent; speeds have been measured at more than 50 knots (U.S. Department of Commerce, 1976e). These winds diminish little, if any, immediately after passing over water, and can extend up to 50 miles out to sea. They are considered to be local strong winds, capable of generating gales, which are most likely in late autumn or winter. Effects of a Santa Ana can be noted in both Sectors 6 and 7.

In Sector 7, winds are more variable than in Sector 6, yet in early winter they are still often northwest, becoming west-northwest in mid-winter with occasional weak east winds. In the spring a wind direction change from north to south takes place gradually, with northwest winds, reinforced by the sea breeze, most common. Wind speeds of 20 to 30 knots occur 10-20 percent of the time, attesting to this reinforcement. Autumn brings a gradual return to winter conditions with the winds becoming a mix of south and north; north gaining the edge as fall turns toward winter. Mean wind speeds and prevailing directions for selected

Table 37

Frequency of Wind Direction by Speed - Annual Percentage

Wind Direction	Wind Velocity (Knots) 0-6	7-16	17-27	28-40	41+	Percentage of Frequency	Mean Speed
N	3.0	3.6	0.4	*	0.0	7.1	8.4
NE	1.6	1.3	0.2	*	*	3.1	7.5
E	1.9	1.3	0.1	*	*	3.4	7.1
SE	1.8	1.7	0.2	*	*	3.7	7.9
S	2.8	2.4	0.3	*	*	5.6	7.8
SW	3.7	4.0	0.4	*	*	8.1	7.9
W	8.0	19.5	4.3	0.4	*	32.2	10.8
NW	6.6	19.2	5.8	0.5	*	32.1	11.8
Variable	*	0.0	0.0	0.0	0.0	*	2.2
Calm	4.6					4.6	0.0
Percentage	34.2	53.0	11.8	1.0	*	100.0	(mean total)

*Frequencies between 0.0% and 0.05%.

From: U.S. Navy Weather Service Command, 1970.

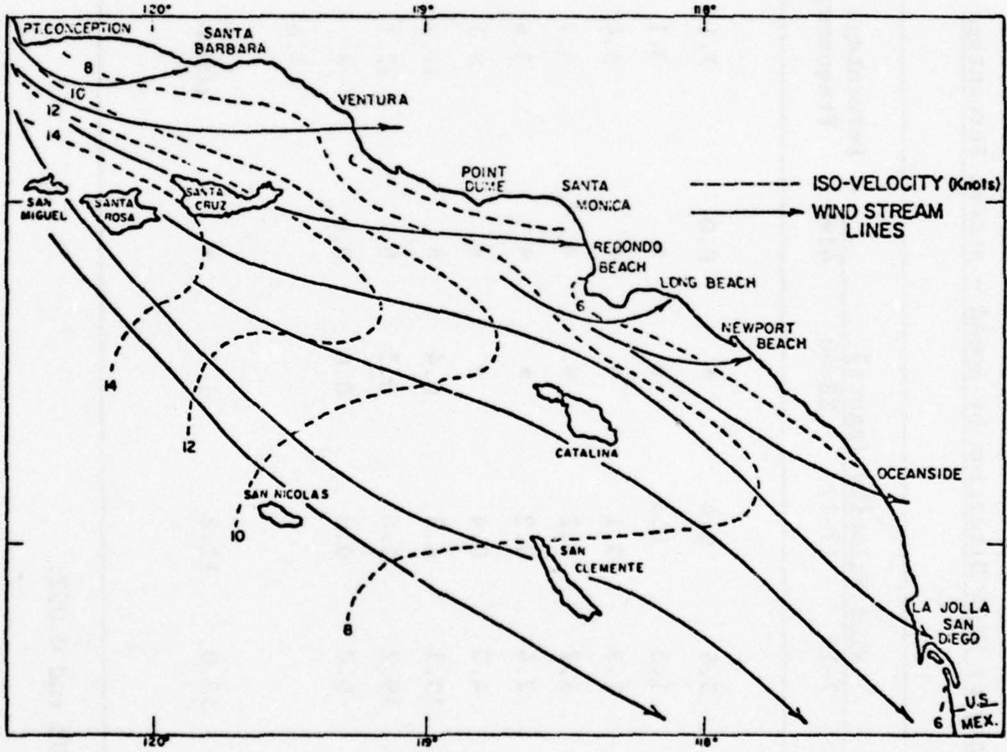


Figure 77. Annual average winds, velocity and direction, of Southern California Coastal Region (from the Allan Hancock Foundation , 1959).

onshore sites within Sectors 6 and 7 are shown in Table 38.

Storms. About once or twice a month a storm moves into northern California offshore waters. While these lows are often weaker than those farther north, some cause gales and rough seas. Gales blow on 4 to 5 days per month, and seas reach 12 feet or more about 8-16 percent of the time. Gales and rough seas are rare south of Los Angeles, but between Los Angeles and San Francisco gales blow on or about 1 to 4 days per month, while seas of 12 feet or more occur about 4-8 percent of the time.

Tropical cyclones originate south of Sectors 6 and 7, off the western Mexico coast, in summer and autumn. About 15 form each season, of which 7 reach hurricane intensity (U.S. Department of Commerce, 1976e). Few come far enough north to affect U.S. coastal waters, and those that do have usually lost their hurricane intensity and are short-lived. However, these storms can be dangerous and have generated winds of more than 120 knots.

Sector 8

Winds. The Washington, Oregon, and upper California coasts are located approximately in the center of the zone of prevailing westerlies with local winds varying from northwest to southwest throughout most of the year. The seasonal cycle of winds on the Pacific northwest coast is largely determined by the circulation about the North Pacific high pressure area and the Aleutian low pressure area. During the summer the North Pacific High reaches its greatest development while the Aleutian low is weak; these conditions favor the development of summer winds generally from the northwest to north over the nearshore and coastal waters of Washington and Oregon. During winter the North Pacific high weakens while the Aleutian low intensifies; resulting winds, frequently of gale force, approach the Washington-Oregon coast from the southwest.

Table 38

Monthly Average Wind Conditions for Onshore Sites in Sectors 6 and 7, Southern California Bight and Northern California Shelf

Month	Mean Speed (Knots) and Direction			
	San Diego	Los Angeles	San Francisco	Eureka
January	4.8 NE	5.8 W	6.1 WNW	6.0 SE
February	5.5 WNW	6.3 W	7.4 WNW	6.2 SE
March	6.2 WNW	6.8 W	8.9 WNW	6.6 N
April	6.6 WNW	7.3 WSW	10.5 WNW	6.9 N
May	6.6 WNW	7.1 WSW	11.5 W	6.8 N
June	6.5 SSW	6.8 WSW	11.2 W	5.0 NW
July	6.1 WNW	6.6 WSW	11.8 NW	5.9 N
August	6.0 WNW	6.5 WSW	11.2 NW	5.0 NW
September	5.7 NW	6.1 WSW	9.6 NW	4.7 N
October	5.4 WNW	5.9 W	8.1 WNW	4.8 N
November	4.8 NE	5.7 W	6.1 WNW	5.2 SE
December	4.7 NE	5.8 W	5.9 WNW	5.5 SE
Annual	5.7 WNW	6.4 W	9.1 WNW	5.9 N

From U. S. Department of Commerce, 1976e.

Offshore winds in the northern reaches of Sector 8 shift from south-southeast in the fall and winter to west in early summer and then reverse the cycle. The same pattern is observed in the central and southern sections of Sector 8, except that during summer the winds continue their clockwise swing and arrive from the northwest and north, respectively. Table 39 gives wind data derived from lightships off the Pacific Northwest coast in the approximate locations of Cape Flattery, the Columbia River, and Cape Mendocino.

Storms. Winter storms usually work their way from the central Pacific northward into the Gulf of Alaska or to the coast of British Columbia. Two or three times a month, on an average, a storm will move directly through the seas off the Washington-Oregon coast. Seas of 12 feet or more are generated 15-20 percent of the time (U.S. Department of Commerce, 1976e). Gales occur on about 3-5 days per winter month and may whip up seas to 20 feet or more up to 4 percent of the time.

Toward the end of the summer the North Pacific high weakens and wind patterns are dominated by a continuing series of low pressure systems migrating from west to east across the Washington-Oregon coast. These occur as individual storms spanning 3-7 day intervals during which time average wind speeds are approximately 10 to 20 knots with maxima of 50-55 knots.

FISHERIES RESOURCES

SECTORS 6 AND 7 (CALIFORNIA)

Almost all of the sport and commercial fisheries of southern California are comprised of pelagic fish or inshore predatory fish, e.g., halibut and rockfish. Bottom fish caught by trawling represent an insignificant fraction of the total catch. By contrast, in northern California and the northwest U.S., trawling and bottom longlining constitute a large

Table 39

Offshore Average Monthly Wind Speed (Knots)

for Sector 8, Northwest Shelf

Month	Mean Speed (Knots) and Direction		
	Cape Flattery	Columbia River	Cape Mendocino
January	18 S	18 SSE	18 SE
February	16 SSE	16 S	19 E
March	14 SW	15 SSW	18 NNE
April	15 SW	13 SW	18 N
May	13 W	12 W	18 N
June	12 W	10 WNW	15 N
July	10 WSW	10 NW	16 N
August	7 SW	10 NW	16 N
September	8 S	11 WNW	14 N
October	13 SSE	14 SSE	13 NNE
November	16 SSE	17 SSE	16 ESE
December	17 SSE	17 SSE	17 SE

From Oregon State University, 1971.

portion of the fish landings. The commercial catch in southern California consists of pelagic species such as sardine, anchovy, Pacific mackerel, jack mackerel, and tunas. Tunas account for most of the California catch. In 1971 tunas made up 63 percent of the volume and 83 percent of the value of California's total landings. However, about 94 percent of the tuna catch is made outside of California waters, to the south and southwest in the tuna grounds off Mexico and Central America.

On the whole, commercial landings in California have declined over the last 20 years whereas landings from sports fishing have increased. Declining from about 25 percent of the U.S. total in 1950, California fisheries have an annual value of approximately $89 million, representing roughly 18-23 percent of the U.S. Total.

Demersal fisheries, being more prevalent in central and northern California than in the south, include several species that range out over the shelf and onto the slope. Those commercial species most likely to be impacted by deep ocean disposal are presented in Table 40.

SECTORS 8 AND 9 (NORTHWEST SHELF AND ALASKA)

Fisheries of the northeast Pacific are very diverse and exhibit considerable overlap with fisheries to the south along the California coast (Tables 40 and 41). Diversity is especially pronounced among the shellfish and demersal finfish. Pelagic fisheries are dominated by five species of Pacific salmon (Oncorhynchus nerka, O. tshawytscha, O. gorbuscha, O. kisutch, and O. keta), which make great oceanic migrations, and the herring (Clupea pallasii), which overwinters on the outer shelf and migrates into nearshore waters in the spring.

From the northeast Pacific, Canadians and Americans annually harvest approximately 1.3 billion pounds valued at about $220 million. While

Table 40

Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to California Fisheries

Species	Occurrence	Depth Range
Dover sole *Microstomus pacificus*	Baja, California to Bering Sea	80-820 m
English sole *Parophrys vetulus*	Baja to Alaska, commercial abundance centered between Santa Barbara and Hecate Strait, B.C.	shore to 370 m
Petrale sole *Eopsetta jordani*	Baja to Alaska, fishery exists between Santa Barbara and British Columbia, California fishery most abundant from Ft. Bragg to Crescent City	18-370 m
Rex sole *Glyptocephalus zachirus*	Canada to Santa Barbara most abundant fishery in Eureka - Crescent City, California area	shore to 650 m
Bocaccic *Sebastes paucispinis*	Baja to Kodiak Island, most abundant trawl fishery from Santa Barbara to Ft. Bragg, California; occurs on rocky and smooth bottoms	75-365 m
Chilipepper *Sebastes goodei*	Baja to Vancouver Island	75-335 m, most abundant from 182-304 m
Pacific hake *Merluccius productus*	Gulf of Alaska to Baja, major concentrations from Vancouver Island to Baja over shelf and slope	50-550 m
Ocean pink shrimp *Pandalus jordani*	Aleutian Islands to San Diego	50-360 m most abundant from 100-180 m
Spot prawn *Pandalus platyceros*	Aleutian Islands to San Diego, abundant in canyons off Monterey and Catalina Islands	50-500 m

Compiled from FAO, 1972; Frey, 1971; Horn, 1974.

Table 41

Demersal Finfish and Shellfish of the Outer Continental Shelf and Upper Slope of Commercial Importance to the Northeast Pacific Fisheries

Species	Occurrence	Depth Range
Pacific ocean perch Sebastes alutus	Entire west coast through Gulf of Alaska into Bering Sea	150- 450 m
Pacific hake Merluccius productus	Gulf of California to Gulf of Alaska	50- 550 m
Sablefish (Black cod) Anoplopoma fimbria	Northern Baja through Gulf of Alaska into Bering Sea	50-1000 m
Alaska Pollock Theraga chalcogramma	Gulf of Alaska into Bering Sea including Aleutian Islands	50- 450 m
Pacific Cod Gadus macrocephalus	West coast through Gulf of Alaska into Bering Sea	50- 450 m
Pacific halibut Hippoglossus stenolepis	West coast through Gulf of Alaska into Bering Sea	50- 450 m
Arrowtooth flounder Atheresthes stomias	West coast through Gulf of Alaska into Bering Sea	50- 650 m
Flathead sole Hippoglossoides elassodon	North of Vancouver Island through Gulf of Alaska into Bering Sea	100- 450 m
Dover sole Microstomus pacificus	Baja to Bering Sea	80- 820 m
Ocean pink shrimp Pandalus jordani	San Diego to Aleutian Islands	50- 360 m
Tanner crab Chionectes opilio C. bairdi	West coast through Gulf of Alaska into Bering Sea, most abundant at 500-730 m off Washington but moves to shallower water less than 200 m in Gulf of Alaska and further north	200-1500 m

(continued)

Table 41 (concluded)

Species	Occurrence	Depth Range
Deepwater prawns Pandalopsis dispar P. borealis	West coast through Gulf of Alaska into Bering Sea	50- 200 m
King crab Paralithodes camtschatica	Southeastern Alaska through Gulf of Alaska to Adak in the Aleutians and into Bering Sea	shallows to 270 m

Compiled from Browning, 1974; FAO, 1972; and Frey, 1971.

this accounts for approximately 25 percent of all Canadian and U.S. fish landings, it does not adequately reflect true productivity of these waters as foreign fishing annually accounts for 2 to 3 times as much as the Canadian - U.S. catch.

In consideration of the great and varied contribution of the demersal fish to the northeast Pacific fisheries, their extension into slope depths is a major concern in selecting a deep ocean disposal site for dredged material. Those demersal fish of commercial importance are presented in Table 41. It should be noted that some species that occur primarily in the California area also extend northward into the Northwest Shelf and Alaska (Table 40).

F. SECTORS OF MINOR IMPORTANCE

ALASKA (SECTOR 9)

GEOMORPHOLOGY

In general, the floor of the Gulf of Alaska is a smooth southwest sloping plain with contours roughly parallel to the western coast of Canada and southeastern Alaska. Many seamounts rise above the plain, some with a relief of more than 3000 m (Menard and Dietz, 1951). Moore (1974) characterizes the continental margin of southwestern Alaska as a magmatic arc plus derived sedimentary deposits, and a parallel eugeosynclinal sequence.

Continental Shelf

A generally wide continental shelf that narrows in approaching the Aleutian Islands is found along the northern and western margins of the Gulf of Alaska. Its width ranges from less than 20 km in the northeastern reaches through about 75 km off the tip of the Alaska Peninsula to a maximum of about 275 km on the Schumagin-Kodiak Shelf south of Kodiak Island (Fullard and Darby, 1970). Numerous rises originate from the sea floor on the shelf portion of the continental margin; several break the sea surface as islands, the most prominent ones being Kodiak and Afognak Islands. Submarine troughs, such as Shelikof Strait, extend transversely across the shelf whereas other minor troughs incise the shelf edge for short distances, giving rise to the very irregular outline of the continental shelf's seaward edge (Figure 78). Cook's Inlet, a shoreward extension of Shelikof Strait, lies between Kinai Peninsula and mainland Alaska; Shelikof Strait is that deeper-water (more than 200 m) stretch between Kodiak Island and the Alaska Peninsula. Another entrance to Cook's Inlet is shallower, less than 200 m, and lies between Afognak Island and the tip of Kenai Peninsula.

Continental Slope

The base of the Canadian-Alaskan continental slope is ill-defined in some places, i.e., northern Gulf of Alaska, but is sharp elsewhere, particularly in the vicinity of the Queen Charlotte Islands. The depth at the base of the slope is generally from 2500 to 3050 m (Menard and Dietz, 1951). From the seaward edge of the slope to a depth of 3600 m, the sea floor off Canada has an average inclination of about 12 feet per mile, 0.2°; from 3600 m to 4600 m, it slopes 9.5 feet per mile, 0.18°.

The descent of the continental slope and the north slope of the Aleutian Trench is illustrated as steplike on the transverse profiles of Gibson (1960). Most prominent of the steps is the Aleutian Bench, approximately 30 km wide and extending for 115 km at a depth of about 2600 m. This smooth, level plain narrows and becomes troughlike westward, whereas its eastern end is broken by Unimak Seamount, a ridge-like structure 16 km wide and 48 km long. A very irregular bench of limited extent lies in 2700-m depths south of Middleton Island. Shuyak Seamount

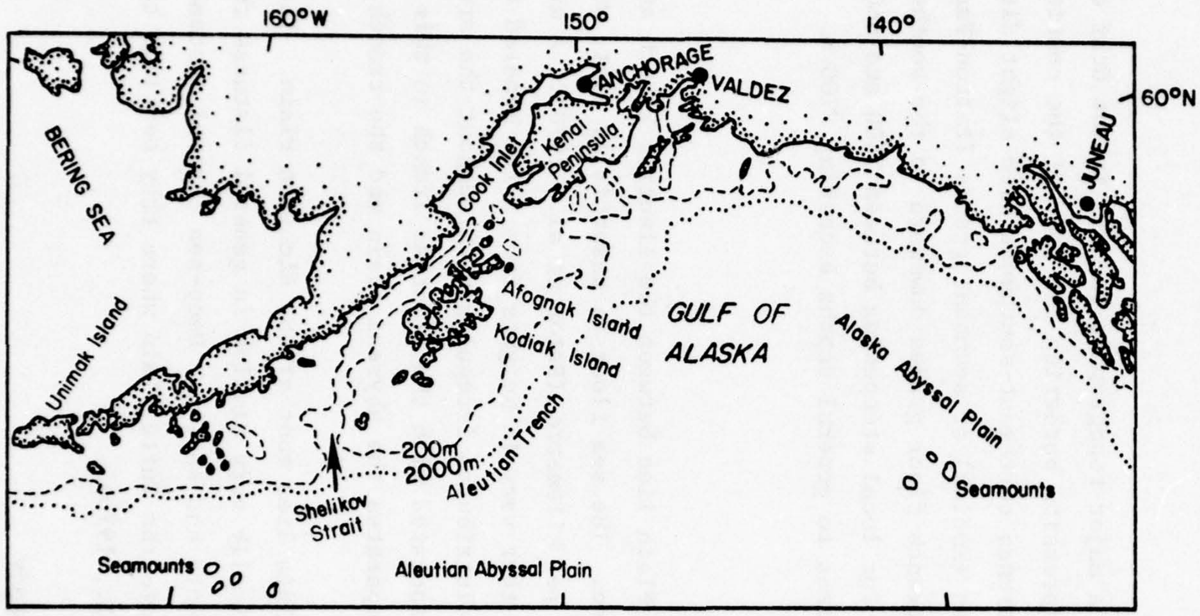


Figure 78. Gulf of Alaska geomorphic features (from Fullard and Darby, 1970)

and several lesser structures rise from this bench. Gibson (1960) notes that although these benches lie well above the general level of the gulf floor, they are roughly at a depth of the foot of the continental slope in other areas.

The Aleutian Trench, a major topographic feature in the Gulf of Alaska, is an asymmetrical depression bordering the foot of the continental slope. This trench trends northeast-southwest with slight direction changes near seamounts (Kodiak) or seamount groups (Patton-Faris Seamount Groups). The trench floor grades downward to the southwest only very slightly except for local steepening between 5400 and 6600 m, beyond which it flattens to general depths exceeding 7100 m.

Abyssal Plain

The Aleutian Abyssal Plain lies between the Aleutian Trench and the Surveyor Fracture Zone. The sea floor is essentially flat, with a small southward dip of 2 m per kilemetre (Peter et al., 1970). A number of knolls and seamounts that vary in heights from a few hundred to over a thousand metres are distributed irregularly throughout the area. There is no outer ridge associated with the Aleutian Trench in this area; only a small swell separates the abyssal plain and the trench.

The Alaska Abyssal Plain lies east of the Aleutian Plain. The two plains are topographically very similar in general flatness that is interrupted by seamounts and knolls. Deep-sea channel systems pass across the plains, into the Tufts Plain where they continue to the southwest (Dehlinger et al., 1970).

OCEANOGRAPHY/METEOROLOGY

Currents

Studies of the geostrophic currents in the Gulf of Alaska provide a good estimate of the direction of the long-term flow patterns established by mass and surface wind stress in the region (Rosenberg, 1972). The general circulation can be described as the counterclockwise Alaska Gyre, which is typically considered to be composed of two flows, the Alaska Current and the Subarctic Current. The Alaska Current is found in the northern and western parts of the Gulf of Alaska. It parallels the shoreline, flowing east to west and persists up to 200 miles or more away from the shore. Farther offshore, in the region lying from about 47°N to 52°N, the easterly flowing Subarctic Current is found. The Council on Environmental Quality (1974) reported that current speeds could not be calculated due to the basic nature of geostrophic calculations; however, they state that reasonable values for the offshore currents would appear to be on the order of 1 knot for the region just off Kodiak Island and 0.1 to 0.5 knots over the rest of the area.

Hydrology

In the estuarine regions of the Gulf of Alaska, shelf-slope areas have two quite distinct water masses. The shelf water tends to be relatively cold and of low salinity while the offshore Gulf of Alaska waters have both higher temperatures and salinities. Typical values for shelf waters would be a salinity of 30-31 ppt and a temperature range of 4-7°C; the offshore waters are characterized by salinities greater than 32 ppt and temperatures ranging up to 10°C (Wright, 1970). The dominant process influencing the water masses is the annual change in Ekman transport caused by the shift in the atmosphere from a low in the winter to a summer high. Intense winter downwelling flushes the shelf with relatively cold, low salinity waters, whereas weak summer upwelling brings warm, more saline waters onto the shelf (Royer, 1975). Typical water column values of temperature, salinity, and oxygen are shown in Figure 79 for the shelf-slope region of the Gulf of Alaska.

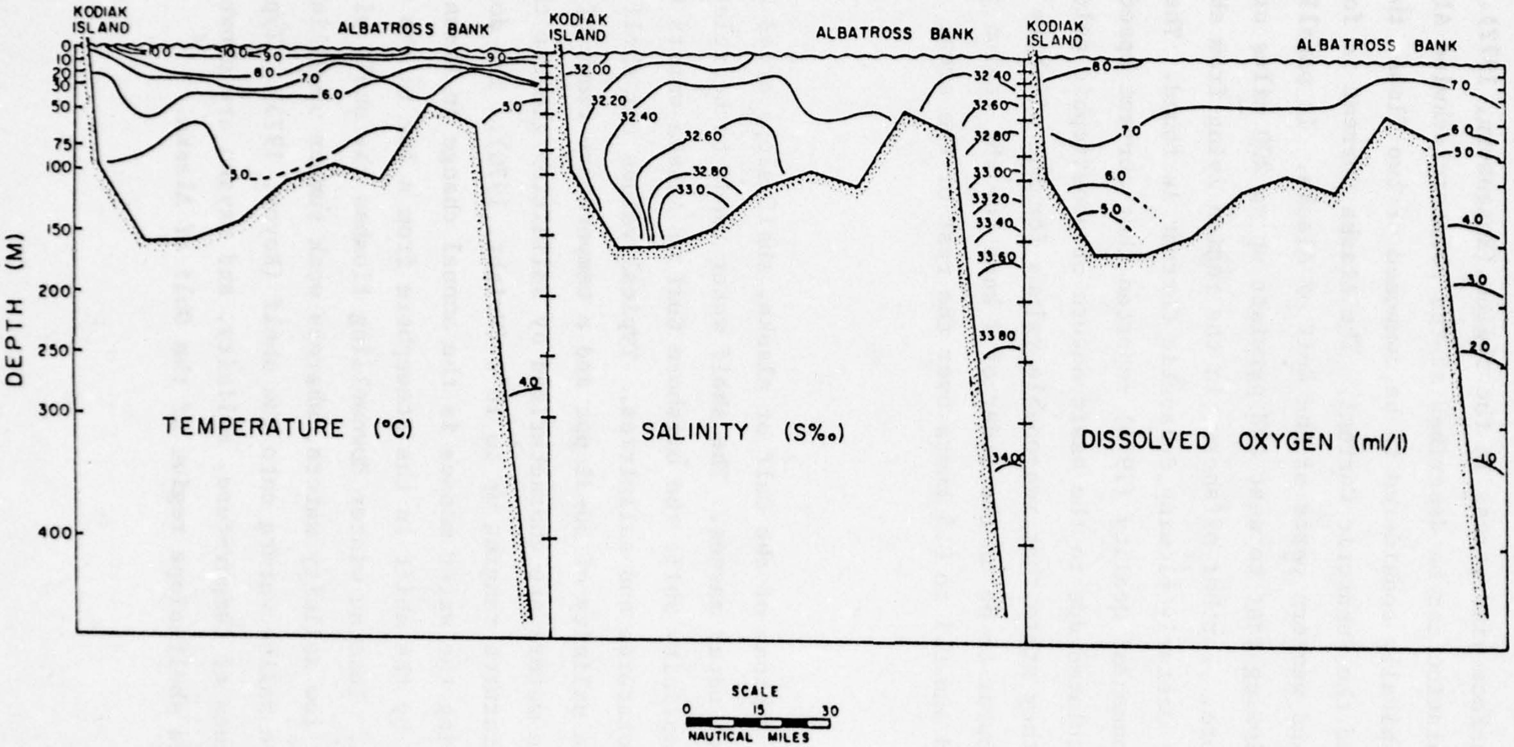


Figure 79. Hydrologic conditions seaward of Kodiak Island, Gulf & Alaska, June 1967 (from Wright, 1970).

Winds and Storms

Direction of winter winds in the Gulf of Alaska is variable. Gales, (winds of greater than 33 knots) which blow 10-20 percent of the time, are most likely in November and December. Wind speeds average 10-20 knots during the winter. Sustained winds from "williwaws" (winds that blow down from the mountains) have reached 74 knots at Cape Spencer, 66 knots at Anchorage, and 50 knots at Yakutat. Gusts of 60 knots or greater occur almost monthly during the winter season.

The changeover from winter to summer is subtle. Storms and strong winds still come but become gales less often. During May-August summer weather features become more apparent with July having gales less than one percent of the time. September, having gales 5-10 percent of the time, marks the transition month between summer and winter.

FISHERIES RESOURCES

The fisheries resources of Alaska are included in the previous section (Section E, the Pacific Coast) along with the Sector 8 (Northwest Pacific Coast) discussion.

HAWAII (SECTOR 10)

GEOMORPHOLOGY

The Hawaiian archipelago stretches across the central Pacific basin from northwest to southeast for a distance of about 2600 km. The major islands are at the southeastern end of the archipelago, spanning a distance of about 640 km, and the rest of the chain, on the northwest, consist of widely scattered small islands, atolls, reefs, and shoals. In essence, the archipelago consist of a tremendous mountain range rising from the sea floor, at a depth of more than 4570 m to a maximum height of 4200 m at the summit of Mauna Kea, an extinct volcano, on the island of Hawaii (Peterson, 1971). Only the upper parts of this oceanic moutain range reach above sea level to form the islands, and by far the greatest part of its mass lies beneath the ocean surface; hundreds of peaks rise high above the sea floor but do not reach sea level. The total area of the eight largest islands is 16,666 km^2, whereas the area occupied by the entire mountain range is greater than 578,000 km^2 (Peterson, 1971).

The Hawaiian Archipelago was built by molten rock extruded during thousands of volcanic eruptions. As long as the volcanos remained beneath the sea their growth was essentially unimpeded by erosion, but when their summits reached the surface of the sea, destructive forces of erosion counteracted the constructive forces of volcanism. Waves, winds and weather dissected and reshaped these rock masses when volcanism slowed or ceased. Where erosion continued long enough, it reduced the islands to sea level.

The earliest activity of the Hawaiian Archipelago was probably at the northwest and moved progressively southeastward, the main Hawaiian Islands being the most recent products of volcanism. This possibility is attested to by atolls, reefs, shoals, and submerged seamounts (remnants of previous islands) at the northwest end along with the fact that the only two currently active volcanoes are located on the island of Hawaii at the easternmost tip of the chain.

Shelf and Slope

The platforms bordering oceanic islands have been appropriately termed insular shelves (Shepard, 1963). Such shelves do not exist around the oceanic islands, but at least narrow platforms are commonly found. The islands lacking shelves include many of those that have had recent volcanic activity; the island of Hawaii with its active volcanoes is almost entirely free of marginal platforms, the widest region being about 9 km off the northwest shore. A common shelf encompasses the islands of Maui, Molokai, Lanai, and Kahoolawe whereas Oahu, Kauai, and Niihau possess individual platforms similar to Hawaii's but greater in average width. The common shelf averages about 18 km in width except for that terrace-like projection that extends southwest of Molokai for approximately 50 km (Fullard and Darby, 1970). Malahoff and Woolard (1970) report that, in general, the Hawaiian area is one of thin sedimentary cover. Only in the trench area does so much as 1 km of sediment appear to be present.

If the base of the slope is considered to be approximately 2000 m, the Hawaiian Islands are footed by three different slope regimes (Figure 80). This topographic discontinuity provides depths necessary for deepwater channels between the islands: Alenuihaha Channel separates Hawaii from the four central islands whereas Kauai Channel lies between Kauai and the center islands. These insular slopes are, overall, much wider than are their adjacent shelves.

Abyssal Realm

Deep basins, with marginal depths ranging from 4650-5050 m, lie to the north and east of the Hawaiian chain. Fan and Grunwald (1971) attribute the clastic sediments (primarily detrital muds but with some silty calcareous sands) that are shed from the Hawaiian Islands into such features of oceanic depth, to transport and deposition by turbidity currents. The Hawaiian Trench, a moat-like structure, is well developed around the southeastern end and flanks of the Hawaiian Ridge and serves as a catchment area for sediments eroded from the ridge (Malahoff and Woolard, 1970).

OCEANOGRAPHY/METEOROLOGY

Hydrography

Gordon (1971) shows the waters off the Hawaiian Islands consisting of

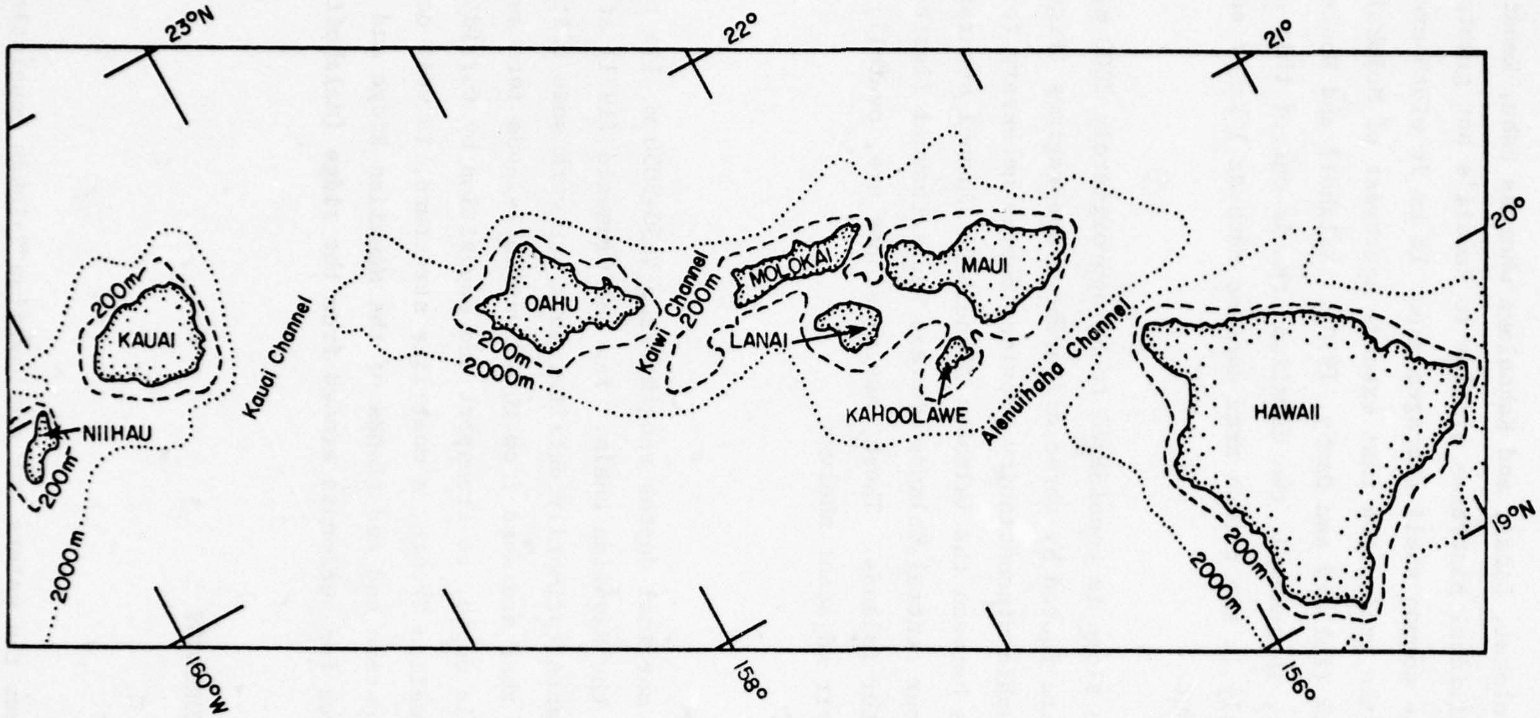


Figure 80. Map of Hawaiian Islands (modified from Malahoff and Woollard, 1970; Fullard and Darby, 1970)

three principal water masses: North Pacific Central Water, North Pacific Intermediate Water, and Pacific Deep Water (Figure 81). The upper few hundred metres is made up of the North Pacific Central Water, which has a salinity maximum at 100 to 200 m of about 35.2 ppt. Besides the halocline, the thermocline also is in this upper portion of the water column (Figure 82). The salinity minimum (34.1-34.2 ppt) at about 400 m marks the core of the North Pacific Intermediate Water and a few hundred metres below it is a well-defined oxygen minimum zone ($<$ 1 ml/l). The very uniform Pacific deep water is found below about 1500 m. Except for the expected seasonal changes in surface waters, temperature, salinity, and dissolved oxygen, for the greatest part, remain essentially constant with time.

Currents

Surface currents flowing around and between islands of the chain have quite mixed speeds and direction both temporally and spatially (Figure 83). In addition, they are strongly influenced locally by tidal cycles and physiography. Net movement, however, is to the west coinciding with the west trade wind drift.

Studies conducted by Neighbor Island Consultants Inc. (1977) showed currents in the Hawaiian Chain to be highly variable and not locally predictable as one would assume based on winds. Their general conclusions about currents around the islands are:

1. Currents will generally show strong tidal variations, frequently including reversals of direction over a tidal cycle.

2. Large non-tidal variations may be superimposed on the basic pattern due to the wind driving, internal wave motions, etc.

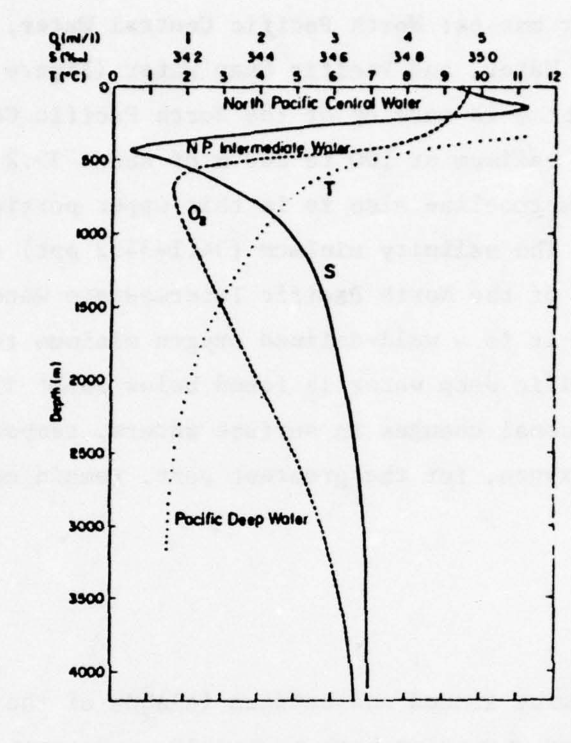


Figure 81. Depth of principal water masses off the Hawaiian Islands (from Gordon, 1971).

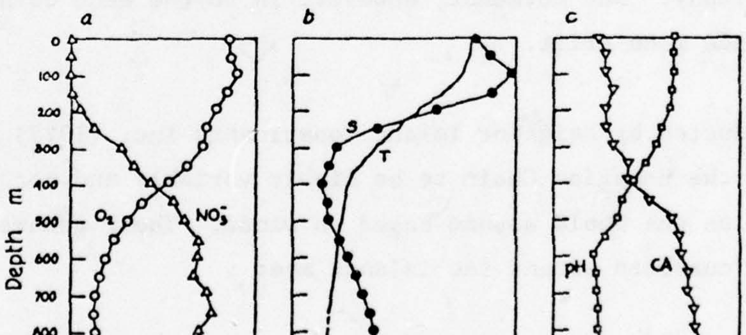


Figure 82. Physical and chemical properties of the water column off the Hawaiian Islands. a) Dissolved oxygen and nitrate, b) Salinity and temperature, c) pH and carbonate alkalinity (from Gunderson and Mountain, 1973).

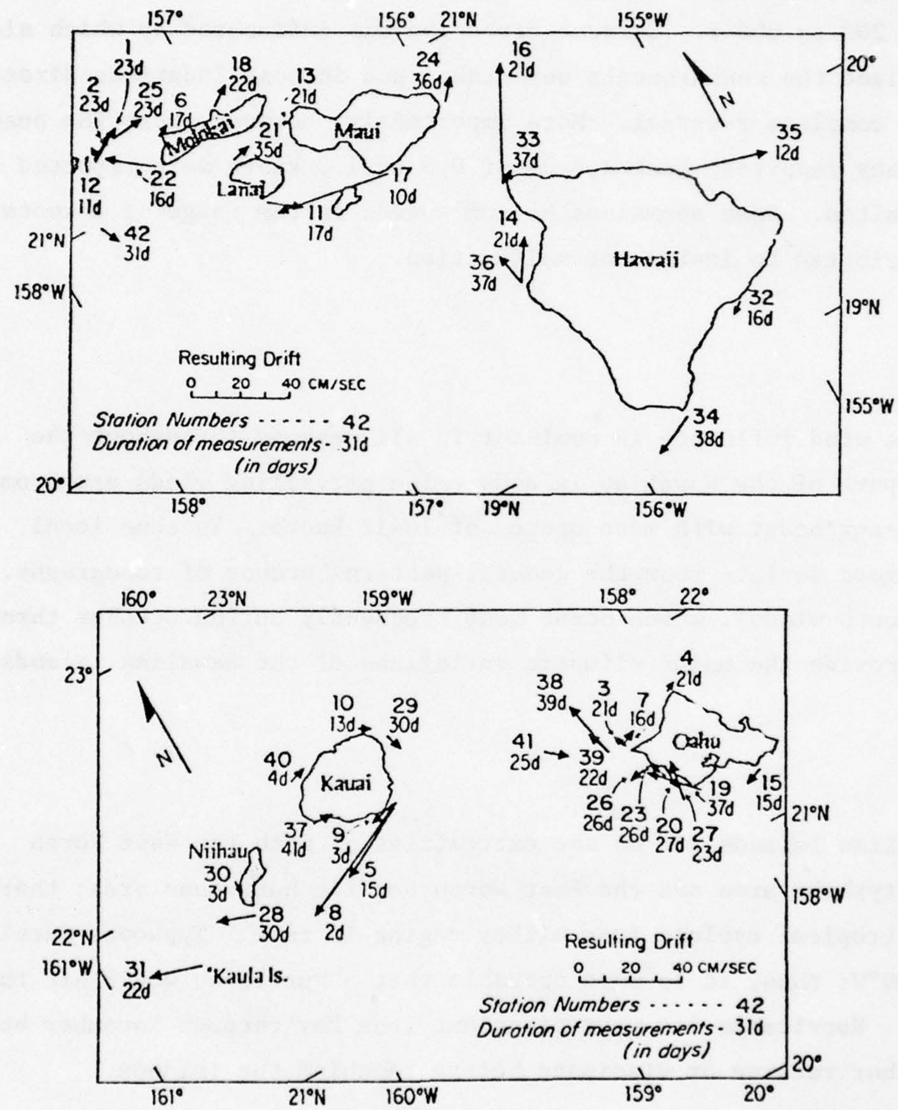


Figure 83. Resulting drift or average vector velocity for current meter stations in the western part of the Hawaiian Archipelago (from Patzert and Wyrtki, 1974).

Also included in the above report were bottom current measurements taken at six proposed dredged material disposal sites with bottom depths ranging from 200 to 600 m. Current direction was influenced by which side of an island the measurements were taken and in some locations direction showed a complete reversal. More importantly, however, were the peak speeds they reported; peak speeds of 0.5 to 1.0 knots were reported for the six sites. Some anomalous bottom speeds in the range of 2 knots were attributed to instrument malfunction.

Winds

The trade wind influence is dominant in all seasons throughout the greater part of the Hawaiian Islands. The prevailing winds are from the east-northeast with mean speeds of 10-12 knots. In some local areas, winds deviate from the general pattern because of topography. Konas (south winds), which occur most frequently during October through April, provide the major climatic variations of the Hawaiian Islands.

Storms

The Hawaiian Islands lie on the extremities of both the West North Pacific typhoon area and the East North Pacific hurricane area; therefore, a tropical cyclone from either region is rare. Typhoons rarely cross 180°W; thus, it is more probable that a hurricane would hit the islands. Hurricanes are most prevalent from May through November but most either recurve or dissipate before reaching the Islands.

FISHERIES RESOURCES

Hawaii fisheries are typically nearshore. About 3/4 of the catch is obtained within 20 miles of the islands. An approximate area of 24,000 square miles is fished regularly; however, 25 percent of the catch is usually made in two small areas comprising only 4.3 percent of the total area fished. Major fishing areas are near the two chief ports, Honolulu on Oahu and Hiko on Hawaii. The intensity of fishing in these two areas appears to be due to their convenience, as biological or oceanographic explanations for their productivity are lacking. The most productive area is the Waianae fishing grounds. Located off the small town of Waianae, a few miles northwest of Honolulu, the area is on the lee side of Oahu and characteristically offers calmer seas.

Per unit area the Waianae fishing area is relatively productive for the open sea, yielding a pelagic catch of about 7 pounds per acre. Putting this figure in perspective, the Iceland banks, although immensely rich in demersal fish, produces about 5.3 pounds per acre. The South Pacific albacore fishery averages 0.009 pounds per acre. For comparison at the other extreme, the Peruvian fishery produces about 400 pounds per acre.

Demersal fish do not contribute much to the Hawaii fishery especially in the two major fishing areas. Five species of tunas and tuna-like fish account for most of the catch, 80 percent of the volume and 65 percent of the value. The Hawaii fishery provides approximately 0.3 percent of the total U.S. volume and 0.7 percent of its value.

The narrowness of the shelf, the steepness of the slope around the Hawaiian Islands, and the paucity of fishing banks preclude a significant demersal fishery. The islands rise steeply from the sea floor, which averages 5000 m in depth. The 100-m coutour is reached just a few miles from shore. Of the few fishing banks, Penguin Bank off the western end of Molokai is most notable. However, the 334-square mile area provides only about 1 percent of the Hawaiian catch.

Demersal fisheries include the snappers and black sea bass. Like most other fisheries of coastal species, the catch of snappers and black sea bass have declined since the 1950's.

The spiny lobster formerly was prominent in Hawaiian fisheries. It too has declined and presently is not intensive. The fishery rarely reaches below 30 m, although large lobsters have been reported at depths of 90-120 m off Oahu.

CARIBBEAN TERRITORIES OF THE U.S. (SECTOR 11)

GEOMORPHOLOGY

Puerto Rico together with St. Croix, St. Thomas, and St. John of the Virgin Islands comprise territories of the United States within the Caribbean Sea. With the exception of St. Croix, these islands rise above the same bank, Puerto Rico-Virgin Island Platform (Griscom and Geddes, 1966), but are separated by water depths of up to 30 m. St. Croix is due south of the Virgins across a chasm, a great fault valley, which at a distance of 36 km south of St. Thomas attains a depth of more than 4600 m (Vaughan, 1916). Frasseto and Northrop (1957) refer to this valley as the Virgin Island Basin and describe it as having a flat floor more than 4300 m deep while being bounded on the north and south by sea scarps having apparent slopes of 9 to 43 degrees. Mona Passage to the west of Puerto Rico and Anegada Passage to the east of the Virgin Islands provide unrestricted connections for the Atlantic Ocean with the Caribbean Sea in Sector 11.

Shelf and Slope

These islands rise from a relatively shallow submerged bank, which falls away into the sea in an irregular pattern. This insular shelf is extremely narrow along the north shore of both Puerto Rico and St. Croix with the 200-m isobath being scarcely more than two or three kilometres from shore in most places. Even though the shelf falls away less rapidly along the south coast, that part of it within 200 m is still quite narrow, less than 17 km. Individual coral heads and coral banks are scattered over the shelf from very near shore to the seaward edge of the shelf. Off St. Thomas and St. John the northern insular shelf is almost twice as wide as the southern one, which averages approximately 13 km in width.

The slope of the Virgin Island Platform is very precipitous. Meyerhoff (1927) describes the gradient off northern St. Croix as dropping 13,656 feet in a horizontal distance of 5 miles; this exceeds 50° declivity. Such a case is probably a maximum, but very deep water can be found in close proximity to both Puerto Rico and St. Croix. Mona Canyon cuts the slope region off northwestern Puerto Rico before fanning out over the Puerto Rico Trench.

Abyssal Realm

The Virgin Island Basin, discussed earlier, and the Puerto Rico Trench, with depths exceeding 8500 m, are included in the deeper aspects of the abyss in Sector 11. Other abyssal features include Muertos Trench, Anegada Passage, Jungfern Passage, and St. Croix Basin (Griscom and Geddes, 1966).

OCEANOGRAPHY/METEOROLOGY

Hydrography

Puerto Rico and the U.S. Virgin Islands are situated in the trade wind belt, and, thus, have very steady winds from the east and east-northeast. In the Caribbean region rainfall is heavier during the summer months when more tropical weather prevails. The highest rainfall is to the east of the Central American isthmus where more than 80 inches falls in the 6-month period from June to November (Gordon, 1966). This results in very high discharges by South American rivers (Amazon, Orinoco, and Magdalena). In addition, the doldrums region of the western

Atlantic, whose surface salinity is relatively low, shifts in the summer from 10°-15°N to 15°-20°N. The combined effect of these summer-fall anomalies results in a tongue-like belt of low salinity water off eastern South America extending into the Caribbean and thus bathing Puerto Rico and the U.S. Virgin Islands with surface salinities in the range of 34.5-35.5 ppt. In contradistinction, winter-spring river discharges are lower and the doldrums are farther south; thus surface salinities are higher, being in the range of 35.5-36.5 ppt (Wust, 1964).

At depths between 100 and 200 m, salinity reaches an absolute maximum in the water column of about 36.9 ppt (influence of the Subtropical Underwater) then decreases to an absolute minimum of about 34.9 at 800 to 1000 m (influence of the Subantarctic Intermediate Water). The temperature structure is of tropical character, i.e., warm surface values and a well-defined thermocline at 100-200 m, which hinders vertical mixing. From 1500 m to the bottom, Caribbean Sea temperatures decrease to about 4°C; whereas, on the Atlantic side of the islands temperatures decrease to about 2°C at 6000 m. It is evident from the above mentioned temperature and salinity profiles that a strong pycnocline exists at 100-200 m.

Circulation

The joining of the North Equatorial Current with the Guiana Current forms the surface currents, which flow by the Puerto Rico - U.S. Virgin Islands area. That portion of the current that flows through the Caribbean Sea is called the Caribbean Current, while the part that flows to the north side of the Caribbean island chain is called the Antilles Current. Since these currents are mainly wind driven, the surface current direction in this region is to the west-northwest.

Since the shelves of the Caribbean Islands are elongated on their east-west axis, the major flow is to the west along the shelf edge; however, local physiography does influence current flow. Although occurring only a few times a year, surface currents may flow easterly when the trade winds are calm (TerEco Corporation, 1973). Tidal influences may override wind driven currents especially in the passages, e.g., Mona Passage, between Puerto Rico and Hispaniola, where north-south component tidal currents may reach 3.5 knots.

Current speed generally diminishes with depth but direction is still to the west (Wust, 1964); however, speeds of 14 cm/sec (0.3 knots) have been reported at a depth of 6599 m on the north wall of the Puerto Rico Trench (Hollister and Heezen, 1966).

Winds and Storms

Winds. Puerto Rico and the U.S. Virgin Islands are located in the "trade wind belt" or belt of strong prevailing winds (blowing from the northeast, east, and southeast). The major seasonal changes in normal wind conditions are related to the normal variations in position and intensity of the Bermuda high and equatorial trough. During December-February trade winds reach their primary maximum in speed (about 25 percent exceed 19 mph). In March-May the trades attain a secondary minimum in normal speeds (about 10 percent exceed 19 mph). During June-August the secondary maximum in normal wind speed occurs (about 26 percent exceed 19 mph). In September-November the primary minimum in normal wind speed occurs (about 7 percent exceed 19 mph).

Storms. Since the islands lie in the path of tropical storms and hurricanes, occasional winds of extreme force are experienced. Although hurricanes have occurred in this region during January, May, July, August, September, October and November, their occurrence in other than July-November is negligibly small. At San Juan, Puerto Rico, during the passage of a hurricane in September 1928, the National Weather Services anemometer blew away after recording an extreme wind speed of

160 mph. This is the highest value recorded in Puerto Rico to date.

FISHERIES RESOURCES

With a population density of over 700 inhabitants per square mile. food is a problem in Puerto Rico. Although antiquated and underdeveloped, the fisheries are of local importance in producing food for the burgeoning population. High per capita consumption of seafood (about 1-1/2 times that of the mainland U.S.) requires that fishery products be imported to meet consumer demand (Shapiro, 1971).

Growth in the Puerto Rico fishery has been severely limited by a persistence in using outdated fishing practices. The most common gear is the fish pot, utilized in waters up to a depth of about 60 m. Usually set in reef areas, their catch includes bottom dwelling species such as groupers, snappers, parrotfish, grunts, wrasses, and spiny lobster. Bottom fish are also taken in reef areas using hand lines. Trolling lines, towed behind boats, are used for pelagic species such as spanish mackerel, king mackerel, and others. Gill nets, weirs, cast nets, hoops, and dip nets are also used in coastal waters.

The north and south shores have extremely narrow shelves characterized by rough bottoms of coral and rock, conditions that are not conducive to bottom trawling. Along the north shore the 200-m isobath is rarely more than 1-2 miles from shore, and the slope drops steeply to a depth of 5000 m. The southern slope is less steep; however, the shelf remains quite narrow. To the east and west, miles of shallow water offer workable fishing areas. A productive shelf area also exists to the southeast. Banks, ranging in depth from 50 to 220 m, extend to the west of Puerto Rico.

Wind and sea conditions especially on the north or Atlantic side of the island are often apt to limit fishing. Inshore waters along the south coast are generally more conducive to small boat fishing.

The waters of the tropical seas that surround Puerto Rico lack the productivity necessary to support an abundance of aquatic resources. This is due primarily to the nutrient limitation of primary production through the general absence of vertical mixing in the water column and the minimal terrestrial runoff, both of which serve to provide nutrients to the euphotic zone.

PART 6. SUITABILITY OF SPECIFIC ENVIRONMENTAL AREAS FOR DISPOSAL OF DREDGED MATERIAL

A. INTRODUCTION

GENERAL VIEW OF SUITABLE VS. UNSUITABLE ENVIRONMENTS

RELATIONSHIP TO "RULES AND REGULATION"

During the course of determining specific environmental areas to recommend for deep ocean disposal of dredged material and to develop criteria to be used by District Engineers in selecting specific disposal sites within these areas, the general and specific criteria for the selection of ocean disposal sites in Sections 228.5 and 228.6 of the Environmental Protection Agency's "Regulations and Criteria for Ocean Dumping" (Federal Register, Part VI, January 11, 1977) were studied.

Apparently, the only designated waste disposal site in the deep ocean in the United States today is the incineration site established in the Gulf of Mexico primarily for the burning of toxic chemical wastes.* The center of this site lies over 1372 m of water on the continental slope about 305 km south of Galveston, Texas. Thus, even though the EPA criteria were developed without specific experience in regard to the disposal of dredged material, they have provided useful insights into EPA's principal concerns for the welfare of the ocean.

Both EPA and the Corps of Engineers have vested interests in ocean disposal stipulated in the Marine Protection, Research, and Sanctuaries Act of 1972 (MPRSA), as amended. Section 103 of MPRSA vests responsi-

---

* Other deep ocean disposal sites are approved only on an interim basis, pending completion of trend assessment surveys (Federal Register, Jan. 11, 1977, Pt. VI, Sec. 228.12(a) and (b).

bility in the Corps, in cooperation with the Environmental Protection Agency, for authorizing the transportation of dredged material for the purpose of discharging it in ocean waters. The District Engineer will authorize such disposal only when he determines that it will not unreasonably degrade the marine environment. He is guided in this determination process by the EPA criteria.

EPA's ocean disposal permit program and its Ocean Dumping Regulations and Criteria were authorized by Section 102 paragraphs (a) and (c) of MPRSA, as amended. In general, the possible use of the deep ocean for disposal of dredged material is compatible with both the general and specific criteria for site selection promulgated in Sections 228.5-228.6 of the "Regulations and Criteria." The findings of this report one "general criterion," Section 228.5 (e):

> "EPA will, whenever feasible, designate ocean dumping sites beyond the edge of the continental shelf and other such sites that have been historically used."

In addition, selection of deep ocean sites will generally minimize the basis for concerns expressed in paragraphs (a), (b), and (c) of Section 228.5. There is, however, one possible area of confusion in paragraph (d) as to EPA's intent:

> "The sizes of ocean disposal sites will be limited in order to localize for identification and control any immediate adverse impacts and permit the implementation of effective monitoring and surveillance programs to prevent adverse long-range impacts ---."

Some people have interpreted this to apply to the area covered by dredged material on the ocean floor and thus have felt that it supported the opinion that disposal should be carried so as to achieve minimal bottom coverage. Supposedly, this would make the task of monitoring effects somewhat easier. As a matter of fact, however, T. A. Wastler (Chief, Marine Protection Branch of EPA) advised TerEco

Corporation on 14 March 1977 that the stipulation was written with particular reference only to limitation of the ocean-surface boundaries of the disposal site and did not apply to the fate of dredged material being dispersed during its fall through deep water.

An incineration site is essentially a planar surface since during incineration the components of the waste plume are gases that will never reach the bottom. And to a large extent also the components of sewage sludge will remain aloft for considerable periods. In contrast, a dredged material disposal site must be viewed as a column that has an air-sea interface, a stratified and dynamic water column, and the sea-sediment interface at the bottom.

When carried out in the usual manner by a hopper dredge or bottom-opening barge the deep ocean disposal of dredged material should have only minimal and temporary effects on pelagic life. During the intitial part of the drop the material occupies a relatively small volume until the "collapse" phase, which in many cases will occur at the pycnocline. The coarser sedimental material and chunks will continue a rapid descent and be less affected by the currents, whereas the fine sediment will be more widely dispersed at and below the pycnocline (Figure 84).

The picture described above is essentially that of the majority of marine scientists interrogated by TerEco Corporation regarding the disposal procedure. It is well stated by Dr. William Newman of Scripps Institution of Oceanography, who said during the Advisory Committee meeting in San Diego, California in August 1976, "Keep the material as intact as possible through the thermocline and then let it disperse." This appears to be a rather straightforward account of what actually happens even when the material has a high PCM. (See the account of W. E. Pequegnat's observations aboard the hopper dredge HARDING at work, Part 3 of this report).

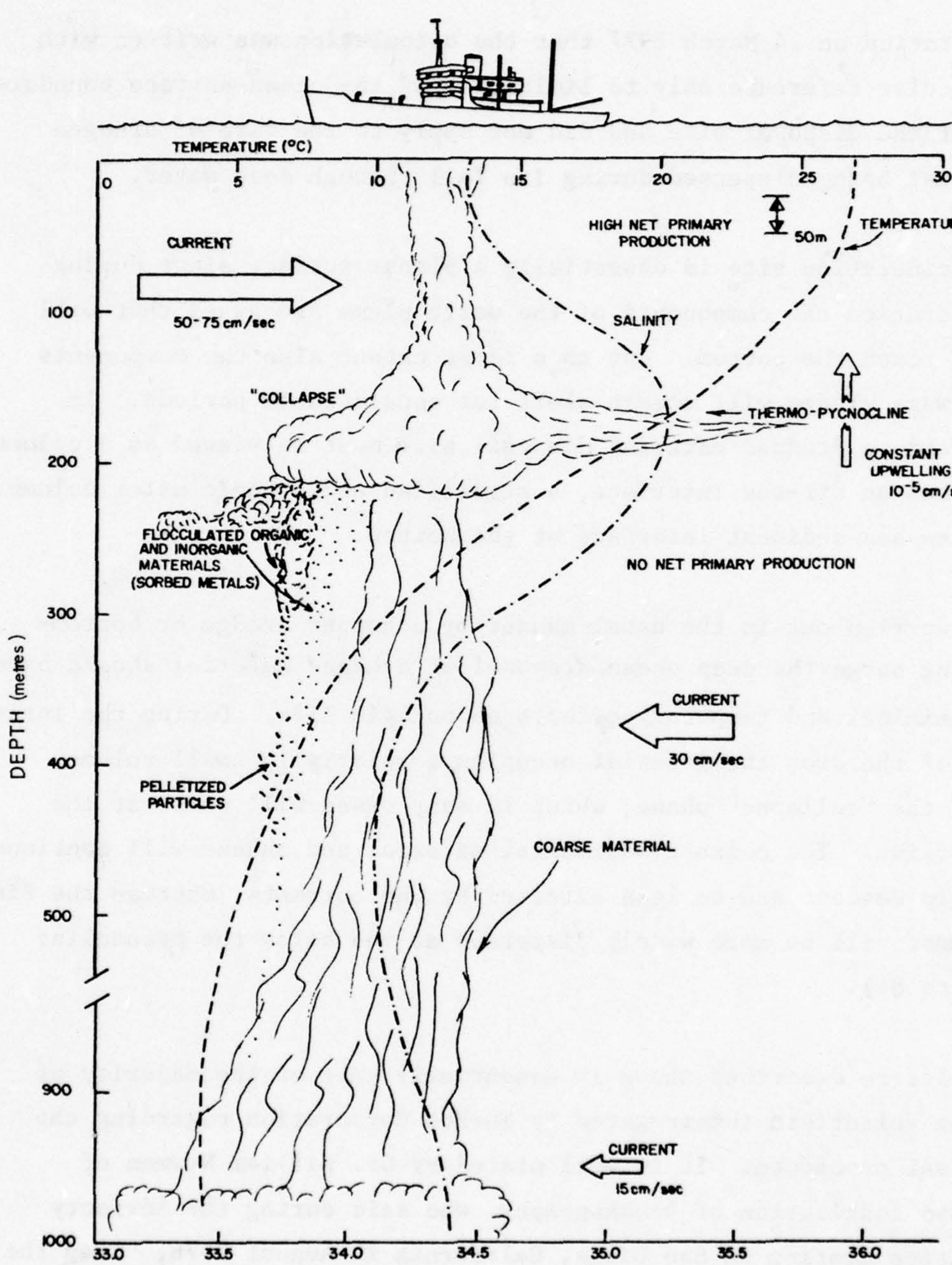


Figure 84. Schematic picture of the disposal of hopper-dredged material into a two-layered deepwater system (1000m) with a strong thermo-pycnocline. Note the depth of high net primary production (25-50m), the spreading of some fine material on the thermocline, and the minimal effect of upwelling as material passes through the thermocline.

RELATIONSHIP TO OCEANOGRAPHIC PARAMETERS

If it is true, as seems to be apparent from the above discussion, that deep ocean disposal can, under proper management, obviate most of the environmental concerns under the site selection criteria in the Regulations and Criteria of 1977, then this report proposes to base the weight of its decision, as to selection of suitable vs. unsuitable areas and environments for dredged material disposal, on oceanographic considerations. It must be remembered, however, that here we are selecting areas, not sites, and that the ocean deeps are simpler and far less variable than the shallow shelf and estuaries.

CATEGORIES FOR RANKING DISPOSAL AREAS

There seems to be no justification for creating an elaborate system for selecting or rejecting disposal areas in the deep sea. Accordingly, it is proposed herewith that areas, in which the District Engineer may wish to select a site for deep ocean disposal, be placed into one of three categories of rank. These are "Favorable," "Neutral," and "Poor." These are to be characterized, as follows:

Favorable: To the extent that an area meets all or most of the oceanographic considerations hereinafter established as selection criteria and does not possess serious deleterious characteristics, then it shall be ranked as "Favorable." In most instances, but not necessarily in all, the area considered to be favorable will be of sufficient geographic extent as to give the District Engineer a considerable geographic span in which to pinpoint the site that he wishes to designate. These should be all-season sites.

Neutral: When an area has no serious deleterious oceanographic problems vis-a-vis ocean disposal of dredged material but does not meet a majority of the oceanographic criteria, it shall be ranked as "Neutral." This will mean that the area may have good sites, but is not as uniformly favorable, as in the top ranking. There may be some restriction as to season for disposal.

Poor: When an area is identified that has serious deleterious oceanographic problems and meets less than a majority of the favorable oceanographic criteria, it shall be ranked as "Poor." Depending upon the size of the area, this ranking may carry with it the implication that no sites should be located in any part of the area.

NEED FOR CRITERIA AS GUIDELINES

As indicated above, criteria are needed as guidelines for both selection of suitable areas and the final site-selection. Here the primary concern is to determine appropriate deep ocean areas for designation of dredged material disposal sites. Certainly many of these will also be used for site selection. However, to select or reject an area may require only a broad brush treatment of the issue, whereas selection of a definitive site will require more detailed information. This is the point at which the selection system is under considerable stress. The amount of reliable and published data applying to the oceanography of the shelf-break/upper continental slope environment is discouragingly meager. Nevertheless, the authors have gleaned whatever useful information has come to their attention and are prepared to develop a system of criteria.

B. DEVELOPMENT OF CRITERIA FOR SITE SELECTION

PHYSICAL OCEANOGRAPHIC CONSIDERATIONS

UNFAVORABLE PHYSICAL CRITERIA

Upwelling

Upwelling is the movement of cool subsurface water upward to form the surface or near-surface layer. It occurs primarily along the eastern sides of the oceans (western edge of continents), as along the west coasts of North America and South America, western and northwestern Africa, and the western coast of India. In this report, upwelling is judged to be an indicator of a poor place to locate a dredged material disposal site, because of its importance to phytoplankton production and ultimately to fisheries; however, it is seasonal and is most important on the shelf.

Although upwelling can be caused by several phenomena, among them the diverging of winds, or the coursing of tidal and internal waves up submarine canyons, or from the driving force of winds blowing equatorward, the latter is by far the most significant cause. Thus, it takes place when the wind blows towards the equator along the coast and the frictional stress of the wind on the water combined with the effect of the rotation of the earth (Coriolis effect) causes water in the surface layer to move away from the shore. It has to be replaced by water which "upwells" from below the surface, but not from great depths. Normally, it comes from depths around 200 m but may range anywhere from 50 to 300 m. The upwelled water has higher concentrations of such nutrients as phosphates, nitrates, and silicates than the original surface water that will have been depleted by biological activity. Since one or more of these three nutrients can be a limiting factor to phytoplankton growth, upwelled water is vital to continuing phytoplankton production.

Even though this report has categorized upwelling as an unfavorable physical oceanographic criterion, it should be noted that nearly everywhere in the world ocean it is a seasonal phenomenon. Hence, off the west coast of North America it does not occur during winter.

Persistent Eddies

It is a characteristic of surface currents in the ocean that they follow an irregular or meandering path. At times, the loops of these meanders become highly constricted, similar to an ox-bow in a meandering river on land, and pinch off to form either clockwise (anticyclonic) or counterclockwise (cyclonic) spinning eddies or rings. These eddies, which may be one or more hundred kilometres in diameter, move off from the parent current and often drift toward the continental shelf and may actually "decay" on the shelf. Their present significance is the fact that they are long-lived (1 to 2 years) and are capable of transporting floatables and keeping fine sediments in suspension and depositing them at the decay points. These are best developed in the Gulf of Mexico and western Atlantic around the Gulf Stream.

Circulation Patterns of Irregular Occurrence

There are areas of offshelf U.S. waters where current patterns are very changeable and are thus highly unpredictable. Such areas should be avoided for establishing disposal sites.

FAVORABLE PHYSICAL CRITERIA

Downwelling

Downwelling is the sinking of surface water to greater depths, the opposite of upwelling. Downwelling is not as well known as upwelling but it is associated with two phenomena, viz., Langmuir circulation and Ekman transport, where in both cases wind is the forcing function

(Figure 85). Ekman transport is the only one of interest to the present discussion. It is related to the Ekman spiral, discussed in Part 1 of this section. A steady wind blowing across an ocean surface causes the surface layer to drift at an angle of 15-20° to the right of the wind direction in the Northern Hemisphere. With increasing depth, the water direction swings more and more to the right until at a certain depth the water is moving opposite to the wind. The net motion of the entire mass of moving water is called Ekman transport and its movement is at right angles to the direction of the wind. Ekman transport can, of course, cause upwelling or downwelling, depending on the direction of the wind relative to the coastline. A southerly wind on the west coast of any continent in the Northern Hemisphere will cause surface waters to move toward a coastline. It tends to pile up there depressing the pycnocline and holding river discharges near the coast. Strong currents moving with the wind can result from this accumulation of water (such as the Davidson current off California and Oregon).

Downwelling is considered to be a favorable physical criterion for dredged material site selection because of low productivity of its waters and because it can cause rapid dispersion of materials at the pycnocline where turbulence may be advantageous. It should be noted, however, that downwelling can be an unfavorable criterion for selection of a site for the disposal of low-density (floating) wastes. Obviously, a steady northerly wind on the east coast might cause movement of material to the shore in regions of low river discharge.

Convergences

A convergence is an area where two currents or flow regimes come together. Often there is subsidence of surface water in the zone of convergence. In some areas of the U.S. offshore water (e.g. the Northwest Gulf of Mexico) these convergences transport water rapidly

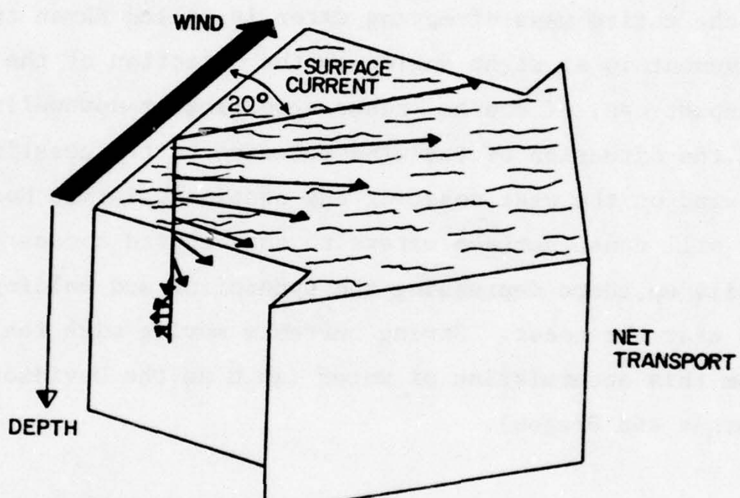


Figure 85. Diagram of Ekman transport of surface water at right angles to wind direction. Note also the Ekman spiral resulting in a progressive shift of current direction to the right with increasing depth.

offshore as well as causing some sinking of waters. These are considered to be plus factors in establishing a disposal site.

Weak and Predictable Current Patterns

In general, predictability of surface water flow is considered to be a plus factor in locating a disposal site. On balance, it is considered advantageous for disposal to take place in a weak but predictable surface flow that will permit fine materials to drop through the thermo-pycnocline before wide dispersal.

CHEMICAL OCEANOGRAPHIC CONSIDERATIONS

UNFAVORABLE CHEMICAL CRITERIA

Oxygen-minimum Zone

Prior to disposal of dredged material, it may be advisable to determine the position of the oxygen-minimum zone. This zone is a horizontal belt of low oxygen conditions that is formed where the oxygen-minimum layer of the water column intersects the bottom. Since the oxygen-minimum layer is an almost universal characteristic of the world ocean, the zone encircles all the ocean basins though its depth is normally uniform on the continental slope of large parts of a given basin, it ranges in depth among all basins from 150 to 1000 metres.

Zones of Metal-rich Surficial Sediments

Prior to disposal of dredged material, it may be advisable to carefully core a proposed disposal site, especially on the continental slope to determine the presence (or absence) or metal-rich surficial sediments. Preferably, this should be done with a box-corer that will not disturb the uppermost centimetres of sediment. High levels of manganese, iron, or arsenic are indicators of areas to be avoided.

It is advised that dredged materials rich in organics not be disposed in either of the above two zones. The BOD and COD of disposed material could create reducing conditions that will facilitate transformation of metals from the relatively insoluble oxide to the soluble metal, e.g., MnO_2 to Mn^{++}. This process can occur in other metals such as arsenic, iron, etc. The solubilized metal ions will move upward through the interstitial water and be incorporated into microfauna and flora or be carried off with resuspension of the surficial sediment. However, it should be noted that $S^{=}$ will precipitate metals as a poorly soluble salt under zero DO.

Conditions in an anoxic basin of the Gulf of Mexico illustrate the point. Manganese has a background concentration of 0.5 ppb in ambient waters, whereas its concentration in the waters of the anoxic basin increases to 10 ppm, a 20,000 fold increase.

Natural Oil Seeps

Regions of oil seeps should be avoided if the dredged material is known to have significant amounts of such substances as DDT and PCB. These are very soluble in oil, as compared with water, and could be made available for incorporation into the food chain.

FAVORABLE CRITERIA

Dissolved Oxygen Sufficiency

In establishing a disposal site for contaminated dredged material, it may be advisable to determine that it has reasonably high levels of dissolved oxygen, i.e., sufficient to renew the DO utilized to satisfy the BOD and COD of the discharged material, even though these criteria are not as good indicators of sediment condition in marine as in freshwater systems. Also, it should be noted that some contaminants, such as cadmium, are mobilized under aerobic conditions. This is yet another instance of the need to know the nature of the material to be disposed.

Bottom Current

At least for contaminated dredged materials, it appears that the disposal environment should have a current of sufficient velocity (4-5 cm/sec.) to carry off and disperse toxins released from the compacting dredged material.

GEOMORPHIC/GEOLOGIC CONSIDERATIONS

UNFAVORABLE GEOLOGIC CRITERIA: LOW-OXYGEN SUBMERGED BASINS

Submarine basins ranging in depth from about 600 to 2100 m and enclosing waters with dissolved oxygen levels varying from 0.2 to 1.5 ml/l exist in offshore regions of the United States. Frequently, these basins are separated from one another by islands and surrounded by submerged ridges. The deepest places on these ridges constitute the sills (or threshhold) of the basin. Their depth in regard to hydrographic conditions of the ambient water column determines the amount and kind of subsill water that will be permitted to enter the basin. Accordingly, the temperature and salinity in each basin is about the same as that of the ambient water at sill depth, but the dissolved oxygen (DO) level may be somewhat lower. In such basins off southern California it was found that the lowest DO values were found in basins whose sill depth was near the oxygen minimum layer at 500-600 metres (Emery and Rittenberg, 1952). It is important to note that even though their oxygen levels are low, these basins are usually not without life, that is, they are not abiotic. Indeed, Hartman and

Barnard (1958, 1960) found life in all of the low-oxygen basins off southern California.

Whether or not such basins should be considered favorable or unfavorable locations for the disposal of dredged material is a debatable issue. They could be areas of maximum precipitation of metals as metal $S^{=}$. And even though they are characterized by low biomass, they are not abiotic and thus could be sites of maximum microbial decomposition of chlorinated hydrocarbons. On the other hand their oxygen values are low enough that the disposing in them of dredged material with high BOD and COD demands could reduce DO to the point where the waters could not sustain life, the consequences of which are not easily predictable. For this reason, these basins are considered here to be borderline unfavorable as disposal sites for most dredged material. The abyssal plain adjacent to the basins or the continental slope above the oxygen minimum layer are considered to be much better loci for disposal.

NEUTRAL GEOLOGIC CRITERIA: SUBMARINE CANYONS

Submarine canyons are viewed by some marine scientists as being rather ideal locations for the establishment of disposal sites for dredged material. On balance this report shares this view but with certain provisos, namely, that consideration of appropriateness be given on a more or less canyon by canyon basis. For instance, even though La Jolla Canyon off southern California has a plus factor in that it heads near shore, it is considered inappropriate because it lies less than a kilometre off of one of the most popular recreational beaches in the region. On the other hand, some of the canyons off both the west and east coasts are in this regard much more suitable and perhaps should be given serious consideration on more general bases.

As Emery and Hulsemann (1963) have pointed out, submarine canyons are intermediate between shelves and basin floors. Their gradients tend to be of intermediate steepness; their axes dissect the walls of the basin; and their heads extend landward of the shelf break. As early as 1955, Menard (1955) had demonstrated that the quantities of sediment in subsea fans and aprons far exceed the volume of rock removed during erosion of the canyons. Since the fans consist mostly of sand, it is evident that the canyons act as conduits for movement of sand from near shore to deep water (Emery, 1960). This, then, is a plus factor in favor of using submarine canyons as dredged material disposal sites. However, some are concerned about the possibility of upcanyon currents that could carry material back up onto the shelf.

It is now known that in the upper parts of canyons there are currents strong enough (20-88 cm/sec.) to account for net downslope transport of sediment (Lyall et al., 1971; Stanley et al., 1971). Currents do alternate upcanyon and downcanyon with periods ranging from less than one hour to near semidiurnal tidal periods (Shepard and Marshall, 1973; Shepard et al., 1974a, b), but Southard and Stanley (1976) report that downcanyon velocities are higher and of longer duration than upcanyon -- providing the basis for net downcanyon transport of sediment in the form of migrating asymmetrical ripples. Such ripples have been observed in canyons to depths exceeding 1000 m.

FAVORABLE GEOMORPHIC CRITERIA

Anoxic Basins

Unlike the low-oxygen basins considered moderately unfavorable for dredged material disposal, the truly anoxic basins that exist off some U.S. coasts may be excellent disposal loci. The reasons for this decision are simply that these basins are not only anoxic but also may well be abiotic. Some of those off the gulf coast have salinities up to 264 ppt, almost seven times that of the ambient sea water (Shokes et al., in press).

Prior to using such basins it must be determined that they are completely ridged so that the sill stands well above the halocline and would preclude discharging material down the slope.

Shelf-Slope Junction

The junction between the continental shelf and the continental slope, which is marked by the shelf-break, is not only a significant geomorphic feature, it is also a very dynamic area. Unfortunately, definitive information on physical processes is lacking.

The shelf-slope junction is considered to be a dynamic environment because of assumptions that the terrigenous sediments now in the deep sea have crossed this junction on their seaward transit. There is apparently no documented justification for the assertion that substantial movements of sediments from shelf to deep sea is restricted to canyons (Stanley et al., 1972). Then, too, the prevailing view is that the shelf edge is characterized by stronger currents and resultant turbulence than on the adjacent slope or shelf. This is supported by the frequent absence of fine-sediment fractions and generally thin cover of sediments.

There is some evidence that there is a maximum in tidal current velocities near the break (Fleming and Revelle, 1939). Maximum tidal velocities are proportional to distance from shore divided by local water depth. Since this ratio is ordinarily largest at the shelf-slope junction, the strongest tidal currents should occur near the shelf-break. The junction is also the shear zone between shelf currents and larger scale circulation in the open ocean. The resulting shear between currents of different speeds and directions will produce large eddies that will inevitably expose the outer shelf to temporarily stronger bottom currents.

There is a great deal of indirect evidence that silt and sand-sized sediments are transported across the shelf-slope junction from temporary resting places on the outer shelf. Stanley et al. (1972b) refer to this as shelf-edge bypassing or spillover.

Since this is a normal process by means of which bottom sediment is continually entrained and shifted on the outermost shelf and is ultimately transferred across the shelf edge and onto the upper slope or into the deep ocean, it appears reasonable to suggest that dredged material could be disposed of just beyond the shelf break without any interference with normal processes. Once past the shelf edge, sediment can be transported down the slope by various gravity-driven systems of transport, such as turbidity currents, slumping, etc.

BIOLOGIC CONSIDERATIONS

UNFAVORABLE BIOLOGIC CRITERIA

Areas of Special Scientific Significance

It is to be expected that in the biologic realm, areas of concern in establishing disposal sites will overlap between scientific and commercial (fisheries) interests. Nevertheless, this report chooses to discriminate between them and will discuss here those primarily of scientific value even though they may have some fisheries value. In the same way some biologic features will have both scientific and aesthetic and even recreational value. Here again this report proposes to treat each under the category to which it is judged it primarily belongs. Obviously, all of these would be much more serious concerns in shallow water, which is yet another substantial value of deep water disposal.

Hard Banks with Regionally Unique Biota. Hard banks are submarine topographic features that are marked elevations of either the shelf or slope that rise to depths of less than 200 m. Frequently, they are "drowned" coral reefs. In some areas, however, the upper reaches of such hard banks may be capped with unique biotal components (Bright & Pequegnat, 1974).

Sand Banks. These shoaling structures, typified by Georges Bank forming the southern boundary of the Gulf of Maine, are important not so much from the standpoint of their benthic biota (as is the case with hard banks) but with their pelagic and demersal faunae. These banks are often covered with thick layers of sand or other unconsolidated sediments. Their importance stems primarily from the associated upwelling caused by their shoaling and the rich ichthyofauna supported by the biologic productivity.

Migratory Pathways. Many marine organisms, both invertebrates and fishes, undergo regular movements between spawning grounds and winter feeding areas. These are best known in relatively shallow water, between the inner shelf and adjacent estuaries, but some are in deeper water and cross the shelf, e.g., Hudson Shelf Valley, which interconnects Hudson Canyon and Hudson River. Disposal in these areas should be avoided, especially during their use as migratory pathways. However, because the dredged material might affect the little known biologic cues by which the organisms are guided to their destinations, it is perhaps best to rule them out entirely as disposal areas.

Biological Features of Special Aesthetic and/or Recreational Value. For the most part such features, which could include coral reefs or other similar biological communities of interest to skin divers, occur in shallow water, but since the communities may be damaged by siltation, care should be taken that it is understood that water circulation in the area will not carry fine material onto the reef or related entity.

FAVORABLE BIOLOGIC CRITERIA

Favorable biologic criteria are perhaps best treated as a listing. Accordingly favorable biologic locational criteria are:

1) On the shelf-slope junction or upper slope where no deep bottom fishery occurs.
2) Below the isobath on the slope that marks the deepest penetration of a bottom fishery in a given area. In any event it is generally understood that the 1000-m isobath marks the deepest commercial fishery in operation today. It is not foreseen that the industry will penetrate into deeper waters in the future.
3) Any general area of the shelf-slope junction or upper slope that is noted for its depauparate pelagic and especially benthic faunae.
4) Any specific area, such as an anoxic basin, that is known to be azoic and which has little chance that its waters will mix with ambient waters above it or that it will spill over into bottom waters on the adjacent shelf or slope.

RESOURCE UTILIZATION CONFLICTS

As Wenk (1969) has pointed out, men have taken fish and salt from the ocean for thousands of years, but only within the past couple of decades have they begun to appreciate the full potential of the resources of the sea. Three factors have generated this interest: (1) oceanography has revealed what is in and under the sea, (2) new technology has made it possible to exploit these resources, and (3) increased population and consequent demand for raw materials have made it economically feasible to meet these demands.

The mineral resources of the ocean floor are found in scattered and rather highly localized deposits and structures on top of and within the sediments of the sea bed. Wenk (1969) organizes them into three groupings (1) fluids and soluble minerals, such as oil, gas, sulfur, and potash, that can be extracted through boreholes; (2) consolidated subsurface deposits, such as coal, iron ore, and other metals that are so far mined only from tunnels originating on land, and (3) unconsolidated surface deposits that can be dredged, such as heavy metals in ancient beaches, oyster shell, sand and gravel, diamonds, and nodules of manganese and phosphorite.

Economic exploitation of any of these materials has so far been confined to the continental shelves. Although mining for manganese nodules may commence within this decade, the productive areas of this resource are far removed from potential deep ocean disposal sites.

Even the fisheries resources occur in scattered and highly localized concentrations, although the loci or schools usually migrate. These concentrations are produced primarily in divergences where upwelling is known to occur. Here again no significant conflict is seen between exploitation of these resources and utilization of the deep ocean for disposal of dredged material. Nevertheless, each resource type is considered briefly below.

FISHERIES

Under no conditions should fishing grounds, for either shellfish or finfish, be affected either directly or (when discernible) indirectly by the disposal of dredged material. These areas will be well known to any District Engineer; hence there should be no difficulty with direct effects (smothering, etc.). However, indirect effects may be connected with the natural history of the species involved or with the bottom circulation patterns in the area. For instance, when a fishery for a given species is seasonal, one should be certain that he is aware whether in the offseason the species stays in the fishing ground or moves elsewhere.

Except in a few cases, which will be discussed in section C of this part, no serious conflict with fisheries are forseen because this report is addressing problems of the deep ocean.

MINERALS

Oil and Gas

Oil and gas represent more than 90 percent by value of all minerals obtained from the oceans and will continue to have the greatest potential for some time to come.

The technology permitting the industry to exploit these resources in deeper and deeper ocean waters is gradually being perfected. It is not anticipated, however, that exploitation of these resources on the upper slope will take place in any substantial manner in the foreseeable future. There are many areas of both the inner and outer continental shelves that have not yet been exploited. Moreover, it is not apparent that there is any serious incompatibility between the industry and selection of disposal sites. It might be that disposal should not occur above a well head in areas where a disposal could conceivably trigger slumping. It is, however, inconceivable at this time that such areal overlaps would need to occur.

Other Minerals

Sulfur. Sulfur is one of the leading industrial chemicals and it is found in the cap rock of salt domes buried within continental and seafloor sediments. Interest in offshore deposits of sulfur continues to develop, especially off the gulf coast. As with the oil industry, no conflict with ocean disposal of dredged material is foreseen so long as producing or potentially producing salt domes are avoided. Actually only 5 percent of the explored salt domes contain commercial quantities of sulfur.

Sand, Gravel, Diamonds, Tin, and Oyster Shell. Of these resources, sand and gravel are the most important in dollar terms, and only these and oyster shell are now mined off the U.S. coast. Presently, there are no indications that such activities will be carried out in deeper waters for a long time to come.

Phosphorite Nodules. These are found in deeper waters of the outer shelf, upper slope, and submarine banks. Large deposits are found off both Florida and California. However, large land deposits are also available; hence offshore exploitation is unlikely.

Manganese Nodules. With the relatively minor exceptions of deposits on Blake Plateau and the Great Lakes, manganese nodules occur only on the Pacific Ocean floor at depths in excess of 4000 m.

Recreation and Navigation. It is not anticipated that deep ocean disposal of dredged material would have any deleterious effects on either recreation or navigation. In fact, it is quite possible that both entities could be benefitted by removing such practices from shallow water where some impacts can occur.

CONFLICT BY PROXIMITY OF OTHER DISPOSAL SITES

It is advisable not to select an area and certainly not a site that coincides with or overlaps an already established interim or designated disposal site. Such an action could preclude effective trend assessment or baseline studies of either or both sites.

C. ANALYSIS OF SUITABILITY BY SECTOR: APPLICATION OF CRITERIA TO SECTORS

GULF COAST (SECTORS 4 AND 5)

UNFAVORABLE DISPOSAL SITE CONSIDERATIONS

Physical Criteria

Upwelling. This is not a criterion of major concern in the Gulf of Mexico; however, the principal area of upwelling in the study-related regions of the Gulf is off the West Florida Shelf. It is periodic, reaching its peak during the later seasonal phases of the northern penetration of the Loop Current. It results from the piling up of water (forcing it upward) where the eastern boundary of the Loop intersects the continental slope. It is most prevalent during late summer and is virtually non-existent in late fall, winter, and early spring.

Loop Current Rings. The separation of eddy rings from the Loop Current in the eastern Gulf of Mexico has been observed by Cochrane (1972), Leipper et al. (1972), and Nowlin and Hubertz (1972). Separation of these clockwise spinning rings has been observed to take place anywhere from May to September. In general, the early season separations occur too far south (toward Yucatan) to be relevant here. Also, these early rings are known to drift only westward. It has been reported, however, that occasional rings that spin off after the Loop has moved into the Northeastern Gulf move eastward and may impinge upon the West Florida Shelf. The velocity at the core of the current in the eddy may reach 113 cm/sec (2.17 kn) and the volume transport of water may reach 40 million m^3/sec (Leipper et al., 1972). Since this is a highly seasonal event and apparently does not occur every year, it is not considered to be a significant criterion for site selection.

Chemical Criteria

Oxygen-Minimum Zone. In the Gulf of Mexico the lowest values of the oxygen-minimum layer intersect the continental slope between depths of about 300 and 600 m (W. Pequegnat et al., 1976). This coincides with the zones of maximum organic content of sediments. The uppermost limit of both these parameters parallels the 180-m isobath (Richards and Redfield, 1954). However, these do not reach their lowest values (about 2.5 ml O_2/l) until 300-m depth in the western gulf and 600 m in the eastern gulf.

Metal-Rich Zone. Prior to establishing a disposal site on the continental slope of the northern Gulf of Mexico, especially west of the Mississippi Delta, it would be worthwhile to check on the levels of manganese dioxide in the surficial sediments. This is not considered to be of major direct concern, however, since this enrichment is likely to occur in the oxygen-minimum zone where one would probably not wish to establish a site.

Geomorphic/Geologic Criteria

In the northern Gulf of Mexico the shelf-slope junction is generally considered to be too shallow (118-135 m) for disposal, except in a few areas that will be designated at the end of this section. Also, there are some areas of special scientific value in the zone that should not be jeopardized.

Biologic Criteria

In the northern Gulf of Mexico there are several hard banks capped by what are presently considered to be the northernmost thriving shallow water coral reefs of this region (Bright and Pequegnat, 1974). Those of particular interest and concern are the East and West Flower Garden Banks, located roughly 107 nautical miles south of Galveston, Texas (27°52' north; 93°48' west) in over 450 ft of water. Since the currents are variable in the vicinity of these reefs, it would not be advisable to locate a disposal site within 10-15 miles of these features.

Resource Conflicts

Although considerable exploratory work remains to be carried out, the principal features of the commercial fishery potential of the outer shelf and slope waters of the Northern Gulf coast may be stated with some precision and assurance. In the eastern sector, essentially from mid-Louisiana to the vicinity of Pensacola, Florida three basic fishery types are supportable:

1) Trawling for royal red shrimp, which reach commercial potential along the western wall of DeSoto Canyon from 180 to 360 m.
2) Midwater trawling for clupeids and carangids.
3) Surface longlining and purse seining for tunas and other pelagic species.

In the western sector, from mid-Louisiana to the South Texas border, the most effective fishing is for bottom and near-bottom species. This includes trawling for snappers and groupers at 183 m and tilefish at 366 m, bottom longlining, and hook and line fishing on the snapper banks. At present none of these fishery potentials is being fully exploited (W. Pequegnat et al., 1976). Some attention should be given to the tilefish potential as a fishery.

The red crab (Geryon quinquedens) is widely distributed on the continental slope of the northern Gulf of Mexico, where Pequegnat (1970) reports it reaches its maximum density of adults at about 900 m depth.

Other Conflicts

There are several deepwater disposal sites, for other than dredged material, in use on an interim basis in Sectors 4 and 5. These will be avoided in recommending areas for designation of sites.

FAVORABLE DISPOSAL SITE CONSIDERATIONS

Physical Criteria

Convergence. A converging occurs in the northern gulf between a current coming northward from the west coast of Mexico and one coming westward from the delta region of Louisiana. This converging stream transports water rapidly offshore, carrying living and nonliving organic materials southward across the continental shelf to the abyssal plain. This convergence migrates on a seasonal basis from off Brownsville in winter to off Galveston in summer. Its transit is marked by a reversal of the coastal current off Texas.

Weak But Predictable Circulation Patterns. The flow of surface water over the continental slope in the western gulf is somewhat less dynamic and is thought to be more predictable than that of the eastern gulf (Nowlin, 1972).

Chemical Criteria

Dissolved Oxygen in Bottom Waters. Everywhere tested in the northern Gulf of Mexico (except, of course, for the anoxic basins) the dissolved oxygen levels in the bottom waters begin to increase steadily with depth from their minimum of 2.5 ml/l at around 350 m or more to a high of around 5 ml/l at and deeper than 3000 m. Values of 3 ml/l or over should be ample to meet the BOD and COD of the disposal material, especially if a bottom current exists.

Bottom Currents. Both Pequegnat (1972) and Moore (1973) have demonstrated the existence of substantial bottom currents in offshelf waters of the Gulf of Mexico. Pequegnat (1972) established the presence of a substantial bottom current on the eastern distal portion of the Mississippi Deep-Sea Fan at depths between 3074 and 3255 m. The averages of current speeds at six stations ranged from a low of 6 cm/sec to 18 cm/sec (0.12-0.35 kn). Moore's (1973) observations were made on the upper continental slope of the northwestern Gulf of Mexico. In general, he found that at depths between 400 and 700 m the general trend was easterly at rates from 0.1 to 0.5 kn, and below that the trend was westerly at an average of 0.3 kn. These observations at diverse depths in opposite extensions of the Gulf support the conjecture that bottom currents of significant speeds are present in the northern Gulf of Mexico. There is no indication that they would in any way transport materials into unfavorable locations.

Geomorphic Criteria

Anoxic Basins. Unlike the low-oxygen basins considered moderately unfavorable for dredged material disposal, the truly anoxic basins that exist off the Louisiana and Texas coasts may make excellent disposal sites. The reasons behind this decision are simply that these basins are not only anoxic but also abiotic. Shokes et al. (in press) have described a huge anoxic basin off Louisiana. Although it is not yet fully explored, it is estimated that it may have an area of 800 km^2. Furthermore, the halocline that separates the ambient waters of the gulf with a salinity of 35ppt from the basin waters with a salinity of 264ppt, is apparently located anywhere from 200 to 300 m below the basin's ridge. At present there is no evidence to indicate that the brine flows out of the basin at any point.

The one great disadvantage of this basin as a disposal site for dredged material is its long distance offshore (over 160 km). Nevertheless, if it proves not to have an outlet over the sill for the brine, it is large enough to receive manifold high-density waste for decades without, so far as is known, untoward effects on the marine environment.

Numerous anoxic brine basins are believed to exist along the continental slope of the western Gulf of Mexico near the 100-m isobath. Some of these lie almost due south of Galveston and others are southeast of Corpus Christi. Their bathymetry should be investigated to determine the position of the halocline relative to the sill.

Canyons and Troughs. Three canyons or canyon-like structures are found in the northern Gulf of Mexico. From east to west there are DeSoto Canyon, which lies some 34 miles southeast of the entrance to Mobile Bay; the Mississippi Trough located some 21 miles southwest of Southwest Pass; and Alaminos Canyon, the head of which is south southwest of Galveston about 130 miles. Any one of these features would provide excellent disposal sites for dredged material, but the last is particularly far offshore.

The Shelf-Slope Junction. Although the gulf is noted for its broad continental shelves, especially off western Florida, central Louisiana, and eastern Texas, there are several areas where the shelf-break occurs at approximately the 60-metre isobath. One such area is due south of Galveston Harbor. Another is due east of Corpus Christi Harbor. The down slope areas between these two points has a relatively depauparate fauna (W. Pequegnat, unpublished data).

ATLANTIC COAST (SECTORS 1, 2, AND 3)

UNFAVORABLE DISPOSAL SITE CONSIDERATIONS

Physical Criteria

Upwelling. Upwelling may occur in local areas under the influence of periodic wind conditions, but it is not of major concern to site selection along the east coast.

Gulf Stream Rings. One of the characteristic features of the Gulf Stream is the meanders of its transit path. Frequently these become sufficiently large to pinch off from the main current to form large eddies or "rings." These form both to the north and south of the northeasterly trending current, but none has been observed to form south of 30°N latitude. In this report interest is in those on the north that have a clockwise circulation and that tend to move back shoreward (southwest). They appear to have two fates, viz., either to move over the slope and onto the shelf to decay or to be entrained by the Gulf Stream again at some southern point (say, near Cape Hatteras). This transit may take up to two years.

It is not certain what influence, if any, these could have on disposal practices for dredged material other than possibly for entrapment of fine sediments. The transport of low-density materials shoreward may be more serious. Anywhere from 5 to 8 rings per year are formed on each side of the Gulf Stream. Each may be from 150 to 300 km in diameter. The tangential velocity in the core ranges up to about 100 cm/sec, keeping materials suspended. Since the rings can concentrate and hold aloft fine sediments with sorbed metals and organic toxins and move them over the slope and possibly deposit them on the shelf, it is perhaps advisable to locate disposal sites outside of known southwesterly paths of these rings.

Circulation Patterns of Irregular Occurrence. There are many uncertainties about the offshore circulation of waters beyond the continental shelf but inside of the Gulf Stream. Patterns are best defined to the north and become less so in the middle area and more clearly defined below Cape Canaveral. Local oceanographic institutions should be consulted for the most recent and complete information for a specific site.

Geomorphic/Geologic Criteria

Large Submarine Canyons. In Sectors 1 and 2 it appears advisable to avoid the large submarine canyons that incise the continental shelf. This is done largely for biologic reasons. No sizable canyons are found in Sector 3.

Biologic Criteria

Submarine Canyons. In Sectors 1 and 2 it is to be noted that the American Lobster and the Giant Red Crab inhabit the bases and immediate vicinity of the large submarine canyons.

Hard Banks and Other Hard Substrata. On the very outer edge of the Continental shelf in Sector 3 there are numerous hard-substratum habitats (*Lithothamnion*, etc.) that are favored sports fishing locations.

Resource Conflicts

Distribution of Species of Established or Potential Commercial Value. As noted above, the deep population of the American Lobster and the Giant Red Crab indicate that disposal in the largest canyons should be avoided. Also, the sports fishing banks are placed in the same category.

FAVORABLE DISPOSAL SITE CRITERIA

Physical Criteria

Downwelling. Downwelling must occur at numerous places off the east coast but it is not discussed to any extent in the literature. Apparently, not enough is known about it to take advantage of its properties. Also, if it does occur it is likely to be over the shelf and not at the depths being discussed in this report.

Convergences. The waters adjacent to the east coast of the United States are generally divided into four separate regimes, viz., (1) coastal water, (2) slope water, (3) the Gulf Stream, and (4) ocean water. Convergences occur between eddies formed in these waters, e.g., between the Gulf of Maine Eddy and the Georges Bank Eddy and between the latter and the Slope Water Current.

Predictable Circulation Patterns. Although it changes in force and width seasonally (best developed in spring), there is usually an eddy over Georges Bank that converges with south-flowing slope water. It is thought that the shoreward part of the slope water mass flows southward to Cape Hatteras where it turns seaward. This may be evidence of a counterclockwise gyre, the seaward limb of which flows northward only to turn shoreward north of Georges Bank and thence southward again to Cape Hatteras. Also, the Gulf Stream rings are involved as perturbations in this circulation.

In the South Atlantic Bight, the movement of the slope water mass is much influenced by the Florida current; hence there tends to be a net northeasterly flow.

Geomorphic/Geologic Criteria

Shelf-Slope Junction. In the Sectors 1 and 2 the shelf-slope junction areas appear to be satisfactory for establishment of disposal sites. In Sector 3, the Florida-Hatteras Slope is appropriate.

Submarine Canyons. The submarine canyons that do not incise the continental shelf are considered appropriate for disposal sites, but the larger ones should be avoided.

PACIFIC COAST (SECTORS 6, 7, AND 8)

UNFAVORABLE DISPOSAL SITE CONSIDERATIONS

Physical Criteria

Upwelling. Upwelling is a common feature of the coastal waters of much of the U.S. Pacific Coast. It is most prominent when the coastal winds are northerly or northwesterly, particularly in spring and summer. However, upwelling associated with tides pushing deep water up to the heads of submarine canyons is non-seasonal (Stevenson and Gorsline, 1958). Seasonal upwelling is most pronounced in southern California in May and June and off northern California and Oregon in summer and early fall. Upwelling in this region causes the formation of a very strong pycnocline. In general, upwelling along the Pacific Coast has its greatest influence on productivity from a distance of about 10 km shoreward.

Unpredictable Currents. The coastal currents are influenced very much by local wind, tides, and the offshore geostrophic current direction. There is a marked tendency for development of onshore surface currents. Furthermore, during periods of weak wind the currents frequently reverse direction. In summer, the current above the thermocline tends to move eastward, whereas water below the thermocline moves westward.

Chemical Criteria

Oxygen-minimum Layer. The amount of dissolved oxygen drops rapidly with depth from a high of about 6 ml/l near the surface to 4 ml/l at 100 m. 2 ml/l at 200 m, and a low of about 0.5 ml/l at 500 to 700 m.

Geomorphic/Geologic Criteria

Submarine Canyons. Submarine canyons are very numerous in the Southern

California Bight, are few in the region from Pt. Conception to Cape Mendocino, and increase again in number from the latter cape to Cape Flattery at the Strait of Juan de Fuca. Although it would seem that such canyons would be good candidates for disposal sites, to use the major canyons would draw criticism from diverse groups. Some of the canyons of southern California are known to be spawning grounds for some fishes and squids. Consideration can be given to use of canyons for dredged material disposal only on a case by case basis.

Low-oxygen Submerged Basins. These basins, which are primarily located in Sector 6 off southern California, may not make good disposal sites (see discussion in Section B of Part 8).

Resource Conflicts

Problems with fishery resources along the Pacific Coast are very sector-related. Deep ocean disposal will have little effect on southern California (Sector 6) fisheries, which are comprised primarily of pelagic fish or inshore predatory species. In northern California (Sector 7), on the other hand, trawling and bottom longlining constitute a large portion of the fish landings. Some species (Table 5-12) range down the slope. In Sector 8 (Oregon and Washington) there is a substantial demersal fishery that extends onto the slope and must be considered on a local basis in making site selections.

FAVORABLE DISPOSAL SITE CONSIDERATIONS

Physical Criteria

Downwelling. Downwelling is a seasonal phenomenon along much of the Pacific Coast, but it becomes most prominent from north of Pt. Conception to Washington. It occurs primarily during the winter period when southerly winds are more prevalent. The Davidson Current results from the downwelling phenomenon.

Other Favorable Currents. The California Current flows southward along the entire Pacific Coast of the U.S. at varying distances offshore. It is rather close to the coast in the north but from Pt. Conception south, it is some 200 km offshore. However, near Ensenada, Mexico it courses eastward toward shore and part of its water turns to flow northwest between the California Current and the coast as a countercurrent. In winter this flow will join the Davidson Current at Pt. Conception, but some water turns back and flows southeast along the continental shelf to complete the loop known as the Southern California Eddy (Kindyushev, 1970). The water in it is a mixture of California Current surface water and upwelled water.

The California Undercurrent flows north at depths between 150 to 800 m in the southern California Bight (Reid, 1963 and 1965). The undercurrent can be traced along the entire U.S. Pacific Coast. It is divided into meandering streams by the trough and ridge topography of the Southern California borderland. It strongly influences the continental slope seaward of the 200-m isobath and also flows into the offshore basins.

GULF OF ALASKA (SECTOR 9)

Deep ocean disposal of dredged material from Valdez and Anchorage in the Gulf of Alaska is not considered feasible. Consider the fact that it is about 260 km from Anchorage to the entrance of Cook Inlet before the depth increases to 180 m. Moreover, in the United States Coast Pilot 9 (U.S. Dept. of Commerce, 1977) one finds the following: the diurnal range of tide is 29 ft; strong currents (1.7 to 6 kn) and swirls near Anchorage make navigation difficult; Cook Inlet has numerous shoals that are boulder strewn; the waters are generally turbid, so much so they are damaging to saltwater pumps and shaft bearings.

Some information on geology, biology, fisheries, etc. of the Gulf of Alaska is provided in Part 5, Section B of this report, but it is not discussed further in Part 3, Section A.

HAWAIIAN ISLANDS (SECTOR 10)

There are five harbors in the Hawaiian Islands that are maintained by the Corps of Engineers and Pearl Harbor for which the U.S. Navy is responsible. The five harbors of principal interest are:

Port Allen (in Hanapepe Bay) on Kauai Island
Nawiliwili Harbor on Kauai Island
Honolulu Harbor on Oahu Island
Kahului Harbor on Maui Island
Hilo Harbor on Hawaii Island

Three of these harbors already have interim dredged material disposal sites that are in deep water:

	Ave. Depth (m)
Port Allen - 21°50'18"N, 159°35'30"W	1540
Nawiliwili - 21°55'30"N, 159°17'00"W	1000
Honolulu - 21°14'30"N, 157°54'30"W	460

Each of these is on a 5-year dredging cycle for maintenance and all will have been dredged during the first half of 1977.

Some studies of these deepwater disposal sites have just been completed and are in draft form; others are planned for the dredging of Pearl Harbor beginning in May 1977. In view of this it seems premature to discuss most oceanographic characteristics of these sites at this time. Perhaps, however, if the Honolulu Harbor interim site is to be moved, it is suggested that it might be moved to either a somewhat shallower or deeper depth, because at 460 m it is amidst the principal population densities of some of the Caridean shrimps of the region that appear to have commercial potential, particularly to Heterocarpus ensifer and H. laevigatus.

PUERTO RICO-U.S. VIRGIN ISLANDS (SECTOR 11)

There are four harbors in Sector 11 that are relevant to the present study:

- Puerto Rico
  - San Juan Harbor
- Virgin Islands
  - Water Bay, St. Thomas
  - Great Cruz Bay, St. John
  - Limetree Bay, St. Croix

These harbors and channels are under the jurisdiction of the Jacksonville District and were last dredged, according to available records, as follows (figures in cubic yards):

San Juan, 1976	877,760 (Personal Communication, Jacksonville District, B. Lancaster, 1977)
Water Bay, 1969	600,000 (VanEepoel, 1969)
Great Cruz Bay, 1969-1970	186,000 (VanEepoel and Grigg, 1970)
Limetree Bay 1965-1973	7,000,000 (Howard, Needles, Tammen and Bergdoff, 1975)

The dredged material from San Juan Harbor was discharged in the interim site at 18°30'10" and 66°08'29" - 66°09'31"W in about 260-300 m of water.

The dredged material from Water Bay was deposited on land over a garbage dump.

The material removed from Great Cruz Bay was deposited on land and was put to multiple uses.

Most of the Limetree Bay material was placed on land in diked areas. The dikes have contributed to a chronic increase in turbidity because of wave erosion.

LITERATURE CITED

Allan Hancock Foundation, University of Southern California. 1959. Oceanographic survey of the continental shelf area of southern California. State Water Poll. Control Bd. Pub. No. 20., Los Angeles, California. 560 pp.

Allan Hancock Foundation, University of Southern California. 1965. An oceanographic and biological survey of the southern California mainland shelf. State of California State Water Control Bd. Pub. No. 24., Los Angeles, California. 232 pp.

Allen, J.R.L. 1970. Physical processes of sedimentation. George Allen and Unwin, Ltd., London. 248 pp.

Andreliunas, V.L. and Hard, C.G. 1972. Dredging Disposal: Real or imaginary dilemma? Water Spectrum 4:16-21.

Anonymous. 1969. BCF's "Oregon II" finds heavy fish concentrations off Louisiana. Comm. Fish. Rev. 31(4):5.

Antoine, J.W. 1972. Structure of the Gulf of Mexico. pp. 1-34. In: R. Rezak and V.J. Henry (eds.) Contributions on the Geological and Geophysical Oceanography of the Gulf of Mexico, Texas A&M Univ., Oceanogr. Ser. Vol. 3, Gulf Publ. Co., Houston. 303 pp.

Antoine, J.W. and Bryant, W.R. 1968. Major transition zones of the Gulf of Mexico: DeSoto and Campeche Canyons. Trans. Gulf Coast Assoc. Geol. Soc. 18:55.

Antoine, J., Bryant, W., and Jones, B. 1967. Structural features of the continental shelf, slope, and scarp, northwestern Gulf of Mexico. Amer. Assoc. Petrol. Geol. Bull. 51:257-262.

Arthur D. Little, Inc. 1974. The national dredging study. Multi-volume report prepared by A.D. Little under contract to the U.S. Army Corps of Engineers.

Austin, G.B., Jr. 1955. Some recent oceanographic surveys of the Gulf of Mexico. Trans. Amer. Geophys. U. 36(5):885-892.

Bader, R.G. 1962. "Some experimental studies with organic compounds and minerals," The environmental chemistry of marine sediments. Occas. Pub. No. 1, Univ. of Rhode Island, Kingston. pp. 42-57.

Ballard, R.D. and Uchupi, E. 1970. Morphology and quaternary history of the continental shelf of the Gulf Coast of the United States. Bull. Mar. Sci. 20(3):547-559.

Barnard, J., Hartman, O., and Jones, G. 1959. Benthic biology of the mainland shelf of California. In: Oceanographic survey of the continental shelf area of southern California. Pub. 20. State Water Poll. Control Bd. Sacramento. pp. 265-429.

Bain, A.G. and Bonnington, A.G. 1970. The hydraulic transport of solids by pipeline. Pergamon Press, Elmsford, New York.

Bascom, W. 1974. The disposal of waste in the ocean. Sci. Amer. 231(2):18-25.

Bayliss, J.D. 1968. Striped bass hatching and hybridization experiments. Ann. Conf. S.E. Game and Fish Comm. Proc. 21:233-244.

Bennett, L.C. and Grim, M.S. 1968. Investigations of the continental shelf structure off the coast of Washington. (Abstract) Trans. Amer. Geophys. U. 49:209.

Bennett, R.H., Keller, G.H., and Busby, R.F. 1970. Mass property variability in three closely spaced deep-sea cores. J. Sediment. Petrol. 40:1038-1043.

Ben-Yaakov, S. 1973. pH buffering of pore water of recent anoxic marine sediment. Limnol. Oceanogr. 18(1):86-94.

Berkowitz, S.P. 1976. A comparison of the neuston and near-surface zooplankton in the northwest Gulf of Mexico. Thesis (M.S. in Oceanography), Texas A&M University. 148 pp.

Berner, R.A. 1964. Stability field of iron minerals in anaerobic marine sediments. J. Geol. 74:826-834.

Berner, R.A. 1971. Principles of Chemical Sedimentology. McGraw-Hill, New York. 240 pp.

Berner, R.A. 1974. Kinetic models for the early diagenesis of nitrogen, sulfur, phosphorus, and silicon in anoxic marine sediments. The Sea, Vol. 5, John Wiley & Sons Inc., New York. pp. 427-450.

Berner, R.A. 1975. Diagenetic models of dissolved species in the interstitial waters of compacting sediments. Amer. J. Sci. 275: 88-96.

Betzer, P.R., Richardson, P.L., and Zimmerman, H.P. 1974. Bottom currents, nepheloid layer, and sedimentary features under the Gulf stream near Cape Hatteras. Mar. Geol. 16:21-29.

Bien, G.S., Contois, D.E., and Thomas, W.H. 1958. The removal of soluble silica from fresh water entering the sea. Geochim. Cosmochim. Acta. 14:35-54.

Bigelow, H.B. and Schroeder, W.C. 1953. Fishes of the Gulf of Maine. U.S. Fish Wildl. Ser., Fish. Bull. 53:577 pp.

Biggs, R.B. 1968. Environmental effects of overboard spoil disposal. J. Sanitary Engineer Div. ASCE. 94(SA3):477-487.

Blumer, M. and Sass, J. 1972. The West Falmouth oil spill II, chemistry. Woods Hole Oceanographic Inst., Tech. Rep. No. 72-19.

Bogdanov, A.S. (ed.). 1969. Soviet-Cuban fishery research. Israel Prog. for Sci. Trans., Jerusalem. 350 pp.

Bogorov, V.G. 1959. Biologicheskaya structura okeana (Biological structure of the ocean). DAN SSSR Vol. 128., No. 4.

Bogorov, V.G. 1966. Produktivnost okeana. Pervichnaya produktsiya i ee ispd'zovanie v pishchevykh tselyakh (Productivity of the Ocean. Primary production and its nutritional value). Vtordi Mezhdunarodnyi okeanografic - heskii kingress, 30 maya-9 iyunya 1966. Synopsis of Reports. Moskva, Izdatel'stvo "Nauka."

Bokuniewicz, H., Gerbert, J.A., Gordon, R.B., Kaminsky, P., Pilbeam, C.C., and Reed, M.W. 1975. Environmental consequences of dredged spoil disposal in Long Island Sound, Phase II. Geophysical studies, Nov. 1973-Nov. 1974. Yale report SR-8 to U.S. Army Corps of Engineers.

Borgstrom, G. 1969. Too Many. Macmillan, New York.

Boucher, F.R. and Lee, G.F. 1972. Adsorption of lindane and dieldrin pesticides on unconsolidated aquifer sands. Environ. Sci. & Tech. 6:538-543.

Boyd, M.B., Saucier, R.T., Keeley, J.W., Montgomery, R.L., Brown, R.D., Mathis, D.B., and Guice, C.J. 1972. Disposal of dredge spoil problem identification and assessment and research program development. U.S. Army Engineer Waterways Exp. Sta., Vicksburg, Miss. Tech. Rep. H-72-8. 121 pp.

Boyle, E., Collier, R., Dengler, A.T., Edmond, J.M., Ng, A.C., and Stallard, R.F. 1974. On the chemical mass-balance in estuaries. Geochim. Cosmochim. Acta. 38:1719-1728.

Braislin, D.B., Hastings, D.D., and Snavely, P.K., Jr. 1971. Petroleum potential of western Oregon and Washington and adjacent continental margin. pp. 229-238. In: I.H. Cram (ed.) Future Petroleum Provinces of the United States-Their Geology and Potential. Amer. Assoc. Petrol. Geol. Mem. 15. Tulsa, Okla.

Brandsma, M.G. and Divoky, D.J. 1976. Development of models for prediction of short term fate of dredged material discharged in the estuarine environment. Prepared for the U.S. Army Engineer Waterways Exp. Sta., Vicksburg, Miss. Contract Report D-76-5. 133 pp. plus 144 pp. of Appendices.

Brannon, J.M., Engler, R.M., Rose, J.R., Hundt, P.G., and Smith, I. 1976. Distribution of manganese, nickel, zinc, cadmium, and arsenic in sediments and in the standard elutriate. U.S. Army Engineer Waterways Exp. Sta., Vicksburg, Miss., Misc. pap. D-76-18: 39 pp.

Brehmer, M.L. 1965. Turbidity and siltation as forms of pollution. J. Soil Water Conserv. 29(4):123-133.

Brehmer, M.L. 1967. A study of the effects of dredging and dredge spoil disposal on the marine environment. Spec. Sci. Rep. #8. Virginia Institute of Marine Science, Gloucester Point, Virginia.

Bricker, O.P., III and Troup, B.N. 1975. Sediment-water exchange in Chesapeake Bay. In: L.E. Cronin (ed.) Estuarine Research, Vol. 1., Academic Press, New York. pp. 3-27.

Bright, T. 1970. Food of deep-sea bottom fishes. pp. 245-252. In: W.E. Pequegnat and F. Chace (eds.) Contributions on the Biology of the Gulf of Mexico, Gulf Publ. Co., Houston.

Bright, T.J. and Pequegnat, L.H. 1974. Biota of the West Flower Garden Bank. Gulf Publ. Co., Houston. 435 pp.

Brodskii, K.A. 1952. O vertikal'nom respredelenii veslonogikh rachkov v severozapadndi chasti tikhogo okeana. (On the vertical distribution of copepods in the northwestern Pacific). Issledovaniya dal'nevostochnykh morei SSSR, Vol. 3. Moskva, Izdatel'stvo AN SSSR.

Broecker, W.S. 1974. Chemical Oceanography. Harcourt Brace Jovanovich. 214 pp.

Brooks, R.R., Presley, B.J., and Kaplan, I.R. 1967. MIBK extraction system for the determination of trace elements in saline waters by atomic absorption spectrophotometry. Talanta. 14:809-816.

Brower, W.A., Meserve, J.M., and Quayle, R.G. 1972. Environmental guide for the U.S. Gulf coast. National Oceanic and Atmospheric Environmental Data Service. Nat. Climatic Center. Asheville, N.C.

Brown, C.L. and Clark, R. 1968. Observations on dredging and dissolved oxygen in a tidal waterway. Water Resour. Res. 4(6):1381-1384.

Browning, R.J. 1974. Fisheries of the North Pacific: History, Species, Gear and Processes. Alaska Northwest Publ. Co., Anchorage. 408 pp.

Brunn, A.F. 1957. Deep sea and abyssal depths. pp. 641-672. In: J.W. Hedgpeth (ed.) Treatise on Marine Ecology and Paleoecology. Mem. 67., Vol. 1. Geol. Soc. Amer., New York.

Bullis, H.R., Jr. 1955. Preliminary report on exploratory long-line fishing for tuna in the Gulf of Mexico and the Caribbean Sea. Comm. Fish. Rev. 17(1):1-15.

Bumpus, D.F. 1973. A description of the circulation on the continental shelf of the east coast of the United States. Progress in Oceanography, Vol. 6, Pergamon Press, New York. pp. 111-156.

Bureau of Land Management. 1977. Draft environmental statement for proposed 1977 outer continental shelf oil and gas lease sale offshore the north Atlantic states. U.S. Dept. of the Interior. 4 Vol. 1380 pp. plus Appendix.

Burk, C.A. and Drake, C.L. 1974. The geology of continental margins. Springer-Verlag, New York. 1009 pp.

Byrne, J.V. 1962. Geomorphology of the continental terrace off the central coast of Oregon. The Ore Bin. 14:65-74.

Byrne, J.V. 1963a. Geomorphology of the Oregon continental terrace south of Coos Bay. The Ore Bin. 25:149-157.

Byrne, J.V. 1963b. Geomorphology of the continental terrace off the northern coast of Oregon. The Ore Bin. 25:201-207.

Carr, J.T. 1967. Hurricanes affecting the Texas Gulf Coast. Rep. 49, Texas Water Development Bd.

Carsey, J.B. 1950. Geology of Gulf coast area and continental slope, Gulf of Mexico. Amer. Assoc. Petrol. Geol. Bull. 34:361-385.

Chen, K.Y., Lu, J.C.S., and Sycip, A.Z. 1976a. Mobility of trace metals during the open water disposal of dredged material and following resedimentation. In: P.A. Krenkel, J. Harrison, and J.C. Burdick III (eds.) Dredging and its Environmental Effects, ASCE, New York. pp. 435-454.

Chen, K.Y., Gupta, S.K., and Sycip, A.F., Lu, J.C.S., Knezevic, M., and Choi, W.W. 1976b. Research study on the effect of dispersion, settling, and resedimentation on migration of chemical constituents during open-water disposal of dredged materials. U.S. Army Engineer Waterways Exp. Sta., Vicksburg, Miss. Contract Rep. D-76-1: 243 pp.

Chesapeake Biological Laboratory. 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. NRI Spec. Rep. No. 3, Univ. of Maryland, Solomons, Maryland. 66 pp.

Chester, R. and Hughes, M.J. 1967. A general technique for the separation of ferro-manganese minerals, carbonate minerals, and absorbed trace elements from pelagic sediments. Chem. Geol. 2: 249-262.

Chester R. and Hughes, M.J. 1969. The trace element geochemistry of a north Pacific pelagic clay core. Deep Sea Res. 16:639-654.

Chew, F., Bein, S.J., and Stimson, J.H.G. 1959. A data report of Florida Gulf Coast cruises. Tech. Rep. 59-1. Mar. Lab., Univ. of Miami, Florida.

Chittenden, M.E. and McEachran, J.D. 1976. Composition, ecology and dynamics of demersal fish communities on the northwest Gulf of Mexico continental shelf, with a similar synopsis for the entire Gulf. Texas A&M Univ. Sea Grant 76-208.

Clark, B.D., Rittal, W.F., Baungartner, D.J., and Bryan, K.V. 1971. The barged ocean disposal of wastes - A review of current practices and methods of evaluation. EPA Prog. No. 16070 FGY, July 1971. EPA Pacific Northwest Water Lab., Corvallis, Oregon. 120 pp.

Cochrane, J.D. 1965. The Yucatan Current. In: Unpublished Report of Dept. of Oceanogr., Texas A&M Univ., Ref. 65-17T:20-27.

Cochrane, J.D. 1972. Separation of an anticyclone and subsequent developments in the Gulf of Mexico loop current from May to September 1969. pp. 91-106. In: L.R.A. Capurro and J.J. Reid (eds.) Contributions on the Physical Oceanography of the Gulf of Mexico. Vol. 2, Gulf Publ. Co., Houston.

Connel, D.W. 1971. Is the Mediterranean dying? New York Times Magazine, Feb. 21, 1971.

Coonley, L.S., Jr., Baker, E.B., and Holland, H.D. 1971. Iron in the Mullica River and Great Bay, New Jersey. Chem. Geol. 7:51-63.

Coull, B.C., Ellison, R.L., Fleeger, J.W., Higgins, R.P., Hope, D.W., Hummon, D.W., Reiger, R.M., Sterrer, W.E., Thiel, H., and Tietjen, J.H. 1977. Quantitative estimates of the meiofauna from the deep sea off North Carolina, U.S.A. Mar. Biol. 39:233-240.

Council on Environmental Quality. 1974. OCS oil and gas - an environmental assessment. Rep. to the President by the Council on Environmental Quality. Washington, D.C.

Crew, H. and Reid, R.O. 1976. Dense effluent dispersion in a stream. J. of the Engineer. Mech. Div., ASCE, Vol. 102, No. EM1, Proc. Pap. 11915. 77-88 pp.

Cronin, L.E., Biggs, R.B., Flemer, D.A., Pfitzenmeyer, H.T., Goodwyn, F., Dovel, W.L. and Ritchie, D.E. 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Natural Resources Inst. Spec. Rep. 3, Univ. of Maryland. 66 pp.

Cry, G.W. 1965. Tropical cyclones of the North Atlantic Ocean. U.S. Weather Bur. Tech. Pap. 55. 148 pp.

Csanady, G.T. 1965. The buoyant motion within a hot gas plume in a horizontal wind. J. Fluid Mech. 22:225-239.

Curray, J.R. 1960. Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico. pp. 221-266. In: Shepard, Phleger, and van Andel (eds.) Recent Sediments, Northwest Gulf of Mexico. Amer. Assoc. Petrol. Geol., Tulsa, Okla.

Darnell, R.M., Pequegnat, W.E., James, B.M., Benson, F.J., and Defenbaugh, R.A. 1976. Impacts of construction activities in wetlands of the United States. U.S. EPA Ecol. Res. Ser., Corvallis, Oregon, EPA Contract No. 68-01-2452. 392 pp.

Defenbaugh, R.E. 1976. A study of the macroinvertebrates of the continental shelf of the northern Gulf of Mexico. PhD. dissertation. Texas A&M University. 425 pp. plus plates.

DeGroot, A.J., DeGoeig, J.J., and Zegers, C. 1971. Contents and behavior of mercury as compared with other heavy metals in sediments from the rivers Rhine and Erns. Geol. 50(3):393-398.

Dehlinger, P., Couch, R.W., McManus, D.A., and Gemperle, M. 1970. Northeast Pacific Structure. p. 133-189. in A.E. Maxwell, ed. The Sea, Vol 4, Part II. Wiley InterScience, New York. 664 p.

Deuser, W.G. 1976. Reducing environments. In: J.P. Riley and S. Skirrow (eds.) Chemical Oceanograpy. Academic Press, New York.

Devol, A.H., Packard, T.T., and Holm-Hansen, O. 1976. Respiratory electron transport activity and adenosine triphosphate in the oxygen minimum of the eastern tropical North Pacific. Deep-Sea Res. 23:963-973.

Dietz, R.S. and Holden, J.C. 1970. The breakup of Pangaea. Sci. Amer. 223(4):30-41.

Dillon, W.P. and Zimmerman, H.B. 1970. Erosion by biological activity in two New England submarine canyons. J. Sediment. Petrol. 40: 542-547.

Doane, R.R. 1957. World Balance Sheet. Harper & Brothers, New York. p. 24.

Drake, D.E. 1976. Suspended sediment transport and mud deposition on continental shelves. pp. 127-158. In: D.J. Stanley and D.J.P. Swift (eds.) Marine Sediment Transport and Environmental Management. Wiley-Interscience, New York.

Duchert, P., Calvert, D.E., and Price, N.B. 1973. Distribution of trace metals in the pore waters of shallow water marine sediment. Limnol. and Oceanogr. 18:605-610.

Duvigneaud, P. and Tanghe, M. 1968. Biosfera i mesto v nei cheloveka. Progress. Moscow (Trans. from: Ecosystems et Biosphere Brussels, 1967). 253 pp.

Ecker, R.M. and Sustar, J.F. 1972. San Francisco Bay dredge material disposal. Proc. 13th Int. Conf. Coastal Engineering. pp. 913-931.

Edge, B.L. and Dysart, B.C. 1972. Transport mechanisms governing sludges and other materials barged to sea. Civil Engineering and Environmental Systems Engineering, Clemson University.

Edwards, S.G. 1971. Geology of the West Flower Garden Bank. Texas A&M Sea Grant Pub. TAMU-SG-71-215: 199 pp.

EG&G Environmental Consultants. 1974. Summary of oceanographic observations in New Jersey coastal waters near 39°28'N latitude and 74°15'W longitude during the period May 1972 through April 1973. Waltham, Mass.

Ehrhardt, M. 1972. Critical problems of the coastal zone. In: B.H. Ketchum (ed.) Waters Edge. MIT Press, Cambridge, Mass. 393 pp.

Einstein, H.A. and Krone, R.B. 1962. Experiments to determine modes of cohesive sediment transport in salt water. J. Geophys. Res. 67:1451-1561.

Eittreim, S. and Ewing, M. 1972. Suspended particulate matter in the deep waters of the North American Basin. pp. 123-168. In: A.L. Gordon (ed.) Studies in Physical Oceanography, Vol. 2. Gordon and Breach, New York.

Elderfield, H. 1976. Manganese fluxes to the oceans. Mar. Chem. 4: 103-132.

Ellis, M.M. 1944. Water purity standards for fresh-water fishes. U.S. Fish Wildl. Ser. Res. Rep. 9, 22 pp.

Elmud, S., Morrison, S., Grant, D., and Nevin, M. 1971. The role of excreted chlorotetrocycline in modifying the decomposition process in feedlot waters. Bull. Environ. Contam. Tax. 6(2):129-132.

Emery, K.O. 1956. Deep standing waves in California basins. Limnol. and Oceanogr. 1:35-41.

Emery, K.O. 1960a. Basin plains and aprons off southern California. J. Geol. 68:464-479.

Emery, K.O. 1960b. The Sea off Southern California - a Modern Habitat of Petroleum. John Wiley & Sons, Inc., New York. 366 pp.

Emery, K.O. 1966. Atlantic continental shelf and slope of the United States. U.S. Geol. Survey Prof. Pap. 529-A.

Emery, K.O. 1968. Relict sediments on continental shelves of the world. Amer. Assoc. Petrol. Geol. Bull. 52(3):445-464.

Emery, K.O. and Rittenberg, S.C. 1952. Early diagenesis of California basin sediments in relation to origin of oil. Amer. Assoc. Petrol. Geol. Bull. 36:735-806.

Emery, K.O. and Hulsemann, J. 1963. Submarine canyons of southern California. Part I. Topography, water, and sediments. Allan Hancock Pacific Expeds. 27:1-80.

Emery, K.O. and Uchupi, E. 1972. Western North Atlantic Ocean: Topography, rocks, structure, water, life, and sediments. Amer. Assoc. Petrol. Geol. Mem. 17, Tulsa, Oklahoma.

Ernst, W. 1970. ATP als indicator fur biomasse mariner sedimente. Oecologia (Berl.). 5:56-60.

Evans, D.W. and Cutshall, N.H. 1973. Effects of ocean water on the soluble-suspended distribution of Columbia River radionuclides. pp. 125-138. In: Radioactive Contamination of the Marine Environment. I.A.E.A.

Ewing, J.A. 1973. Wave-induced bottom currents on the outer shelf. Mar. Geol. 15:M31-M35.

Ewing, J.I., Edgar, N.I., and Antoine, J.S. 1968. Structure of the Gulf of Mexico and Caribbean Sea. pp. 321-358. In: Maxwell (ed.) The Sea, Vol. 4, Part II, Wiley-Interscience, New York.

Ewing, M., Ericson, D.B., and Heezen, B.C. 1958. Sediments and topography of the Gulf of Mexico. pp. 995-1053. In: L.G. Weeks (ed.) Habitat of Oil. Amer. Assoc. Petrol. Geol., Tulsa, Oklahoma.

Ewing, M., Eitterim, S.L., Ewing, J.L., and LePichon, X. 1971. Sediment transport and distribution in the Argentine Basin. 3. Nepheloid layer and processes of sedimentation. pp. 49-77. In: L.H. Ahrens, F. Press, S.K. Runcorn, and H.C. Urey (eds.) Physics and Chemistry of the Earth. 8. Pergamon Press, New York.

Fan, P-F and Grunwald, R.R. 1971. Sediment distribution in the Hawaiian Archipelago. Pac. Sci. XXV(4):484-488.

Farrington, J. and Quinn, J.G. 1973. Petroleum hydrocarbons in Narragansett Bay. I. Survey of hydrocarbons in sediments and clams. Estuarine Coastal Mar. Sci. 1:71-79.

Fillos, J. and Molof, A.H. 1972. Effect of benthal deposits on oxygen and nutrient economy of flowing waters. J. Water Poll. Control Fed. 44(4):644-662.

Fleming, R.H. and Revelle, R. 1939. Physical processes in the oceans. pp. 48-141. In: P.D. Trask (ed.) Recent Marine Sediments. Amer. Assoc. Petrol. Geol.

Folger, D.C. 1970. Wind transport of land-derived mineral, biogenic, and industrial matter over the North Atlantic. Deep-Sea Res. 17: 337-352.

Folger, D.W. 1972a. Texture and organic carbon content of bottom sediments in some estuaries of the United States. pp. 391-408. In: B.W. Nelson (ed.) Environmental Framework of Coastal Plain Estuaries. GSA Mem. 133.

Folger, D.W. 1972b. Characteristics of estuarine sediments of the United States. U.S. Dept. of Interior, Geol. Survey, Prof. Pap. 742. (Stock #2401-2112).

Food and Agriculture Organization. 1972. Atlas of the living resources of the seas. Food and Agr. Organ. of the United Nations, Dept. of Fish., Rome, Italy.

Fournier, R.O. 1971. Studies on pigmented microorganisms from aphotic marine environments II North Atlantic distribution. Limnol. and Oceanogr. 16:952-961.

Frassetto, R. and Northrop, J. 1957. Virgin Islands bathymetric survey. Deep-Sea Res. 4:138-146.

Frey, H.W. 1971. California's living marine resources and their utilization. Resources Agency of Calif., Dept. of Fish and Game. 148 pp.

Friebertshauser, M.A. and Duxbury, A.C. 1972. A water budget study of Puget Sound and its subregions. Limnol. and Oceanogr. 17(2):237-247.

Fritz, R.L. 1965. Autumn distribution of groundfish species in the Gulf of Maine and adjacent waters, 1955-1961. Serial Atlas of the Marine Environment, Folio 10, Amer. Geogr. Soc., New York.

Fulk, R., Gruber, D., and Wallschleger, R. 1975. Laboratory study of the release of pesticide and PCB materials to the water column during dredging and disposal operations. U.S. Army Corps of Engineers Waterways Exp. Sta., Vicksburg, Miss., Contract Rep. D-75-6, Dec. 1975.

Fullard, H. and Darby, H.C. 1970. Aldine University Atlas. Aldine Publ. Co., Chicago. 208 pp.

Gaille, R.S. 1969. A preliminary review of the potential deep-water fishery off Texas between 50 and 300 fm. Comm. Fish. Rev. 31(4): 28-29.

Galt, J.A. 1971. A numerical investigation of pressure-induced storm surges over the continental shelf. J. Phys. Oceanogr. 1:82-91.

Gambrell, R.P., Khalid, R.A., and Patrick, W. H., Jr. 1976a. Physio-chemical parameters that regulate mobilization and immobilization of toxic heavy metals. pp. 418-434. In: P.A. Krenkel, J. Harrison, and J.C. Burdick III (eds.) Dredging and its Environmental Effects. ASCE, New York.

Gambrell, R.P., Khalid, R.A., Collard, V.R., Reddy, C.N., and Patrick, W.H., Jr. 1976b. The effect of pH and redox potential on heavy metal chemistry in sediment-water systems affecting toxic metal bio-availability. pp. 581-604. In: Dredging: Environmental Effects and Technology. WODCON VII Proc., San Pedro, California.

Garrison, L.E. and Martin, R.G., Jr. 1973. Geologic structures in the Gulf of Mexico basin. Geol. Surv. Prof. Pap. 773. U.S. Government Printing Office, Washington, DC.

Gates, B.J. and Travis, J. 1969. Isolation and comparative properties of shrimp trypsin. Biochem. 8:4483-4489.

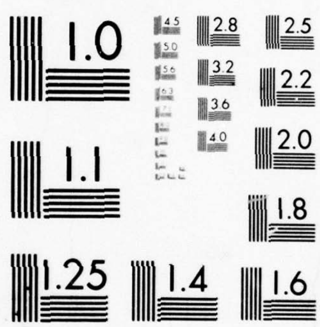
Gaul, R.D. 1966. Circulation over the continental margin of the northeast Gulf of Mexico. Dept. of Oceanogr., Texas A&M Univ. Ref. 66-18 T.

Gealy, B.L. 1955. Topography of the continental slope of the northwest Gulf of Mexico. Geol. Soc. Amer. Bull. 66:203-228.

AD-A053 183 TERECO CORP COLLEGE STATION TX F/G 13/2
AN ASSESSMENT OF THE POTENTIAL IMPACT OF DREDGED MATERIAL DISPO--ETC(U)
JAN 78 W E PEQUEGNAT, D D SMITH, R M DARNELL DACW39-76-C-0125
UNCLASSIFIED WES-TR-D-78-2 NL

7 OF 7
AD
A053183

END
DATE
FILMED
6-78
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Gerlach, S.A. 1971. On the importance of marine meiofauna for benthos communities. Oecologia (Berl.) 6:176-190.

Gibbs, R.J. 1973. Mechanisms of trace metal transport in rivers. Science. 180:71-73.

Gibson, M.S. 1960. Submarine topography in the Gulf of Alaska. Bull. Geol. Soc. Amer 71:1087-1108.

Goldberg, E.D. and Arrhenius, G.D.S. 1958. Chemistry of Pacific pelagic sediments. Geochim. Cosmochim. Acta. 13:153-212.

Goldhaber, M. and Kaplan, I.R. 1974. "The sulfur cycle," The Sea, Vol. 5, Wiley-Interscience, New York. pp. 599-655.

Gordon, A. 1966. Caribbean Sea - oceanography. Encyclopedia of Oceanography. Reinhold Publ. Co., New York. 1021 pp.

Gordon, D.C., Jr. 1971. Distribution of particulate organic carbon and nitrogen at an oceanic station in the central Pacific. Deep-Sea Res. 18:1127-1134.

Gordon, R.B. 1973a. Dispersion of dredge spoil dumped in a tidal stream: observations at the New Haven dump site. Yale report to U.S. Army Corps of Engineers, New Haven, Conn.

Gordon, R.B. 1973b. Dispersion of dredge spoil dumped in near-shore waters. Yale report to U.S. Army Corps of Engineers, New Haven, Conn.

Gordon, R.B. 1974. Dispersion of dredge spoil dumped in near-shore waters. Estuarine and Coastal Mar. Sci. 2:349-358.

Gordon, R.B., Rhoads, D.C., and Turekian, K. K. 1972. The environmental consequences of dredge spoil disposal in central Long Island Sound: I. The New Haven spoil ground and New Haven Harbor. Dept. Geol. and Geophys., Yale Univ. 39 pp.

Grassle, J., Sanders, H., Hessler, R., Rowe, G., and McLellan, T. 1975. Pattern and zonation: a study of the bathyal megafauna using the research submersible Alvin. Deep-Sea Res. 22:457-481.

Gray, J.S. and Ventilla, R.J. 1971. Pollution effects on micro- and meiofauna of sand. Mar. Poll. Bull. 2(3):39-43.

Great Lakes Research Center. 1968. Preliminary Report on Effects of spoil disposal at Sandusky, Ohio. In: Dredging and Water Quality Problems of the Great Lakes. U.S. Army Corps of Engineers Buffalo District, Vol. 3, App. A21. 23 pp.

Gren, G.G. 1976. Hydraulic dredges, including boosters. pp. 115-124. In: P.A. Krenkel, J. Harrison, and J.C. Burdick III (eds.) Dredging and its Environmental Effects. ASCE, New York.

Griggs, G.B., Carey, A.G., and Kulm, L.D. 1969. Deep-sea sedimentation and sediment-fauna interaction in Cascadia Channel and on Cascadia Abyssal Plain. Deep-Sea Res. 16(2):157-170.

Grim, M.S., Bennett, L.C., and Harman, R.A. 1968. Shallow seismic profiling of the continental shelf off Gray's Harbor, Washington. (Abstract) Trans. Amer. Geophys. U. 49:209.

Griscom, A. and Geddes, W.H. 1966. Island-arc structure interpreted from aeromagnetic data near Puerto Rico and the Virgin Islands. Geol. Soc. Amer. Bull. 77:153-162.

Gross, M.G. 1965. The carbonate content of surface sediments from the northeast Pacific Ocean. Northwest Sci. 39(3):85-92.

Gross, M.G. 1970. Waste-solid disposal in coastal waters of North America. Marine Science Res. Center, informal report. State Univ. of New York, Stony Brook, New York.

Gross, M.G. 1972. Geologic aspects of waste solids and marine waste deposits, New York metropolitan region. Geol. Soc. Amer. Bull. 83:3163-3176.

Guinasso, N.L., Jr. and Schink, D.R. 1975. Quantitative estimates of biological mixing rates in abyssal sediments. J. Geophys. Res. 80:3032-3043.

Gunderson, K. and Mountain, C.W. 1973. Oxygen utilization and pH changes in the ocean resulting from biological nitrate formation. Deep-Sea Res. Vol. 20, Pergamon Press, New York. pp. 1083-1091.

Gunter, G. 1967. Some relationships of estuaries to the fisheries of the Gulf of Mexico. pp. 621-638. In: G.H. Lauff (ed.) Estuaries Pub. No. 83, AAAS, Washington, D.C.

Hackenjos, C.B. 1976. Environmental effects of dredging: Critique-remarks. pp. 6-7. In: Dredging: Environmental Effects and Technology. WODCON VII, Proc., San Pedro, California.

Haedrich, R., Rowe, G., and Polloni, P. 1975. Zonation and faunal composition of epibenthic populations on the continental slope south of New England. J. Mar. Res. 33:191-212.

Hann, R., Jr. and Slowey, J.F. 1972. Sediment analysis - Galveston Bay. Texas A&M Univ. Environ. Engineering Div. Tech. Rep. 24. 57 pp.

Hansen, D. 1970. Gulf stream meanders between Cape Hatteras and the Grand Banks. Deep-Sea Res. 17:495-511.

Haque, R., Schmedding, D.W., and Freed, V.H. 1974. Aqueous solubility, adsorption and vapor behavior of polychlorinated biphenl Aroclor 1254. Environ. Sci. and Tech. 17:495-511.

Harbison, R.N. 1968. Geology of DeSoto Canyon. J. Geophys. Res. 73(16):5175-5185.

Harding, J.L. and Nowlin, W.D., Jr. 1966. Gulf of Mexico. In: R.W. Fairbridge (ed.) The Encyclopedia of Oceanography, Reinhold, New York. 1021 pp.

Harman, W.N. 1972. Benthic substrates: their effects on fresh-water mollusca. Ecology. 53(2):271-277.

Harrison, W. 1967. Environmental effects of dredging and spoil deposition. Proc. First World Dredging Conf., New York. pp. 535-559.

Harrison, W. 1970. Environmental effects of dredging and spoil deposition. In: Proc. World Dredging Conf. I., Tokyo, WODCON, San Pedro, California, 535 pp.

Hart, J.L. 1973. Pacific fishes of Canada. Bull. 180, Fish. Res. Bd. Can., Ottawa. 580 pp.

Hartman, O. and Barnard, J.L. 1958. The benthic fauna of the deep basins off southern California. Allan Hancock Pacific Expeds. 22:1-67.

Hartman, O. and Barnard, J.L. 1960. The benthic fauna of the deep basins off southern California. Part II. Allan Hancock Pacific Expeds. 22:69-297.

Havens, D.S. and Morales, A.R. 1972. Biodeposition as a factor in sedimentation of fine suspended solids in estuaries. pp. 121-130. In: B.W. Nelson (ed.) Environmental Framework of Coastal Plain Estuaries. Geol. Soc. Amer. Mem. 133.

Havens, J.M., Shaw, D.M., and Levine, E.R. 1973. Offshore weather and climate. In: Coastal and offshore environmental inventory-Cape Hatteras to Nantucket Shoals. Mar. Pub. Ser. No. 3, Univ. of Rhode Island.

Hayes, S.P. and Halpern, D. 1976. Observations of internal waves and coastal upwelling off the Oregon coast. J. Mar. Res. 34(2):247-267.

Hedgpeth, J.W. 1953. An introduction to the zoogeography of the northern Gulf of Mexico with reference to the invertebrate fauna. Pub. Inst. Mar. Sci. 3:111-224.

Heezen, B.C. and Ewing, M. 1952. Turbidity currents and submarine slumps, and the 1920 Grand Banks earthquake. Amer. J. Sci. 250: 849-873.

Heezen, B.C. and Drake, C.L. 1964. Grand Banks slump. Amer. Assoc. Petrol. Geol. Bull. 48:221-225.

Hempel, G. and Weiker, H. 1972. The neuston of the subtropical and boreal northeastern Atlantic Ocean. A review. Mar. Biol. 13(1): 70-88.

Herbich, J.B. 1975. Coastal and Deep Ocean Dredging. Gulf Publ. Co., Houston. 622 pp.

Hessler, R. and Sanders, M. 1967. Faunal diversity in the deep-sea. Deep-Sea Res. 14:65-78.

Hirst, D.M. and Nicholls, G.D. 1958. Techniques in sedimentary geochemistry. I. Separation of the detrital and non-detrital fractions of limestones. J. Sediment. Petrol. 28:461-468.

Hodson, R., Holm-Hansen, O., and Azam, F. 1976. Improved methodology for ATP determination in marine environments. Mar. Biol. 34: 143-149.

Holeman, J.N. 1968. The sediment yield of major rivers of the world. Water Resour. Res. 4:737-747.

Hollister, C.D. and Heezen, B.C. 1966. Ocean bottom currents. Encyclopedia of Oceanography, Reinhold Publ. Co., New York. 1021 pp.

Hollister, C.D. and Heezen, B.C. 1972. Geologic effects of ocean bottom currents, western North Atlantic. pp. 19-35. In: A.L. Gordon (ed.) Studies in Physical Oceanography, Georg. Wust Tribute, 2. Gordon & Breach, New York.

Hopkins, T.S. 1972. The effects of physical alteration on water quality in Mulatto Bayou, Escambia Bay. Q.J. Fla. Acad. Sci. 35(1): 2.

Horn, M.F. 1974. Fishes. pp. 11-1 through 11-124. Vol. II. In: M.D. Dailey, B. Hill, and N. Lansing (eds.) A summary of knowledge of the Southern California Coastal Zone and offshore areas. Report prepared for Bureau of Land Management, U.S. Dept. of Interior, Contract #08550-CT4-1.

Horne, R.A., Mahler, A.J., and Rosello, R.C. 1971. The marine disposal of sewage sludge and dredge spoil in the waters of the New York Bight. NTIS Government Rep. Announcements. 71(12):143-144.

Howard, Needles, Tammen, and Bergdoff. 1975. Proposed offshore crude oil terminal and submarine pipeline, St. Croix, U.S. Virgin Islands. Environmental Impact Assessment Report. Alexandria, Virginia. 242 pp.

Howell, J.V. 1975. Glossary of geology and related sciences. Nat. Acad. Sci. - Nat. Res. Council Pub. 501. Amer. Geol. Inst., Washington, DC. 325 pp.

Huang, T.C. and Goodell, H.C. 1970. Sediments and sedimentary processes of eastern Mississippi Cone, Gulf of Mexico. Amer. Assoc. Petrol. Geol. Bull. 54(11):2070-2100.

Huang, J. and Liao, C. 1970. Adsorption of pesticides by clay minerals. J. Sanitary Engineer. 96:1057-1078.

Huet, M. 1965. Water quality criteria for fish life. pp. 160-167. In: C. Tarzwell (ed.) Biological Problems in Water Pollution. U.S. Public Health Serv. Pub. No. 999-WP-25.

Hulbert, M.H. and Givens, D.N. 1975. Geotechnical and chemical property relationships for Wilkinson Basin, Gulf of Maine, sediments. J. Sediment. Petrol.

Huntsman, A.C. 1924. Oceanography. pp. 274-290. In: Handbook of the British association for the advancement of Science, Toronto.

Huston, J. 1970. Hydraulic Dredging. Cornell Maritime Press. 318 pp.

Ichiye, T. 1968. Marine geological research and exploration. Under Sea Technology Handbook/Directory. Compass Publ., Arlington, Virginia. 10 pp.

Ichiye, T., Kuo, H. and Carnes, M.R. 1973. Assessment of currents and hydrography of the eastern Gulf of Mexico. Dept. of Oceanogr., Texas A&M Univ., Contribution No. 601.

Idyll, C.P. 1964. Abyss: The Deep Sea and the Creatures That Live In It. Thomas Y. Crowell Co., New York. 396 pp.

Ingle, R.M. 1952. Studies on the effect of dredging operations upon fish and shellfish. Fla. Bd. Conserv., Tech. Ser. 5:1-26.

Ingle, R.M., Ceurvels, A.R., and Leinecker, R. 1955. Chemical and biological studies of the muds of Mobile Bay. Rep. to the Div. of Seafoods, Alabama Depart. Conserv., Univ. of Miami Contribution 139.

IEC, 1973. Ocean Waste Disposal in Selected Geographic Areas. For U.S. Environmental Protection Agency Ocean Disposal Prog. Off. Contract 68-01-1796, July.

Irukayoma, K. 1967. The pollution of Minimata Bay and Minimata disease. Adv. in Water Poll. Res. 3:153.

Iselin, C. 1936. A study of the circulation of the western North Atlantic. Pap. phys. Oceanogr. 4(4):101 pp.

Iwamoto, T. 1965. Summary of tuna observations in the Gulf of Mexico on cruises of the exploratory fishing vessel Oregon, 1950-63. Comm. Fish. Rev. 27(1):7-14.

James, B.M. 1972. Systematics and biology of the deep-water Palaeotaxodonta (Mollusca: Bivalvia) from the Gulf of Mexico. Ph.D. dissertation. Texas A&M Univ. 182 pp.

JBF Scientific Corp. 1975. Dredging technology study, San Francisco Bay and Estuary. A report to the Corps of Engineers, San Francisco District, Contract DACW 07-75-C-0045. 240 pp.

Jeffrey, L.M., Pequegnat, W.E., Kennedy, E.A., Vos, A., and James, B.M. 1974. Pelagic tar in the Gulf of Mexico and Caribbean Sea. N.B.S. Spec. Pub. 409, Marine Pollution Monitoring (Petroleum), Proc. of a Symposium and workshop held at N.B.S., Gaithersburg, Maryland. 317 pp.

Jerlov, N.G. 1951. Optical studies of the ocean waters. Rep. Swed. Deep Sea Exped. 3:1-59.

Jerlov, N.G. 1953. Particle distribution in the ocean. In: H. Patterson (ed.) Reports of the Swedish Deep-sea Expedition, Vol. III. Goteborg: Elanders. pp. 73-125.

Johnson, R.G. 1974. Particulate matter at the sediment-water interface in coastal environments. J. Mar. Res. 32:313-330.

Juhl, R. 1974. Fishery Resources - commercial. p. 211-226. In: Proc. Marine Environmental Implications of Offshore Drilling in the Eastern Gulf of Mexico Jan. 31 to Feb. 2, 1974. SUSIO, St. Petersburg, Florida. 455 pp.

Jux, U. 1961. The palynologic age of diapiric and bedded salt in the Gulf coastal plain province. La. Geol. Surv. Bull. 46 pp.

Kanwisher, J.W. 1962. Proc. Symp. Univ. of Rhode Island, Narragansett Marine Lab., Occ. Pub. 1. pp. 13-19.

Kaplan, E.H., Welker, J.R. and Kraus, M.G. 1974. Some effects of dredging on populations of macrobenthic organisms. Fish. Bull. 72(2):445.

Karl, D.M., LaRock, P.A., Morse, J.W., and Sturges, W. 1976. Adenosine triphosphate in the North Atlantic ocean and its relationship to the oxygen minimum. Deep-Sea Res. 23:81-88.

Keeley, J.W. and Engler, R.M. 1974. Discussion of regulatory criteria for ocean disposal of dredged materials: elutriate test rationale and implementation guidelines. U.S. Army Engineer Waterways Exper. Sta., Vicksburg, Miss., Misc. Pap. D-74-14. 18 pp.

Kelling, G. and Stanley, D.J. 1976. Sedimentation in canyon, slope, and base-of-slope environments. pp. 379-435. In: D.J. Stanley and D.J.P. Swift (eds.) Marine Sediment Transport and Environmental Management. John Wiley & Sons, New York.

Kemp, M.A. 1949. Soil pollution in the Potomac River Basin. J. Amer. Water Works Assoc. 41(9):792-796.

Ketchum, B.H. 1972. The Waters Edge: Critical Problems of the Coastal one. MIT Press, Cambridge, Mass. 393 pp.

Ketchum, B., Redfield, A., and Ayers, C. 1951. Oceanography in the New York Bight. Pap. in Phys. Oceanogr. and Meteorol., Contribution 549, MIT and WHOI,

Khalid, R.A., Gambrell, R.P., and Patrick, W.H., Jr. 1975. Sorption and release of mercury by Mississippi River sediment as affected by pH and redox potential, presented at 15th annual Hanford Life Sci. Symposium. Richland, Washington.

Kharker, D.P., Turekian, K.K., and Bertine, K.K. 1968. Stream supply of dissolved silver, molybdenum, antimony, selenium, chromium, cobalt, rubidium and cesium to the oceans. Geochim. Cosmochim. Acta. 32:285-298.

Kindyushev, V.I. 1970. Seasonal variations of water masses in the California region of the Pacific Ocean. Ocean. 10:458-464.

Koh, R.C.Y. and Chang, Y.C. 1973. Mathematical model for barged ocean disposal of wastes. Environ. Protection Tech. Ser., EPA 660/2-73-029. U.S. Environ. Protection Agency, Washington, D.C.

Komar, P.D., Neudeck, R.H., and Kulm, L.D. 1972. Observations and significance of deep-water oscillatory ripple marks on the Oregon Continental Shelf. pp. 143-180. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey (eds.) Shelf Sediment Transport: Process and Pattern. Dowden, Hutchinson, and Ross, Stroudsburg, Pennsylvania.

Krenkel, P.A. 1974. Mercury: environmental consideration part II. CRC Critical Rev. in Environ. Control. 4:251-339.

Krenkel, P.A., Harrison, J., Burdick, J.C., III. (eds.) 1976. Dredging and its environmental effects. Proc. of Specialty Conf., Mobile, Alabama, January 26-28, ASCE, New York. 1037 pp.

Krishnappan, B.G. 1975. Dispersion of granular material dumped in deep water. Scientific Series 55, Inland Water Directorate, Can. Center for Inland Waters, Burlington, Ontario, 1975. 41 pp.

Kroll, J. and Niiler, P. 1976. The transmission and decay of barotropic topographic Rossby waves incident on a continental shelf. J. Phys. Oceanogr. 6(4):432-450.

Krone, R.B. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. Final Rep. Hydraulic Engineering Lab. and Sanitary Engineering Res. Lab., Univ. of California, Berkeley. 110 pp.

Krone, R.B. 1976. Engineering interest in the benthic boundary layer. pp. 143-156. In: I.N. McCave (ed.) The Benthic Boundary Layer. Plenum Press, New York.

Kuenen, Ph. H. 1939. The cause of coarse deposits at the outer edge of the shelf. Geol. Mijorbouw. 1:36-39.

Kulm, L.D. and Fowler, G.A. 1970. Study of the continental margin off the state of Oregon. U.S. Geol. Surv. Tech. Rep. No. 4. Dept. of Oceanogr., Oregon State Univ., Corvallis. Ref. No. 70-2. 43 pp.

Kundu, P.K., Allen, J.S., and Smith, R.L. 1975. Model decomposition of the velocity field near the Oregon coast. J. Phys. Oceanogr. 5:683-704.

Kundu, P.K., and Allen, J.S. 1976. Some three-dimensional characterizations of low-frequency current fluctuations near the Oregon coast. J. Phys. Oceanogr. 6:181-199.

LaFond, E.C. 1961. Internal wave motion and its geological significance. pp. 61-77. In: Mahadevan Vol. Osmania Univ. Press, Andrha Pradesh, India.

LaFond, E.C. 1962. Internal waves 1. pp. 731-751. In:M.N. Hill (ed.) The Sea. Vol. 1. Wiley-Interscience, New York.

Lagler, K.F., Bardach, J.E., and Miller, R.R. 1962. Ichthyology. John Wiley & Sons, Inc., New York. 545 pp.

Lee, G.F. and Plumb, R.H. 1974. Literature review on research study for the development of dredged material disposal criteria. Inst. for Environ. Stud. Univ. Texas, Dallas, DMRP Rep. D-74-1. 145 pp.

Lee, G.F., Piwoni, M.D., Lopez, J.M., Mariani, G.M., Richardson, J.S., Homer, D.H., and Saleh, F. 1975. Research study for the development of dredged material disposal criteria. U.S. Army Corps of Engineers, Waterways Exper. Sta., Vicksburg, Miss. 381 pp.

Lehner, P. 1969. Salt tectonics and Pleistocene stratigraphy on continental slope of northern Gulf of Mexico. Amer. Assoc. Petrol. Geol. Bull. 53(12):2431-2479.

Leim, A.H. and Scott, W.B. 1966. Fishes of the Atlantic coast of Canada. Bull. 155, Fish. Res. Bd. Can., Ottawa. 487 pp.

Leipper, D.F. 1970. A sequence of current patterns in the Gulf of Mexico. Dept. of Oceanography, Texas A&M Univ. (Unpublished manuscript), Ref. 67-9T.

Leipper, D.F., Cochrane, J.D., and Hewitt, J.B. 1972. A detached eddy and subsequent changes (1965). pp. 107-117. In: L.R.A. Capurro and J.L. Reid (eds.) Contributions on the Physical Oceanograpy of the Gulf of Mexico, Vol. 2, Gulf Publ. Co., Houston.

Lewis, K.B. 1971. Slumping on a continental slope at 1°-4°. Sediment. 16:97-101.

Lipka, D.A. 1975. The systematics and zoogeography of cephalopods from the Gulf of Mexico. Ph.D. dissertation, Texas A&M Univ., Oceanogr. Dept. 351 pp.

Lonsdale, P. and Southard, J.B. 1974. Experimental erosion of North Pacific red clay. Mar. Geol. 17:M51-M60.

Loosanoff, V.L. 1961. Effects of turbidity on some larval and adult bivalves. Gulf Carib. Fish Inst. Proc.

Loosanoff, V.L. and Tommers, F.D. 1948. Effects of suspended silt and other substances on rate of feeding of oysters. Science. 107(2768):69-70.

Lowman, F.G., Phelps, D.K., McClin, R., Devega, V.R., Depodovani, I.O., and Garcia, R.J. 1966. Interactions of the environmental and biological factors on the distribution of trace elements in the marine environment. pp. 249-265. In: Disposal of Radioactive Wastes into Seas, Oceans, and Surface Waters. IAEA, Vienna.

Lyall, A.K., Stanley, D.J., Giles, H.N., and Fisher, A. 1971. Suspended sediment and transport at the shelfbreak and on the slope. Mar. Tech. Soc. J. 5:15-26.

Lynn, J.B., III. 1975. Sea-surface topography of the Gulf of Mexico based on ship drift. M.S. Thesis, Texas A&M Univ. 56 pp.

MacIntyre, F. 1974. The top millimeter of the ocean. Sci. Amer. 230(5):62-77.

Malahoff, A. and Woollard, G.P. 1970. Geophysical studies of the Hawaiian Ridge and Murray Fracture Zone. pp. 73-131. In: A.E. Maxwell (ed.) The Sea, Vol. 4. Part II. Wiley-Interscience, New York. 664 pp.

Mallory, C.W. and Meccia, R.M. 1975. Concepts for the reclamation of dredged material. pp. 180-214. In: Proc. of the Seventh Dredging Seminar. Sea Grant Rep. TAMU-SG-76-105.

Manheim, F.T. 1976. Interstitial waters of marine sediments. pp. 115-186. In: J.P. Riley and R. Chester (eds.) Chemical Oceanography. Vol. 6, Academic Press, New York.

Manheim, F.T., Hathaway, J.C., and Uchupi, E. 1972. Suspended matter in surface waters of the northern Gulf of Mexico. Limnol. and Oceanogr. 17:17-27.

Manheim, F.T. and Sayles, F.L. 1974. Composition of origin of interstitial waters of marine sediments based on deep sea drill cores. pp. 527-568. In: The Sea. Vol. 5, Wiley-Interscience, New York.

Marcus, S.O. 1973. Environmental conditions within specified geographical regions. Offshore east and west coasts of the United States and in the Gulf of Mexico. NOAA. Environ. Data Ser., Washington, D.C.

Marçuzzi, G. and Pilleri, G. 1971. On the zoogeography of Cetacea. In: G. Pilleri (ed.) Investigations on Cetacea. Berne. 182 pp.

Marshall, N.B. 1966. The life of fishes. World Publ. Co., New York. 402 pp.

Marshall, N.B. 1971. Explorations in the Life of Fishes. Harvard Books in Biology, No. 7. Harvard Univ. Press, Cambridge, Mass. 204 pp.

Martin, R.G., Jr. 1972. Structural features of the continental margin, northeastern Gulf of Mexico. Geol. Surv. Prof. Pap. 800-B. U.S. Govt. Print. Off., Washington, D.C. pp. B1-B8.

Maurer, D., Biggs, R., Leathem, W., Kinner, P., Treasure, W., Otley, M., Watling, L. and Kemas, V. 1974. Effects of spoil disposal on benthic communities near the mouth of Delaware Bay. Univ. of Delaware.

Mauriello, J.J. 1967. Experimental use of shelf unloading hopper dredge for rehabilitation of an ocean beach. pp. 369-395. In: Proc. WODCON 67, First World Dredging Conf.

May, E.B. 1973. Environmental effects of hydraulic dredging in estuaries. Ala. Mar. Res. Bull. 9:1-85.

McCave, I.N. 1975. Vertical flux of particles in the ocean. Deep-Sea Res. 22:491-502.

McClelland, B. 1974. Geologic engineering properties related to construction of offshore facilities on the mid-Atlantic continental shelf. pp. 217-242. In: L.E. Cronin and R.E. Smith (eds.) Marine Environmental Implications of Offshore Oil and Gas Development in the Baltimore Canyon Region of the mid-Atlantic Coast. Proc. of Estuarine Res. Fed. Outer Continental Shelf Conf. and Workshop ERF 75-1. Estuarine Res. Found., Virginia Inst. Mar. Sci., Wachapreague, Virginia. 504 pp.

McClennen, C.E. 1973. New Jersey continental shelf near bottom current meter records and recent sediment activity. J. Sediment. Petrol. 43(2):371-380.

McDermott, D.J., Heesen, T.C., and Young, D.R. 1974. DDT in bottom sediments around five Southern California outfall systems. So. Calif. Coastal Water Res. Proj., El Segundo, Calif. No. TM217.

McHugh, J.L. 1967. Estuarine nekton. In: G.H. Lauff (ed.) Estuaries. Amer. Assoc. Adv. Sci., Pub. 83:581-620.

McHugh, J.L. 1976. Living resources of the United States continental shelf. AIBS Symposium (TerEco Corp.) Ecology and Management of the Continental Shelf. Lecture. New Orleans.

McManus, D.A. 1964. Major bathymetric features near the coast of Oregon, Washington, and Vancouver Island. Northwest Sci. 38(3):65-82.

McManus, D.A. and McGary, N. 1967. Topography of an intermediate borderland, the continental terrace off Washington. (Abstract) Prog. 63rd. Annual Meeting. Geol. Soc. Amer. pp. 145-146.

McNeill, W.J., Wells, R.A., and Brickell, D.C. 1964. Disappearance of dead pink salmon eggs and larvae from Sashin Creek, Baranoff Island, Alaska. U.S.F.Q.W.S., Spec. Sci. Pre., Fish. 485. 13 pp.

Meade, R.H. 1972. Transport and deposition of sediment in estuaries. G.S.A. Mem. 133:91-120.

Meccia, R.M. 1975. Dredged material disposal effects and alternatives. pp. 29-42. In: Proc. of the Seventh Dredging Seminar. Sea Grant Rep. TAMU-SG-76-105.

Menard, H.W. 1955. Deep-sea channels, topography, and sedimentation. Amer. Assoc. Petrol. Geol. Bull. 39:236-255.

Menard, H.W. 1960. Possible pre-Pleistocene deep-sea fans of central California. Geol. Soc. Amer. Bull. 71(8):1271-1278.

Menard, H.W. 1964. Marine Geology of the Pacific. McGraw-Hill Book Co., New York. 271 pp.

Menard, H.W. and Dietz, R.S. 1951. Submarine geology of the Gulf of Alaska. Bull. Geol. Soc. Amer. 62:1263-1285.

Menzies, R.J., Pilkey, O.H., Blackwelder, B.W., Dexter, D., Haling, P., and McCloskey, L. 1966. A submerged reef off North Carolina. Inst. Rev. Gesamten Hydrobiol. 51:393-431.

Meyerhoff, H.A. 1927. Tertiary physiographic development of Porto Rico and the Virgin Islands. Geol. Soc. Amer. Bull. 38:557-576.

Milliman, J.D., Pilkey, O.H., and Ross, D.A. 1972. Sediments of the continental margin off the eastern United States. Geol. Soc. Amer. Bull. 83:1315-1334.

Milne, J. 1897. Sub-oceanic changes. Geog. J. 10:129-146, 259-289.

Mohr, A.W. 1974. Development and future of dredging. J. of the Waterways and Harbors and Coastal Engineering Div., May. pp. 69-83.

Mohr, A.W. 1976. Mechanical Dredges. pp. 125-138. In: P.A. Krenkel, J. Harrison, and J.C. Burdick III (eds.) Dredging and its Environmental Effects. ASCE, New York.

Moiseev, P.A. 1971. The living resources of the world ocean. Israel Prog. for Sci. Trans., Jerusalem. Nat. Sci. Found., Washington, D.C. 334 pp.

Mooers, C.N.K. 1976. Introduction to the physical oceanography and fluid dynamics of continental margins. pp. 7-21. In: D.J. Stanley and D.J.P. Swift (eds.) Marine Sediment Transport and Environmental Management. John Wiley & Sons, New York.

Mooers, C.N.K., Collins, C.A., and Smith, R.L. 1976. The dynamic structure of the frontal zone in the coastal upwelling region of Oregon. J. Phys. Oceanogr. 6(1):3-21.

Moore, D.G. and Schumway, G. 1959. Sediment thickness and physical properties: Pigeon Point Shelf, California. J. Geophys. Res. 64(3):367-374.

Moore, E. 1937. Effects of silting on the productivity of waters. Trans. of the 2nd No. Amer. Wildl. Conf. pp. 658-661.

Moore, G.T. 1973. Submarine current measurements, northwest Gulf of Mexico. Trans. Gulf Coast Assoc. Geol. Soc. 23:245-255.

Moore, H.B. 1960. The muds of the Clyde Sea area. III. Chemical and physical conditions: rate of sedimentation and infauna. Mar. Biol. Assoc. UK, J. 17:325-358.

Moore, J.C. 1974. The ancient continental margin of Alaska. pp. 811-816. In: C.A. Burk and C.L. Drake (eds.) The Geology of Continental Margins. Springer-Verlag, New York. 1009 pp.

Morgenstern, N. 1967. Submarine slumping and the initiation of turbidity currents. pp. 189-220. In: A.F. Richards (ed.) Marine Geotechnique, Univ. of Illinois Press, Urbania, Illinois.

Morris, B.F. 1975. The neuston of the Northwest Atlantic. Thesis (Ph.D. in Oceanography), Dalhousie Univ. pp. 1-54, 1-77, 1-69, 1-12, and 1-18.

Morton, J.W. 1976. Ecological impacts of dredging and dredge spoil disposal: a literature review. M.S. thesis, Cornell Univ.

Mosser, J.L., Fisher, N.S., and Wurster, C.F. 1970. Polychlorinated biphenyls and DDT alter species composition in mixed cultures of algae. Science. 197:533-535.

Muller, G. and Forstner, U. 1975. Heavy metals in sediments of the Rhine and Elbe estuaries: Mobilization or mixing effects. Environ. Geol. 1:33-39.

Murray, C.N. and Murray, L. 1973. Adsorption-desorption equilibria of some radionuclides in sediment-fresh-water, and sediment-seawater systems. pp. 105-124. In: Radioactive Contamination of the Marine Environment. IAEA, Vienna.

Nardi, J. 1959. Pumping solids through a pipeline. Mining Engineering, September.

National Academy of Sciences. 1971. Marine environmental quality. NAS. 107 pp.

National Academy of Sciences. 1975. Assessing potential ocean pollutants. Report of study panel on assessing potential ocean pollutants to Ocean Affairs Bd., Nat. Res. Council. 438 pp.

National Academy of Sciences. 1976. Disposal in the Marine Environment: An oceanographic assessment. NAS, Washington, D.C. pp. 1-76.

Neighbor Island Consultants, Inc. 1977. Environmental surveys of deep ocean dredge spoil disposal sites in Hawaii. Corps of Engineers, Pacific Ocean Division, Dr. James Maragos, Proj. Director.

Nelson, W.R. and Carpenter, J.S. 1968. Bottom longline explorations in the Gulf of Mexico. A report on "Oregon II's" first cruise. Comm. Fish. Rev. 39(10):57-62.

Newell, G.E. and Newell, R.C. 1963. Marine Plankton: a practical guide. Hutchinson Educ. LTD., London. 221 pp.

New England Aquarium Corporation. 1974. A study of the effect of turbid mixtures on biological materials. Final Rep. to U.S. Army Engineers, New England Div., Waltham, Mass.

Nimmo, D., Wilson, P., Blackman, A. and Wilson, A. 1971. Polychlorinated biphenyl absorbed from sediments by fiddler crabs and pink shrimp. Nature. 231:50-53.

Nissenbaum A., Baedecker, M.J., and Kaplan, I.R. 1972. Dissolved organic matter from interstitial water of a reducing marine fjord. Adv. Org. Geochim., Proc. 5th Int. Conf. pp. 427-440.

National Oceanic and Atmospheric Administration. 1976. Report to the Congress on ocean dumping research, January through December 1975. Public Law 92-532, Title II, Section 201. Dept. of Commerce, June. 39 pp.

Nowlin, W.D. 1972. Winter circulation patterns and property distributions. In: L.R.A. Capurro and J.L. Reid (eds.) Contributions on the Physical Oceanography of the Gulf of Mexico, Vol. 2, Gulf Publ. Co., Houston. pp. 1-51.

Nowlin, W.D., Jr., Hubertz, J.M., and Reid, R.O. 1968. A detached eddy in the Gulf of Mexico. J. Mar. Res. 26(2):185-186.

Nowlin, W.D., Jr. and Hubertz, J.M. 1972. Contrasting summer circulation patterns for the eastern Gulf. pp. 119-137. In: L.R.A. Capurro and J.L. Reid (eds.) Contributions on the Physical Oceanography of the Gulf of Mexico, Vol. 2, Gulf Publ. Co., Houston.

Nowlin, W.D., Jr. and Parker, C.A. 1974. Effects of a cold-air outbreak on shelf waters of the Gulf of Mexico. J. Phys. Oceanogr. 4(3):467-486.

Owen, D.M., Sanders, H.L., and Hessler, R.R. 1967. Bottom Photography as a Tool for Estimating Benthic Populations. p. 229-234. In J.B. Hensey ed. Deep-Sea Photography, Johns-Hopkins, Univ. Press. Baltimore. 310 p.

Pararas-Carayannis, G. 1973. Ocean dumping in the New York Bight. An assessment of environmental studies. U.S. Corps of Engineers Coastal Engineering Res. Center.

Parin, N.V. 1968. Ikhtiofauna okeanskoy ipipelagiali (Ichthyofauna of the epipelagic zone): Moscow, Akad. Nauk SSSR, Inst. Okeanologii, Izel. "Nauka," 206 pp. (Trans. by Israel Prog. for Sci. Trans., Jerusalem, 1970.)

Parker, C.E. 1971. Gulf stream rings in the Sargasso Sea. Deep-Sea Res. 18:981-993.

Parker, P.C. (ed.). 1974. Pollutant transfer to the marine environment. NSF/IDOE workshop. Pt. Aransas, Texas Jan 11-12, 1974.

Parker, R.H. and Curray, J.R. 1956. Fauna and bathymetry of banks on continental shelf, Northwest Gulf of Mexico. Bull. Amer. Assoc. Petrol. Geol. 49(10):2428-2439.

Parks, G.A. 1975. Adsorption in the marine environment. pp. 415-496. In: J.P. Riley and G. Skirrow (eds.) Chemical Oceanography, Vol. 1, Academic Press, New York.

Patzert, W.C. and Wyrtki, K. 1974a. Anticyclonic flow around the Hawaiian Islands indicated by current meter data. J. Phys. Oceanogr. 4(4):673-676.

Patzert, W.C. and Wyrtki, K. 1974b. Resulting drift or average vector velocity for current meter stations in the western part of the Hawaiian Archipelago. J. Phys. Oceanogr. 4(4):673-676.

Pavlova, Y.V. 1966. Seasonal variations of California current. Oceanology, USSR Acad. of Sci. 6(6):806-814.

Pearce, J.B. 1969. The effects of waste disposal in the New York Bight. U.S. Bur. Sp. Fish. and Wildl., Sandy Hook Mar. Lab., Interim Rep.

Pearce, J.B. 1972. Biological survey of submerged refuse. Mar. Poll. Bull. 3(10):157-158.

Pearcy, W.C. 1964. Some distributional features of mesopelagic fishes off Oregon. J. Mar. Res. 22(1):83-102.

Pennak, R.W. and Van Gerpen, E.D. 1974. Bottom fauna production and physical nature of the substrate in a northern Colorado trout stream. Ecology. 28(1):42-48.

Pequegnat, L.H., Wormuth, J.H., and McEachran, J.D. 1976a. Neuston. pp. 187-233. In: Environmental assessment of the South Texas Outer Continental Shelf, chemical and biological survey component, Second Quarterly Report for 1976. Prepared for the Bureau of Land Management, Washington, D.C. by the Univ. of Texas and Texas A&M Univ., and Rice Univ.

Pequegnat, L.H., Wormuth, J.H., and McEachran, J.D. 1976b. Neuston. pp. 269-324. In: Environmental studies, South Texas Outer Continental Shelf, Biology and Chemistry, Third Quarterly Report for 1976. Prepared for the Bureau of Land Management, Washington, DC by the Univ. of Texas, Texas A&M Univ., and Rice Univ.

Pequegnat, L.H., Wormuth, J.H., and McEachran, J.D. 1977a. Neuston. pp. 287-320. In: Environmental Studies, South Texas Outer Continental Shelf, Biology and Chemistry, Fourth Quarterly Report for 1976. Prepared for the Bureau of Land Management, Washington, DC by the Univ. of Texas, Texas A&M Univ., and Rice Univ.

Pequegnat, L.H., Wormuth, J.H., and McEachran, J.D. 1977b. Neuston. pp. 67-92. In: Environmental Studies, South Texas Outer Continental Shelf, Biology and Chemistry, Fifth Quarterly Report for 1976. Prepared for the Bureau of Land Management, Washington, DC by the Univ. of Texas, Texas A&M Univ., and Rice Univ.

Pequegnat, W.E. 1970. Deep-water brachyuran crabs. pp. 171-204. In: W.E. Pequegnat and F.A. Chace, Jr. (eds.) Contribution on the Biology of the Gulf of Mexico. Texas A&M Univ. Oceanogr. Studies, vol. 1, Gulf Publ. Co., Houston.

Pequegnat, W.E. 1974. Some effects of platforms on the biology of the continental shelf. Proc. of Estuarine Res. Fed. Outer Continental Shelf Conf. and Workshop. ERF75-1. VIMS. pp. 455-468.

Pequegnat, W.E. 1975. Meiobenthos ecosystems as indicators of the effects of dredging. pp. 573-583. In: Estuarine Research, Vol. II, Geol. and Engineering, Academic Press, New York.

Pequegnat, W.E., James, B.M., Bouma, A.H., Bryant, W.R., and Fredericks, A.D. 1972. Photographic study of deep-sea environments of the Gulf of Mexico. pp. 67-128. In: R. Rezak and V.J. Henry (eds.) Contributions on the Geological and Geophysical Oceanography of the Gulf of Mexico. Texas A&M Univ. Oceanogr. Studies, Vol. 3. Gulf Publ. Co., Houston.

Pequegnat, W.E., Darnell, R.M., James, B.M., Kennedy, E.A., Pequegnat, L.H., and Turner, T.J. 1976. Ecological aspects of the upper continental slope of the Gulf of Mexico. Prepared for Div. of Minerals Environ. Assessment. Bureau of Land Management Contract No. 08550-CT4-12. 305 pp. plus appendices.

Peter, G., Erickson, B.H., and Grim, P.J. 1970. Magnetic structure of the Aleutian Trench and Northeast Pacific Basin. pp. 191-222. In: A.E. Maxwell (ed.) The Sea, Vol. 4, Part II. Wiley-Interscience, New York. 664 pp.

Peterson, D.W. 1971. Petroleum potentials of Hawaii. pp. 161-169. In: I.H. Cram (ed.) Future Petroleum Provinces of the United States Their Geology and Potential. Amer. Assoc. Petrol. Geol. Mem. 15. Tulsa, Oklahoma.

Pfister, R.M., Dugan, P.R., and Frea, J.I. 1969. Microparticulates: isolation from water and identification of associated chlorinated pesticides. Science. 166:878-879.

Pierce, J.W. 1976. Suspended sediment transport at the shelf break and over the outer margin. pp. 437-458. In: D.J. Stanley and D.J.P. Swift (eds.) Marine Sediment Transport and Environmental Management. John Wiley and Sons, New York.

Plank, W.S., Zaneveld, J.R.V., and Pak, H. 1973. Distribution of suspended matter in the Panama Basin, J. Geophys. Res., 78: 7113-7121.

Pratt, R.M. 1968. Atlantic continental shelf and slope of the United States-physiography and sediments of the deep-sea basin. U.S. Geol. Sruv. Prof. Pap. 529-B.

Presley, B.J., Kolodny, Y., Nissenbaum, A., and Kaplan, I.R. 1972. Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia--II, Trace element distribution in interstitial water and sediment. Geochim. Cosmochim. Acta. 36:1073-1090.

Price, N.B. 1976. Chemical diagenesis in sediments. In: J.P. Riley and N. Chester (eds.) Chemical Oceanography. Academic Press, New York.

Proni, J.R., Newman, F.C., Sellers, R.L., and Parker, C. 1976. Acoustic tracking of ocean-dumped sewage sludge. Science. 193:1005-1007.

Rass, T.S. 1959. Glubokovodnye Ryby (Deepwater Fishes). In: Itog; Nauki. Dostizheniya Okeanologii, Vol. 1, Moskova, Izdatel'stvo AN SSSR.

Rayburn, R. 1975. Food of deep-sea demersal fishes of the northwestern Gulf of Mexico. M.S. Thesis, Texas A&M Univ., Oceanogr. Dept. 119 pp.

Raymont, J.E.G. 1963. Plankton and Productivity in the Oceans. Pergamon Press, New York. 660 pp.

Rebel, T.P. 1974. Sea Turtles. Univ. of Miami Press, Coral Gables, Florida. 250 pp.

Recht, H.L. and Ghassemi, M. 1970. Kinetic and mechanism of precipitation and nature of precipitation obtained in phosphate removal from water after using Al and Fe salts. FWQA Rep. 1701 EKI-04170. 77 pp.

Reid, J.L., Jr. 1963. Direct measurements of a small surface eddy off northern Baja California. J. Mar. Res. 21:205-218.

Reid, J.L., Jr. 1965. Physical oceanography of the region near Point Arguella. Univ. of Calif., Inst. of Mar. Resour. pp. 65-69.

Reid, J. 1970. The summer meiobenthos of the Pamlico River Estuary, North Carolina, with particular reference to the harpacticoid copepods. M.S. Thesis, North Carolina State Univ.

Rhoads, D.C. and Young, D.K. 1974. Organism-sediment relations on the muddy sea floor. Oceanogr. Mar. Biol. Annual Rev. 12:263-300.

Richards, F.A. 1970. Organic matter in natural waters. Univ. of Alaska. Inst. of Mar. Sci. Oceanogr. Pub. 1.

Richards, F.A. and Redfield, A.C. 1954. A correlation between the oxygen content of sea water and the organic content of marine sediments. Deep-Sea Res. 1:279-281.

Richardson, P. 1976. Gulf stream rings. Oceanus. Woods Hole Oceanographic Inst., Woods Hole, Mass. 19(3):65-68.

Ricker, W.E. 1945. Natural mortality among Indiana bluegill sunfish. Ecology. 26(2):111-121.

Rinkel, M.O. 1971. Results of Cooperative Investigation - A Pilot Study of the Eastern Gulf of Mexico. Gulf and Carribbean Fisheries Institute. Proceedings of 23rd Annual Sesseion. Wilhelmstadt, Curacao. November 1970.

Rittenburg, S.C., Emery, K.O., and Orr, W.L. 1955. Regeneration of nutrients in sediments of marine basins. Deep-Sea Res. 3:23-45.

Roberts, M.H., Jr. 1974. Biology of Benthic Fauna. Chapter 4. pp. 156-327. In: M.H. Roberts and others (eds.) A Socio-Economic Environmental Baseline Study for the South Atlantic Region between Cape Hatteras, North Carolina and Cape Canaveral, Florida.

Roberts, M.H., Jr., Diaz, R.J., Bender, M.E., and Huggett, R.J. 1975. Acute toxicity of chlorine to selected estuarine species. J. Fish. Res. Bd. Can. 32(12):2525-2528.

Rodin, L.E., Bazilevich, N.I., and Roxov, N.N. 1975. Productivity of the world's main ecosystems. In: Productivity of World Ecosystems. Nat. Acad. Sci., Washington, D.C.

Rogers, B.A. 1969. The tolerance of fishes to suspended solids. M.S. Thesis, Univ. of Rhode Island, Kingston, Rhode Island.

Rogers, R.M. 1976. Distribution of meiobenthic organisms in San Antonio Bay in relation to season and habitat disturbance. In: A.H. Bouma (ed.) Shell Dredging and Its Influence on Gulf Coast Environments, Gulf Publ. Co., Houston. pp. 337-344.

Rosenberg, D.H. 1972. A review of the oceanography and renewable resources of the Northern Gulf of Alaska. Sea Grant Rep. 73-3, Inst. of Mar. Sci., Univ. of Alaska.

Rounsefell, G.A. 1972. Ecological effects of offshore construction. J. Mar. Sci. 2(1):89 pp. plus appendices.

Rowe, G. 1971. Benthic biomass and surface productivity. pp. 441-454. In: J.D. Costlow (ed.) Fertility of the Sea, Vol. 2, Gordon and Breach, New York.

Rowe, G., Polloni, P., and Horner, S. 1974. Benthic biomass estimates from the northwestern Atlantic Ocean and the northern Gulf of Mexico. Deep-Sea Res. 21:641-650.

Rowe, G.T. and Menzel, D.W. 1971. Quantitative benthic samples from the deep Gulf of Mexico with some comments on the measurement of deep-sea biomass. Bull. Mar. Sci. 21(2):556-566.

Royer, T.C. 1975. Seasonal variations of waters in the northern Gulf of Alaska. Deep-Sea Res. 22:403-416.

Rusnak, G.A. 1966. The continental margin of northern and central California. pp. 325-335. In: E.H. Bailey (ed.) Geology of Northern California. Calif. Div. Mines and Geol. Bull. No. 190. 508 pp.

Ryden, J.C., Syers, J.K., and Harris, R.F. 1973. Phosphorus in runoff and streams. Adv. Agron. 25:1-45.

Saila, S.B., Polgar, T.T., and Rogers, B.A. 1968. Results of studies related to dredged sediment dumping in Rhode Island Sound. Proc. Annual Northeastern Reg. Antipoll. Conf. July 22-24, 1968. pp. 71-80.

Saila, S.B., Pratt, S.D., and Polgar, T.T. 1971. Providence Harbor improvement spoil disposal site evaluation study--phase II. Rep. to Bureau of Sport Fish. and Wildl., Mar. Exper. Sta., Univ. of Rhode Island, Kingston, Rhode Island.

Saila, S.B., Pratt, S.D., and Polgar, T.T. 1972. Dredge spoil disposal in Rhode Island Sound. Tech. Rep. No. 2, Univ. of Rhode Island. 48 pp.

Saila, S.B. and Pratt, S.D. 1973. Mid-Atlantic Bight fisheries. In: S.B. Saila (ed.) Coastal and Offshore Environmental Inventory-Cape Hatteras to Nantucket Shoals. Univ. of Rhode Island, Mar. Exper. Sta. Grad. School of Oceanogr.

Sanders, H.L. 1958. Benthic studies in Buzzards Bay I Animal-sediment relationships. Limnol. and Oceanogr. 3(3):245-258.

Sandy Hook Laboratory. 1972. The effects of waste disposal in the New York Bight. U.S. Dept. of Comm. Nat. Mar. Fish. Ser. 70 pp.

Saucier, R.T. 1976. Environmental effects of dredging: Critique-opening remarks. pp. 2-3. In: Dredging: Environmental Effects & Technology. WODCON VII Proc., San Pedro, Calif.

Saunders, P. 1971. Anticyclonic eddies formed from shoreward meanders of the Gulf Stream. Deep-Sea Res. 18:1207-1219.

Schindler, J.E., Alberts, J.J., and Honick, K.R. 1972. A preliminary investigation of organic-inorganic associations in a stagnating system. Limnol. and Oceanogr. 17(6):952-957.

Schlee, J. and Pratt, R.M. 1970. Atlantic continental shelf and slope of the United States-gravels of the northeastern part. U.S. Geol. Surv. Prof. Pap. 529H.

Schneider, E.D., Fox, P.J., Hollister, C.D., Needham, H.D., and Heezen, B.C. 1967. Further evidence of contour currents in the western North Atlantic. Earth Planet. Sci. Letter. 2:351-359.

Schubel, J.R. 1971. Estuarine circulation and sedimentation. pp. VI-117. In: J.R. Schubel (ed.) The Estuarine Environment: Estuaries and Estuarine Sedimentation. Am. Geol. Inst. Short Course Lecture Notes, Amer. Geol. Inst., Washington, D.C.

Servizi, J.A., Gordon, R.W., and Martens, D.W. 1969. Marine disposal of sediments from Bellingham Harbor as related to sockeye and pink salmon fisheries. Int. Pacific Salmon Fish. Comm. Prog. Rep. No. 23.

Shapiro, S. (ed.). 1971. Our Changing Fisheries. U.S. Govt. Print. Off., Washington, D.C. 534 pp.

Shelton, R.G.J. 1971. Sludge dumping in the Thames estuary. Mar. Poll. Bull. 2(2):24-27.

Shen, H.W. and the Committee on Sedimentation, Hydraulics Div. 1970. Sediment Transportation Mechanics: J. Transportation of Sediment in Pipes. J. Hydraulics Div., ASCE, Vol. 96, HY7, July.

Shepard, F.P. 1973. "Salt" domes related to Mississippi submarine trough. Geol. Soc. Amer. Bull. 48:1349-1362.

Shepard, F.P. 1960. Mississippi Delta: Marginal environments, sediments and growth. pp. 56-81. In: F.P. Shepard, F.B. Phleger, and Tj.H. Van Andel (eds.) Recent Sediments, Northwest Gulf of Mexico. Amer. Assoc, Petrol. Geol., Tulsa, Oklahoma.

Shepard, F.P. 1963. Submarine Geology. Harper & Row, New York. pp. 557.

Shepard, F.P. 1973. Submarine Geology, 3rd Ed., Harper and Row, New York. pp. 517.

Shepard, F.P. and Emery, K.O. 1941. Submarine topography off the California coast: Canyons and tectonic interpretations. Geol. Soc. Amer., Spec. Pap. 31. 171 pp.

Shepard, F.P. and Dill, R.F. 1966. Submarine Canyons and Other Sea Valleys. Rand McNally, Chicago. pp. 381.

Shepard, F.P. and Marshall, N.F. 1973a. Storm-generated currents in LaJolla submarine canyons, California. Mar. Geol. 15(1):M-19 - M-24.

Shepard, F.P. and Marshall, N.F. 1973b. Currents along floors of submarine canyons. Amer. Assoc. Petrol. Geol. Bull. 57:244-264.

Shepard, F.P., Marshall, N.F., and McLaughlin, P.A. 1974a. Internal waves advancing along submarine canyons. Science. 183:195-198.

Shepard, F.P., Marshall, N.F., and McLaughlin, P.A. 1974b. Currents in submarine canyons. Deep-Sea Res. 21:691-706.

Sherk, J.A., Jr. 1971. The effects of suspended and deposited sediments on estuarine organisms: literature summary and research needs. Chesapeake Biol. Lab., Solomons, Maryland, Contribution No. 443. 73 pp.

Sherk, J.A., O'Connor, J.M., Neumann, D.A., Prince, R.D., and Wood, K.V. 1974. Effects of suspended and deposited sediments on estuarine organisms. Phase II. NTIS Pub. No. AD-A011 372.

Shokes, R.F. 1976. Rate-dependent distributions of lead-210 and interstitial sulfate in sediments of the Mississippi River Delta, Tech. Rep. 76-1-T. Dept. of Oceanogr., Texas A&M Univ.

Shokes, R.F., Trabant, P., Presley, B.J., and Reid, D. (in press). An anoxic hypersaline basin in the northern Gulf of Mexico. Science.

Slotta, L.S., Sollitt, C,K., Bella, D.A., Hancock, D.H., McCauley, J.E., and Parr, R. 1973. Effects of hopper dredging and in channel spoiling (Oct. 4, 1972) in Coos Bay, Oregon. Oregon State Univ., Interdisciplinary Studies of the School of Engineering and the School of Oceanogr., July, 1973. 133 pp.

Smayda, T.J. 1969. Some measurements of the sinking rates of fecal pellets. Limnol. and Oceanogr. 14:621-626.

Smith, D.D. 1973. Marine disposal of selected solid wastes--major beneficial uses of ocean space. AIChE Symp. Ser. Vol. 68(122):132-136.

Smith, D.D. 1975. Disposal of dredged material--a key environmental consideration in the construction of major nearshore and coastal marine facilities. Petrol. Div. Amer. Soc. of Mech. Engineers Annual Meeting.

Smith, D.D. and Brown, R.P. 1971. Ocean disposal of barge-delivered liquid and solid wastes from U.S. coastal cities. U.S. Environmental Protection Agency, Solid Waste Manage. Off., Dillingham Corp., LaJolla, California. Pub. No. SW-19c. 119 pp.

Smith, D.D. and Graham, K.F. 1976. The effects of institutional constraints on dredging projects: San Diego Bay, a case history. pp. 119-141. In: Dredging: Environmental Effects and Technology. WODCON VII Proc., San Pedro, California.

Smith, L.L., Jr. and Moyle, J.B. 1944. A biological survey and fishery management plan for the streams of the Lake Superior North watershed. Minn. Dept. Conserv., Div. Game and Fish. Tech. Bull. 28 pp.

Sorokin, Y.I. 1971. Abundance and production of bacteria in the open water of the central Pacific. Oceanology. 10:796-807.

Southard, J.B. and Stanley, D.J. 1971. Shelf-break processes and sedimentation. pp. 351-377. In: D.J. Stanley and D.J.P. Swift (eds.) Marine Sediment Transport and Environmental Management. John Wiley & Sons, New York.

Spencer, E.W. 1962. Basic Concepts of Physical Geology. Thomas E. Cromwell Co., New York. 472 pp.

St. Amant, L.S. 1971. Impacts of oil on the Gulf coast. Trans. Wildl. Manage. Inst., Washington, D.C.

Stanley, D.J. and Silverberg, N. 1969. Recent slumping on the continental slope off Sable Island Bank, southeast Canada. Earth Planet Sci. Lett. 6:123-133.

Stanley, D.J., Fenner, P., and Kelling, G. 1972a. Currents and sediment transport at the Wilmington Canyon shelfbreak, as observed by underwater television. pp. 621-644. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey (eds.) Shelf Sediment Transport: Process and Pattern. Dowden, Hutchinson and Ross, Stroundsburg, Pennsylvania.

Stanley, D.J., Swift, D.J. P., Silverberg, N., James, N.P., and Sutton, R.G. 1972b. Later Quaternary progradation and sand spill over on the outer continental margin off Nova Scotia, Southeast Canada. Smithsonian Contrib. Earth Sci. 8:88 pp.

Sternberg, R.W., Creager, J.S., Glassley, W., and Johnson, J. 1976. An investigation of the hydraulic regime and physical nature of bottom sedimentation at the Columbia River dump site. DACW 57-75-C-0063. Draft Rep., Dept. of Oceanogr., Univ. of Washington to Corps of Engineers.

Stevenson, R.E. and Gorsline, D.S. 1956. A shoreward movement of cool subsurface water. Trans. Amer. Geophys. U. 57:553-557.

Stevenson, R.E., Uchupi, E., and Gorsline, D.S. 1959. Some characteristics of sediments on the mainland shelf off southern California. pp. 59-109. In: Allan Hancock Foundation (ed.) Oceanography survey of the continental shelf area of southern California. State Water Poll. Control Bd. Pub. No. 20. 560 pp.

Stickney, R.R. 1973. Effects of hydraulic dredging on estuarine animal studies. World Dredging Mar. Const. 34-37.

Stickney, R.R. and Perlmutter, D. 1975. Impact of intercoastal waterway maintenance dredging on a mud bottom benthic community. Biol. Conserv. 7:211.

Struhsaker, P. 1969. Demersal fish resources: Composition distribution and commercial potential of the continental shelf stocks off southeastern United States. Fish. Ind. Res. 4:261-300.

Subba Rao, D.V. 1973. Effects of environmental perturbations on short-term phytoplankton production off Lawson's Bay, a tropical coastal embayment. Hydrobiologia. 43:77-91.

Sverdrup, H., Johnson, M., and Fleming, R. 1942. The Oceans, Their Physics, Chemistry, and General Biology. Prentice-Hall, Englewood Cliffs, New Jersey. 1087 pp.

Sullivan, B. and Hancock, D.R. 1973. Zooplankton and dredging: Literature review and suggestions for research. Dept. Oceanogr. Oregon State Univ. Appendix G-1. pp. 199-211.

Tait, R.V. and DeSanto, R.S. 1972. Elements of Marine Ecology. Springer-Verlag, New York. 327 pp.

Taylor, J.L. and Saloman, C.H. 1968. Some effects of hydraulic dredging and coastal development in Boca Ciega Bay, Florida. U.S. Fish Wildl. Serv., Fish. Bull. 67(2):213-241.

TerEco Corporation. 1972. The hydrobiological zones of the western Gulf of Mexico. A report to Arthur D. Little Co., Cambridge, Mass. prepared by TerEco Corporation under contract #A10208. Dec. 1972.

TerEco Corporation. 1973. A bio-environmental study of the southern aspect of St. Croix, U.S. Virgin Islands. A report to Brown & Root, Inc. 7 Nov. 1973. College Station, Texas. 220 pp.

TerEco Corporation. 1974. A field monitoring study of the effects of organic chloride waste incineration on the marine environment in the northern Gulf of Mexico. Rep. for Shell Chemical Co., Houston. 32 pp. plus appendices.

Thiel, H. 1975. The size structure of the deep-sea benthos. Int. Revues. Hydrobiol. 60:576-606.

Thompson, J.R. 1973. Ecological effects of offshore dredging and beach nourishment: a review. Misc. Pap. No. 1-73. U.S. Army Corps of Engineers, Coastal Engineering Res. Center, Washington, D.C.

Thompson, J., Turekian, K.K. and McCaffrey, R.J. 1975. The accumulation of metals in the release from sediments of Long Island Sound. pp. 28-44. In: L.E. Cronin (ed.) Estuarine Research, Vol. 1, Academic Press, New York.

Thorson, G. 1950. Reproductive and larval ecology of marine bottom invertebrates. Biol. Rev. 25:1-45.

Thorson, G. 1957. Bottom communities (sublittoral or shallow shelf). pp. 461-534. In: J.W. Hedgpeth (ed.) Treatise on Marine Ecology and Paleoecology, Vol. 1, Geol. Soc. Amer, New York. Mem. 67.

Toth, S.J. and Ott, A.N. 1970. Characterization of bottom sediments: cation exchange capacity and exchangeable cation status. Environ. Sci. and Tech., Vol. 4, N. 11, Nov. pp. 935-939.

Towill Corporation. 1972. Environmental assessment of maintenance dredging operations. Rep. to U.S. Army Corps of Engineers, Pacific Ocean Div., Honolulu, Hawaii.

Trefry, J.H. and Presley, B.J. 1976a. Heavy metals in sediments from San Antonio Bay and the northwest Gulf of Mexico. Environ. Geol. 1:283-294.

Trefry, J.H. and Presley, B.J. 1976b. Heavy metal transport from the Mississippi River to the Gulf of Mexico. pp. 39-76. In: H.L. Windom and R.A. Duce (eds.) Marine Pollutant Transfer, D.C. Health.

Turner, J.S. 1960. A comparison between buoyant vortex rings and vortex paris. J. Fluid Mech. 7:419-432.

Uchupi, E. 1967a. Bathymetry of the Gulf of Mexico. Gulf Coast Assoc. Geol. Soc. Trans. 17:161-172.

Uchupi, E. 1967b. Slumping on the continental margin southeast of Long Island, New York. Deep-Sea Res. 14:635-639.

Uchupi, E. 1968. Atlantic continental shelf and slope of the United States - physiography. U.S. Geol. Surv. Prof. Pap. 529-C.

Uchupi, E. and Emery, K.O. 1963. The continental slope between San Francisco, California and Cedros Island, Mexico. Deep-Sea Res. 10:397-447.

U.S. Army Corps of Engineers. 1969. Dredging and water quality problems in the Great Lakes. Buffalo District, U.S. Army Corps of Engineers, Pilot Prog. Summ., Buffalo, New York. 16 pp.

U.S. Army Corps of Engineers. 1972. Appendix C. Climate, Meteorology and Hydrography. In: North Atlantic Regional Water Resources Study. U.S. Army Corps of Engineers-North Atlantic Div. 245 pp.

U.S. Army Corps of Engineers. 1973. Report on Gulf coast deep water port facilities: Texas, Louisiana, Mississippi, Alabama and Florida. Dept. of the Army Lower Mississippi Valley Division, Vicksburg, Miss. June 1973. 116 pp. plus appendices A-H.

U.S. Army Corps of Engineers. 1975. Dredge disposal study San Francisco Bay and estuary. Appendix L. Ocean Disposal of Dredged Material. U.S. Army Corps of Engineers-San Francisco Div. Sept. 53 pp.

U.S. Army Corps of Engineers. 1976. Third annual report. Environmental Effects Lab., Waterways Exper. Sta., Vicksburg, Miss. Jan. 77 pp.

U.S. Department of Commerce. 1975. United States Coast Pilot 2, Atlantic Coast, Eastport to Cape Cod. 10th Ed. NOAA National Ocean Surv., Washington, DC. 257 pp.

U.S. Department of Commerce. 1976a. United States Coast Pilot 1. Atlantic Coast, Eastport to Cape Cod. 13rd Ed. NOAA National Ocean Surv., Washington, D.C. 255 pp.

U.S. Department of Commerce. 1976b. United States Coast Pilot 3, Atlantic Coast, Sandy Hook to Cape Henry. 14th Ed. NOAA National Ocean Surv., Washington, D.C. 219 pp.

U.S. Department of Commerce. 1976c. United States Coast Pilot 4, Atlantic Coast, Cape Henry to Key West. 14th Ed. NOAA National Ocean Surv., Washington, D.C. 234 pp.

U.S. Department of Commerce. 1976d. United States Coast Pilot 5, Atlantic Coast, Gulf of Mexico, Puerto Rico, and Virgin Islands. 9th Ed. NOAA National Ocean Survey, Washington, D.C. 348 pp.

U.S. Department of Commerce. 1976e. United States Coast Pilot 7, Pacific Coast, California, Oregon, Washington, and Hawaii. 12th Ed. NOAA National Ocean Surv., Washington, D.C. 400 pp.

U.S. Department of Interior. 1970a. Effects on fish resources of dredging and spoil disposal in San Francisco and San Pablo Bays, California. U.S. Dept. Inter. Fish. Wildl. Serv., Spec. Rep. 36 pp.

U.S. Department of Interior. 1970b. National estuary study. Fish and Wildl. Ser. U.S. Govt. Print. Off., Washington, D.C.

U.S. Department of Interior. 1975. Draft environmental statement. Proposed 1976. Outer Continental Shelf Oil and Gas Lease Sale Offshore the Mid-Atlantic States. OCS Sale No. 40. Bureau of Land Management. 3 Vols.

U.S. Department of Interior. 1976. Final environmental impact statement, proposed 1976. Outer Continental Shelf Oil and Gas Lease Sale #44, Gulf of Mexico. Vol. 1. Bureau of Land Management, Dept. of Interior.

U.S. Department of Interior. 1977. Draft environmental impact statement, proposed 1977 outer continental shelf oil and gas lease sale #43, South Atlantic. Bureau of Land Management.

U.S. Environmental Protection Agency. 1976a. Ocean disposal in the U.S. - 1976. 4th annual report of the Environmental Protection Agency. 76 pp.

U.S. Environmental Protection Agency. 1976b. Preliminary report on Kepone levels found in human blood from the general population of Hopewell, Va. Health Effects Res. Lab., Res. Triangle Park, North Carolina. 16 pp.

U.S. Environmental Protection Agency. 1977. Ocean Dumping. Final Revision of Regulations and Criteria. Federal Register, Vol. 42, No. 7, Part VI, Jan. 11. pp. 2462-2590.

U.S. Navy Hydrographic Office. 1972. Environmental-acoustics atlas of the Caribbean Sea and Gulf of Mexico. Vol. II - Marine environment. AD-752-494. U.S. Naval Oceanogr. Off. Spec. Rep. 189, Washington, D.C. 190 pp.

U.S. Navy Weather Service Command. 1970. Summary of synoptic meterological observations, North American coastal marine areas. Vol. 2 and Vol. 7. 635 pp. each.

U.S. Tarrif Commission. 1962-1973. Synthetic organic chemicals: U.S. production and sales. 1961-1972. U.S. Govt. Print. Off., Washington, D.C.

VanEepoel, R.P. 1969. Effects of dredging in Water Bay, St. Thomas, Virgin Islands Dept. of Health, Water Poll. Rep. No. 2.

VanEepoel, R.D. and Griggs, D.I. 1970. Effects of dredging at Great Cruz Bay, St. John, Virgin Islands. Caribbean Res. Inst. Dept. of Health, Water Poll. Rep. No. 5.

Vaughan, T.W. 1916. Virgin and Leeward Islands. Washington Adac. Sci. J. VI(3):53-66.

Vinogradov, M.E. 1955. Vertikal'nye migratsii zooplanktona i ikh rol'v pitanii glubokovodnoi pelagicheskoi fauny (Vertical migrations of zooplankton and their role in the diets of deep-sea pelatic fauna.) Trudy IOAN SSSR, Vol. 13. Moskva, Izdatel' stvo. AN SSSR.

Voss, G., Opresko, L., and Thomas, R. 1973. The potentially commercial species of octopus and squid of Florida, the Gulf of Mexico and the Caribbean Sea. Sea Grant Field Guide Ser. No. 2, Univ. of Miami. 33 pp.

Wakeman, T.H. 1974. Release of trace constituents from sediments resuspended during dredging operations. U.S. Army Corps of Engineers, San Francisco. Amer. Chem. Soc. Conf. 9 pp.

Wakeman, T.H. 1976. The Biological Ramifications of Dredging and Disposal Activities. pp. 53-68. In: Dredging: Environmental Effects & Technology. WODCON VII Proc., San Pedro, California.

Wakeman, T.H. and Fong, C.C. 1975. Biological impacts of dredged material disposal on the San Francisco Bay. Offshore Tech. Conf. 7th Annual: Proc. Vol. 2. pp. 133-141.

Waldron, K.D. 1963. Synopsis of biological data on Skipjack Katsuwonus pelamis. (Linnaeus) 1758 (Pacific Ocean). F.A.O. Fish Rep. 2(6).

Walford, L.A. 1938. Effects of currents on distribution and survival of the eggs and larvae of the haddock (Melanogrammus aeglefinus) on Georges Bank. U.S. Bur. Fish. Bull., Vol. 49. pp. 1-73.

Wallen, I.E. 1951. The direct effect of turbidity on fishes. Bull. Okla. Agr. Mech. Coll., Biol. Ser. 48(2):27 pp.

Wenk, E., Jr. 1969. The physical resources of the ocean. pp. 83-91. In: The Ocean. W.H. Freeman and Co., San Francisco.

Weidenroth, W. 1968. An examination of the problems associated with the transportation of sand-water-mixtures in pipelines and centrifugal pumps. In: Proceedings World Dredging Conference, WODCON II. Rotterdam, The Netherlands.

Weikert, H. 1972. Verteilung and tagesperiodik des evertebratenneriston im subtropischen nordostatlantik wahrend der "Atlantischen Kuppenfahrten 1967" von S.S. METEOR. METEOR Forsch. Erg. 11:30-87.

Whitehouse, N.G., Jeffrey, L.M., and Debrecht, J.D. 1960. Differential settling tendencies of clay minerals in saline waters. pp. 1-79. In: A. Swineford (ed.) Clay and Clay Minerals. Pergamon Press, Oxford.

Wieser, W. 1959. The effects of grain size on the distribution of small invertebrates inhabiting the beaches of Puget Sound. Limnol. and Oceanogr. 4(2):181-194.

Wigley, R. 1968. Benthic invertebrates of the New England fishing banks. Underwater Natur. 5:8-13.

Wigley, R. and McIntyre, A.D. 1964. Some quantitative comparisons of offshore meiobenthos and macrobenthos south of Martha's Vineyard. Limnol. and Oceanogr. 9:485-493.

Wilkins, W.D. and Persuad, D. 1976. Open water material disposal monitored. World Dredging. Aug.

Wilson, W. 1950. The effects of sedimentation due to dredging operations on oysters in Copano Bay, Texas. Annual Rep., Mar. Lab. Texas Game, Fish & Oyster Comm. 1948-49.

Windom, H.L. 1972. Environmental aspects of dredging in estuaries. J. Waterways, Harbors & Coastal Engineering Div., ASCE, New York. 98:475-487.

Windom, H.L. 1973. Processes responsible for water quality changes during pipeline dredging in marine environments. pp. 761-806. In: Proc. World Dredg. Conf. V., WODCON Assoc.

Windom, H.L. 1975. Water-quality aspects of dredging and dredge-spoil disposal in estuarine environments. pp. 559-571. In: L.E. Cronin (ed.) Estuarine Research, Vol. 2, Academic Press, New York.

Windom, H.L. 1976a. Environmental aspects of dredging in the coastal zone. CRC Critical Rev. in Environ. Control. 6(2):91-109.

Windom, H.L. 1976b. Geochemical interactions of heavy metals in southeastern salt marsh environments. Ecol. Res. Ser., EPA 600/3-76-023.

Windom, H.L., Stickney, R.R., and Dunstan, W.M. 1974. Research to determine the environmental response to the deposition of spoil on salt marshes using diked and undiked techniques. NTIS Rep. AD-A010 410.

Wollast, R. and de Broeu, F. 1971. Study of dissolved silica in the estuary of the Scheldt. Geochim. Cosmochim. Acta. 35:613-620.

Wright, F.F. 1970. An oceanographic reconnaissance of the waters around Kodiak Island, Alaska. Inst. of Mar. Sci. Univ. of Alaska. Rep. No. R70-19:21 pp.

Wright, W.R. 1976. The limits of shelf water south of Cape Cod. J. Mar. Res. 34(1):1-14.

Wright, W.R. and Worthington, L.V. 1970. The water masses of the North Atlantic Ocean: A volumetric census of temperature and salinity. Serial atlas of the marine environment folio 19. Amer. Geogr. Soc.

Wright, W.R. and Parker, C.E. 1976. A volumetric temperature/salinity census for the Middle Atlantic Bight. Limnol. and Oceanogr. 21: 563-571.

Wust, G. 1964. Stratification and circulation in the Antillean - Caribbean basin. Part 1: Spreading and mixing of the water types. Columbia Univ. Press, New York. 201 pp.

Wyllie, J.G. 1966. Geostrophic flow of the California current at the surface and at 200 meters. CALCOF, Atlas No. 4. 288 pp.

Wyrtki, K. 1975. Fluctuations of the dynamic topography in the Pacific Ocean. J. Phys. Oceanogr. 5:450-459.

Yamamoto, S. and Alcauskas, J.B. 1975. Ocean disposal of dredged material. Appendix L, Incl. Two. In: Dredge Disposal Study, San Francisco Bay and Estuary. U.S. Army Engineer District, San Francisco. 43 pp.

Young, D. and Jon, T. 1976. Metals in scallops. In:1976 Annual Report of the Southern California Coastal Water Research Project. SCCWRP, El Seguro, California.

Zaitsev, V.P. 1970. Marine neustonology. K.A. Vinogradov (ed.) (Trans. by Israel Prog. for Sci. Trans.), Jerusalem, 1971. 264 pp.

Zandi, I. and Govatos, G. 1967. Heterogeneous flow of solids in pipelines. J. Hydraulics Div., ASCE HY3, May. pp. 145-159.

Zharov, V.L. and Torin, Yu.A. 1964. Biologiya i raspredelenie zheltoperovo tuntsa (*Neothunnus albacora* Lowe) v tropicheskoi chasti atlanticheskogo okeana. (Biology and distribution of yellowfin tuna, *Neothunnus albacora* Lowe, in the tropical Atlantic). Trudy Atlanticheskogo Nauchno Issledovate'skogo Instituta Rybnogo Khozyaistva i Okeanograffii, No. 11.

BIBLIOGRAPHY

Adams, J.K. and Buchwald, V.T. 1969. The generation of continental shelf waves. J. Fluid Mech. 35:815-826.

Aleem, A.A. 1972. Effect of river outflow on management of marine life. Mar. Biol. 15:200-208.

Allen, J.S. 1973. Upwelling and coastal jets in a continuously stratified ocean. J. Phys. Oceanogr. 3(3):245-257.

Allen, J.S. 1975. Coastal trapped waves in a stratified ocean. J. Phys. Oceanogr. 5(2):300-325.

Anderlini, V.C., Chapman, J.W., Girvin, D.C., McCormick, S.J., Newton, A.S., and Risebrough, R.W. 1975. Heavy metal uptake study. Appendix H, pollutant uptake. In: Dredge Disposal Study, San Francisco Bay and Estuary. U.S. Army Engineer District, San Francisco.

Anderson, D. and Gill, A.E. 1975. Spin-up of a stratified ocean, with applications to upwelling. Deep-Sea Res. 22(9):583-596.

Anonymous. 1961. Climatological and Oceanographic Atlas for Mariners. Volume II. North Pacific Ocean. Office of Climatology and Oceanographic Analysis Division.

Anonymous. 1971. Sea bottom explorations off N.J. coast could affect ocean dumping. Commerce Today. 11(5):30.

Anonymous. 1973. Ocean canyon studies provide basis for new waste dumping tasks. Commerce Today. Jan. 22. 3(8):12.

Apel, J.R., Proni, J.R., Byrne, H.M., and Sellers, R.L. 1975. Near-simultaneous observations of intermittent internal waves on the continental shelf from ship and spacecraft. Geophys. Res. Letters. 2(4):128-131.

Arlt, G. 1975. Remarks on indicator organisms (meiofauna) in the coastal waters of the GDR. Merentutkimuslait, Julk. (239):272-279.

Arnal, R.E. 1972. A short survey of the environment at the dumping site for Santa Cruz Harbor dredging. Moss Landing Marine Lab., Tech. Publ. No. 72-6. 20 pp.

BIBLIOGRAPHY (Continued)

Baines, P.G. 1974. The generation of internal tides over steep continental slopes. Phil. Trans. Roy. Soc. London, Ser. A. 277:27-58.

Bakus, G.J. 1968. Sedimentation and benthic invertebrates of Fanning Island, Central Pacific. Mar. Geol. 6:45-51.

Bane, G.W. 1965. Results of drift bottle studies near Puerto Rico. Carib. J. Sci. 5:173-174.

Barnard, J.L. 1958. Amphipod crustaceans as fouling organisms in Los Angeles-Long Beach Harbors with reference to the influence of seawater turbidity. Calif. Fish and Game. 44(2):161-170.

Barnard, J.L. and Reish, D.J. 1959. Ecology of Amphipoda and Polychaeta of Newport Bay. Calif. Allan Hancock Found. Occas. Paper No. 21.

Barnes, C.A. and Paquette, R.G. 1954. Circulation near the Washington coast. Dept. of Oceanogr., Univ. of Washington, Tech. Rep. No. 17.

Barrett, J.R. 1965. Subsurface currents off Cape Hatteras. Deep-Sea Res. 12:173-184.

Basco, D.R., Bouma, A.H., and Dunlap, W.A. 1974. Assessment of the factors controlling the long term fate of dredged material deposited in unconfined subaqueous disposal areas. Dredged Material Research Program, U.S. Army Engineer Waterways Experiment Station, Contract Rep. D-74-8.

Bastian, D.F. 1975. Effects of open-water disposal of dredged material on bottom topography along Texas Gulf coast. NTIS Rep. AD-A002 659.

Baughman, G.L., Gordon, J.A., Wolfe, N.L. and Zepp, R.G. 1973. Chemistry of organomercurials in aquatic systems. EPA Ecol. Res. Ser., EPA-660/3-73-012 (Sept. 1973). 97 pp.

Beardsley, R.C. and Butman. B. 1974. Circulation on New England continental shelves: response to strong winter storms. Geophys. Res. Letters. 1(4):181-184.

Beardsley, R.C. and Flagg, C.N. 1976. The water structure, mean currents, and shelf water/slope water front on the New England continental shelf. Proc. 1975 Liege Colloquium on Hydrodynamics, Univ. of Liege, Belgium.

Berg, R.H. 1970. The oxygen uptake demand of resuspended bottom sediments. Water Poll. Control Res. Ser., EPA 16070 DCD, Sent. 1970.

Birchfield, G.E. 1972. Theoretical aspects of wind-driven currents in the sea or lake of variable depth with no horizontal mixing. J. Phys. Oceanogr. 2(4):355-366.

Birchfield, G.E. 1973. An Ekman model of coastal currents in a lake or shallow sea. J. Phys. Oceanogr. 3(4):419-428.

Bireley, L.E. and Buck, J.D. 1975. Microbiology of a former dredge spoil disposal area. Mar. Poll. Bull. 6(7):107-110.

Blanton, J. 1971. Exchange of Gulf stream water with North Carolina shelf water in Onslow Bay during stratified conditions. Deep-Sea Res. 18(2):167-178.

Blumer, M., Hunt, J.M., Atema, J., and Stein, L. 1973. Interaction between marine organisms and oil pollution. Off. of Res. and Monitoring. EPA-R3-73-042.

Blumsack, S.L. 1972. The transverse circulation near a coast. J. Phys. Oceanogr. 2(1):34-40.

Boehmer, R., Westneat, A., and Cook, D. 1975. Effects of suspended marine sediments on selected commercially-valuable fish and shellfish of Massachusetts. Offshore Tech. Conf., 7th Annual, Proc. Vol. 1:133-141.

Bourke, R.H. and Pattullo, J.G. 1974. Seasonal variation of the water mass along the Oregon-northern California coast. Limmol. and Oceanogr. 19(2):190-198.

Bowan, M.J. and Weyl, P.K. 1972. Hydrographic study of the shelf and slope waters of New York Bight. New York State Univ., Mar. Sci. Res. Ctr., Tech. Rep. Ser. No. 16. 49 pp.

Bowden, K.F. 1965. Horizontal mixing in the sea due to a shearing current. J. Fluid Mech. 21(2):83-95.

Bowen, V.T., Olsen, J.S., Osterberg, C.L., and Ravera, J. 1971. Ecological interactions of marine radioactivity. pp. 200-222. In: Radioactivity in the Marine Environment, Rep. of Panel on Radioactivity in the Marine Environment, Comm. on Oceanogr. Nat., Res. Council, Nat. Acad. of Sci.

Breuer, J.P. 1962. An ecological survey of the lower Laguna Madre of Texas, 1953-1959. Publ. Inst. Mar. Sci., Univ. Tex. 8:153-185.

BIBLIOGRAPHY (Continued)

Brooks, D.A. 1975. Wind-forced continental shelf waves in the Florida current. Univ. of Miami. Tech. Rep. No. 75026.

Brooks, I.H. and Niiler, P.P. 1975. The Florida current at Key West: Summer 1972. J. Mar. Res. 33(1):83-92.

Brower, W.A., Sisk, D.D., and Quayle, R.G. 1972. Environmental guide for seven U.S. ports and harbor approaches. NOAA Environmental Data Service, Nat. Climatic Ctr., Ashville, N.C. 166 pp.

Buck, D.H. 1957. Effects of turbidity on fish and fishing. Trans. of the N. Amer. Wildl. Conf. 21:249-261

Buelow, R.W. 1968. Ocean disposal of waste material. Trans. of the National Symposium on Ocean Sciences and Engineering of the Atlantic Shelf. pp. 311-337.

Bumpus, D.F. 1955. Circulation over the continental shelf south of Cape Hatteras. Trans. Amer. Geophys. U. 36(4):601-611.

Bumpus, D.F. 1960. Sources of water contributed to the Bay of Fundy by surface circulation. J. Fish. Res. Bd., Can. 17(2):181-197.

Bumpus, D.F. 1965. Residual drift along the bottom on the continental shelf in the middle Atlantic Bight area. Limnol. and Oceanogr. No. 10, Suppl. 2:R50-R53.

Bumpus, D.F. 1973. Physical oceanography: continental shelf. Coastal and Offshore Environmental Inventory, Cape Hatteras to Nantucket Shoals, Mar. Publ. Ser. No. 2., Univ. of Rhode Island. 1-1 - 1-33.

Bumpus, D.F. and Lauzier, L.M. 1965. Surface circulation on the continental shelf off eastern North America between Newfoundland and Florida. In: Serial Atlas of the Marine Environment, Folio 7, Amer. Geogr. Soc., New York.

Bybee, J.R. 1969. Effects of hydraulic pumping operations on the fauna of Tijuana Slough. Calif. Fish and Game. 55(3):213-220.

Cairns, J., Jr. 1968. Suspended solids standards for the protection of aquatic organisms. Proc. 22nd Ind. Waste Conf. Purdue Univ. Engineering Bull. 129(1):16-27.

Cannon, G.A. 1972. Wind effects on currents observed in Juan de Fuca submarine canyon. J. Phys. Oceanogr. 2:281-285.

Cannon, G.A., Laird, N.P., and Ryan, T. 1972. Currents observed in Juan de Fuca submarine canyon and vicinity. Tech. Rep. ERL 252-POL 14, NOAA.

Cannon, G.A., Laird, N.P., and Ryan, T.V. 1975. Flow along the continental slope off Washington, Autumn 1971. J. Mar. Res. 33 suppl. pp. 97-107.

Carmody, D.J. 1973. Trace metals in sediments of the New York Bight. Mar. Poll. Bull. 4(9):132-135.

Carricker, M.R. 1967. Ecology of estuarine benthic invertebrates: a perspective. pp. 442-487. In: G.H. Lauff (ed.) Estuaries. Amer. Assoc. Adv. Sci. Publ. No. 83. Washington, DC.

Carrit, D.E. and Goodgal, S. 1954. Sorption reactions and some ecological implications. Deep-Sea Res. 1:224-243.

Chambers, G.V. and Sparks, A.K. 1959. An ecological survey of the Houston ship channel and adjacent bays. Publ. Inst. of Mar. Sci. Univ. of Tex. 6:213-250.

Chapman, C.R. 1968. Channelization and spoiling in Gulf Coast and South Atlantic estuaries. pp. 93-106. In: J.S. Newsom (ed.) Proc. of the Marsh and Estuary Management Symposium. T.J. Moran's Sons, Inc., Baton Rouge, La.

Chase, J. 1954. A comparison of certain north Atlantic wind, tide gauge and current data. J. Mar. Res. 13(1):22-31.

Cheng, T.C. 1970. Hartmanella tahitiensis sp. n., an amoeba associated with mass mortalities of the oyster Crassostrea commercialis in Tahiti, French Polynesia. J. Invert. Pathol.

Chew, F. 1955. On the offshore circulation and convergence mechanism in the red tide region off the west coast of Florida. Trans. Amer. Geophys. U. 36:963-974.

Chew, F. and Berberian, G.A. 1970. Some measurements of current by shallow drogues in the Florida current. Limnol. and Oceanogr. 15(1):88-99.

Chiba, K. and Ohshima, Y. 1957. Effect of suspending particles on the pumping and feeding of marine bivalves, especially of Japanese neck-clam. Bull. Jap. Soc. of Sci. Fish. 23:348-359.

Chutter, F.M. 1969. Effects of silt and sand on the invertebrate fauna of streams and rivers. Hydrobiologia. 34:57-76.

BIBLIOGRAPHY (Continued)

Coachman, L.K. and Aegaard, K. 1966. On the exchange through Bering Strait. Limnol. and Oceanogr. 11:44-59.

Coachman, L.K. and Aagaard, K. 1974. Physical oceanography of Arctic and sub-Arctic Seas. pp. 1-72. In: H. Nelson and Y. Herman (eds.) Arctic Geology and Oceanography. Springer-Verlag, New York.

Cobb, P.A. 1972. Effects of suspended solids on larval survival of the eastern lobster, Homarus americanus. 8th Annual Conf. and Expo. Mar. Tech. Soc. 11(13):395-402.

Cobbs, J.S. 1968. Delay of moult by the larvae of Homarus americanus. J. Fish. Res. Bd. Can. 25(10):2251-2253.

Cochran, J.K. and Osmond, J.K. 1976. Sedimentation patterns and accumulation rates in the Tasman Basin. Deep-Sea Res. 23:193-210.

Cole, H.A. 1973. Implications of disposal of wastes to the North Sea. Chem. and Ind. 1973:162.

Collier, A. and Hedgpeth, J. 1950. An introduction to the hydrography of tidal waters of Texas. Univ. of Tex. Inst. of Mar. Sci. 1(2):121-194.

Collins, C.A., Mooers, C.N.K., Stevenson, M.R., Smith, R.L., and Pattullo, J.G. 1968. Direct current measurements in the frontal zone of a coastal upwelling region. J. Oceanogr. Soc. of Jap. 24:295-306.

Collins, C.A. and Pattullo, J.G. 1970. Ocean currents above the continental shelf off Oregon as measured with a single array of current meters. J. Mar. Res. 28(1):51-68.

Colton, J.B. 1968a. Recent trends in subsurface temperature in the Gulf of Maine and contiguous waters. J. Fish. Res. Bd. Can. 25(11):2423-2737.

Colton, J.B. 1968b. Temperature conditions in the Gulf of Maine and adjacent waters during 1968. J. Fish. Res. Bd. Can. 26(10): 2746-2751.

Copeland, B.J. 1970. Estuarine classification and responses to disturbances. Trans. Amer. Fish. Soc. 99:826-835.

BIBLIOGRAPHY (Continued)

Copeland, B.J. and Dickens, F. 1974. Systems resulting from dredging spoil. pp. 151-167. In: Odum, B.J. Copeland, H.T., and E.A. McMahan (eds.) Coastal Ecological Systems of the United States, Vol. 3. Conserv. Found., Washington, D.C.

Cordone, A.J. and Kelley, D.W. 1961. The influences of inorganic sediment on the aquatic life of streams. Calif. Fish and Game. 47(2):189.

Corliss, J. and Trent, L. 1971. Comparison of phytoplankton production between natural and altered areas in West Bay, Texas. Fish. Bull. 69:829-832.

Cottam, C. 1968. Research needs in estuarine areas of the Gulf Coast. pp. 227-240. In: J.D. Newson (ed.) Marsh and Estuary Management Symposium, Proc. T.J. Moran's Sons, Inc., Baton Rouge, La.

Courtenay, W.R., Harrema, D.J., Thompson, M.J., Azzinaio, W.P., and Monthans, J.V. 1974. Ecological monitoring of beach erosion control projects, Broward County, Florida and adjacent areas. Tech. Mem. CERC-TM-41., Florida Atlantic Univ. Boca Raton, Fl. 88 pp.

Cresswell, G.H. 1967. Quasi-synoptic monthly hydrography of the transition region between coastal and slope water south of Cape Cod, Massachusetts. Woods Hole Oceanogr. Inst., Rep. 67-35.

Cronin, L.E. 1969. Biological aspects of coastal waste disposal; background paper for coastal waste disposal workshop. Nat. Resour. Inst., Univ. of Maryland, Ref. No. 69-99. 36 pp.

Csanady, G.T. 1973. Wind-induced baroclinic motions at the edge of the continental shelf. J. Phys. Oceanogr. 3(3):274-279.

Csanady, G.T. 1974. Barotropic currents over the continental shelf. J. Phys. Oceanogr. 4(3):357-371.

Cutchin, D. and Smith, R.L. 1973. Continental shelf waves: low-frequency variation in sea level and currents over the Oregon continental shelf. J. Phys. Oceanogr. 3(1):73-82.

Dale, N.G. 1974. Bacteria in intertidal sediments: Factors related to their distribution. Limnol. and Oceanogr. 19(3):509-518.

Dallaire, E.E. 1971. Ocean dumping: what and where, if at all. Civil Engineering. ASCE 41(11):58-62.

Davenport, S. 1972. How to defile the deep blue sea. New York Times, Nov. 26. Sec. 4:4.

Davis, H.C. 1960. Effects of turbidity producing materials in sea water on eggs and larvae of the clam (Venus (Mercenaria) mercenaria). Biol. Bull. 118(1):48-54.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Bd. Can. 32(12):2295-2332.

De Clerk, R., Van De Veld, J., and Vyncke, W. 1973. On the effects of dumped organic industrial waste deriving from the production of proteolytic enzymes on density, distribution, and quality of fish and shrimps. Ministry of Agri., Belgium, Aquaculture. 2(4):323.

DeCoursey, P.J. and Vernberg, W.B. 1975. The effects of dredging in a polluted estuary on the physiology of larval zooplankton. Water Res. 9(2):149.

Deep-sea mining, ecological disturbance. Environ. Rep., Feb. 24, 1975. pp. 160.

Delisi, D.P. and Orlanski, I. 1975. On the role of density jumps in the reflexion and breaking of internal gravity waves. J. Fluid. Mech. 69(3):445-464.

de Sylva, D.P. and Scotton, L.N. 1972. Larvae of deep-sea fishes (Stomiatoidea) from Biscayne Bay, Florida, U.S.A., and their ecological significance. Mar. Biol. 12(2):122.

Dethlefsen, V. 1973. Problems with dumping of red mud in shallow waters. A critical review of selected literature. Aquaculture. 2(3):267-380.

Dickson, R.R. 1975. A review of current European research into effects of offshore mining on the fisheries. Offshore Tech. Conf., 7th annual, Proc., Vol. 1. pp. 103-117.

Dodge, R.E., Aller, R.C., and Thomson, J. 1974. Coral growth related to resuspension of bottom sediments. Nature. 247:574-576.

Dodimead, A.J., Favorite, F., and Hirano, T. 1963. Review of oceanography of the subarctic Pacific region. Intern. N. Pacific Fish. Bull. 13:195.

BIBLIOGRAPHY (Continued)

Dressel, D.M. 1971. The effects of thermal shock and chlorine on the estuarine copepod Acartia tonsa. M. Sc. Thesis, Univ. Virginia, Charlottesville, Va. 57 pp.

Drifmeyer, J.E. 1975. Lead, zinc, and manganese in dredge-spoil pond ecosystems. Environ. Conserv. 2(1):39.

Duce, R.A., Parker, P.L., and Giam, C.S. 1974. Pollutant transfer to the marine environment. NSF/IDOE Pollutant Transfer Workshop, Jan. 1974. 55 pp.

Düing, W.O. 1973. Some evidence for long period barotropic waves in the Florida current. J. Phys. Oceanogr. 3(3):343-346.

Düing, W. 1974. Synoptic studies of transients in the Florida current. Proc. McArthur Workshop on Feasibility of Extracting Useable Energy from the Florida Current, Palm Beach Shores, Florida, Feb. 27 - March 1.

Düing, W.O. and Johnson, D.R. 1972. High resolution current profiling in the straits of Florida. Deep-Sea Res. 19:259-274.

Düing, W.O. and Johnson, D. 1975. Southward flow under the Florida current. Science. 173:428-430.

Duursma, E.K. and Gross, M.G. 1971. Marine sediments and radioactivity. pp. 147-160. In: Radioactivity in the Marine Environment, Rep. of Panel on Radioactivity in the Marine Environment, Comm. on Oceanogr., Nat. Res. Council, Nat. Acad. Sci. 272 pp.

Duursma, E.K. and Marchand, M. 1974. Aspects of organic marine pollution. Oceanogr. Mar. Biol.: Ann. Rev. 12:315-431.

Ellis, M.M. 1936. Erosion silt as a factor in aquatic environment Ecology. 17:29-42.

Elmgren, R. 1975. Benthic meiofauna as indicator of oxygen conditions in the northern Baltic proper. Merentutkimuslait. Julk. (239):265-271.

Ewing, M. and Thorndike, E.M. 1965. Suspended matter in deep ocean water. Science. 147(3663):1291-1294.

Fan, L.N. and Brooks, N.H. 1967. Turbulent buoyant jet into stratified or flowing ambient fluids. W.M. Keck Lab. of Hydraulics and Water Resources, Rep. KH/R/15, Pasadena, California Inst. of Tech.

BIBLIOGRAPHY (Continued)

Filice, F.P. 1959. The effects of wastes on the distribution of bottom invertebrates in the San Francisco Bay estuary. Wassmann J. Biol. 17(1):1-11.

First, M.W. 1969. Waste incineration at sea and ocean disposal of non-floating residues. 62nd Annual Meet. Air Poll. Control Assoc., New York, 8-12 June 1969. Pap. No. 69-33.

Fisher, A., Jr. 1972. Entrainment of shelf water by the Gulf stream northeast of Cape Hatteras. J. Geophys. Res. 77(18):3248-3255.

Fitzgerald, W.F., Kaltenback, A.J., and Lyons, W.B. 1972. Heavy metals in interstitial waters of dredge spoil material: recommended sampler and experimental procedure. Rep. to New England Div. U.S. Army Corp. of Engineers, Dept. of Geol. and Mar. Sci. Inst., Univ. of Connecticut, Groton, Conn.

Fleming, R.H. and Heggarty, D. 1962. Recovery of drift bottles released in the southeastern Chukchi Sea and northern Bering Sea. Dept. of Oceanogr., Univ. of Washington, Tech. Rep. No. 70.

Ford, W.L. and Miller, A.R. 1952. The surface layer of the Gulf stream and adjacent waters. J. Mar. Res. 11(3):267-280.

Forristal, G.Z. 1974. Three dimensional structure of storm generated currents. J. Geophys. Res. 79(18):2721-2729.

Fuglister, F.C. 1951. Annual variations in current speeds in the Gulf Stream system. J. Mar. Res. 10:119-127.

Gannon, J.E. and Beeton, A.M. 1971. Procedures for determining the effects of dredged sediments on biota-benthos viability and sediment selectivity tests. J. Water Poll. Control Fed. 43:392-398.

Garrett, C. 1972. Tidal resonance in the Bay of Fundy and Gulf of Maine. Nature. 238(5365):441-443.

Garrison, G.R. and Becker, P. 1976. The Barrow submarine canyon: a drain for the Chukchi Sea. J. Geophys. Res. 81(24):4445-4453.

Garvine, R.W. 1971. A simple model of coastal upwelling dynamics. J. Phys. Oceanogr. 1(3):169-179.

Gaul, R.D. 1967. Circulation over the continental margin of the northeast Gulf of Mexico. Ph.D. Dissertation, Texas A&M Univ. Jan. 1967. 156 pp.

BIBLIOGRAPHY (Continued)

Gaul, R.D. and Boykin, R.E. 1964. Northeast Gulf of Mexico hydrographic survey data collected in 1963. Dept. of Oceanogr., Texas A&M Univ. Ref. 64-26 T.

Gaul, R.D. and Boykin, R.E. 1965. Northeast Gulf of Mexico hydrographic survey data collected in 1964. Dept. of Oceanogr., Texas A&M Univ. Ref. 65-8 T.

Gaul, R.D., Boykin, R.E., and Letzring, D.E. 1966. Northeast Gulf of Mexico hydrographic survey data collected in 1965. Dept. of Oceanogr., Texas A&M Univ. Ref. 66-26 T.

Gerba, C.P. 1975. Effects of particulates on virus survival in seawater. J. Water Poll. Control Fed. 47(1):93-103.

Giese, G.S. 1971. Physical measurements of the coastal water south of western Puerto Rico. Symposium on Investigations and Resources of the Caribbean Sea and adjacent regions, Willemstad, Curacao, 18-26 November 1968. UNESCO. pp. 89-90.

Gifford, F. 1959. Statistical properties of a fluctuating plume dispersion model. Advance. in Geophys. 6:117-137.

Giles, J.H. and Zamora, G. 1973. Cover as a factor in habitat selection by juvenile brown (<u>penaeus aztecus</u>) and white (<u>P. setiferus</u>) shrimp. Trans. Amer. Fish. Soc. 102(1):144-145.

Gill, A.E. and Clarke, A.J. 1974. Wind-induced upwelling, coastal currents and sea-level changes. Deep-Sea Res. 21(5):325-345.

Gill, A.E. and Schumann, E.H. 1974. The generation of long shelf waves by the wind. J. Phys. Oceanogr. 4(1):83-90.

Ginsburg, R.N. and Lowenstam, H.A. 1958. The influence of marine bottom communities on the depositional environment of sediments. J. Geol. 66:310.

Glude, J.B. and Landers, W.D. 1953. Biological effects on hard clams of hand raking and power dredging. Spec. Sci. Rep. 110. U.S. Fish. and Wildl. Serv.

Gopalan, U.K. and Young, J.S. 1975. Incidence of shell disease in shrimp in the New York Bight. Mar. Poll. Bull. 6:149-152.

Gordon, A. 1967. Circulation of the Caribbean Sea. J. Geophys. Res. 72(24):6207-6224.

BIBLIOGRAPHY (Continued)

Gotthardt, G.A. 1973. Observed formation of a Gulf Stream anticyclonic eddy. J. Phys. Oceanogr. 3(2):237-238.

Gotthardt, G.A. and Potocsky, G.J. 1974. Life cycle of a Gulf Stream anticyclonic eddy observed from several oceanographic platforms. J. Phys. Oceanogr. 4(1):131-134.

Graus, R.R. and MacIntyre, I.G. 1976. Light control of growth form in colonial reef corals: computer simulation. Science. 193:895-897.

Greenspan, H.P. 1956. The generation of edge waves by moving pressure distributions. J. Fluid Mech. 1(6):574-592.

Grigg, D.I. 1970. Some effects of dredging on water quality and coral reef ecology. Carib. Conserv. Assoc. Environ. Newsletter. 1(2):7.

Gross, M.G., Morse, B., and Barnes, C.A. 1969. Movement of near-bottom waters on the continental shelf off the northwestern United States. J. Geophys. Res. 74(28):7044-7047.

Gunter, G. 1957. How does siltation affect fish production? Nat. Fisherman. 38(3):18-19.

Gunter, G., Mackin, J.G., and Ingle, R.M. 1964. A report to the district engineer on the effect of the disposal of spoil from the inland waterway, Chesapeake and Delaware Canal, in Upper Chesapeake Bay. U.S. Army Corps of Engineers Off., Philadelphia, Pa. 51 pp.

Gustafson, C.G. 1970. PCB's-prevalent and persistent. Environ. Sci. Tech. 4(10):814-819.

Gustafson, J.F. 1972. Beneficial effects of dredging turbidity. World Dredging and Mar. Constr. 8(13):44-45, 47-48, 50-52.

Haight, F.J. 1942. Coastal currents along the Atlantic coast of the United States. Spec. Pub. U.S. Coast and Geodetic Surv. 230:73 pp.

Halcrow, W., Mackay, O.W., and Bogan, J. 1974. PCB levels in Clyde marine sediments and fauna. Mar. Poll. Bull. 5:134.

Halpern, D. 1974. Variations in the density field during coastal upwelling. Tethys. 6(1-2):363-374.

BIBLIOGRAPHY (Continued)

Halpern, D. 1976. Structure of a coastal upwelling event observed off Oregon during July 1973. Deep-Sea Res. 23(6):495-508.

Hann, R.W., Jr., Zapatka, T.F., Zapatka, M.C., and Baskin, C. 1976. History of ocean dumping in the Gulf of Mexico. Civil Engineering Dept. Texas A&M Univ., College Station, TX. 87 pp.

Hansen, R.S. 1971. Great Lakes dredging--problems and remedies. World Dredging and Mar. Constr. 7:16-20.

Hara, T.J., Law, Y.M.C., and MacDonald, S. 1976. Effects of mercury and copper on the olfactory responses in rainbow trout, Salmo gairdneri. J. Fish. Res. Bd. Can. 33(7):1568-1573.

Harker, A. 1973. Design criteria for effective dredge spoil disposal sites. IAPC Conf., Washington, DC, June 5-7. pp. 227.

Harris, J.E. 1972. Characterization of suspended matter in the Gulf of Mexico - I. Spatial distribution of suspended matter. Deep-Sea Res. 19:712-726.

Harrison, W., Lynch, M.P., and Altschaeffl, A.G. 1964. Sediments of lower Chesapeake Bay with emphasis on mass properties. J. Sediment. Petrol. 34(4):727-755.

Harrison, W., Norcross, J.J., Pore, N.A., and Stanley, E.M. 1967. Circulation of shelf waters off the Chesapeake Bight, surface and bottom drift of continental waters between Cape Henlopen, Delaware and Cape Hatteras, North Carolina. U.S. Environ. Sci. Serv. Admin., ESSA Prof. Pap. (3): 86 pp.

Hatai, S. 1956. Results of coral studies at the Palao tropical biological station. Proc. 6th Pacific Sci. Congress. pp. 599-603.

Heezen, B.C., Ewing, M., and Menzies, R.J. 1955. The influence of submarine turbidity currents on abyssal productivity. Oikos. 6(II):170-182.

Heimstra, N.W. and Damkot, D.K. 1972. Some effects of silt turbidity on behavior of juvenile large mouth bass and green sunfish. Tech. Pap. of Bureau of Sport Fish. and Wildlife. No. 20.

Hela, I., de Sylva, D., and Carpenter, C.A. 1955. Drift currents in the red tide area of the eastern-most region of the Gulf of Mexico. Rep. to Florida Bd. of Conserv., Univ. of Miami Mar. Lab. 55(11): 31 pp.

BIBLIOGRAPHY (Continued)

Helfrich, P. and Kohn, A.J. 1955. A survey to estimate the major biological effects of a dredging operation by the Lihue Plantation Co., Ltd., on North Kapoa Reef, Kapoa, Kauai. Univ. of Hawaii, Misc. Rep. 31 pp.

Hellier, T.R., Jr. and Kornicker, L.S. 1962. Sedimentation from a hydraulic dredge in a bay. Publ. Inst. of Mar. Sci., Univ. of Tex. 8:212-215.

Herbert, D.W.M. and Merkens, J.C. 1961. The effects of suspended mineral solids on the survival of trout. J. Air and Water Poll. 5(1):46-55.

Herbert, D.W.M. and Richards, J.M. 1963. The growth and survival of fish in some suspensions of solids of industrial origin. Intern. J. Air and Water Poll. 7:297-302.

Herbich, J.B. and Greene, W.S. 1975. Bibliography on dredging. (3rd ed.) Tech. Rep. Ctr., Texas A&M Univ., Civil Engineering Dept., CDS Rep. 179. Vol. C. 3.

Hicks, S., Goodheart, A.J., and Iseley, C.W. 1965. Observations of the tide on the Atlantic continental shelf. J. Geophys. Res. 70(8):1827-1830.

Hood, D.W. 1971. Impingement of Man on the Oceans. Wiley-Interscience, New York. 738 pp.

Hourston, A.S. and Herlinveaux, R.H. 1957. A "Mass Mortality" of fish in Alberni Harbour, B.C. Fish. Res. Bd. Can. Pacific Progress Rep. 109:3-6.

Howe, M.R. 1962. Some direct measurements of the non-tidal drift on the continental shelf between Cape Cod and Cape Hatteras. Deep-Sea Res. 9:445-445.

Hseuh, Y. and O'Brien, J.J. 1971. Steady coastal upwelling induced by an along-shore current. J. Phys. Oceanogr. 1(3):180-186.

Hseuh, Y. and Ou, H-W. 1975. On the possibilities of coastal, mid-shelf, and shelf break upwelling. J. Phys. Oceanogr. 5(4):570-682.

Huang, J.C., Hinkle, L.A., Tsai, K.C., and Manappan, M. 1974. Pollution potential of aquatic sediments. NTIS, PS-239 258.

Hubbard, J.A.E.B. and Pocock, Y.P. 1972. Sediment rejection by recent scleractinian corals: a key to palaeo-environmental reconstruction. Geol. Rundschau. 61(2):598-626.

Hufford, G.L. 1973. Warm water advection in the southern Beaufort Sea, August-September 1971. J. Geophys. Res. 78:2702-2707.

Hufford, G.L. 1974. On apparent upwelling in the southern Beaufort Sea. J. Geophys. Res. 79(9):1305-1306.

Hufford, G.L. 1975. Some characteristics of the Beaufort Sea shelf current. J. Geophys. Res. 80(24):3456-3468.

Hurlburt, H.E. and Thompson, J.D. 1973. Coastal upwelling on a betaplane. J. Phys. Oceanogr. 3(1):16-32.

Huthnance, J.M. 1975. On trapped waves over a continental shelf. J. Fluid Mech. 69(4):689-704.

Huyer, A. and Pattullo, J.G. 1969. Comparison between wind and current observations over the continental shelf off Oregon, summer, 1969. J. Geophys. Res. 77(18):3215-3220.

Huyer, A. and Smith, R.L. 1974. A subsurface ribbon of cool water over the continental shelf off Oregon. J. Phys. Oceanogr. 4(3):381-391.

Huyer, A., Pillsbury, R.D., and Smith, R.L. 1975. Seasonal variation of the alongshore velocity field over the continental shelf off Oregon. Limnol. and Oceanogr. 20(1):90-95.

Huyer, A., Smith, R.L., and Pillsbury, R.D. 1974. Observations in a coastal upwelling region during a period of variable winds (Oregon coast, July 1972). Tethys. 6:391-404.

Ichiye, T. 1962. Storm surges on a continental shelf. National Hurricane Research Project No. 50. Pt. 1, U.S. Weather Bureau. pp. 255-266.

Ichiye, T. and Sudo, H. 1971. Mixing processes between shelf and deep sea waters off the Texas coast. Dept. of Oceanogr., Texas A&M Univ., Ref. 71-19-T. 30 pp.

IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN. 1975. Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP). Scientific criteria for the selection of sites for dumping of wastes in the sea. Rep. and Studies. No. 3. 1975.

BIBLIOGRAPHY (Continued)

Ingraham, W.J. 1963. The geostrophic circulation and distribution of water properties off the coasts of Vancouver Island and Washington, spring and fall. Fish. Bull. 66(2):223-250.

Iselin, C.O'D. 1936. A study of the circulation of the western north Atlantic. Pap. Phys. Oceanogr. and Meteorol. 8(1):39 pp.

Jackson, T.C. 1976. PCB time bomb: the growing menace of polychlorinated biphenyl (PCB) pollution. Oceans. 9(4):58-63.

Jeane, G.S. and Pine, R.E. 1975. Environmental effects of dredging and spoil disposal. J. Water Poll. Control Fed. 47(3) pt. 1: 553-561.

Jelesnianski, C.P. 1965. Numerical calculation of storm tides induced by a tropical storm impinging on a continental shelf. Monthly Weather Rev. 93(6):343-358.

Jenkinson, I.R. 1972. Sludge dumping and benthic communities. Mar. Poll. Bull. 3(7):102-105.

Jensen, A., Rystad, B., and Melsom, S. 1976. Heavy metal tolerance of marine phytoplankton. II. Copper tolerance of three species in dialysis and batch cultures. J. Exp. Mar. Biol. Ecol. 22:249-256.

Jernelov, A. 1972. Mercury--a case study of marine pollution. pp. 161-196. In: Nobel Symposium 20, The Changing Chemistry of the Oceans.

Johnson, R.G. 1974. Particulate matter at the sediment-water interface in coastal environments. J. Mar. Res. 32:313-330.

Johnson, W.R., Van Lee, J.C., and Mooers, C.N.K. 1976. A cyclesonde view of coastal upwelling. J. Phys. Oceanogr. 6(4):556-574.

Jones, D. and Wills, M.S. 1956. The attenuation of light in sea and estuarine waters in relation to the concentration of suspended solid matter. J. Mar. Biol. Assoc. of UK. 35:431.

Jordaan, J.M., Jr. 1965. Effects of hydrographic changes due to nearshore dredger dumping on wave refraction and littoral sand balance. Proc. 9th Coastal Engineering Conf. pp. 310-322.

Jorgensen, C.B. 1949. Rate of feeding by Mytilus in different kinds of suspension. Mar. Biol. Assoc. of UK. 28:333-344.

BIBLIOGRAPHY (Continued)

Kaplan, E.H., Welker, J.R., Kraus, M.G., and McCourt, S. 1975. Some factors affecting the colonization of a dredged channel. Mar. Biol. 32:193-204.

Kautsky, H. 1972. Pollution of the ocean--occurrence, deposition and effect of waste materials in the sea. UMSCHAU in Wiss. and Tech., Sept. 72(18):587.

Keller, G., Lambert, D., Rowe, G., and Staresinic, N. 1973. Bottom currents in the Hudson Canyon. Science. 180:181-183.

Ketchum, B.H. and Corwin, N. 1964. The persistence of 'winter' water on the continental shelf south of Long Island, New York. Limnol. and Oceanogr. 9(4):467-476.

Kielman, J., and Duing, W. 1974. Tidal and sub-inertial fluctuations in the Florida current. J. Phys. Oceanogr. 4(2):277-236.

Kinney, P.J., Loder, T.C., and Groves, J. 1971. Particulate and dissolved organic matter in the Amerasian Basin of the Arctic Ocean. Limnol. and Oceanogr. 16:132-136.

Klasik, J.A. and Pilkey, O.H. 1975. Processes of sedimentation on the Atlantic continental rise off the southeastern U.S. Mar. Geol. 19:69-89.

Kolehmainen, S.E. 1973. Siltation experiments on corals _in situ_. Contribution #0007, Puerto Rico Intern. Undersea Lab. 12 pp.

Lackey, J.B., Morgan, G.B., and Hart, O.H. 1959. Turbidity effects in natural waters in relation to organisms and the uptake of radioisotopes. Univ. Fla. Engineering Ind. Exper. Sta., Tech. Pap. 167. 13(8):1-9.

LaFond, E.C. and Pritchard, D.W. 1952. Physical oceanographic investigations in the eastern Bering and Chukchi Seas during the summer of 1947. J. Mar. Res. 11(1):69-86.

Lavelle, J.W., Keller, G.H., and Clarke, T.L. 1975. Possible bottom current response to surface winds in Hudson shelf channel. J. Geophys. Res. 80(15):1953-1956.

Lear, D.W. 1974. Environmental survey of two interim dumpsites middle Atlantic Bight: suppl. rep., operation FETCH, cruise rep. 5-10, November, 1973. NTIS Rep. PB-239 257, October, 1974. (122).

Lear, D.W. 1975. Effects of ocean disposal activities on mid-continental shelf environment off Delaware and Maryland, EPA 903/9-75-015, January, 1975.

Lear D.W. and Pasch, G.G. 1975. Effects of ocean disposal activities on mid-continental shelf environment of Delaware and Maryland. NTIS Rep. PB-239-256.

Leathem, W., Kinner, P., Maurer, D., Biggs, R., and Treasure, W. 1973. Effect of spoil disposal on benthic invertebrates. Mar. Poll. Bull. 4(8):122-125.

Lee, G.F. 1973. Chemical aspects of bioassay techniques for establishing water quality criteria. Water Res. 7:1525-1546.

Lee, T.N. 1975. Florida current spin-off eddies. Deep-Sea Res. 22:753-765.

LeGore, R.S. 1973. Absence of acute effects on threespine sticklebacks (Gasterosteus aculeatus) and Coho salmon (Oncorhynchus kisutch) exposed to resuspended harbor sediment contaminants. J. Fish. Res. Bd. Can. 30(8):1240-1242.

Lahmann, E.J. 1975. Ocean waste disposal (A bibliography with abstracts). NTIS/PS-75/462/2ST.

Leipper, D.F. 1954. Physical oceanography of the Gulf of Mexico. Fish. Bull. 89:119-137.

Leipper, D.F. 1967. Observed ocean conditions and hurricane Hilda, 1964. J. Atmos. Sci. 24(2):182-196.

Leipper, D.F. 1970. A sequence of current patterns in the Gulf of Mexico. J. Geophys. Res. 75(3):637-657.

Light, M. and Henderson, S.J. 1974. Oceanography in the Gulf of Maine and adjacent waters in support of the International Commission for Northwest Atlantic Fisheries. U.S. Coast Guard Oceanogr. Rep. No. 65. 149 pp.

Littler, M.M. and Murray, S.N. 1975. Impact of sewage on the distribution, abundance and community structure of rocky intertidal macro-organisms. Mar. Biol. 30:277-291.

Liu, D.H.W., Martin, K.D., and Norwood, C.R. 1975. San Francisco Bay benthic community study. Appendix D. In: Dredge Disposal Study, San Francisco Bay and Estuary. U.S. Army Engineer District, San Francisco.

Livingston, R.J. 1975. Impact of kraft pulp-mill effluents on estuarine and coastal fishes in Apalachee Bay, Florida, U.S.A. Mar. Biol. 32:19-48.

Lomon, F.G., Rice, T.R., and Richards, F.A. 1971. Accumulation and redistribution of radionuclides by marine organisms. pp. 161-199. In: Radioactivity in the Marine Environment, Rep. of Panel on Radioactivity in the Marine Environment, Committee on Oceanogr. Nat. Res. Council, Nat. Acad. of Sci. 272 pp.

Lund, E.J. 1957a. A quantitative study of clearance of a turbid medium and feeding by the oyster. Publ. Inst. Mar. Sci., Univ. of Tex. 4(2):296-312.

Lund, E.J. 1957b. Self-silting, survival of the oyster as a closed system, and reducing tendencies of the environment of the oyster. Publ. Inst. Mar. Sci., Univ. of Tex. 4(2):313-319.

Lund, E.J. 1957c. Self-silting by the oyster and its significance for sedimentation geology. Publ. Inst. Mar. Sci., Univ. of Tex. 4(2):320-327.

Lunz, G.R. 1938. Oyster culture with references to dredging operations in South Carolina and the effects of flooding of the Santee River in April 1936 on oysters in the Cape Romain area of South Carolina (part II). March, 1952. U.S. Army Engineer District, Charleston, C.E., Charleston, SC. 135 pp.

Lunz, G.R. 1942. Investigation of the effects of dredging on oyster leases in Duval County, Florida. In: Handbook of Oyster Survey, Intracoastal Waterway Cumberland Sound to St. Johns River. Spec. Rep. U.S. Army Corps of Engineers, Jacksonville, Fl.

Lynde, R.E. 1973. Physical oceanography: tides. Coastal and Offshore Environmental Inventory, Cape Hatteras to Nantucket Shoals, Mar. Publ. Series No. 2, Univ. of Rhode Island, 1-46 - 1-60.

McEwen, G.F., Thompson, T.G., and Van Cleve, R. 1930. Hydrographic sections and calculated currents in the Gulf of Alaska. Rep. Int. Fish. Comm. 4:13-36.

McKelvey, V.E., Tracey, J.I., Stoertz, G.E., and Vedder, J.G. 1969. Subsea mineral resources and problems related to their development. Geol. Survey Circ. 619.

BIBLIOGRAPHY (Continued)

McNider, T.R. and O'Brien, J.J. 1973. A multi-layer transient model of coastal upwelling. J. Phys. Oceanogr. 3(3):258-273.

Mackay, D.W., Halcrow, W., and Thornton, E. 1972. Sludge dumping in the Firth of Clyde. Mar. Poll. Bull. 3(1):7-10.

Mackay, D.W. and Topping, G. 1970. Preliminary report on the effects of sludge disposal at sea. Effluent and Water Treatment J. 5:641-649.

Mackin, J.G. 1960. Canal dredging and silting in Louisiana. Rep. from Texas A&M Res. Found. Mar. Lab., Project 23.

Mackin, J.G. 1961. Canal dredging and silting in Louisiana bays. Publ. Inst. Mar. Sci., Univ. of Tex. 7:262-314.

Manheim, F.T., Meade, R.H., and Bond, G.C. 1970. Suspended matter in surface waters of the Atlantic continental margin from Cape Cod to the Florida Keys. Science. 167:371-376.

Manning, J.H. 1957. The Maryland soft shell clam industry and its effect on tidewater resources. Md. Dept. Res. and Educ., Chesapeake Biol. Lab. Rep. No. 22. 25 pp.

Marking, L.L. and Lennon, R.E. 1968. Bioassay of taconite wastes against fish and other aquatic organisms. U.S. Dept. of Interior Bureau of Sport Fish. and Wildlife, Fish Control Lab., La Crosse, Wisc.

Marmer, H.A. 1954. Tides and sea level in the Gulf of Mexico. Fish. Bull. No. 89. pp. 101-118.

Marshall, A.R. 1968. Dredging and filling. pp. 107-113. In: J.D. Newsom (ed.) Proc. of the Marsh and Estuary Management Symposium. T.J. Moran's Sons, Inc., Baton Rouge, La.

Maul, G.A., Norris, D.R., and Johnson, W.R. 1974. Satellite photography of eddies in the gulf loop current. Geophys. Res. Letters. 1(6):256-258.

Maurer, D. 1967. Burial experiments on marine pelecypods from Tomales Bay, California. Veliger. 9:376-381.

Maurer, D. 1974. Effect of spoil disposal on benthic communities near the mouth of Delaware Bay. NTIS Rep. OM-74-10961/2WP, 1974.

Meade, R.H. 1969. Landward transport of bottom sediments in estuaries of the Atlantic coastal plain. J. Sediment. Petrol. 39(1):222-234.

Metcalf, W.G. and Stalcup, M.C. 1974. Drift bottle returns from the eastern Caribbean. Bull. Mar. Sci. 24(2):392-395.

Miller, A.R. 1950. A study of mixing processes over the edge of the continental shelf. J. Mar. Res. 9(2):145-159.

Miyata, M. and Groves, G.W. 1971. A study of the effects of local and distant weather on sea level in Hawaii. J. Phys. Oceanogr. 1(3):203-213.

Mooers, C.N.K. and Smith, R.L. 1968. Continental shelf waves off Oregon. J. Geophys. Res. 73(2):549-557.

Mortimer, C.H. 1971. Chemical exchange between sediments and water in the Great Lakes--speculations on probable regulatory mechanisms. Limnol. and Oceanogr. 16(2):387-404.

Mountain, D.G., Coachman, L.K., and Aagaard, K. 1976. On the flow through Barrow Canyon. J. Phys. Oceanogr. 6(4):461-470.

Murakami, A. 1975. Pollution of sea bottom deposit, VMI to SORA. 50(2-3):27-39.

Murray, A.P. 1973. Protein absorption by suspended sediments: effects of pH, temperature, and concentration. Environ. Poll. 4(5):301-312.

Mysak, L.A. 1967. On the theory of continental shelf waves. J. Mar. Res. 25:205-227.

Mysak, L.A. 1968a. Edgewaves on a gently sloping continental shelf of finite width. J. Mar. Res. 26(1):24-33.

Mysak, L.A. 1968b. Effects of deep sea stratification and current on edge waves. J. Mar. Res. 26(1):34-42.

Mysak, L.A. and Harmon, B.V. 1969. Low-frequency sea level behavior and continental shelf waves off North Carolina. J. Geophys. Res. 74(6):1397-1405.

Mysak, L.A. and Tang, C.L. 1974. Kelvin wave propagation along an irregular coastline. J. Fluid Mech. 64(2):241-261.

BIBLIOGRAPHY (Continued)

Nakamura, R., Suzuki, Y., and Ueda, T. 1975. Influence of marine sediment on the accumulation of radionucludes by green alga (Ulva pertusa). J. Radiation Res. 16(4):224-236.

Nash, C.B. 1974. Environmental characteristics of a river estuary. J. Mar. Res. 6:147-174.

National Marine Fisheries Service. 1972. The effects of waste disposal in the New York Bight, summary final report. National Mar. Fish. Serv., Middle Atlantic Coastal Fish. Ctr., Sandy Hook Lab., Highlands, NJ Inform. Rep. No. 2. 70 pp.

National Marine Fisheries Service. 1974. Cruise report NOAA Ship DELAWARE II, 13-28 June 1974 and 5-10 August 1974. Surf clam survey. Middle Atlantic Coastal Fish. Ctr., Resource Assessment Investigations, Oxford Lab., Oxford, Md.

National Marine Fisheries Service. 1975a. Cruise Report, NOAA ship DELAWARE II, 12-24 February, 1975. Cruise D-75-2. Middle Atlantic Coastal Fish Ctr., Ecosystems Investigations, Sandy Hook Lab., Highlands, NJ.

National Marine Fisheries Service. 1975b. Cruise report, NOAA ship ALBATROSS IV, 7-16 August 1975 and 27 September October, 1975. Sea scallop survey. Middle Atlantic Coastal Fish Ctr., Ecosystems Investigations, Sandy Hook Lab., Highlands, NJ.

National Oceanic and Atmospheric Administration. 1974. Report to Congress on ocean dumping and other man-induced changes to ocean ecosystems. Dept. of Commerce. 96 pp.

National Oceanic and Atmospheric Administration. 1975. Ocean dumping in the New York Bight. Dept. of Commerce, Tech Rep. ERL 321-MESA2.

NAVOCEANO. 1973. Preliminary report environmental investigations of a dredge soil disposal site near New London, Connecticut. Naval Oceanogr. Off. Phys. Oceanogr. Div., Washington, DC DAVOCEANO Tech. Note No. 7300-3-73. 87 pp.

Niiler, P.P. and Mysak, L.A. 1971. Barotropic waves along the eastern continental shelf. Geophys. Fluid Dynamics. 2:273-288.

Niiler, P.P. and Richardson, W.S. 1973. Seasonal variability of the Florida current. J. Mar. Res. 31:144-167.

BIBLIOGRAPHY (Continued)

Norcross, J.J. and Stanley, E.M. 1967. Inferred surface and bottom drift, June 1963 through October 1964. Circulation of shelf waters off the Chesapeake Bight. Prof. Pap. ESSA. 3(2):11-42.

Norris, D.P., Birke, L.E., Cockburn, R.T., and Parker, D.S. 1973. Marine waste disposal--a comprehensive environmental approach to planning. J. Water Poll. Control Fed. 45(1):52-70.

Nowlin, W.D., Jr. 1972. Winter circulation patterns and property distributions. Texas A&M Univ. Oceanogr. Studies, Vol. 2, Gulf Publ. Co., Houston, Texas. pp. 3-51.

Nowlin, W.D., Jr. and McLellan, H.J. 1967. A characterization of the Gulf of Mexico waters in winter. J. Mar. Res. 25(1):29-59.

Nowroozi, A.A., Ewing, M., Nafe, J.E., and Fleigel, M. 1968. Deep ocean current and its correlation with the ocean tide off the coast of northern California. J. Geophys. Res. 73:1921-1932.

O'Brien, J.J. 1973. Time dependent coastal upwelling. J. Phys. Oceanogr. 3(1):33-46.

Odum, H.T. 1963. Productivity measurements in Texas turtle grass and the effects of dredging on intracoastal channel. Univ. of Tex. Publ. Inst. Mar. Sci. 9:48-58.

Odum, H.T. and Hoskin, C.M. 1958. Comparative studies on the metabolism of marine waters. Univ. of Tex. Publ. Inst. Mar. Sci. 5:16-46.

Oertel, G.F. 1974. Report on the hydrologic and sedimentologic study of the offshore spoil disposal area, Savannah, Georgia. NTIS Rep. AD-A010 411.

Okubo, A. 1962. Horizontal diffusion from an instantaneous point-source due to oceanic turbulence. Chesapeake Bay Inst., TR 32. 132 pp.

Okubo, A. 1965. A note on the horizontal diffusion from an instantaneous point-source in a non-uniform flow. J. Oceanogr. Soc. Jap. 22: 35-40.

Olson, B.H. and Cooper, R.C. 1976. Comparison of aerobic and anaerobic methylation of mercuric chloride by San Francisco Bay sediments. Water Res. 10:113-116.

O'Neal, G. and Sceva, J. 1971. The effects of dredging on water quality. World Dredging and Mar. Constr. 7(14):24-28, 30-31.

BIBLIOGRAPHY (Continued)

Oosten, J.V. 1948. Turbidity as a factor in the decline of Great Lakes fishes with special reference to Lake Erie. Trans. of Amer. Fish. Soc. 75:281-322.

Oppenheimer, C.H. and Jannasch, H.W. 1962. Some bacterial populations in turbid and clear sea water near Port Aransas, Texas. Univ. Tex. Publ. Inst. Mar. Sci. 8:56-60.

Orlanski, I. 1969. The influence of bottom topography on the stability of jets in a baroclinic fluid. J. Atmos. Sci. 26(6):1216-1232.

Pacquette, R.G. and Bourke, R.H. 1974. Observations on the coastal current of Arctic Alaska. J. Mar. Res. 32(2):195-207.

Padan, J.W. 1971. Marine mining and the environment. Impingement of man on the oceans. John Wiley & Sons, New York. pp. 553-56.

Paffenhofer, G.A. 1972. The effects of suspended "red mud" on mortality, body weight, and growth of the marine planktonic copepod, *Calanus hegolandicus*. Water, Air, and Soil Poll. 1:314-321.

Palmer, H.D. and Lear, D.W. 1973. Environmental survey of an interim ocean dumpsite, Middle Atlantic Bight Cruise Rep. 1-5, May 1973. NTIS Rep. PB229-761/2WP.

Pamatmat, M.M., Jones, R.S., Sanborn, H., and Bhagwat, A. 1973. Oxidation of organic matter in sediments. EPA Ecol. Res. Ser., EPA-660/ 3-73-005 (Sept. 1973). 104 pp.

Paskausky, D.F. 1971. Numerically predicted changes in the circulation of the Gulf of Mexico accompanying a simulated hurricane passage. J. Mar. Res. 29(3):214-225.

Pattullo, J. and Denner, W. 1965. Processes affecting seawater characteristics along the Oregon coast. Limnol. and Oceanogr. 10(3): 443-450.

Patullo, J.G., Burt, W.V., and Kulm, S.A. 1969. Oceanic heat content off Oregon: its variations and their causes. Limnol. and Oceanogr. 14(2):279-287.

Patzert, W.C. 1969. Eddies in Hawaiian waters. Hawaii Inst. Geophys. HIG 69-8.

Patzert, W.C. 1973. Current meter data: an indication of either subtropical countercurrent or anticyclonic island circulation. J. Geophys. Res. 78:7919-7922.

BIBLIOGRAPHY (Continued)

Patzert, W.C. and Wyrtki, K. 1974. Anticyclonic flow around the Hawaiian Islands indicated by current meter data. J. Phys. Oceanogr. 4(4):673-676.

Peakall, D.B. 1975. PCB's and their environmental effects. CRC Critical Rev. in Environ. Control. 5:469-500.

Pearce, J.B. 1970. The effects of solid waste disposal on benthic communities in the New York Bight. FAO Tech. Conf. on marine pollution and its effects on living resources and fishing, Rome, Italy, 9-18 December.

Pearson, J. and Bender, E.S. 1975. Effects of discharge from a dredge spoils site on Carroll Island, Md. NTIS, AD-A012 206/9ST.

Pedlosky, J. 1974a. Longshore currents, upwelling and bottom topography. J. Phys. Oceanogr. 4(2):214-266.

Pedlosky, J. 1974b. Longshore currents and the onset of upwelling over bottom slope. J. Phys. Oceanogr. 4(3):310-320.

Peng, E.Y. and Hseuh, Y. 1974. Further results from diagnostic modeiling of coastal upwelling. Tethys. 6(1-2):425-432.

Peterson, D.H., Conomas, T.J., Broenkow, W.W., and Scrivani, E.P. 1975. Processes controlling the dissolved silica distribution in San Francisco Bay. pp. 153-187. In: L.E. Cronin (ed.) Estuarine Research, Vol. 1, Academic Press, Inc., New York. 738 pp.

Phillips, J.H., Haderlie, E.E., and Lee, W.L. 1975. An analysis of the dymanics of DDT in marine sediments. EPA Ecol. Res. Ser. EPA-660/3-75-013. 98 pp.

Pratt, S.D., Saila, S.B., and Sissenwine, M.P. 1973. Dredge spoil disposal in Rhode Island Sound. Mar. Exp. Sta. Univ. of Rhode Island, Kingston, RI.

Prinsenberg, S.J. and Rattray, M., Jr. 1974. Generation and dissipation of coastal internal tides. Deep-Sea Res. 21:263-281.

Radtke, L.D. and Turner, J.L. 1967. High concentrations of total dissolved solids spawning migrations of striped bass, Roccus saxatilis, in the San Joaquin River, California. Trans. Amer. Fish. Soc. 96(4):405-407.

Rajan, K.C. and Nair, N.B. 1974. Effluent resistance of some species of interstitial animals to industrial wastes. Bol. Inst. Oceanogr. Univ. Oriente. 13:125-218.

BIBLIOGRAPHY (Continued)

Rao, D.V. 1973. Effects of environmental perturbation or short-term phytoplankton production off Lawson's Bay, a tropical coastal embayment. Hydrobiologia. 43:77-92.

Rao, P.K., Strong, A.E., and Koffler, R. 1971. Gulf stream meanders and eddies as seen in satellite infrared imagery. J. Phys. Oceanogr. 1(3):237-239.

Rattray, M., Jr. 1960. On the coastal generation of internal tides. Tellus. 12:54-62.

Redfield, A.C. 1968. The influence of the continental shelf on the tides of the Atlantic coast of the United States. J. Mar. Res. 17:432-448.

Reed, R.K. and Halpern, D. 1976. Observations of the California undercurrent off Washington and Vancouver Island. Limnol. and Oceanogr. 21(3):389-398.

Reid, J.L., Jr. 1963. Measurements of the California countercurrent off Baja, California. J. Geophys. Res. 68:4819-4822.

Reid, J.L., Jr. 1972. Measurements of the California current at a depth of 250 meters. J. Mar. Res. 20(2):134-137.

Reid, R.O. 1956. Approximate response of water level on a sloping shelf to a wind fetch which moves toward shore. Beach Erosion Bd., Corps of Engineers, U.S. Army, Tech. Mem. No. 83. 44 pp.

Renfro, W.C. 1973. Transfer of ^{65}Zn from sediment by marine polychaete worms. Mar. Biol. 21(4):305-316.

Renfro, W.C., McCauley, J.E., Glenn, B., Bourke, R.H., Hancock, D.R., and Hager, S.W. 1971. Oceanography of the nearshore coastal waters of the Pacific northwest relating to possible pollution. U.S. EPA Water Poll. Control Res. Ser. No. 16070EOK 07/71. 615 pp.

Rhoads, D.C. 1974. Organism-sediment relations on the muddy sea floor. Oceanogr. and Mar. Biol. Ann. Rev. 12:263-300.

Riley, G.A. 1937. The significance of the Mississippi River drainage for biological conditions in the northern Gulf of Mexico. J. Mar. Res. 1:60-74.

Ritchie, D.E. 1970. Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay. Project F. Fish. Natural Resour. Inst., Spec. Rep. No. 3, Chesapeake Biol. Lab., Solomons, Md.

BIBLIOGRAPHY (Continued)

Ritchie, J.C. 1972. Sediment, fish and fish habitats. J. Soil and Water Conserv. 27(3):124-125.

Robe, R.Q. 1974. North Atlantic standard monitoring sections A5, A6, and A7, 1967-1969. U.S. Coast Guard Oceanogr. Rep. No. 67. 305 pp.

Roberts, D. 1975. The effects of pesticides on byssus formation in the common mussel, Mytilus edulis. Environ. Poll. 8:241-254.

Robinson, M. 1957. The effect of suspended materials on the reproductive rate of Daphnia magna. Univ. of Tex. Publ. Inst. of Mar. Sci. 4:265-279.

Roden, G.I. 1969. Winter circulation in the Gulf of Alaska. J. Geophys. Res. 74:4523-4532.

Roden, G.I. 1974. Thermohaline structure, fronts, and sea-air energy exchange of the trade wind region east of Hawaii. J. Phys. Oceanogr. 4(2):168-182.

Roels, O.A. 1974. Environmental impact of deep ocean mining. Mining Congress J. 60(8):34.

Rohatgi, N. and Chen, K.Y. 1975. Transport of trace metals by suspended particulates on mixing with seawater. J. Water Poll. Control Fed. 47:2298-2316.

Rose, C.D. 1973. Mortality of market-sized oysters (Crassostrea virginica) in the vicinity of a dredging operation. Chesapeake Sci. 14(2):135-138.

Rowe, G.T. and Menzies, R.J. 1968. Deep bottom currents off the coast of North Carolina. Deep-Sea Res. 15:711-719.

Roy, K.J. and Smith, S.V. 1971. 1971. Sedimentation and coral reef development in turbid water: Fanning Lagoon. Pacific Sci. 25: 234-248.

Sameoto, D.D. 1969. Physiological tolerances and behavior responses of five species of Haustoridae (Amphipoda:Crustacea) to five environmental factors. J. Fish. Res. Bd. Can. 26:2283-2298.

Sanders, H. and Hessler, R. 1969. Ecology of the deep-sea benthos. Science. 163:149-1424.

Sandy Hook Marine Laboratory. 1970. The effects of waste disposal in the New York Bight - Interim Rep. for January 1, 1970. U.S. Bureau of Sport Fish. and Wildl., Sandy Hook Lab., Highlands, NJ.

BIBLIOGRAPHY (Continued)

Scarlett, H. 1976. Dredging spoil site now a shrimp farm. Houston Post. September 8.

Schleske, C.L., Rothman, E.D., Stoermer, E.F., and Santiago, M.A. 1974. Responses of phosphorus limited Lake Michigan phytoplankton to factorial enrichments with nitrogen and phosphorus. Limnol. and Oceanogr. 19(3):409-419.

Schmitz, W.J., Jr. 1974. Observations of low-frequency current fluctuations on the continental slope and rise near site D. J. Mar. Res. 32(2):233-25.

Schmitz, W.J., Jr. and Richardson, W.S. 1968. On the transport of the Florida Current. Deep-Sea Res. 15:679-693.

Schneck, H.M. 1972. U.S. survey indicates dumping off Sandy Hook hurts sea life. New York Times, June 15, 1972. p. 18.

Schott, F., and Duing, W. 1976. Continental shelf waves in the Florida straits. J. Phys. Oceanogr. 6(4):451-460.

Scruton, P.C. and Moore, D.G. 1953. Distribution of surface turbidity off Mississippi Delta. Bull. Amer. Assoc. Petrol. Geol. 37(5): 1067-1074.

Shapiro, S. (ed.). 1971. Our Changing Fisheries. U.S. Govt. Print. Off., Washington, DC. 534 pp.

Shaw, P.A. and Mago, J.A. 1943. The effect of mining silt on yield of fry from salmon spawning beds. Calif. Fish and Game. 29:29-41.

Shepard, F.P. 1939. Near-shore sediments--hemipelagic deposits. pp. 219-229. In: Recent Marine Sediments, A symposium. Amer. Assoc. Petrol. Geol., Tulsa, Oklahoma.

Shepard, F.P. 1975. Progress of internal waves along submarine canyons. Mar. Geol. 19:131-138.

Shepard, F.P. and Marshall, N.F. 1969. Currents in LaJolla and Scripps submarine canyons. Science. 165:177-178.

Sherk, J.A. 1972. Current status of the knowledge of the biological effects of suspended and deposited sediments in Chesapeake Bay. Chesapeake Sci. 13: supplement S137.

Sherk, J.A. 1974. Effects of suspended and deposited sediments on estuarine organisms. Phase II. NTIS Rep. AD-A011 372, March, 1974. 299 pp.

BIBLIOGRAPHY (Continued)

Sherk, J.A., O'Connor, J.M., and Neumann, D.A. 1975. Effects of suspended and deposited sediments on estuarine environments. pp. 541-558. In: L.E. Cronin (ed.) Estuarine Research, Vol. 2, Academic Press, New York.

Shih, H.H. 1971. A literature survey of ocean pollution. NTIS Rep. AD-743 101, May. 116 pp.

Sholkovitz, E. 1975. Changes in the composition of the bottom water of the Santa Barbara Basin: effect of turbidity currents. Deep-Sea Res. and Oceanogr. Abstr. 22(1):10.

Sikka, H., Butler, G.L., and Rice, C.P. 1976. Effects, uptake, and metabolism of Methoxychlor, Mirex, and 2, 4-D in seaweeds. Ecol. Res. Ser. EPA 600/3-76-048.

Singamsetti, S.R. 1966. Diffusion of sediment in a submerged jet. ASCE, J. Hydraulic Div. 92(HY2):153-168.

Sissenwine, M.B. and Saila, S.B. 1975. Rhode Island Sound dredge spoil disposal and trends in the floating trap fishery. Univ. of Rhode Island Mar. Reprint. 30(9).

Slotta, L.S. 1974. Dredging problems and complications. pp. 39-52. In: Coastal Zone Management Problems. Oregon State Univ., Water Resour. Res. Inst. SEMN WR 018-74.

Slotta, L.S. and Williamson, K.J. 1974. Estuarine impacts related to dredge spoiling. Proc. of 6th Dredging Seminar. p. 20.

Small, L.F. and Curl, H., Jr. 1968. The relative contribution of particulate chlorophyll and river tripton to the extinction of light off the coast of Oregon. Limnol. and Oceanogr. 13(1):84-91.

Smalley, A.H. 1974. Sand, gravel dredging effects on Tennessee River analyzed. World Dredging and Mar. Constr. 10(6):33-35.

Smith, D.R. 1967. Comparison of theoretical ocean diffusion models. U.S. Naval Radiological Defense La . USNRDL-TR-67-50.

Smith, K.L., Jr. 1974. Oxygen demands of San Diego Trough sediments: an in situ study. Limnol. and Oceanogr. 19(6):939-944.

Smith, K.L. Jr. and Teal, J.M. 1973. Deep-sea benthic community respiration: an in situ study at 1850 meters. Science. 179:282-283.

BIBLIOGRAPHY (Continued)

Smith, R.L. 1974. A description of current, wind and sea level variation during coastal upwelling off the Oregon coast, July-August 1972. J. Geophys. Res. 79:435-443.

Smith, R.L., Pattullo, J.G., and Lane, R.K. 1966. An investigation of the early stage of upwelling along the Oregon coast. J. Geophys. Res. 71:1135-1140.

Smith, W.F.G., Medina, F.A., and Abella, B.A.F. 1951. Distribution of vertical water movement calculated from surface drifter vectors. Bull. Mar. Sci. 1(3):187-195.

Southard, J.B. and Cacchione, D.A. 1972. Experiments on bottom sediment. pp. 83-98. In: D.J.P. Swift, D.B. Duane, and O.H. Pilkey (eds.) Shelf Sediment Transport: Process and Pattern, Hutchinson and Ross, Stroudsburg, Pa.

Stalcup, M.C., Metcalf, W.G., and Johnson, R.G. 1975. Deep Caribbean inflow through the Anegada-Jungfern Passage. J. Mar. Res. 33 (suppl):15-35.

Stanley, S.M. 1970. Relations of shell form to life habits of the bivalve (Mollusca). Geol. Soc. Amer. Mem. 125:296 pp.

Stefansson, U. and Richards, F.A. 1964. Distributions of dissolved oxygen, density and nutrients off the Washington and Oregon coasts. Deep-Sea Res. July. pp. 355-380.

Stefansson, U. and Atkinson, L.P. 1967. Physical and chemical properties of the shelf and slope waters off North Carolina. Duke Univ. Mar. Lab., December.

Stefansson, U., Atkinson, L.P., and Bumpus, D.F. 1971. Hydrographic properties and circulation of the North Carolina shelf and slope waters. Deep-Sea Res. 18:383-420.

Stevenson, M.R., Garvine, R.W., and Wyatt, B. 1974. Lagrangian measurements in a coastal upwelling zone off Oregon. J. Phys. Oceanogr. 4(3):321-336.

Stirling, E.A. 1975. Some effects of pollutants on the behavior of the bivalve Tellina tenuis. Mar. Poll. Bull. 6:122-124.

Stommel, H. 1949. Horizontal diffusion due to oceanic turbulence. J. Mar. Res. 8(3):199-225.

BIBLIOGRAPHY (Continued)

Stross, R.G. and Stottlemeyer, J.R. 1965. Primary production in the Patuxent River. Chesapeake Sci. 6:125-140.

Stumpf, H.G. and Rao, P.K. 1975. Evolution of Gulf Stream eddies as seen in satellite infrared imagery. J. Phys. Oceanogr. 5(2):388-393.

Sturges, W. 1965. Water characteristics of the Caribbean Sea. J. Mar. Res. 23:147-162.

Sverdrup, H.V. and Fleming, R.H. 1941. The waters off the coast of southern California, March to July 1937. Bull. Scripps Inst. of Oceanogr. 4(10):261-378.

Swallow, J.C. and Worthington, L.V. 1961. An observation of deep countercurrent in the western north Atlantic. Deep-Sea Res. 8:1-19.

Swift, J.H. and Aagaard, K. 1976. Upwelling near Samalga Pass. Limnol. and Oceanogr. 21(3):399-408.

Sykes, J.E. and Hall, J.R. 1970. Comparative distribution of mollusks in dredged and undredged portions of an estuary, with a systematic list of species. Fish. Bull. 68(2):299-306.

Taylor, C.B. and Stewart, H.B., Jr. 1959. Summer upwelling along the east coast of Florida. J. Geophys. Res. 64(1):33-40.

Taylor, J.L., Hall, J.R., and Saloman, C.H. 1970. Mollusks and benthic environments in Hillsborough Bay, Florida. U.S. Fish Wildl. Serv., Fish. Bull. 68(2):191-202.

TerEco Corporation. 1976. Ecological aspects of the upper continental slope of the Gulf of Mexico. Rep. prepared for U.S. Dept. of Interior, Bureau of Land Management. Contract #08550-CT4-12. 305 pp.

Thayer, G.W., Wolfe, D.A., and Williams, R.B. 1975. The impact of man on seagrass systems. Amer. Sci. 63:288-296.

Thorson, G. 1956. Marine level bottom communities of recent seas, their temperature adaptation and their "balance" between predators and food animals. Trans. NY. Acad. Sci., Ser. 2, Vol. 28. No. 8.

Tsai, C-F. 1973. Water quality and fish life below sewage outfalls. Trans. Amer. Fish. Soc. 102(2):281-292.

Uda, M. 1963. Oceanography of the Subarctic Pacific Ocean. J. Fish. Res. Bd. Can. 20(1):119-179.

BIBLIOGRAPHY (Continued)

U.S. Naval Oceanographic Office. 1965. Oceanographic atlas of the North Atlantic Ocean. Section I, tides and currents. Publ. No. 700. U.S. Naval Oceanogr. Off., Washington, DC.

U.S. Naval Oceanographic Office. 1972. Environmental-acoustics atlas of the Caribbean Sea and Gulf of Mexico, Volume II - marine environment. AD-752 494, U.S. Naval Oceanogr. Off. Spec. Rep. 189, Washington, DC. 190 pp.

U.S. Navy Weather Service Command. 1970. Summary of synoptic meteorological observations, North American coastal marine areas. Vol. 2 and Vol. 7. 632 pp. each.

Verduin, J. 1954. Phytoplankton and turbidity in western Lake Erie. Ecology. 35(4):550-561.

Volkmann, G. 1962. Deep current observations in the western north Atlantic. Deep-Sea Res. 9:493-500.

Voorhis, A.D. 1968. Measurements of vertical motion and the partition of energy in the New England slope water. Deep-Sea Res. 15:599-608.

Voorhis, A.D., Webb, D.C., and Millard, R.C. 1976. Current structure and mixing in the shelf/slope water front south of New England. J. Geophys. Res. 81(21):3695-3708

Walford, L.A. and Wicklund, R.I. 1968. Monthly sea temperature structure from the Florida Keys to Cape Cod. Serial Atlas of the Marine Environment, Folio 15, Amer. Geogr. Soc., New York.

Walsh, J.J., Kelley, J.C., Whitledge, T.E., MacIssac, J.J., and Huntsman, S.A. 1974. Spin-up of the Baja California upwelling ecosystem. Limnol. and Oceanogr. 19(4):553-572.

Wang, D. 1975. Coastal trapped waves in a baroclinic ocean. J. Phys. Oceanogr. 5(2):326-333.

Wangersky, P. 1976. Particulate organic carbon in the Atlantic and Pacific oceans. Deep-Sea Res. 23(5):457-465.

Weatherly, G.L. 1975. A numerical study of time-dependent turbulent Ekman layers over horizontal and sloping bottoms. J. Phys. Oceanogr. 5(2):288-299.

Webster, F. 1961. A description of Gulf Stream meanders off Onslow Bay. Deep-Sea Res. 8:130-148.

BIBLIOGRAPHY (Continued)

Welander, P. 1961. Numerical prediction of storm surges. Advances in Geophysics, Vol. 8, Academic Press, New York. pp. 315-379.

Wells, H.W. and Gray, I.E. 1960. Summer upwelling off the northeast coast of North Carolina. Limnol. and Oceanogr. 5(1):108-109.

Wilber, C.G. 1971. Turbidity. pp. 1157-1165. In: O. Kinne (ed.) Marine Ecology, Wiley Interscience, New York.

Williams, A.B. 1958. Substrates as a factor in shrimp distribution. Limnol. and Oceanogr. 3(3):283-290.

Wilson, B.W. 1971. Tsunami responses of San Pedro Bay and shelf, California. ASCE Proc., J. of Waterways, Harbors, and Coastal Engineering Div., 97, No. WW2. Pap. 8107-239-258.

Wilson, J. 1959. The effects of erosion, silt and other inert materials on aquatic life. Trans. 2nd Sem. Biol. Problems Water Poll.

Wooster, W.S. and Jones, J.H. 1970. California undercurrent off northern Baja, California. J. Mar. Res. 28:235-250.

Worthington, L.V. 1966. Recent oceanographic measurements in the Caribbean Sea. Deep-Sea Res. 13:731-739.

Wright, W.R. 1976. The limits of shelf water south of Cape Cod. J. Mar. Res. 34(1):1-14.

Wunsch, C., Hansen, D.V., and Zetler, B.D. 1969. Fluctuations of the Florida current inferred from sea level records. Deep-Sea Res. 16 (suppl.):447-470.

Wüst, G. 1964. Stratification and circulation in the Antillean-Caribbean basins. Columbia Univ. Press, New York. 201 pp.

Wyatt, B., Burt, W., and Patullo, M. 1972. Surface currents off Oregon as determined from drift bottle returns. J. Phys. Oceanogr, July. 2:286-293.

Wyrtki, K. and Graefe, V. 1967. Approach of tides to the Hawaiian Islands. J. Geophys. Res. 72(8):2069-2071.

Wyrtki, K., Graefe, V., and Patzert, W. 1969. Current observations in the Hawaiian archipelago. Hawaii Inst. Geophys. HIG 69-15.

BIBLIOGRAPHY (Concluded)

Yonge, C.M. 1953. Aspects of life on muddy shores. pp. 29-49. In: S.M. Marshall and A.P. Orr (eds.) Essays in Marine Biology. Oliver and Boyd, London.

Young, D.L. and Barber, R.T. 1973. Effects of waste dumping in New York Bight on the growth of natural populations of phytoplankton. Environ. Poll. 5:237-252.

Young, J.S. and Pearce, J.B. 1975. Shell disease in crabs and lobsters from New York Bight. Mar. Poll. Bull. 6:101-105.

Zetler, B.D. and Hansen, D.V. 1972. Tides in the Gulf of Mexico. pp. 265-275. In: L.R.A. Capurro and J.L. Reid (eds.) Contributions on the Physical Oceanography of the Gulf of Mexico. Vol. 2, Gulf Publ. Co., Houston.

Zimmerman, H.B. 1971. Bottom currents on the New England continental rise. J. Geophys. Res. 76(24):5865-5876.

Zirino, A. and Yamamoto, S. 1972. A pH-dependent model for the chemical speciation of copper, zinc, cadmium and lead in seawater. Limnol. and Oceanogr. 17:661-671.

APPENDIX A

ROSTER OF ADVISORY PANEL MEMBERS

SAN DIEGO ADVISORY COMMITTEE MEETING

NAME, ADDRESS, PHONE NUMBER

Dr. Kenneth J. Chen
Director, Environmental Engineering Program
University of Southern California
Los Angeles, California 90007

Dr. Joe S. Creager
Department of Oceanography, WB-10
University of Washington
Seattle, Washington 98195
206/543-4130
543-5099

Dr. Robert Engler
Environmental Effects Laboratory
USAE Waterways Experiment Station, CE
Vicksburg, Ms. 39180
601/636-3111

Mr. Barry Holliday
Environmental Effects Laboratory
USAE Waterways Experiment Station, CE
Vicksburg, Ms. 39180
601/636-3111

Professor John D. Isaacs
Director, Institute of Marine Resources
Mail Code A-027
Scripps Institution of Oceanography
LaJolla, California 92093

Mr. Phillip Keilor
1800 University Avenue
Madison, Wisconsin 53706
608/263-3260

Dr. Ray B. Krone
Civil Engineering Department
University of California at Davis
Davis, California 95616
916/752-1435

Dr. Reuben Lasker
Acting Director
Southwest Fisheries Center
P.O. Box 271
LaJolla, California 92038
714/453-2820

NAME, ADDRESS, PHONE NUMBER

Mr. Bill Musser
EPA, Marine Protection Branch (WH-548)
401 M. Street, SW
Washington, D.C. 20460
202/245-3051

Dr. William Newman
Director, Ocean Research Programs
Scripps Institution of Oceanography
LaJolla, California 92093

Dr. Willis E. Pequegnat, President
TerEco Corporation
Box 2848
College Station, Texas 77840
713/846-0211

Dr. Bobby J. Presley
TerEco Corporation
Box 2848
College Station, Texas 77840

Professor Robert O. Reid
TerEco Corporation
Box 2848
College Station, Texas 77840
713/846-0211

Dr. David Smith, President
David Smith and Assoc.
2428 Amity Street
San Diego, California 92109
714/273-3250

Mr. John Sustar
U.S. Army Engineers, South Pacific Division
630 Sansome Street
San Francisco, California 94111
415/556-0662

Mr. Ronald Wills
U.S. Army Engineers, South Pacific Division
630 Sansome Street
San Francisco, California 94111
415/556-0662

Dr. David R. Young
6154 Via Escondido
Malibu, California 90265
213/322-3080

KEY BISCAYNE ADVISORY COMMITTEE MEETING

NAME, ADDRESS, PHONE NUMBER

Mr. Vyto Andreliunas
Chief of Operations, New England Division
U.S. Army Corps of Engineers
424 Trapelo Road
Waltham, Mass. 02154
617/894-2400, Ext. 320

Mr. Harvey Bullis
Director, S.E. Fisheries Center
National Marine Fisheries Service
75 Virginia Drive Beach
Miami, Florida 33149
305/361-5761

Dr. Steve Cobb
Environmental Effects Laboratory
USAE Waterways Experiment Station, CE
Vicksburg, Ms. 39180
601/636-3111

Dr. Robert Dill
Director of Fairleigh-Dickinson University
West Indies Laboratory
P.O. Annex Box 4010
Christensted, St. Croix
U.S. Virgin Islands 00820
809/773-3339

Mr. Robert Farragut
S.E. Fisheries Center

Dr. M. Grant Gross
Director, Chesapeake Bay Institute
Macaulay Hall, Room 104
Johns Hopkins University
Charles and 34th Street
Baltimore, Maryland 21218
301/366-3300, Ext. 1482

Mr. Carl Hard
New England Division
U.S. Army Corps of Engineers
424 Trapelo Road
Waltham, Mass. 02154
617/894-2400, Ext. 522

Mr. Barry Holliday
Environmental Effects Laboratory
USAE Waterways Experiment Station, CE
Vicksburg, Ms. 39180
601/636-3111

NAME, ADDRESS, PHONE NUMBER

Dr. Bela James
TerEco Corporation
Box 2848
College Station, Texas 77840
713/846-0211

Mr. Bill Musser
EPA, Marine Protection Branch (WH-548)
401 M. Street, SW
Washington, D.C. 20460
202/245-3051

Dr. Harold D. Palmer
Dames & Moore
Suite 700
7101 Wisconsin Avenue
Washington D.C. 20014
301/652-2215

Dr. Willis E. Pequegnat, President
TerEco Corporation
Box 2848
College Station, Texas 77840
713/846-0211

Dr. John Proni
Atlantic Oceanographic & Meteorological Labs
15 Rickenbacker Causeway
Miami, Florida 33149
305/361-3361

Dr. Douglas Segar
NOAA-NOS-EDL
Rockville, Maryland 20852
202/443-8585

Dr. David Smith, President
David Smith and Assoc.
2428 Amity Street
San Diego, California 92109
714/273-3250

Dr. Andrew Vastano
TerEco Corporation
Box 2848
College Station, Texas 77840
713/846-0211

Dr. Herbert L. Windom
Skidaway Institute of Oceanography
P.O. Box 13687
Savannah, Georgia 31406
912/352-1631

APPENDIX B

EPA 1977 OCEAN DUMPING
REGULATIONS AND CRITERIA

EXCERPTS PERTAINING TO
OCEAN DISPOSAL OF DREDGED MATERIAL

federal register

TUESDAY, JANUARY 11, 1977

PART VI

ENVIRONMENTAL PROTECTION AGENCY

OCEAN DUMPING

Final Revision of Regulations and Criteria

(1) For each six-month period, if any, following the effective date of the permit;

(2) For any other period of less than six months ending on the expiration date of the permit; and

(3) As otherwise required in the conditions of the permit.

(b) *Reports of emergency dumping.* If material is dumped without a permit pursuant to paragraph (c) (4) of § 220.1, the owner or operator of the vessel or aircraft from which such dumping occurs shall as soon as feasible inform the Administrator, Regional Administrator, or the nearest Coast Guard district of the incident by radio, telephone, or telegraph and shall within 10 days file a written report with the Administrator or Regional Administrator containing the information required under § 224.1 and a complete description of the circumstances under which the dumping occurred. Such description shall explain how human life at sea was in danger and how the emergency dumping reduced that danger. If the material dumped included containers, the vessel owner or operator shall immediately request the U.S. Coast Guard to publish in the local Notice to Mariners the dumping location, the type of containers, and whether the contents are toxic or explosive. Notification shall also be given to the Food and Drug Administration, Shellfish Sanitation Branch, Washington, D.C. 20204, as soon as possible.

PART 225—CORPS OF ENGINEERS DREDGED MATERIAL PERMITS

Sec.
225.1 General.
225.2 Review of Dredged Material Permits.
225.3 Procedure for invoking economic impact.
225.4 Waiver by Administrator.

AUTHORITY: 33 U.S.C. 1412 and 1418.

§ 225.1 General.

Applications and authorizations for Dredged Material Permits under section 103 of the Act for the transportation of dredged material for the purpose of dumping it in ocean waters will be evaluated by the U.S. Army Corps of Engineers in accordance with the criteria set forth in Part 227 and processed in accordance with 33 CFR 209.120 with special attention to § 209.120(g) (17) and 33 CFR 209.145.

§ 225.2 Review of Dredged Material Permits.

(a) The District Engineer shall send a copy of the public notice to the appropriate Regional Administrator, and set forth in writing all of the following information:

(1) The location of the proposed disposal site and its physical boundaries;

(2) A statement as to whether the site has been designated for use by the Administrator pursuant to section 102 (c) of the Act;

(3) If the proposed disposal site has not been designated by the Administrator, a statement of the basis for the proposed determination why no previously designated site is feasible and a description of the characteristics of the proposed disposal site necessary for its designation pursuant to Part 228 of this Subchapter H;

(4) The known historical uses of the proposed disposal site;

(5) Existence and documented effects of other authorized dumpings that have been made in the dumping area (e.g., heavy metal background reading and organic carbon content);

(6) An estimate of the length of time during which disposal will continue at the proposed site;

(7) Characteristics and composition of the dredged material; and

(8) A statement concerning a preliminary determination of the need for and/or availability of an environmental impact statement.

(b) The Regional Administrator will within 15 days of the date the public notice and other information required to be submitted by paragraph (a) of § 225.2 are received by him, review the information submitted and request from the District Engineer any additional information he deems necessary or appropriate to evaluate the proposed dumping.

(c) Using the information submitted by the District Engineer, and any other information available to him, the Regional Administrator will within 15 days after receipt of all requested information, make an independent evaluation of the proposed dumping in accordance with the criteria and respond to the District Engineer pursuant to paragraphs (d) or (e) of this section. The Regional Administrator may request an extension of this 15 day period to 30 days from the District Engineer.

(d) When the Regional Administrator determines that the proposed dumping will comply with the criteria, he will so inform the District Engineer in writing.

(e) When the Regional Administrator determines that the proposed dumping will not comply with the criteria he shall so inform the District Engineer in writing. In such cases, no Dredged Material Permit for such dumping shall be issued unless and until the provisions of § 225.3 are followed and the Administrator grants a waiver of the criteria pursuant to § 225.4.

§ 225.3 Procedure for invoking economic impact.

(a) When a District Engineer's determination to issue a Dredged Material Permit for the dumping of dredged material into ocean waters has been rejected by a Regional Administrator upon application of the Criteria, the District Engineer may determine whether, under § 103 (d) of the Act, there is an economically feasible alternative method or site available other than the proposed dumping in ocean waters. If the District Engineer makes any such preliminary determination that there is no economically feasible alternative method or site available, he shall so advise the Regional Administrator setting forth his reasons for such determination and shall submit a report of such determination to the Chief of Engineers in accordance with 33 CFR §§ 209.120 and 209.145.

(b) If the decision of the Chief of Engineers is that ocean dumping at the designated site is required because of the unavailability of feasible alternatives, he shall so certify and request that the Secretary of the Army seek a waiver from the Administrator of the Criteria or of the critical site designation in accordance with § 225.4.

§ 225.4 Waiver by Administrator.

The Administrator shall grant the requested waiver unless within 30 days of his receipt of the notice, certificate and request in accordance with paragraph (b) of § 225.3 he determines in accordance with this section that the proposed dumping will have an unacceptable adverse effect on municipal water supplies, shellfish beds and fishery areas (including spawning and breeding areas), wildlife, or recreational areas. Notice of the Administrator's final determination under this section shall be given to the Secretary of the Army.

PART 226—ENFORCEMENT

Sec.
226.1 Civil penalties.
226.2 Enforcement hearings.
226.3 Determinations.
226.4 Final action.

AUTHORITY: 33 U.S.C. 1412 and 1418.

§ 226.1 Civil penalties.

In addition to the criminal penalties provided for in section 105(b) of the Act, the Administrator or his designee may assess a civil penalty of not more than $50,000 for each violation of the Act and of this subchapter. Upon receipt of information that any person has violated any provision of the Act or of this subchapter, the Administrator or his designee will notify such person in writing of the violation with which he is charged, and will convene a hearing no sooner than 60 days after such notice, at a convenient location, before a hearing officer. Such hearing shall be conducted in accordance with the procedures of § 226.2.

§ 226.2 Enforcement hearings.

Hearings convened pursuant to § 226.1, shall be hearings on a record before a hearing officer. Parties may be represented by counsel and will have the right to submit motions, to present evidence in their own behalf, to cross-examine adverse witnesses, to be apprised of all evidence considered by the hearing officer, and to receive copies of the transcript of the proceedings. Formal rules of evidence will not apply. The hearing officer will rule on all evidentiary matters, and on all motions, which will be subject to review pursuant to § 226.3.

§ 226.3 Determinations.

Within 30 days following adjournment of the hearing, the hearing officer will in all cases make findings of facts and recommendations to the Administrator including, when appropriate, a recommended appropriate penalty, after consideration of the gravity of the violation, prior violations by the person charged, and the demonstrated good faith by such person in attempting to achieve rapid compliance with the provisions of the Act and this subchapter. A copy of the findings and recommendations of the hearing officer shall be provided to the person charged at the same time they are forwarded to the Administrator. Within 30 days of the date on which the hearing officer's findings and recommendations are forwarded to the Administrator, any party objecting thereto may file written exceptions with the Administrator.

§ 226.4 Final action.

A final order on a proceeding under this Part will be issued by the Administrator, or by such other person designated by the Administrator to take such final action, no sooner than 30 days following receipt of the findings and recommendations of the hearing officer. A copy of the final order will be served by registered mail (return receipt requested) on the person charged or his representative. In the event the final order assesses a penalty, it shall be payable within 60 days of the date of receipt of the final order, unless judicial review of the final order is sought by the person against whom the penalty is assessed.

PART 227—CRITERIA FOR THE EVALUATION OF PERMIT APPLICATIONS FOR OCEAN DUMPING OF MATERIALS

Subpart A—General

Sec.
227.1 Applicability.
227.2 Materials which satisfy the environmental impact criteria of Subpart B.
227.3 Materials which do not satisfy the environmental impact criteria of Subpart B.

Subpart B—Environmental Impact

227.4 Criteria for evaluating environmental impact.
227.5 Prohibited materials.
227.6 Constituents prohibited as other than trace contaminants.
227.7 Limits established for specific wastes or waste constituents.
227.8 Limitations on the disposal rates of toxic wastes.
227.9 Limitations on quantities of waste materials.
227.10 Hazards to fishing, navigation, shorelines or beaches.
227.11 Containerized wastes.
227.12 Insoluble wastes.
227.13 Dredged Materials.

Subpart C—Need for Ocean Dumping

227.14 Criteria for evaluating the need for ocean dumping and alternatives to ocean dumping.
227.15 Factors considered.
227.16 Basis for determination of need for ocean dumping.

Subpart D—Impact of the Proposed Dumping on Esthetic, Recreational and Economic Values

227.17 Basis for determination.
227.18 Factors considered.
227.19 Assessment of impact.

Subpart E—Impact of the Proposed Dumping on Other Uses of the Ocean

227.20 Basis for determination.
227.21 Uses considered.
227.22 Assessment of impact.

Subpart F—Special Requirements for Interim Permits Under Section 102 of the Act

Sec.
227.23 General requirement.
227.24 Contents of environmental assessment.
227.25 Contents of plans.
227.26 Implementation of plans.

Subpart G—Definitions

227.27 Limiting Permissible Concentration (LPC).
227.28 Release zone.
227.29 Initial mixing.
227.30 High-level radioactive waste.
227.31 Applicable marine water quality criteria.
227.32 Liquid, suspended particulate, and solid phases of a material.

Subpart A—General

§ 227.1 Applicability.

(a) Section 102 of the Act requires that criteria for the issuance of ocean disposal permits be promulgated after consideration of the environmental effect of the proposed dumping operation, the need for ocean dumping, alternatives to ocean dumping, and the effect of the proposed action on esthetic, recreational and economic values and on other uses of the ocean. This Part 227 and Part 228 of this Subchapter H together constitute the criteria established pursuant to section 102 of the Act. The decision of the Administrator, Regional Administrator or the District Engineer, as the case may be, to issue or deny a permit and to impose specific conditions on any permit issued will be based on an evaluation of the permit application pursuant to the criteria set forth in this Part 227 and upon the requirements for disposal site management pursuant to the criteria set forth in Part 228 of this Subchapter H.

(b) With respect to the criteria to be used in evaluating disposal of dredged materials, this section and Subparts C, D, E, and G apply in their entirety. To determine whether the proposed dumping of dredged material complies with Subpart B, only §§ 227.4, 227.5, 227.6, 227.9, 227.10 and 227.13 apply. An applicant for a permit to dump dredged material must comply with all of Subparts C, D, E, G and applicable sections of B, to be deemed to have met the EPA criteria for dredged material dumping promulgated pursuant to section 102(a) of the Act. If, in any case, the Chief of Engineers finds that, in the disposition of dredged material, there is no economically feasible method or site available other than a dumping site, the utilization of which would result in noncompliance with the criteria established pursuant to Subpart B relating to the effects of dumping or with the restrictions established pursuant to section 102(c) of the Act relating to critical areas, he shall so certify and request that the Secretary of the Army seek a waiver from the Administrator pursuant to Part 225.

(c) The Criteria of this Part 227 are established pursuant to section 102 of the Act and apply to the evaluation of proposed dumping of materials under Title I of the Act. The Criteria of this Part 227 deal with the evaluation of proposed dumping of materials on a case-by-case basis from information supplied by the applicant or otherwise available to EPA or the Corps of Engineers concerning the characteristics of the waste and other considerations relating to the proposed dumping.

(d) After consideration of the provisions of §§ 227.28 and 227.29, no permit will be issued when the dumping would result in a violation of applicable water quality standards.

§ 227.2 Materials which satisfy the environmental impact criteria of Subpart B.

(a) If the applicant satisfactorily demonstrates that the material proposed for ocean dumping satisfies the environmental impact criteria set forth in Subpart B, a permit for ocean dumping will be issued unless:

(1) There is no need for the dumping, and alternative means of disposal are available, as determined in accordance with the criteria set forth in Subpart C; or

(2) There are unacceptable adverse effects on esthetic, recreational or economic values as determined in accordance with the criteria set forth in Subpart D; or

(3) There are unacceptable adverse effects on other uses of the ocean as determined in accordance with the criteria set forth in Subpart E.

(b) If the material proposed for ocean dumping satisfies the environmental impact criteria set forth in Subpart B, but the Administrator or the Regional Administrator, as the case may be, determines that any one of the considerations set forth in paragraphs (a) (1), (2) or (3) of this section applies, he will deny the permit application; provided however, that he may issue an interim permit for ocean dumping pursuant to paragraph (d) of § 220.3 and Subpart F of this Part 227 when he determines that:

(1) The material proposed for ocean dumping does not contain any of the materials listed in § 227.5 or listed in § 227.6, except as trace contaminants; and

(2) In accordance with Subpart C there is a need to ocean dump the material and no alternatives are available to such dumping; and

(3) The need for the dumping and the unavailability of alternatives, as determined in accordance with Subpart C, are of greater significance to the public interest than the potential for adverse effect on esthetic, recreational or economic values, or on other uses of the ocean, as determined in accordance with Subparts D and E, respectively.

§ 227.3 Materials which do not satisfy the environmental impact criteria set forth in Subpart B.

If the material proposed for ocean dumping does not satisfy the environmental impact criteria of Subpart B, the Administrator or the Regional Administrator, as the case may be, will deny the permit application; provided however, that he may issue an interim permit pursuant to paragraph (d) of § 220.3 and

Subpart F of this Part 227 when he determines that:

(a) The material proposed for dumping does not contain any of the materials listed in Section 227.6 except as trace contaminants, or any of the materials listed in § 227.5;

(b) In accordance with Subpart C there is a need to ocean dump the material; and

(c) Any one of the following factors is of greater significance to the public interest than the potential for adverse impact on the marine environment, as determined in accordance with Subpart B:

(1) The need for the dumping, as determined in accordance with Subpart C; or

(2) The adverse effects of denial of the permit on recreational or economic values as determined in accordance with Subpart D; or

(3) The adverse effects of denial of the permit on other uses of the ocean, as determined in accordance with Subpart E.

Subpart B—Environmental Impact

§ 227.4 Criteria for evaluating environmental impact.

This Subpart B sets specific environmental impact prohibitions, limits, and conditions for the dumping of materials into ocean waters. If the applicable prohibitions, limits, and conditions are satisfied, it is the determination of EPA that the proposed disposal will not unduly degrade or endanger the marine environment and that the disposal will present:

(a) No unacceptable adverse effects on human health and no significant damage to the resources of the marine environment;

(b) No unacceptable adverse effect on the marine ecosystem;

(c) No unacceptable adverse persistent or permanent effects due to the dumping of the particular volumes or concentrations of these materials; and

(d) No unacceptable adverse effect on the ocean for other uses as a result of direct environmental impact.

§ 227.5 Prohibited materials.

The ocean dumping of the following materials will not be approved by EPA or the Corps of Engineers under any circumstances:

(a) High-level radioactive wastes as defined in § 227.30;

(b) Materials in whatever form (including without limitation, solids, liquids, semi-liquids, gases or organisms) produced or used for radiological, chemical or biological warfare;

(c) Materials insufficiently described by the applicant in terms of their compositions and properties to permit application of the environmental impact criteria of this Subpart B;

(d) Persistent inert synthetic or natural materials which may float or remain in suspension in the ocean in such a manner that they may interfere materially with fishing, navigation, or other legitimate uses of the ocean.

§ 227.6 Constituents prohibited as other than trace contaminants.

(a) Subject to the exclusions of paragraphs (f), (g) and (h) of this section, the ocean dumping, or transportation for dumping, of materials containing the following constituents as other than trace contaminants will not be approved on other than an emergency basis:

(1) Organohalogen compounds;

(2) Mercury and mercury compounds;

(3) Cadmium and cadmium compounds;

(4) Oil of any kind or in any form, including but not limited to petroleum, oil sludge, oil refuse, crude oil, fuel oil, heavy diesel oil, lubricating oils, hydraulic fluids, and any mixtures containing these, transported for the purpose of dumping insofar as these are not regulated under the FWPCA;

(5) Known carcinogens, mutagens, or teratogens or materials suspected to be carcinogens, mutagens, or teratogens by responsible scientific opinion.

(b) These constituents will be considered to be present as trace contaminants only when they are present in materials otherwise acceptable for ocean dumping in such forms and amounts in liquid, suspended particulate, and solid phases that the dumping of the materials will not cause significant undesirable effects, including the possibility of danger associated with their bioaccumulation in marine organisms.

(c) The potential for significant undesirable effects due to the presence of these constituents shall be determined by application of results of bioassays on liquid, suspended particulate, and solid phases of wastes according to procedures acceptable to EPA, and for dredged material, acceptable to EPA and the Corps of Engineers. Materials shall be deemed environmentally acceptable for ocean dumping only when the following conditions are met:

(1) The liquid phase does not contain any of these constituents in concentrations which will exceed applicable marine water quality criteria after allowance for initial mixing; provided that mercury concentrations in the disposal site, after allowance for initial mixing, may exceed the average normal ambient concentrations of mercury in ocean waters at or near the dumping site which would be present in the absence of dumping, by not more than 50 percent; and

(2) Bioassay results on the suspended particulate phase of the waste do not indicate occurrence of significant mortality or significant adverse sublethal effects including bioaccumulation due to the dumping of wastes containing the constituents listed in paragraph (a) of this section. These bioassays shall be conducted with appropriate sensitive marine organisms as defined in § 227.27(c) using procedures for suspended particulate phase bioassays approved by EPA, or, for dredged material, approved by EPA and the Corps of Engineers. Procedures approved for bioassays under this section will require exposure of organisms for a sufficient period of time and under appropriate conditions to provide reasonable assurance, based on consideration of the statistical significance of effects at the 95 percent confidence level, that, when the materials are dumped, no significant undesirable effects will occur due either to chronic toxicity or to bioaccumulation of the constituents listed in paragraph (a) of this section; and

(3) Bioassay results on the solid phase of the wastes do not indicate occurrence of significant mortality or significant adverse sublethal effects due to the dumping of wastes containing the constituents listed in paragraph (a) of this section. These bioassays shall be conducted with sensitive benthic organisms using benthic bioassay procedures approved by EPA, or, for dredged material, approved by EPA and the Corps of Engineers. Procedures approved for bioassays under this section will require exposure of organisms for a sufficient period of time to provide reasonable assurance, based on considerations of statistical significance of effects at the 95 percent confidence level, that, when the materials are dumped, no significant undesirable effects will occur due either to chronic toxicity or to bioaccumulation of the constituents listed in paragraph (a) of this section; and

(4) For persistent organohalogens not included in the applicable marine water quality criteria, bioassay results on the liquid phase of the waste show that such compounds are not present in concentrations large enough to cause significant undesirable effects due either to chronic toxicity or to bioaccumulation in marine organisms after allowance for initial mixing.

(d) When the Administrator, Regional Administrator or District Engineer, as the case may be, has reasonable cause to believe that a material proposed for ocean dumping contains compounds identified as carcinogens, mutagens, or teratogens for which criteria have not been included in the applicable marine water quality criteria, he may require special studies to be done prior to issuance of a permit to determine the impact of disposal on human health and/or marine ecosystems. Such studies must provide information comparable to that required under paragraph (c)(3) of this section.

(e) The criteria stated in paragraphs (c) (2) and (3) of this section will become mandatory as soon as announcement of the availability of acceptable procedures is made in the FEDERAL REGISTER. At that time the interim criteria contained in paragraph (e) of this section shall no longer be applicable. As interim measures the criteria of paragraphs (c) (2) and (3) of this section may be applied on a case-by-case basis where interim guidance on acceptable bioassay procedures is provided by the Regional Administrator or, in the case of dredged material, by the District Engineer; or, in the absence of such guidance, permits may be issued for the dumping of any material only when the following conditions are met, except under an emergency permit:

(1) Mercury and its compounds are present in any solid phase of a material in concentrations less than 0.75 mg/kg,

or less than 50 percent greater than the average total mercury content of natural sediments of similar lithologic characteristics as those at the disposal site; and

(2) Cadmium and its compounds are present in any solid phase of a material in concentrations less than 0.6 mg/kg, or less than 50 percent greater than the average total cadmium content of natural sediments of similar lithologic characteristics as those at the disposal site; and

(3) The total concentration of organohalogen constituents in the waste as transported for dumping is less than a concentration of such constituents known to be toxic to marine organisms. In calculating the concentration of organohalogens, the applicant shall consider that these constituents are all biologically available. The determination of the toxicity value will be based on existing scientific data or developed by the use of bioassays conducted in accordance with approved EPA procedures; and

(4) The total amounts of oils and greases as identified in paragraph (a)(4) of this section do not produce a visible surface sheen in an undisturbed water sample when added at a ratio of one part waste material to 100 parts of water.

(f) The prohibitions and limitations of this section do not apply to the constituents identified in paragraph (a) of this section when the applicant can demonstrate that such constituents are (1) present in the material only as chemical compounds or forms (e.g., inert insoluble solid materials) non-toxic to marine life and non-bioaccumulative in the marine environment upon disposal and thereafter, or (2) present in the material only as chemical compounds or forms which, at the time of dumping and thereafter, will be rapidly rendered non-toxic to marine life and non-bioaccumulative in the marine environment by chemical or biological degradation in the sea; provided they will not make edible marine organisms unpalatable; or will not endanger human health or that of domestic animals, fish, shellfish, or wildlife.

(g) The prohibitions and limitations of this section do not apply to the constituents identified in paragraph (a) of this section for the granting of research permits if the substances are rapidly rendered harmless by physical, chemical or biological processes in the sea; provided they will not make edible marine organisms unpalatable and will not endanger human health or that of domestic animals.

(h) The prohibitions and limitations of this section do not apply to the constituents identified in paragraph (a) of this section for the granting of permits for the transport of these substances for the purpose of incineration at sea if the applicant can demonstrate that the stack emissions consist of substances which are rapidly rendered harmless by physical, chemical or biological processes in the sea. Incinerator operations shall comply with requirements which will be established on a case-by-case basis.

§ 227.7 *Limits established for specific wastes or waste constituents.*

Materials containing the following constituents must meet the additional limitations specified in this section to be deemed acceptable for ocean dumping:

(a) Liquid waste constituents immiscible with or slightly soluble in seawater, such as benzene, xylene, carbon disulfide and toluene, may be dumped only when they are present in the waste in concentrations below their solubility limits in seawater. This provision does not apply to materials which may interact with ocean water to form insoluble materials;

(b) *Radioactive materials, other than* those prohibited by § 227.5, must be contained in accordance with the provisions of § 227.11 to prevent their direct dispersion or dilution in ocean waters;

(c) Wastes containing living organisms may not be dumped if the organisms present would endanger human health or that of domestic animals, fish, shellfish and wildlife by:

(1) Extending the range of biological pests, viruses, pathogenic microorganisms or other agents capable of infesting, infecting or extensively and permanently altering the normal populations of organisms;

(2) Degrading uninfected areas; or

(3) Introducing viable species not indigenous to an area.

(d) In the dumping of wastes of highly acidic or alkaline nature into the ocean, consideration shall be given to: (1) the effects of any change in acidity or alkalinity of the water at the disposal site; and (2) the potential for synergistic effects or for the formation of toxic compounds at or near the disposal site. Allowance may be made in the permit conditions for the capability of ocean waters to neutralize acid or alkaline wastes; provided, however, that dumping conditions must be such that the average total alkalinity or total acidity of the ocean water after allowance for initial mixing, as defined in § 227.29, may be changed, based on stoichiometric calculations, by no more than 10 per cent during all dumping operations at a site to neutralize acid or alkaline wastes.

(e) Wastes containing biodegradable constituents, or constituents which consume oxygen in any fashion, may be dumped in the ocean only under conditions in which the dissolved oxygen after allowance for initial mixing, as defined in § 227.29, will not be depressed by more than 25 per cent below the normally anticipated ambient conditions in the disposal area at the time of dumping.

§ 227.8 Limitations on the disposal rates of toxic wastes.

No wastes will be deemed acceptable for ocean dumping unless such wastes can be dumped so as not to exceed the limiting permissible concentration as defined in § 227.27; provided that this § 227.8 does not apply to those wastes for which specific criteria are established in § 227.11 or 227.12. Total quantities of wastes dumped at a site may be limited as described in § 228.8.

§ 227.9 *Limitations on quantities of waste materials.*

Substances which may damage the ocean environment due to the quantities in which they are dumped, or which may seriously reduce amenities, may be dumped only when the quantities to be dumped at a single time and place are controlled to prevent long-term damage to the environment or to amenities.

§ 227.10 Hazards to fishing, navigation, shorelines or beaches.

(a) Wastes which may present a serious obstacle to fishing or navigation may be dumped only at disposal sites and under conditions which will ensure no unacceptable interference with fishing or navigation.

(b) Wastes which may present a hazard to shorelines or beaches may be dumped only at sites and under conditions which will insure no unacceptable danger to shorelines or beaches.

§ 227.11 Containerized wastes.

(a) Wastes containerized solely for transport to the dumping site and expected to rupture or leak on impact or shortly thereafter must meet the appropriate requirements of §§ 227.6, 227.7, 227.8, 227.9 and 227.10.

(b) Other containerized wastes will be approved for dumping only under the following conditions:

(1) The materials to be disposed of decay, decompose or radiodecay to environmentally innocuous materials within the life expectancy of the containers and/or their inert matrix; and

(2) Materials to be dumped are present in such quantities and are of such nature that only short-term localized adverse effects will occur should the containers rupture at any time; and

(3) Containers are dumped at depths and locations where they will cause no threat to navigation, fishing, shorelines, or beaches.

§ 227.12 Insoluble wastes.

(a) Solid wastes consisting of inert natural minerals or materials compatible with the ocean environment may be generally approved for ocean dumping provided they are insoluble above the applicable trace or limiting permissible concentrations and are rapidly and completely settleable, and they are of a particle size and density that they would be deposited or rapidly dispersed without damage to benthic, demersal, or pelagic biota.

(b) Persistent inert synthetic or natural materials which may float or remain in suspension in the ocean as prohibited in paragraph (d) of § 227.5 may be dumped in the ocean only when they have been processed in such a fashion that they will sink to the bottom and remain in place.

§ 227.13 Dredged materials.

(a) Dredged materials are bottom sediments or materials that have been dredged or excavated from the navigable waters of the United States, and their disposal into ocean waters is regulated by the U.S. Army Corps of Engineers using the criteria of applicable sections of Parts 227 and 228. Dredged material consists primarily of natural sediments or materials which may be contaminated by municipal or industrial wastes or by runoff from terrestrial sources such as agricultural lands.

(b) Dredged material which meets the criteria set forth in the following paragraphs (1), (2), or (3) is environmentally acceptable for ocean dumping without further testing under this section:

(1) Dredged material is composed predominantly of sand, gravel, rock, or any other naturally occurring bottom material with particle sizes larger than silt, and the material is found in areas of high current or wave energy such as streams with large bed loads or coastal areas with shifting bars and channels; or

(2) Dredged material is for beach nourishment or restoration and is composed predominantly of sand, gravel or shell with particle sizes compatible with material on the receiving beaches; or

(3) When: (i) The material proposed for dumping is substantially the same as the substrate at the proposed disposal site; and

(ii) The site from which the material proposed for dumping is to be taken is far removed from known existing and historical sources of pollution so as to provide reasonable assurance that such material has not been contaminated by such pollution.

(c) When dredged material proposed for ocean dumping does not meet the criteria of paragraph (b) of this section, further testing of the liquid, suspended particulate, and solid phases, as defined in § 227.32, is required. Based on the results of such testing, dredged material can be considered to be environmentally acceptable for ocean dumping only under the following conditions:

(1) The material is in compliance with the requirements of § 227.6; and

(2) (i) All major constituents of the liquid phase are in compliance with the applicable marine water quality criteria after allowance for initial mixing; or

(ii) When the liquid phase contains major constituents not included in the applicable marine water quality criteria, or there is reason to suspect synergistic effects of certain contaminants, bioassays on the liquid phase of the dredged material show that it can be discharged so as not to exceed the limiting permissible concentration as defined in paragraph (a) of § 227.27; and

(3) Bioassays on the suspended particulate and solid phases show that it can be discharged so as not to exceed the limiting permissible concentration as defined in paragraph (b) of § 227.27.

(d) For the purposes of paragraph (c) (2), major constituents to be analyzed in the liquid phase are those deemed critical by the District Engineer, after evaluating and considering any comments received from the Regional Administrator, and considering known sources of discharges in the area.

Subpart C—Need for Ocean Dumping

§ 227.14 Criteria for evaluating the need for ocean dumping and alternatives to ocean dumping.

This Subpart C states the basis on which an evaluation will be made of the need for ocean dumping, and alternatives to ocean dumping. The nature of these factors does not permit the promulgation of specific quantitative criteria of each permit application. These factors will therefore be evaluated if applicable for each proposed dumping on an individual basis using the guidelines specified in this Subpart C.

§ 227.15 Factors considered.

The need for dumping will be determined by evaluation of the following factors:

(a) Degree of treatment useful and feasible for the waste to be dumped, and whether or not the waste material has been or will be treated to this degree before dumping;

(b) Raw materials and manufacturing or other processes resulting in the waste, and whether or not these materials or processes are essential to the provision of the applicant's goods or services, or if other less polluting materials or processes could be used;

(c) The relative environmental risks, impact and cost for ocean dumping as opposed to other feasible alternatives including but not limited to:

(1) Land fill;
(2) Well injection;
(3) Incineration;
(4) Spread of material over open ground;
(5) Recycling of material for reuse;
(6) Additional biological, chemical, or physical treatment of intermediate or final waste streams;
(7) Storage.

(d) Irreversible or irretrievable consequences of the use of alternatives to ocean dumping.

§ 227.16 Basis for determination of need for ocean dumping.

(a) A need for ocean dumping will be considered to have been demonstrated when a thorough evaluation of the factors listed in § 227.15 has been made, and the Administrator, Regional Administrator or District Engineer, as the case may be, has determined that the following conditions exist where applicable:

(1) There are no practicable improvements which can be made in process technology or in overall waste treatment to reduce the adverse impacts of the waste on the total environment;

(2) There are no practicable alternative locations and methods of disposal or recycling available, including without limitation, storage until treatment facilities are completed, which have less adverse environmental impact or potential risk to other parts of the environment than ocean dumping.

(b) For purposes of paragraph (a) of this section, waste treatment or improvements in processes and alternative methods of disposal are practicable when they are available at reasonable incremental cost and energy expenditures, which need not be competitive with the costs of ocean dumping, taking into account the environmental benefits derived from such activity, including the relative adverse environmental impacts associated with the use of alternatives to ocean dumping.

(c) The duration of permits issued under Subchapter H and other terms and conditions imposed in those permits shall be determined after taking into account the factors set forth in this section. Notwithstanding compliance with Subparts B, D, and E of this Part 227 permittees may, on the basis of the need for and alternatives to ocean dumping, be required to terminate all ocean dumping by a specified date, to phase out all ocean dumping over a specified period or periods, to continue research and development of alternative methods of disposal and make periodic reports of such research and development in order to provide additional information for periodic review of the need for and alternatives to ocean dumping, or to take such other action as the Administrator, the Regional Administrator, or District Engineer, as the case may be, determines to be necessary or appropriate.

Subpart D—Impact of the Proposed Dumping on Esthetic, Recreational and Economic Values

§ 227.17 Basis for determination.

(a) The impact of dumping on esthetic, recreational and economic values will be evaluated on an individual basis using the following considerations:

(1) potential for affecting recreational use and values of ocean waters, inshore waters, beaches, or shorelines;

(2) potential for affecting the recreational and commercial values of living marine resources.

(b) For all proposed dumping, full consideration will be given to such nonquantifiable aspects of esthetic, recreational and economic impact as:

(1) responsible public concern for the consequences of the proposed dumping;

(2) consequences of not authorizing the dumping including without limitation, the impact on esthetic, recreational and economic values with respect to the municipalities and industries involved.

§ 227.18 Factors considered.

The assessment of the potential for impacts on esthetic, recreational and economic values will be based on an evaluation of the appropriate characteristics of the material to be dumped, allowing for conservative rates of dilution, dispersion, and biochemical degradation during movement of the materials from a disposal site to an area of significant recreational or commercial value. The following specific factors will be considered in making such an assessment:

(a) Nature and extent of present and potential recreational and commercial use of areas which might be affected by the proposed dumping;

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Pequegnat, Willis E
An assessment of the potential impact of dredged material disposal in the open ocean / by Willis E. Pequegnat ... [et al.], TerEco Corporation, College Station, Texas. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
642, 2, 6 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-78-2)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW39-76-C-0125 (DMRP Work Unit No. 1A11)
Literature cited: p. 567-607.
Bibliography: p. 609-642.
1. Dredged material disposal. 2. Environmental effects. 3. Marine environment. 4. Ocean waste disposal. I. TerEco Corporation. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-78-2.
TA7.W34 no.D-78-2