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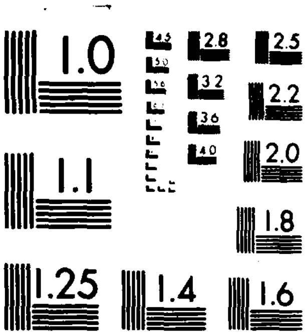

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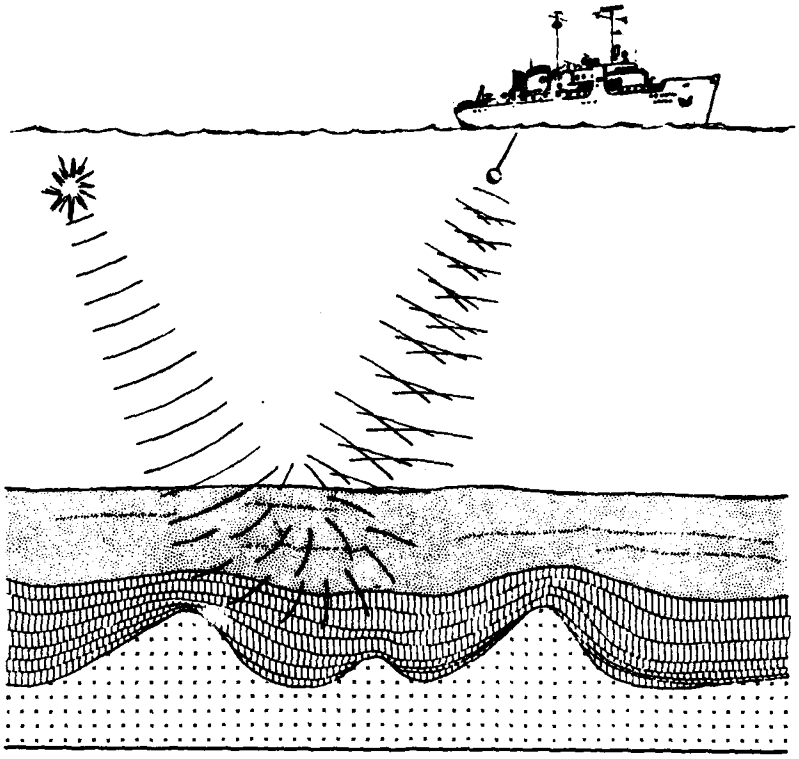
Global Analysis of the Shallow Geology of Large-Scale Ocean Slopes



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ABSTRACT

Large-scale ocean slopes have continental-slope dimensions (e.g., slope inclinations exceeding 1° for relief of 2000 m). Approximately 40% are related to continental margins, 40% to features with oceanic crust, and 20% to unknown origins or overlap with the first two groups. Of the slopes, 75% are laterally continuous (lateral slopes), and the remaining 25% form the sides of conical-shaped features.

Groupings and ranges have been established for the following lateral slope parameters: ocean section, top boundary province, bottom boundary province, relief, slope angle, surface-sediment grain size, plate-tectonic association, shape, outcrop type in the upper 200 m, percent of slope with outcrop, sediment thickness, and basement type. Mapping and computer adaption of parameter compilations reveal global data distributions, global averages, parameter relationships, and applied classification methods. Global averages are 3.8° for slope angle, 3035 m for relief, and 38% for percent of slope with outcrop. Strongest relationships occur among top boundary province, bottom boundary province, plate-tectonic association, and surface-sediment type.

Preferred clustering of parameter relationships reveal four model groups for lateral slopes. Group I centers around strong association of broad shelves, rises, and divergent plate-tectonic association. Group II includes high-relief slopes associated with subduction and high-angle slopes associated with translation. Group III contains the slopes of oceanic features and carbonate surface sediments. Group IV, the smallest group, includes outer trench walls.

INTRODUCTION

Objectives

The motivation for this thesis is the absence of a comprehensive evaluation of the shallow geology of large-scale ocean slopes. The objective is to define the ranges, groupings and relationships of data which describe morphology, sedimentation and shallow geological structure associated with all ocean slopes having continental-slope dimensions. This objective is achieved as follows:

1. Geometric criteria are defined.
2. Geographic slope areas are mapped.
3. Data are identified and evaluated to define groupings and ranges.
4. Selected data are shown on maps and graphs.
5. Interpretations and conclusions are formulated from the compilations.

Background Studies

Large-scale ocean slopes include the vast majority of continental slopes, the slopes of many intra-oceanic features (often of unknown origin), most slopes associated with island arcs, ocean volcanoes, and a small proportion of the total extent of fracture zones and ridge-crest features. Although no available studies characterize the geology for the total range of slopes, various studies explore specific aspects.

The most comprehensive studies deal with continental slopes (e.g., Dietz, 1964; Emery, 1950, 1968, 1977, 1979; Lewis, 1974; Bouma, 1979; Dickinson and Seely, 1979). These studies relate continental slopes to continental margins and stress thc interplay of shelf, slope, and rise in the evolutionary development of the margin. Such an approach gives an overview of possible continental slope environments.

Descriptive elements of slopes were revealed in previous studies. Dietz (1964) stressed the association of slopes to the original tectonic formation of a continental margin, to the sedimentary strata, and to recent modification by erosion and deposition. Lewis (1974) implied that slope shapes tend to be prograded when associated with large sediment input and/or narrow shelves. Emery (1979) presented a comprehensive worldwide classification of continental margins based on an extensive review of seismic profiles. It can be inferred from his study that continental slopes are associated with tectonic origin of the margin, tectonic and sedimentary dams, the intensity of recent sedimentation, the influence of recent sedimentary processes, and the morphological provinces which border the upper and lower boundaries of the slopes.

Dickinson and Seely (1979) presented evolutionary models for geological features associated with subduction zones. These features consist of fore-arc regions, outer trench slopes, back-arc slopes and remnant arcs. They are associated with some of the most extreme slopes in the oceans. The term "continental slope" was found to be ambiguous in classifying these large-scale ocean slopes, because associated margins may or may not consist of true continental crust.

In their evolutionary models for intra-oceanic features, Carlson and others (1980) pointed out additional ambiguities in the definition of continental slopes. Crusts of intra-oceanic features are continental, oceanic, or unknown, and large-scale slopes often occupy the flanks of these features. It is difficult to classify these slopes as continental slopes because intra-oceanic features are anomalously small as compared to continents, their tops generally have little or no exposed land, and their crust may not be continental.

Conical ocean features include seamounts, ocean islands, guyots and atolls. Seamounts are submerged volcanoes; ocean islands are volcanoes exposed above sea level; guyots are volcanoes once exposed and eroded to the wave-base and later submerged; and atolls are volcanoes with reef caps (Menard and Ladd, 1963). This established grouping is somewhat irrelevant in classifying slopes because its basis concerns the nature of the top of the feature. Nevertheless, some generalizations can be made. The shallow structure of the slopes is dominated by the presence of basaltic basement because slopes are the sides of volcanoes. Guyots tend to have more abrupt boundaries between the upper slopes and top provinces than do seamounts. Islands may contribute terrigenous sediments to the slopes; however, the amount is usually small. The carbonate cap on atolls ranges from tens of meters up to 1400 meters for Eniwetok (Menard, 1964), and the slope angle for the cap is usually very steep. Also, reef carbonates are a source of slope sediment.

Other slopes underlain by oceanic crust are fracture zones, high relief ridge crest features, and certain carbonate banks. These slopes are not numerous and generally overlap with slopes of conical features.

It is apparent that slopes evolve from diverse origins and that evolutionary classifications are too generalized to produce complete descriptions. However, insight may be gained by use of descriptive associations of slopes to plate-tectonic origin, sedimentary history and structural development. Consequently, it is important to extract analytic elements of studies so as to characterize slope regions.

Definition of Shallow Geology on Slopes

The shallow geology of slopes includes aspects of morphology, sedimentation and tectonics associated with the upper 500 m of slope materials beneath the slope surface. It is extemely complex because of the vast range of geological environments, processes, and ages of rocks and sediments. The types of available geological data are voluminous, and selectivity is necessary to make realistic compilations. For this reason, shallow geology in this study is biased to best represent a primary motive, the characterization of slopes according to their acoustic response. The following list outlines some guidelines:

1. The primary concern is to define morphology and material from the sediment-water interface to a depth of 200 m. Less emphasis is placed upon deeper material.

2. Definition of slope materials should correlate with acoustic velocity data.

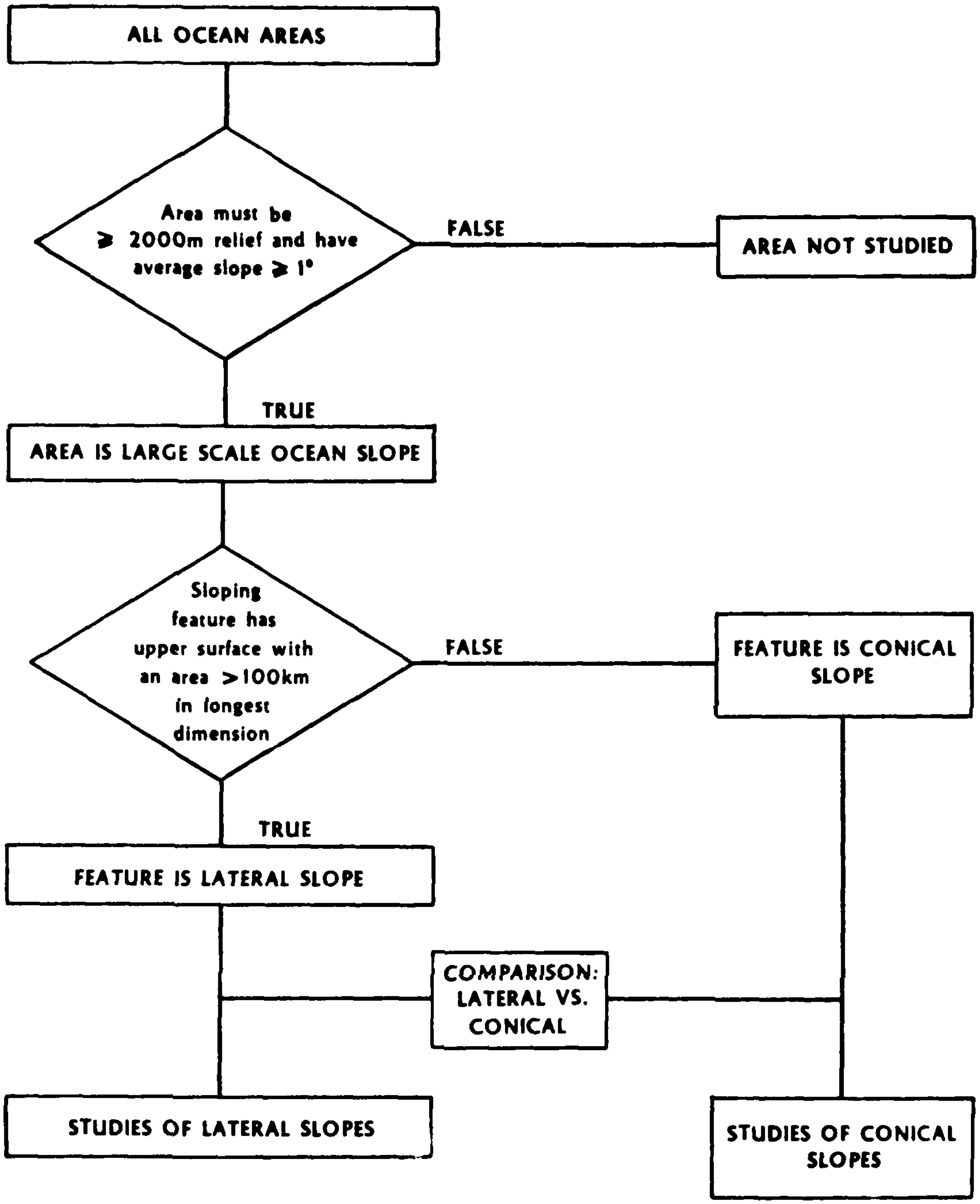
3. Data parameters must be adaptable to generalization for the entire water-depth range of the slope and for a lateral slope length of about 100 km.

A wide range of geological phenomena were explored. Data concerning average slope angle, total relief, slope shapes, border provinces, surface-sediment type, grain size and sedimentary processes were compiled to define the acoustic interaction with the sediment-water interface. Sedimentary rocks, crystalline basement, and other high velocity materials were identified as to their depth, frequency and rock type. Certain sedimentary units such as diapirs or deformed sedimentary rocks are identified and can be used to imply tectonic association. Finally, plate-tectonic associations are identified to infer tectonic influences on shallow slope materials. In other words, the shallow geology presents a very generalized picture of the physical elements of the slope environment and disregards much of the stratigraphy and structural geology except where related to outstanding acoustic response. This approach works well for characterizing the worldwide extent of slopes because the necessary descriptive data are obtainable.

Selection of Large-Scale Ocean Slopes

Designation of slope areas is based upon geometric criteria of average slope angle and relief. A large-scale ocean slope is defined as an ocean bottom which has an average slope of at least 1° for a minimum relief of 2000 m (Figure 1). Slope areas were mapped from unpublished U.S. Naval Oceanographic Office (NAVOCEANO) bathymetry maps of a scale of 1"=1° longitude (see Map I for slope locations). As a first step, contour spacings were examined to find steep areas exceeding 2000 m. For areas with acceptable relief, average slopes were measured for their steepest 2000 m relief range. If average slopes were found to exceed 1° inclination, the area was designated as a large-scale ocean slope. Finally, all sloping areas up-slope and down-slope to the 2000 m range were measured to include all sections which met the slope criteria.

FIGURE 1. Geometric classification of large-scale ocean slopes. Slopes that have average inclination of greater than 1° for 2000 m relief were designated study areas. Lateral and conical slopes were defined on the basis of the size of the top-of-slope province.


ALL OCEAN AREAS
Area must be ≥ 2000m relief and have average slope ≥ 1°
FALSE
AREA NOT STUDIED
TRUE
AREA IS LARGE SCALE OCEAN SLOPE
Sloping feature has upper surface with an area >100km in longest dimension
FALSE
FEATURE IS CONICAL SLOPE
TRUE
FEATURE IS LATERAL SLOPE
COMPARISON: LATERAL VS. CONICAL
STUDIES OF LATERAL SLOPES
STUDIES OF CONICAL SLOPES

Map I depicts the geographic distribution of large-scale ocean slopes which meet the slope criteria. The map establishes a geographic base on which to compile geological data.

Lateral and Conical Slopes

Visual inspection of the distribution of slopes (Map I) reveals an obvious discontinuity in their occurrence. Intra-oceanic areas contain significant quantities of seamounts, islands, guyots, and atolls. Because these features are approximately cone-shaped, slopes which form their sides are designated conical slopes. On the other hand, most continental slopes and slopes associated with oceanic plateaus and ridges extend laterally for great distances. These slopes are called lateral slopes. As defined for this study, conical slopes have a largest top-of-slope dimension of less than 100 km, and tops of lateral slopes have larger dimensions (Figure 1). The division of conical and lateral slopes is necessary for the following reasons:

1. As determined by lateral continuity, the geometries of conical and lateral slopes are different. An analogy is comparison of a mountain to a ridge.
2. The geometric division between lateral and conical slopes involves little overlap.
3. The geology of conical slopes (mostly volcanoes) is quite different than that of lateral slopes (mostly continental margins).
4. Geologic and bathymetric data concerning conical slopes are much sparser than for lateral slopes.

5. No reasonable method could be devised to include conical slopes in a data base with lateral slopes.

The distances along slopes were measured to derive the quantity of both conical and lateral slopes. Distances along lateral slopes were measured parallel to the intermediate depth contour of the slope. Measurement of conical slopes was more complicated. Conical features were assumed to resemble true cones. Bracey (1981) measured randomly selected basal sections of North Atlantic and North Pacific seamounts. From his data, the average radius of a basal section was calculated for a world average seamount. By using one-half this basal radius the author calculated a circumference for a cone halfway between the apex and the base. This average circumference was multiplied by the number of conical features found in each ocean section (Table I, part a). The resulting conical distances for each ocean section can be compared to the lateral slope distances.

Table I shows the equivalent distances of lateral and conical slopes for the total world oceans and by ocean sections (see Figure 2 for outlines of ocean sections). Lateral slopes generally outnumber conical slopes by 3 to 1. Whereas the North Pacific has the highest percentage of conical and combined slopes, the Indian Ocean has the highest percentage of lateral slopes and second highest of combined types. The South Pacific has the third highest percentage for each of conical, lateral, and combined slopes. The remainder of the ocean sections collectively have less than half the percentage for any slope type.

TABLE I. EQUIVALENT DISTANCES OF LATERAL AND CONICAL SLOPES

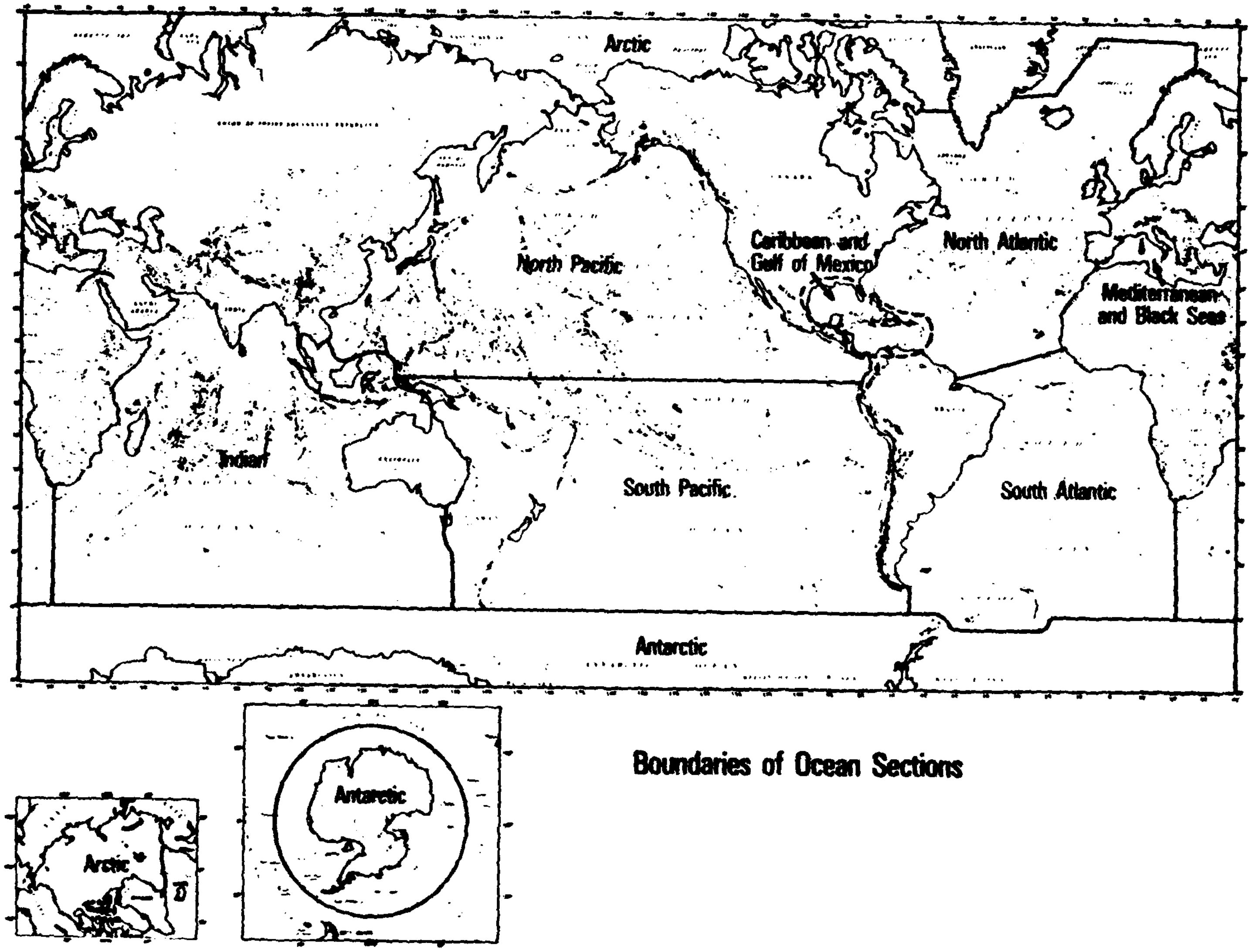
a. Conical Slopes

OCEAN AREA	NUMBER OF OCCURRENCES OF seamounts	NUMBER OF OCCURRENCES OF islands	TOTAL CONICAL FEATURE	% TOTAL WORLD
1. Indian	88	14	102	6.2%
2. North Pacific	823	79	902	55.1%
3. South Pacific	247	128	375	22.9%
4. North Atlantic	87	31	118	7.2%
5. South Atlantic	100	8	108	6.6%
6. Med. & Black Seas	-	-	-	-
7. Arctic	-	-	-	-
8. Antarctic	30	1	31	1.9%
TOTAL	1375	261	1636	99.9%

b. Lateral and Conical Slopes

OCEAN AREA	TOTAL LATERAL SLOPE (KM) AND % OF TOTAL OCEAN AREA		TOTAL CONICAL SLOPE (KM)	RATIO CONICAL/LATERAL	TOTAL SLOPE AND % OF TOTAL WORLD FOR EACH OCEAN AREA	
1. Indian	81100	26%	6408	.08	87508	21%
2. North Pacific	68500	22%	56674	.83	125174	30%
3. South Pacific	58800	19%	23561	.40	82361	20%
4. North Atlantic	35700	11%	7414	.21	43114	10%
5. South Atlantic	29400	9%	6785	.23	36185	9%
6. Med. & Black Seas	10000	3%	-	0	10000	2%
7. Arctic	11600	4%	-	0	11600	3%
8. Antarctic	17400	6%	1948	.11	19348	4%
TOTAL	312500	100%	102790	.33	415290	99%

FIGURE 2. Boundaries of ocean sections (see Parameter I, Table II).



Boundaries of Ocean Sections

COMPILATIONS OF LATERAL SLOPES

For this study, a compilation consists of a collective geologic topic which characterizes all lateral slopes by various groupings which best exhibit the topic's variation. A compilation involves formulation of a collective topic, grouping of the topic, and finally assigning the grouping scheme to the geographic extent of lateral slopes. Several compilations were completed in this section, and their products are world maps which depict various data groupings for geologic topics. These are average slope, surface-sediment type, and plate-tectonic associations of slopes. Other compilations were relegated to the data base section for geographic representation and only the grouping schemes are presented in this section. A third group of compilations consists of those topics which are not suitable to worldwide mapping because of the scale of study or the lack of worldwide data. These compilations are presented as discussions and are omitted from the data base sections.

Compilations are presented to characterize the geology of a thin layer of material found on large-scale ocean slopes. They are grouped according to morphology, surface sediments, and shallow structure. Efforts were made to quantify groupings, to stress compilation of data which relate to geometry of slopes, and to define physical properties of geologic features.

Morphology

Morphology is the geometry of the interface between the ocean bottom and the water column. Several parameters were chosen to characterize morphology. Average slope angle and total relief define the numerical dimensions of slopes. With addition of a slope shape, the subtle variations of slope angle and secondary topography become apparent. Finally, definition of boundary provinces reveals the geometric relationship of the slope to its upper and lower extremities.

Average Slope Angle

Characterization of slopes by average slope angle requires a fixed relief range. Shepard (1973) measured average slope angle for various worldwide locations of continental slopes by fixing the relief at 1800 m and disregarding the intermediate-relief topography. A similar method was used in the present study; however, 2000 m relief was used and the steepest sections of ocean slopes were measured. Average slope measurements were compiled from NAVOCEANO bathymetry at a scale of 1" = 1° longitude (over 10 x the scale of Map I). Slope regions were outlined at this scale by using the slope criteria.

Slope areas were grouped according to average slope-angle ranges (Map I). Measurement of slope angles was based upon contour spacings which decrease exponentially with increasing slope angles. A logarithmic grouping is used: 1-2°, 2-4°. 4-8°, greater than 8°.

Total Relief

Although average slope angle applies only to the steepest 2000 m, total relief is a measure of the entire slope. Total relief values were calculated by subtracting the shallowest depth from the deepest, and data were tabulated in incremental 1000 m ranges. In general, the higher-relief slopes have the greater chance of having steeper slopes because a higher relief creates more 2000 m options.

Shapes of Slopes

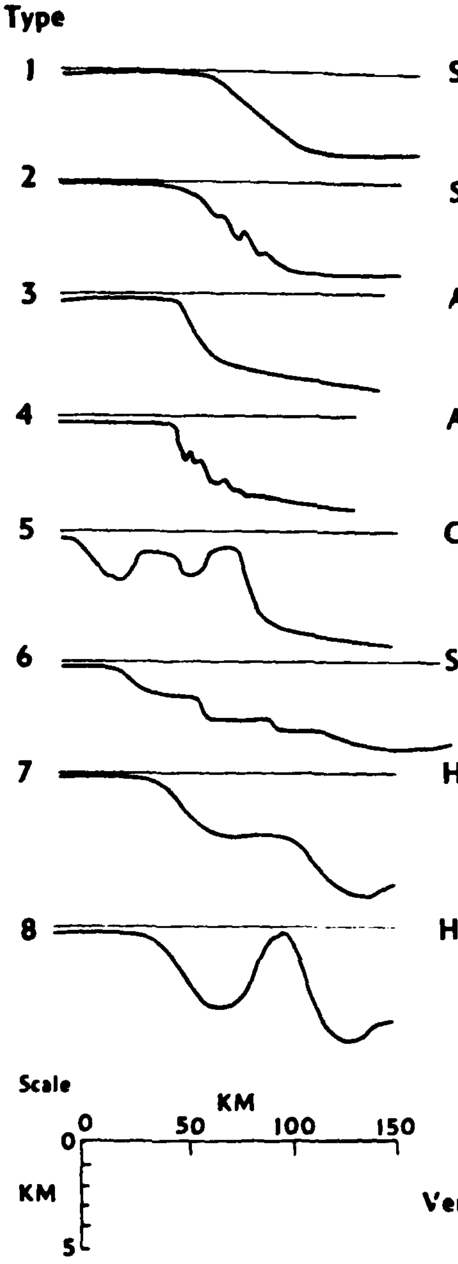
Slope shape is a relative measure of the variability of slope angles and secondary topography. Designation of shape geometries is highly subjective. The grouping scheme is defined using both relative and quantitative criteria. Shape types (Figure 3) were developed according to three major guidelines:

1. The shape types should reflect geological shape models proposed in the literature.
2. A roughness (secondary topography) scale should be implemented into the classification.
3. Individual shape types should characterize existing slope shapes as determined by analysis of the profile compilation (Appendix II).

The relative configurations and roughness groupings are illustrated in a complete classification of shape slopes (Figure 3). The ranges used to specify groups are absolute, and any slope profile can be assigned to only one group.

FIGURE 3. Slope shapes. The classification is based upon the relative variability of slope angles and bottom roughness.

Slope Shapes



Sigmoidal Smooth-
Convex upper slope, no roughness >200m relief

Sigmoidal Rough-
Convex upper slope, roughness 200-1000m relief present.

Abrupt Smooth-
Concave upper slope, no roughness >200m relief.

Abrupt Rough-
Concave upper slope, roughness 200-1000m relief present.

Complex-
>1000m but <2000m relief of anomalous topography.

Step-
Steps <2000m relief interupt a continuous slope

High Relief Step
Individual slopes with relief >2000m seperated by flat intraslope region.

High Relief Complex
Individual slopes with relief >2000m seperated by trough.

Vertical Exaggeration X 10

Previous geologic studies pointed out elements of slope shapes which prove useful in formulating a worldwide classification. Shape models were proposed for prograding slopes (Sangree and others, 1978), fore-arc slopes (Dickinson and Seely, 1979), and continental slopes (Emery, 1979). All these models are highly qualitative; nevertheless, some basic ideas were adopted. Shape types 1 and 2 (Figure 3) differ from types 3 and 4 in that the former have convex upper slopes and the latter have concave shapes. Sangree and others (1978) suggested that a convex shelf-slope break infers prograded sediment in a low-energy environment, and the concave break infers a high-energy environment. Convex slopes were also implied by the occurrence of a trench-slope break for simple fore-arc slopes (Dickinson and Seely, 1979). Similarly, the convex shape characterizes many seamount shapes (Bracey, 1981) as well as other slopes which have higher than average slope angles (Stanley, 1975). In a very diagrammatic representation of continental slopes, Emery (1979) suggested that mature prograded slopes best resemble the type 1 shape, whereas initial, youthful and truncated mature slopes resemble types 2, 4 or 5. High-relief slope shapes often exhibit multiple shapes (Types 7 and 8), and these shapes best resemble the complex fore-arc slopes (Dickinson and Seely, 1979).

Characterization of bottom roughness was arbitrarily assigned to the shape types (Figure 3). A scale of increasing relief of the maximum bottom roughness correlates with the type sequence of 1 and 3 (lowest roughness) to 2 and 4 (medium roughness) to 5 (highest roughness). Each roughness grouping has definite relief intervals so that a shape can be measured and categorized without ambiguity. Types 6-8 were not included in the roughness scheme. Types 6 and 7 have step-like roughness with no measurable relief. Types 7 and 8 have highest roughness in that the secondary topography reaches the dimensions of the primary shapes of other slopes.

Boundary Provinces

Lateral slopes are elongate geographic areas which connect with shoal areas at the top of the slope and deep areas at the bottom. The geometric forms of the boundaries are flat or slightly inclined tops of variable width, and a variety of bottom shapes such as depressions, flat areas, or a gently inclined area. Terms which generally describe these areas are shelf, ocean plateau, rise, trench, and trough. The list is neither adequate to describe all types of boundary provinces, nor is it totally geometric in its approach because sedimentary and tectonic processes are implied. For this reason, boundary provinces were defined according to basic geometric form and genetic inferences were disregarded except where specified.

Top boundary provinces were evaluated as to their size and depth. Shelves were defined as the flat or gently inclined areas which generally occur at depths of less than 300 m and connect with a land mass. A narrow shelf was arbitrarily defined as less than 100 km wide and a broad shelf as wider. This division crudely separates Pacific-type shelves from those in the Atlantic. Where a land mass is exposed with no obvious shelf top, the top was designated as island/no shelf. An ocean plateau resembles a shelf, but it may occur at any depth and is not connected with a significant land mass. An ocean plateau may occur in intra-oceanic regions at very shallow depths or at a continental margin at minimum depths of greater than 300 m. The shortest top dimension of an ocean plateau must exceed 100 km. If the top dimension is less than 100 km, the no-top classification was assigned to the feature which is typically a seamount.

Bottom provinces were evaluated according to shape and slope inclination. A rise connotes a sediment wedge; however, the definition used here is a gently inclined slope at the base of the primary slope province. Where slope bottoms into a flat province, the bottom province was designated as a no-bottom classification. The final two bottoms, trench and trough, are similar in that both are depressions. The definition of a trench is not purely geometric. All depressions associated with obvious subduction zones were designated as trenches. Trenches usually have steeper and higher-relief slopes associated with the seaward side of the depression than troughs. Troughs are commonly found at the base of oceanic features such as seamounts. All depressions which are not associated with subduction or former subduction zones were designated as troughs.

Surface Sediments

Analysis of sediment lying near the water-sediment interface on slopes is complicated. Ideally, surface sediments represent Holocene sedimentary regimes for a particular geographic area. If sedimentation rates are known, the thickness of the Holocene sediments can be calculated. In reality, slope sediments undergo a wide range of sedimentary and tectonic processes such as mass movement, faulting, and erosion. Surface sediments may be absent because of erosion or nondeposition.

Bottom surfaces may be basement outcrop or surfaces of older sediments. Surface sediments may vary in grain size and composition down slope.

An adequate representation of surface sediments is difficult to compile considering the scale of this study. For the most part, surface sediments should be Quaternary sediment. The compilation of surface sediments (Map II) represents the average of variations with depth and ignores the effects of local sedimentary processes. These topics are inadequately studied worldwide and too variable over short distances to be considered for worldwide compilations. However, they should never be overlooked when evaluating a specific slope environment.

Average Type and Grain Size

The purpose of this compilation (Map II) is to standardize a worldwide distribution of slope sediment data which can be adapted to a geoacoustic model. The sediment classification differentiates sediment types which imply varying porosity and/or water content, in addition to presenting the best available grain-size data. For the most part, surface-sediment data were compiled from the geologic literature and many aspects of the available data are unimportant for purposes of this study. Extraction of needed data was often impossible. The compilation used in this thesis leans heavily toward Soviet data because it is standardized and contains readily available bulk grain size and biogenic fraction of surface sediments (Lisitzin, 1972, 1975, 1975a) (Anonymous, 1975) (Kort, 1970, 1970a). Data from western scientists generally cannot be standardized because of the varied classification schemes and scientific purposes. Consequently, the Soviet data forms the basis of the compilations and pertinent western studies were used to supplement and check the Soviet base.

Major sediment types are terrigenous, biogenic, and nonbiogenic pelagic sediments. Terrigenous sediments consist predominantly of originally fluvial sediments; however, ice-rafted sediments are important in polar regions, aeolian sediments in arid regions and volcanogenic sediments near arcs (Lisitzin, 1972). Biogenic slope sediments are dominantly pelagic, calcareous Foraminifera and nannoplankton. Benthonic forams are common in lesser amounts and pteropods may occur in warm climates at depths less than 3000 m. Siliceous sediments consist of diatomaceous sediments in the high latitudes and radiolarian sediments in the equatorial regions, but siliceous sediments are rarely the dominant sediment on slopes. Pelagic nonbiogenic sediments generally have a higher water content than terrigenous sediments. A fourth group is transitional between the biogenic and nonbiogenic components (see Map II).

It is difficult to formulate a standard grain-size grouping from compiled data sources. Two major problems exist: correlation of grain size distribution to mean grain size and correlation of the Soviet size scale to the Wentworth-Udden scale used by western scientists.

Western studies generally describe grain size by a ternary diagram which is a plot of grain-size distribution and a description term that has quantitative boundaries (JOIDES, 1977). Mean grain size may be calculated from a detailed size analysis. Unfortunately the two results, mean grain size and the descriptive term, cannot be accurately related. The only way to overcome this problem is to compare the detailed analysis of available studies. This is beyond the scope of this thesis.

The Soviets, more so than western scientists, have collected worldwide sediment data and have published crude ranges of each major size division (Figure 4). Like the western phi scale, the Soviets use a log scale; however, the groupings are different from the Wentworth-Udden system. Lisitzin (1972) correlated the Soviet scale with western grain size usage. He linked ranges of mean grain size to Soviet distribution maps and correlated the mean grain sizes to western terminology. In Figure 4, the sediment groupings of fine-medium silt, fine silt and clay correspond to western mean grain-size studies in phi terms. Correlation of distributions to the mean grain-size data can be accomplished only by assuming normal distributions and this occurrence is unlikely. On Map II the most accurate groupings (fine silt and clay) are derived from the Soviet data. The fine to medium silt group is partially inferred from western studies (Scholl and others, 1968, Frazer and others, 1972).

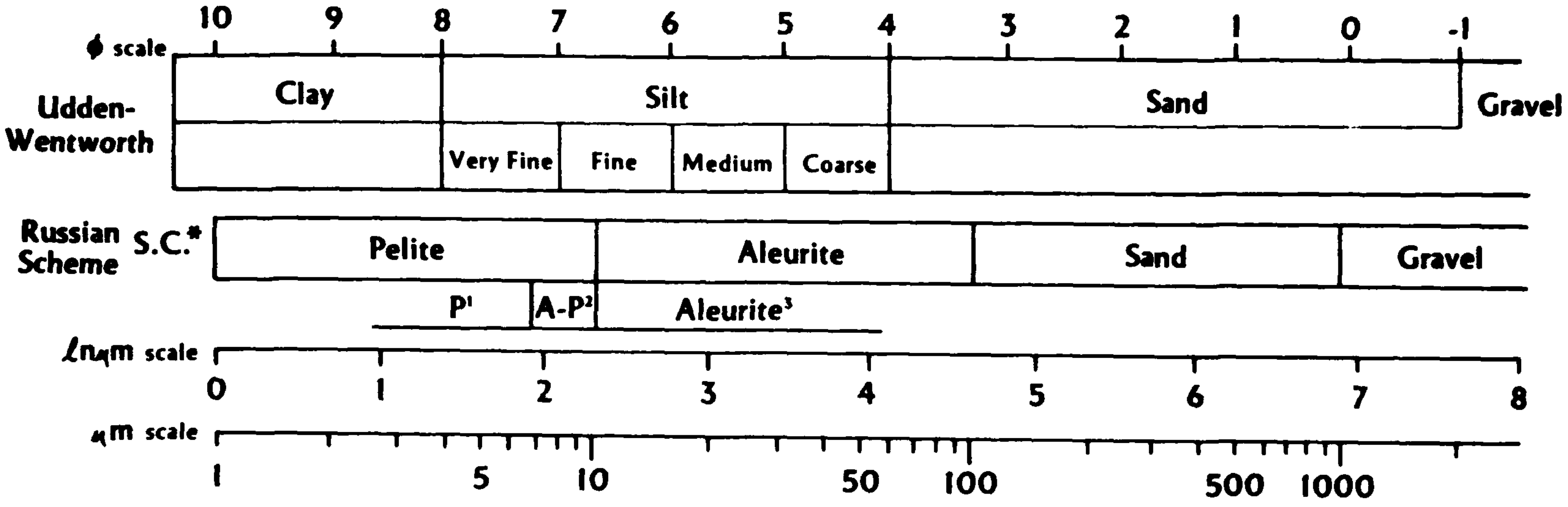
The groupings which delineate surface-sediment groups can be correlated to velocity-ratio data (Hamilton, 1980). By plotting Hamilton's mean grain-size ranges for each sediment type, one can assign velocity ratios to slope sediments (Figure 5).

Small-Scale Variation

The large-scale sedimentary regime for a slope region is dependent upon regional sediment source and climate (Lisitzin, 1972). For example, terrigenous input for glacial regions is generally coarse grained and immature, whereas a tropical river may transport fine grained clays. Also, sparsity of terrigenous source may give way to biogenic sediments (Lisitzin, 1972). Such concepts are displayed by the surface sediment compilation (Map II).

FIGURE 4. Comparison of grain-size schemes. Western size scales (phi, Udden-Wentworth) are compared to the Soviet scheme (pelite, aleurite-pelite, and aleurite, Lisitzin, 1972), and to metric scales.

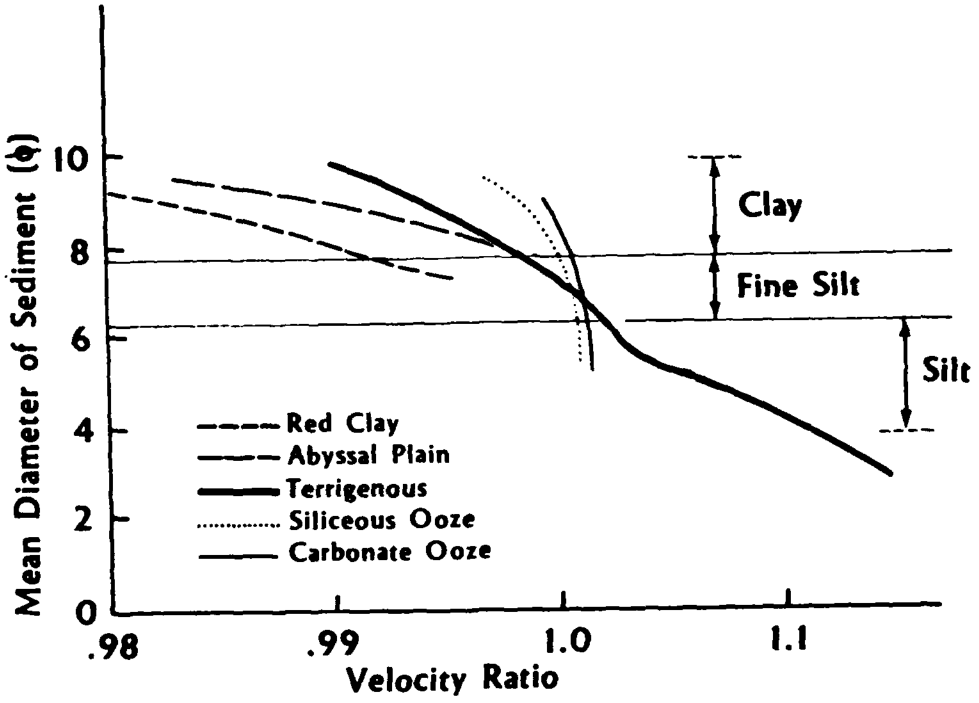
Comparison of Grain-Size Schemes



*Sub-colloidal

1. Pelite-70% of sediments <10μm
2. Aleurite-Pelite - 50%-70% of sediments<10μm
3. Aleurite - >50% of sediments >10μm

FIGURE 5. Velocity ratios for surface sediments. Velocity ratios are determined by surface-sediment type and average grain size. Adapted from Hamilton (1980).


Mean Diameter of Sediment (ϕ)
10
8
6
4
2
0
.98
.99
1.0
1.1
Velocity Ratio
Clay
Fine Silt
Silt
Red Clay
Abyssal Plain
Terrigenous
Siliceous Ooze
Carbonate Ooze

Numerous small-scale variations can radically alter the character of the generalized surface sediments. Mass movement of sediment, ubiquitous canyons and slope gullies, grain size and compositional variation down slope, and modification by bottom currents are recognized as the most important sources of variation. These phenomena also influence the character of bottom morphology and the outcrop of older structure on slopes. The small scale of these phenomena places them beyond the scope of this study. Slope environments are not mapped in sufficient detail to reveal occurrence of all these variations. Consequently, it is unrealistic to include their compilation. However, relationships are recognized concerning the interaction of small-scale variation to other slope parameters. For this reason, a brief summary is offered for each major phenomenon.

Mass movement of sediment on slopes is dependent upon volume of sediment supply, strength of the sediment, "triggering" by tectonic movement, oversteepening by erosion of deposition and probably numerous undetermined sources (Morgenstern, 1967). Because a variety of factors cause mass movement, the occurrence of slumps, turbidites, or various other types of movement are difficult to evaluate. For example, whereas slumping has occurred on slopes of 1°, sediment on slopes of up to 35° may remain unmoved (Morgenstern, 1967).

Various types of mass movement have been studied (Lowe, 1979; Nardin and others, 1979) and each type moves according to gravity and momentum. As compared to movement in other ocean regions, intra-slope movement is dominated by collapse and down-slope movement of relatively undeformed sedimentary units called slumps or glides. These sedimentary features are a large source of slope roughness. They are characterized by steep up-slope "scars" (which resemble escarpments in cross-section) and down-slope knolls or talus piles which often have rotated but intact bedding (Nardin and others, 1979).

Deposits caused by sediment flows are also important. Their placement, however, is generally at the base of slopes or behind dam structures. Sediment flows can range from debris flows to turbidites (Nardin and others, 1979) and they often result from initial slide processes. Turbidites are most common on the floor of submarine canyons and on rises. They result from slumping on intra-slope regions, erosional slumping of canyon walls, or introduction of sediments at the canyon head (Shepard and Dill, 1965).

Submarine canyons and slope gullies are common on slopes. They form indentations of variable width, length and depth, and are a prime source of bottom roughness. Various hypotheses attribute their origin to erosional processes related to river sources or submarine sediment slumping and turbidity currents (Shepard and Dill, 1966). They have steep walls which often cut into the older structure of the slopes. Off the east coast of the United States, most submarine canyon walls are truncated sedimentary strata, whereas off the California coast, canyons cut into crystalline rocks (Shepard and Dill, 1966). Canyons are recognized as both active (with erosional walls and floored by turbidites) and inactive (covered by a layer of recent pelagic or hemipelagic sediment) (Shepard, 1981).

Major down-slope variations in sediment composition and grain size are caused by distance from terrigenous source, lack of certain biogenic production below photic zone depths, and dissolution of carbonate sediments below the carbonate compensation depth (CCD). Grain size generally decreases with depth for both carbonate and terrigenous sediments and carbonate sediments dissolve below the CCD. However, the variations may be overidden by mass movement processes and bottom currents.

A simplistic view of terrigenous sediment on continental margins includes a sandy shelf, a silty slope and a clayey rise. The decrease in grain size is attributable to distance from terrigenous sources (Bouma, 1979). The same trend exists across slope regions where upper slopes have coarser muds than lower slopes. MacIlvaine and Ross (1979), for the New England slope; Krissek and others (1980), for the Peru slope; and Murdma and Bezrukov (1970), for the Southern Kurile fore-arc region; found somewhat linear decreases in grain size of terrigenous sediments with depth on slopes. On the other hand, Doyle and others (1979) and Keller and others (1979) found no variation for silty clays recovered from the slope off the northeastern United States; however, adjacent shelf and rise sediments were found to be coarser and finer, respectively.

Carbonate sediments on slopes show similar down-slope trends for different reasons. Except for the mass movement of sediments and occasional shelf spillover, the predominant carbonate slope sediment is pelagic Foraminifera and nannoplankton (Moore and others, 1976; Scoffin and others, 1980; Mullins and Neuman, 1979: Schlager and Chermak, 1979). Average grain size of pelagic carbonates decreases linearly from about 0.03 mm at 1600 m to less than 0.004 mm at 4000 m for sediments on the gently inclined Ontong-Java Plateau (Johnson and others, 1977). This trend coincides with a slight decrease in carbonate content. The decrease in grain size evidently resulted from breakdown or dissolution of pelagic tests.

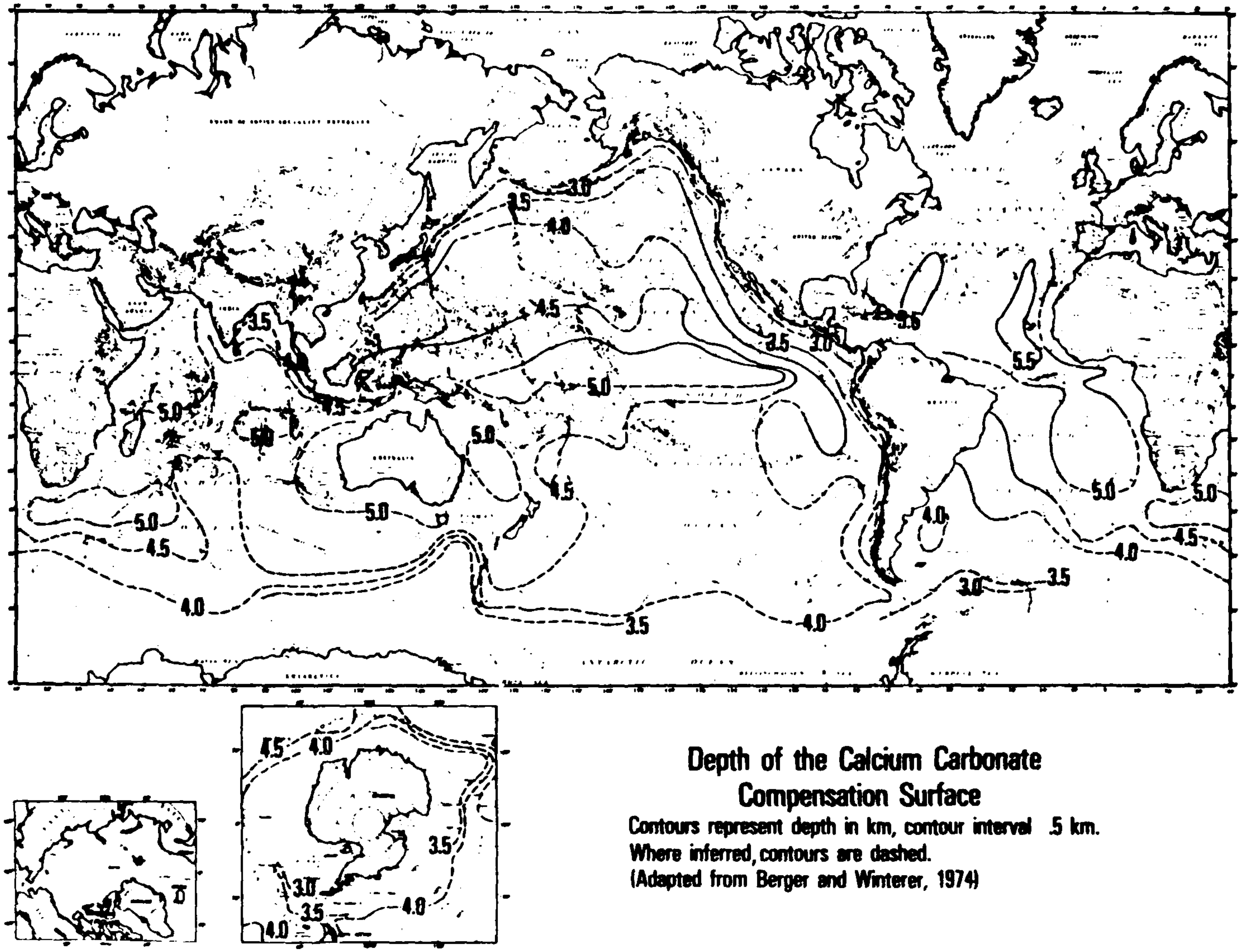
Carbonate surface sediments are absent below the CCD (Figure 6, Berger and Winter, 1974). Sediments on the basal sections of slopes below the CCD will have sediment compositions which reflect sources other than those of pelagic carbonates. For example, equatorial regions may have significant quantities of basal radiolaria and high latitude slopes may have diatoms. Other areas may have hemipelagic sediments. In the absence of any significant sediment source, red clay may be the major surface sediment at the base of the slope.

Subduction processes may greatly alter the character of sediments at the base of fore-arc slopes. In studying surface sediments from the Oregon-Washington slope, Carson (1977) found overconsolidated and dewatered sediments at the base of the slope and underconsolidated sediments on upper slopes. He attributed tectonism due to subduction as the cause of the anomalous basal sediments. If similar occurrences exist for other fore-arc regions, it can be expected that subduction complexes (Karig, 1977) will have anomalous sediment properties.

Modification of sediments by bottom currents may be an important but variable influence upon surface sediment on slopes. Paths of bottom currents are often unknown worldwide, but they are suggested by sediment drifts near the base of slopes and scouring of slope walls, especially for intra-oceanic features and constricted areas. Off the southeastern coast of the United States, the Gulf Stream scours the slope wall off the Blake Plateau (Emery and Uchupi, 1972). Bottom currents do not play a major role in sedimentation for slopes off the northeastern United States (Doyle and others, 1979).

Internal waves are suggested as another modifying source for slope sediments (Bouma, 1979), but their effect is unsubstantiated. It is

FIGURE 6. Depth of the Calcium Carbonate Compensation Surface. Adapted from Berger and Winterer (1974).



Depth of the Calcium Carbonate Compensation Surface

Contours represent depth in km, contour interval .5 km.
Where inferred, contours are dashed.
(Adapted from Berger and Winterer, 1974)

suggested that deposition occurs downslope and just upslope of the breaking point. Erosion occurs further upslope.

Plate-Tectonic Association

A classification of slopes was implemented to indicate ongoing and initial tectonic processes associated with plate tectonic theory (Map III). Problems arising in formulating such a map include the lack of definitive data worldwide and the lack of rigid groupings which totally characterize one region as opposed to another. Consequently, speculation and a priority scheme were implemented into the classification. The primary purpose of the map is to classify all lateral slopes as a distinctive tectonic class so that the tectonic class can be contrasted with other slope characteristics. Many ambiguities arise in defending the scheme because slopes were implied to be associated with tectonic situations. Actually, slope characteristics may or may not be related to the tectonic situation.

The major division in the classification scheme is the separation of active and passive plate margins (Figure 7). Active-associated slopes are slopes in Cenozoic-Mesozoic megasuture belts of the world where subduction and translation are occurring (Anonymous, 1979). These regions are characterized by mountain building, volcanism, and anomalous heat flow. Areas outside the megasuture zones are not plate margins. A different scheme was used to classify slopes outside megasuture zones. Such slopes include many slopes in ocean basins as well as those adjacent to continents. An arbitrary division was made to divide these two major types of features. Although the division is not tectonically motivated, it avoids the problem of the origin of intra-oceanic features. Figure 7 outlines the tectonic classification utilized on Map III. The classification separates slopes according to their local association with current plate tectonic activity. Major data sources for this compilation are: Anonymous (1979), Emery (1979), Dickinson and Seely (1979) and many papers listed in Appendix I.

Slopes in megasutures were first classified according to their association to present plate movement (Anonymous, 1979). Slopes associated with subduction are fore-arc regions, outer trench walls and back-arc walls. Slopes associated with translation occur near active strike-slip movement. In the past, many of these slopes were associated with subduction (e.g., western Aleutians, Puerto Rican fore-arc region, Burdwood Bank). Many slopes in megasutures are not associated with presently-active plate boundaries. Such slopes are the apparent passive slopes of small basins and remnant arcs.

Slopes located outside mega-sutures were divided into intra-oceanic features and rifted continental margins. Rifted continental margins have either translational or divergent origin.

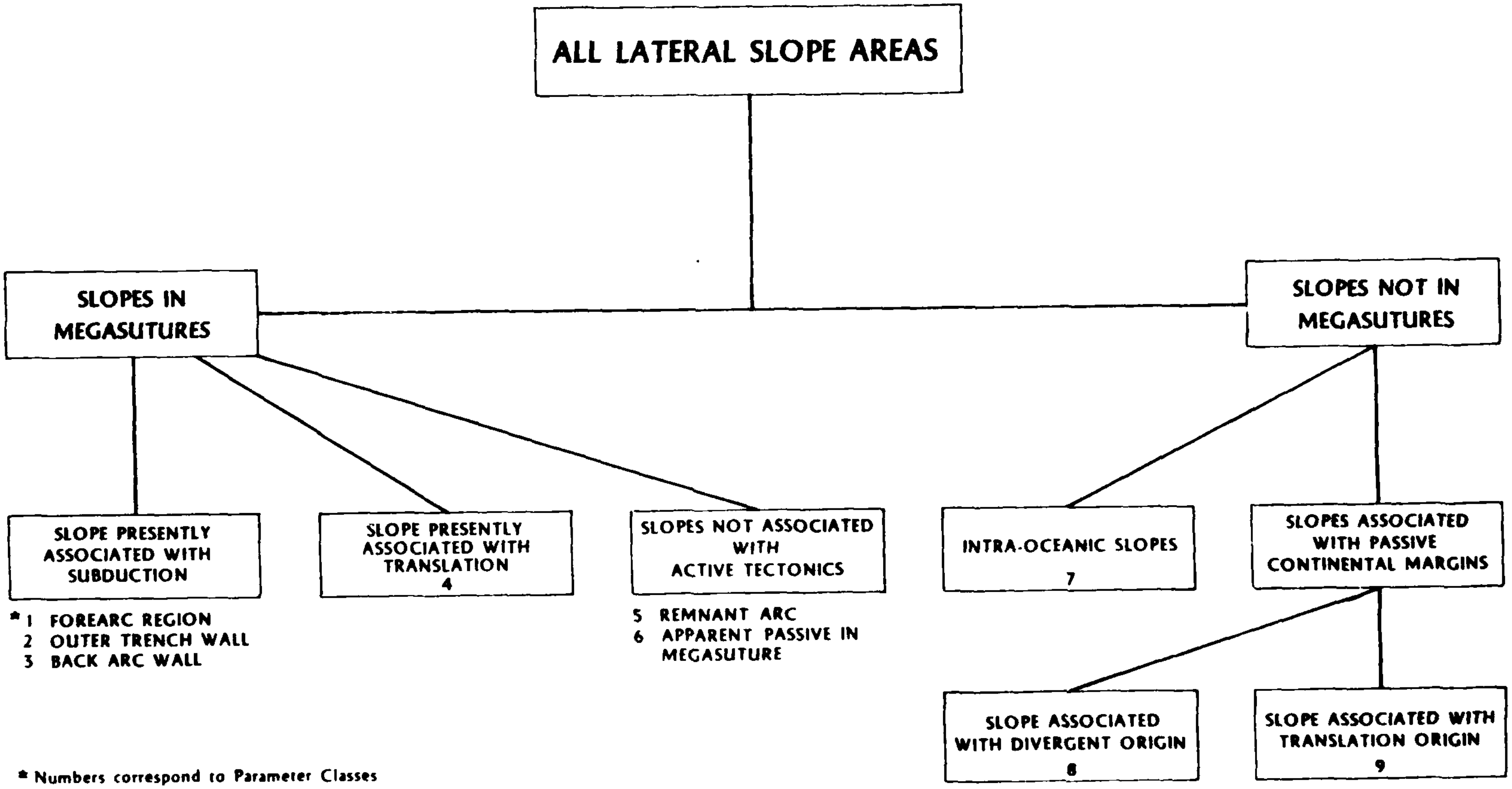
Shallow Structure

Structure in the Top 200 m

Profiles shown in Appendix II were examined to characterize the types of outcrop found in the upper 200 m of slopes. An outcrop is defined as an acoustic horizon in the upper 200 m which indicates a sharp rise in acoustic velocity as compared to overlying or adjacent reflections. In geological terms, an outcrop usually represents

FIGURE 7. Plate-tectonic association of slopes. This classification scheme distinguishes slopes associated with active plate movement from those with passive association.

PLATE-TECTONIC ASSOCIATIONS OF SLOPES



* Numbers correspond to Parameter Classes

crystalline or lithified rocks which lie unconformably beneath prograded sediments or are exposed on a slope. The nature of the outcrop is evaluated from papers listed in the bibliographies (Appendix I) and the profiles.

Outcrops were identified as geological rock units, and the percentage of the slope with outcrop was measured. Major sedimentary outcrops are deformed sedimentary rocks, truncated sedimentary rocks, diapirs and reefs. Crystalline outcrops are both continental and oceanic rocks. Acoustic basement refers to nondetermined high impedance outcrops. The extent and type of outcrop were determined from profiles in Appendix II. For the most part, only one outcrop was identified for a single profile. However, oceanic crystalline basement often occurred simultaneously with deformed or truncated sedimentary rocks. The extent of each outcrop was noted in terms of percent of the total vertical axis.

Outcrop types have significant geological implications. The presence of older structure near the surface of a slope indicates the presence of unconformities, nondeposition or tectonism. The prograded outcrop type indicates the absence of a significant near-surface outcrop. Because minor unconformities are likely to be present on all profiles, they were overlooked. Deformed sedimentary rocks (and sediment) compose what is referred to as a subduction complex (Karig and Sharman, 1975). Truncated sedimentary rocks (and sediment) represent exposed angular unconformities. Truncated units may be escarpments and indicate current scour, tectonism, or extreme mass movement of sediment (Emery, 1979; Shepard and Dill, 1966). Diapirs and reefs often form sedimentary dams. For example, the lower slope of the Northern Gulf of Mexico is formed by a salt wall called the Sigsbee Escarpment.

Similarly, the Blake-Bahama Escarpment is a reefal dam (Emery and Uchupi, 1972).

Various types of basement outcrops were classified. Acoustic basement is an unidentified acoustic horizon which is the deepest horizon observed on a seismic profile. Oceanic basement is either basinal crust or pinnacle (oceanic volcanoes) structures normally situated at the base of a slope. Pinnacle structures are often associated with trunucated or deformed sedimentary rock outcrops. Continental basement normally occurs as a massive block which might underlie the total slope.

Total Sediment Thickness

Sediment thickness is a measure of the thickness of sediment and sedimentary rock to a chosen basement datum. Measurement of sediment thickness on slopes is very difficult for the following reasons:

1. Basement is rarely identified on seismic profiles.
2. Thickness is highly variable.
3. The slope is often near the boundary between continental and oceanic type crust.
4. Seismic profiling across sloping bottoms is highly distorted by vertical exaggeration and complex geology. Appearance of structure is often ambiguous.

Sediment thickness was measurable for only half the profiles in Appendix II. Deepest observed basement datums are acoustic basement, crystalline basement, diapirs, and reefs.

DATA BASE FOR LATERAL SLOPES

The data base consists of a tabulation of slope parameters in computer-compatible format. Grouping is predominantly subjective; slope areas are divided into equally-spaced stations.

Thirteen parameters were formulated from the slope compilations (Tables II and III). Each parameter represents a geologic compilation for all lateral slopes. The variation within each parameter is represented by a group of parameter classes. For example, surface sediment type is a parameter. Its parameter classes are terrigenous, 30-50% carbonate, greater than 50% carbonate, greater than 50% carbonate and biogenic silica, and pelagic clay.

Parameters were evaluated using either of two spacial schemes. For parameters 1-8 (Table II) the lengths of all lateral slopes were divided into 3125 equally spaced 100 km stations, and parameter class designations were assigned to each station. On the other hand, parameters 9-13 (Table III) were tabulated from 520 profiles (Appendix II) and parameter class designations were assigned to stations which coincide with profile locations (Map IV). Although only 17% of all stations have coincident profiles, an attempt was made to use only those profiles which are spacially representative of all lateral slope areas. Only one profile could be included for a single station. The dual nature of spacial tabulation of data was treated as follows:

1. Stations with no profiles were evaluated for parameters 1-8 (Table II).
2. Stations which include profiles were evaluated for parameters 1-13 (Tables II and III).

TABLE II. PARAMETERS 1-8

TABULATED PARAMETERS FOR 3125 EQUALLY SPACED 100 KM STATIONS

PARAMETER	PARAMETER CLASS	CARD DESIGNATION**	% OF TOTAL
1. Ocean Section*	Indian	1	26
	North Pacific	2	22
	South Pacific	3	19
	North Atlantic	4	11
	South Atlantic	5	9
	Medit. and Black Seas	6	3
	Arctic	7	4
	Antarctic	8	6
2. Top Boundary Province	Shelf (>100 km)	1	27
	Shelf (<100 km)	2	22
	Island	3	17
	Ocean Plateau	4	20
	No-Top Classification	5	14
3. Bottom Boundary Province	Rise	1	34
	Trench	2	18
	Trough	3	11
	No-Bottom Classification	4	27
4. Relief	2000 m	1	17
	2001-3000 m	2	44
	3001-4000 m	3	33
	4001-5000 m	4	13
	5001-6000 m	5	
	6001-7000 m	6	
	7001-8000 m	7	
	8001-9000 m	8	
	9001-10000 m	9	
5. Slope Angle	1-2°	1	24
	2-4°	2	31
	4-8°	3	35
	>8°	4	11
6. Surface Sediment Type	Terrigenous	1	38
	30-50% Carbonate	2	22
	>50% Carbonate	3	34
	>50% Carbonate and Biogenic Silica	4	4
	Pelagic Clay	5	3
7. Surface-Sediment Grain Size	No data	0	4
	Silt	1	13
	Fine Silt	2	
	Clay	3	4
8. Plate-Tectonic Association	Complex Forearc Region†	1	11
	Simple Forearc Region†	2	8
	Outer Trench Wall	3	3
	Backarc Wall	4	2
	Remnant Arc	5	1
	Active Translation	6	7
	Apparent Passive	7	11
	Intra-oceanic	8	22
	Passive Divergent	9	28
	Passive Translation	10	7

* see Figure 2 for boundaries
** see Figure 9
† defined by Dickinson and Seely (1979)

TABLE III. PARAMETERS 9-13

TABULATED PARAMETERS FOR 520 PUBLISHED SEISMIC AND BATHYMETRIC PROFILES*

PARAMETER	PARAMETER CLASS	CARD DESIGNATION	% OF TOTAL
9. Shape	Sigmoidal Smooth	1	15
	Sigmoidal Rough	2	29
	Abrupt Smooth	3	10
	Complex	4	14
	Step	5	10
	High-Relief Step	6	7
	High-Relief Complex	7	3
	Abrupt Rough	8	12
10. Outcrop Type in the Upper 200 m	Not Determined	0	18
	No Outcrop (prograded Sed.)	1	16
	Truncated Sed. and Sed. Rocks	2	15
	Diapirs	3	2
	Deformed Sed. and Sed. Rocks	4	21
	Reef	5	2
	Acoustic Basement	6	5
	Crystalline Block	7	4
	Crystalline Pinnacles	8	4
	Crystalline Pinnacles and Truncated Sed./Sed. Rocks	9	5
	Crystalline Pinnacles and Deformed Sed./Sed. Rocks	10	7
11. Outcrop Percent	0%	0	14
	1-9%	1	6
	10-19%	2	4
	20-29%	3	7
	30-39%	4	3
	40-49%	5	5
	50-59%	6	4
	60-69%	7	4
	70-79%	8	10
	80-89%	9	1
	90-100%	10	1
	Not Determined	11	40
12. Sediment Thickness	Not Determined	0	50
	0-200 m	1	10
	200-400 m	2	7
	400-800 m	3	4
		4	0
	1000-2000 m	5	2
	>2000 m	6	1
	500-1000 m	7	16
	>1000 m	8	9
		9	0
	400-1000 m (inclusive)	10	21
	>1000 m (inclusive)	11	12
13. Basement Type	Not Determined	0	50
	Diapirs	1	5
	Reef	2	3
	Acoustic Basement	3	32
	Crystalline	4	8
	Diapirs and Acoustic Basement	5	1

* see Appendix II for Profiles

Any single slope station was characterized by a maximum of thirteen parameter-class designations.

Data Format

Computer punch cards were used to record tabulated data. Each card contains data for one station. Punched data include the station number, the profile number (if a profile is present), and the parameter-class designations. Figure 8 illustrates the card format for a station with a corresponding profile. A total of 3125 cards comprise the data base.

Problems with the Data Base

When judging the quality of data base findings and uses, the reader should keep in mind several unresolved problems.

1. Only lateral slopes are evaluated in the data base; conical slopes are not.

2. Two spacial schemes (stations and profiles) with unequal coverage are combined to offer representative sampling of lateral slopes.

3. Chosen parameters are assumed to represent valid slope characteristics. Many other parameters which characterize slopes had to be omitted because no practical application to the data base could be realized.

4. The grouping of many parameters is subjective. Although existing geologic terminology determines some parameter classes, others were defined by the author on the basis of inspection of the total range

FIGURE 8. Computer card format for recording data for a single station on one punched card. Most tabulations are parameter class card designations listed on Tables II and III. An index to station locations is available on request. Card designations of ocean section for profiles are: 0 for no profile, 1 for Arctic, 2 for Antarctic, 3 for Mediterranean and Black Seas, 4 for East Atlantic, 5 for West Atlantic, 6 for East Pacific, 7 for West Pacific, and 8 for Indian. Ocean boundaries for profiles and profile numbers are shown on Map IV.

The station tabulated on the figure is for Antarctic profile 17. The card designations indicate that the station is characterized by a broad shelf at its top, a rise at its base, relief of 200-3000 m, slope of 2-4°, fine silt-size terrigenous surface sediment, a passive translation tectonic association, a sigmoidal smooth shape, no outcrop in the upper 200 m, and sediment thickness of 500-1000 m to acoustic basement.

COMPUTER CARD FORMAT

	Punched Data	Column Number
Ocean Section	8	1
Station Designation	1	2
	6	3
	0	4
Blank		5
Top Province	1	6
Blank		7
Bottom Province	2	8
Blank		9
Relief	0	10
	2	11
Blank		12
Slope Angle	2	13
Blank		14
Sediment Type	1	15
Blank		16
Sediment Size	2	17
Blank		18
Plate Tectonic Association	1	19
	0	20
Blank		21
Ocean Section for Profiles	2	22
Profile Number	0	23
	1	24
	7	25
Blank		26
Shape	1	27
Blank		28
Outcrop Type	0	29
	1	30
Blank		31
Outcrop %	0	32
	0	33
Blank		34
Sediment Thickness	7	35
Blank		36
Basement Type	3	37
Blank		38
→		39

of compilations. "Natural" grouping of slope characteristics is usually unknown and impossible.

5. Great disparity exists in the quality and coverage of tabulated data. Best data are for the North Atlantic and North Pacific, poorest data for the Arctic and Antarctic. Data composing the surface-sediment size compilation are unreliable and often impossible to standardize. Only 50% of profiles (Appendix II) reveal definitive total sediment thickness and deepest observed basement, 60% reveal outcrop frequency and 82% reveal outcrop type.

DATA BASE ANALYSIS

Analyses are based upon computer counting and sorting of slope stations and corresponding data distributions. Various data presentations were constructed to define data distributions, to reveal relationships among parameters, and to group parameters. Order of presentation is cumulative in that later analyses in this section incorporate earlier ones.

Global Data Distribution

A distribution is the frequency of all parameter classes for a group of stations. Distributions were formed by sorting occurrences of parameter classes for all stations and counting the number of stations assigned to each parameter class. Because the sum of parameter classes for a single parameter always equals the global number of stations, frequencies of parameter classes were represented by percentages.

The global distribution of parameter classes represents all lateral slopes (Tables II and III). The distribution reveals the occurrence of a variety of geological phenomena related to the world as a whole. For example, the global distribution for slope surface-sediment type is 38% terrigenous, 22% carbonate (30-50% $CaCO_3$), 38% biogenic (>50% $CaCO_3$ and SiO_2), and 3% pelagic clay.

Plate I shows the global distribution of all combinations of two parameter classes. Each single matrix for two parameters represents 100% of all lateral slopes. Precise percentages are listed for the most frequent combinations on Table IV, and these combinations are dominantly representative of top province, bottom province, plate-tectonic association and surface-sediment type.

Numerical Scale Parameters

Four parameters chosen for the data base consist of parameter-class divisions which can be treated as numerical scales. These parameters are average slope, relief, surface-sediment grain size and outcrop percentage. The presence of numerical scales opens a new dimension to data analysis. First of all, the parameter-class distributions might be evaluated as to their suitability for statistical analysis. For the most part, the sampling techniques used in this study are not precise enough to warrant formal statistical analysis. In all cases, data were grouped into ranges and averaged values were assigned to discrete parameter classes. Because Chi square analyses of distributions always fall far below acceptable levels for normal distribution, it is important not to take the data beyond statistical limits.

Correlation coefficients (r) for combinations of numerical scale parameters reveal significant positive correlation at the .05 level for slope and relief, slope and outcrop frequency, and outcrop frequency and sediment size (Figure 9). These correlations are very weak, and significance of correlation is attributed to the large size of the populations. The predictibility of one parameter from another correlated parameter is similarly weak for all correlations. For example, the best-fit linear regression equation for the strongest correlation (slope and relief) accurately characterizes only 18% (r^2) of all possible predictions. The weakness of the correlations is attributed to the natural scatter of the data as well as the sampling method of using ranges of data rather than discrete values. Nevertheless, significant correlations do exist and their presence warrants further geological investigation.

TABLE IV. MOST FREQUENT COMBINATIONS OF TWO PARAMETER CLASSES*

% OF TOTAL LATERAL SLOPE POPULATION	PARAMETER CLASS COMBINATIONS	
23	Broad Shelf	Rise
20	Rise	Passive Divergent
19	No-Bottom Class.	Intra-oceanic
18	Terrigenous	Deformed Sed./Sed. Rks
18	Rise	Sigmoidal Rough
17	Ocean Plateau	Intra-oceanic
16	Forearc Region	Deformed Sed./Sed. Rks
16	Broad Shelf	Terrigenous
16	>50% Biogenic	Intra-oceanic
16	Trench	Forearc Region
15	Indian	>50% Biogenic
14	Trench	Forearc Region
14	Trench	Deformed Sed./Sed. Rks
14	Terrigenous	Sigmoidal Rough
13	Rise	Truncated Sed./Sed. Rks
12	Terrigenous	Passive Divergent
12	North Pacific	Terrigenous
12	Ocean Plateau	>50% Biogenic
12	Broad Shelf	Sigmoidal Smooth
12	Broad Shelf	No Outcrop
12	Broad Shelf	Truncated Sed./Sed. Rks
12	Rise	No Outcrop
11	Indian	No Bottom Class.
11	Terrigenous	Forearc Region
11	Passive Divergent	Truncated Sed./Sed. Rks
10	Indian	Ocean Plateau
10	Indian	Rise
10	South Pacific	>50% Biogenic
10	Narrow Shelf	Terrigenous
10	Rise	Terrigenous
10	Rise	Sigmoidal Smooth
10	Rise	No Outcrop
10	>50% Biogenic	Passive Divergent
10	Passive Divergent	Sigmoidal Smooth
10	Passive Divergent	Sigmoidal Rough
10	Passive Divergent	No Outcrop
10	Passive Divergent	Truncated Sed./Sed. Rks

*for Parameters 1-3, 6, 8-10 (Tables II and III)

FIGURE 9. Correlation coefficients for numerical scale parameters. Significant correlations at the .05 level occur for slope and relief, outcrop frequency and slope, and outcrop frequency and sediment size.

(r)
Correlation Coefficients
(Linear)

x Value

	Slope	Relief	Sediment Size	Outcrop Frequency
Slope	☒	.41	.08	.36
Relief	.42	☒	.10	.10
Sediment Size	.03	.05	☒	.25
Outcrop Frequency	.33	.07	.24	☒

(r^2) *

	Slope	Relief	Sediment Size	Outcrop Frequency
Slope	☒	.17	.01	.13
Relief	.18	☒	.01	.01
Sediment Size	.00	.00	☒	.06
Outcrop Frequency	.11	.00	.06	☒

y Value

* Indicates the fraction of total measurements which can be explained by a linear equation (assuming normal distribution).

Slope-Relief Index

Mean slope and relief values were calculated for all parameter class subpopulations and are listed on Plate I. (A parameter-class subpopulation is a group of all the stations which exhibit a specific parameter-class designation.) The mean values of each subpopulation were plotted on a graph with axes of slope and relief. Most subpopulations reflect the positive correlation between slope and relief, and mean values plotted close to the regression curves indicated on Figure 10. Subpopulation means were compared to the means for the total population of lateral slopes, and the resulting comparisons were the basis for defining the slope-relief index.

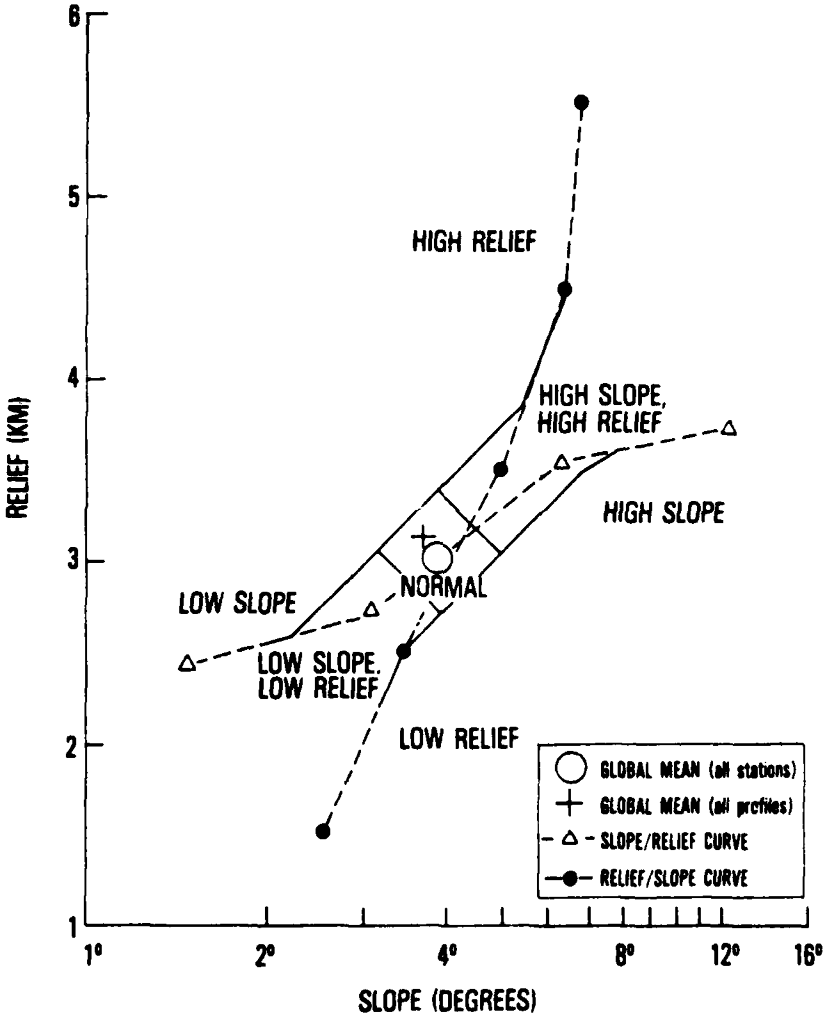
Figure 10 illustrates the constraints and derivation of the slope-relief index. Arbitrary boundaries for designation of indices were formulated as follows:

1. The average slope-relief values were plotted for all subpopulations and the total slope population.

2. A small but arbitrary range around the global means was assigned to designate normal slope-relief indices. The small range was chosen to include only a small number of subpopulation means.

3. Crude regression curves were drawn based upon the average values for the total slope and relief ranges of discrete groupings. Two curves resulted: one for x/y and one for y/x. It is assumed that mean values for subpopulations which plot near these curves indicate the positive correlation between slope and relief. Therefore, small windows were arbitrarily assigned using the regression curves as boundaries for extreme values and the normal range for values near the global means. High slope, high relief designations are enclosed to the right of the

FIGURE 10. Correlation graph of slope and relief. See text for explanation of slope-relief index.


6
5
4
3
2
1
RELIEF (KM)
1°
2°
4°
8°
12°
16°
SLOPE (DEGREES)
HIGH RELIEF
HIGH SLOPE, HIGH RELIEF
HIGH SLOPE
NORMAL
LOW SLOPE
LOW SLOPE, LOW RELIEF
LOW RELIEF
○ GLOBAL MEAN (all stations)
+ GLOBAL MEAN (all profiles)
- △ - SLOPE/RELIEF CURVE
—●— RELIEF/SLOPE CURVE

normal designation, and low slope, low relief designations are to the left.

4. Subpopulations which have mean values outside the correlation window have anomalous influence by either slope or relief. Such subpopulations are designated as low slope, high slope, low relief or high relief.

5. Parameter class subpopulations are listed in Table V and in Plate II according to their assigned slope-relief indices. The index is useful in determining variation of both slope and relief in relation to a third parameter.

Parameter Sequence by Slope-relief Means

Slope and relief means for subpopulations offer clues as to the nature of parameter grouping. It was discovered that parameter-class subpopulations which make up a single parameter often plot in distinctive trends on slope-relief axes. Shape parameter class subpopulations plot in a linear sequence which represents the positive correlation between slope and relief. The mean values established a sequential order for the shape groupings. This order ranges from low slope, low relief to high slope, high relief, and groupings are listed as follows:

SHAPE PARAMETER CLASSES

sigmoidal smooth increasing slope-relief
step
sigmoidal rough
complex
abrupt smooth
abrupt rough
high relief ↓

The positive correlation of slope and relief is well reflected in grouping of three parameters: shape, top province, and active elements of

TABLE V. SLOPE-RELIEF INDICES FOR PARAMETER CLASSES

NORMAL (N)	HIGH RELIEF (HR)	HIGH SLOPE, HIGH RELIEF (HS, HR)	HIGH SLOPE (HS)	LOW RELIEF (LR)	LOW SLOPE, LOW RELIEF (LS, LR)	LOW SLOPE (LS)
North Atlantic	South Atlantic	North Pacific	Caribbean		Indian South Atlantic Antarctic Arctic Med. and BLK seas	
	Island	Narrow Shelf		No-Top Class.	Broad Shelf Ocean Plateau	
	Trench	Trough			No-Bottom Class. Rise	
Terrigenous >50% Carb. 30-50% Carb.				Pelagic Clay	>50% $CaCO_3$/Bio. SiO_2	
Fine Silt	Silt Fore-arc Reg.	Active Trans.	Back-arc	Pelagic Clay Intra-oceanic Remnant Arc	Passive Div. Apparent Pass. Outer Tr. Wall	Passive Trans.
Sigmoidal Rough Complex		Abrupt Rough High Relief Sh.			Sigmoidal Smooth	Step
Abrupt Smooth Crystalline Bk.	Deformed Sed. Rk. Pinnacle/Def. Sed. Rk.		Reef	Pinnacle/Ridge	No Outcrop Truncated Sed. Rk. Acoustic Bsm Thin Sed.	Diapirs Thick Sed.

plate-tectonic association. On the the other hand, certain parameters have ordered parameter classes which reflect variation with slope only. These parameters are bottom province, passive elements of plate-tectonic association, and outcrop type. Surface-sediment size has obvious sequence due to variation with relief only. Surface-sediment type groupings plot well with normal ranges and show little variation with slope and relief. In summary, the basis for grouping was found to correlate with five arrangements of slope and relief:

1. both slope and relief in a positive linear trend
2. only slope, no variation with relief
3. only relief, no variation with slope
4. no variation with slope or relief
5. random variation with slope and relief.

Table VI shows sequence of selected parameters.

Variation Matrix

The variation matrix (Plate II) illustrates the results of several studies of parameter-class subpopulations. It shows the relationships that each subpopulation has with all other data parameters. Relationships are defined by relative and absolute associations.

Relative Associations

When a subpopulation and the global population have equivalent data distributions, the subpopulation is representative of the global population. More likely, however, the distributions will be different. Figure 11 illustrates the comparison of the North Atlantic subpopulation to the

TABLE VI. PARAMETER SEQUENCE BY SLOPE-RELIEF MEANS

Slope-relief Dependence

	TOP PROVINCE	SHAPE	ACTIVE PLATE ASSOCIATION
LS, LR	Broad Shelf	Sigmoidal Smooth	Outer Trench Wall
	Ocean Plateau	Step	Remnant Arc
	No Top Class.	Sigmoidal Rough	
		Complex	Active Translation
↓	Narrow Shelf	Abrupt Smooth	Backarc Wall
HS,	Island	Abrupt Rough	
HR		High Relief	Forearc Region

Slope Dependence

	BOTTOM PROVINCE	OUTCROP TYPE	PASSIVE PLATE ASSOCIATION
LS	Rise	Diapirs	Passive Translation
	No Bottom Class.	No Outcrop	Passive Divergent
		Truncated Sed.	
	Trench	Acoustic Bsm	Apparent Passive
↓	Trough	Crystalline Bk.	Intra-oceanic
HS		Reef	

LS (low slope), LR (low relief), HS (high slope), HR (high relief) global population for top and bottom province parameters. Obvious distribution differences are that North Atlantic slopes have higher frequencies of broad shelf, rise, and troughs, and lower frequencies of the remaining parameter class designations. It can be inferred that the North Atlantic has positive associations with higher frequency parameter classes and negative associations with those of lower frequency.

Based upon inspection of distributions of all parameter class subpopulations as compared to the global population, an arbitrary variation scheme was devised to assure a standard definition of positive and negative associations. Where the frequency of a subpopulation designation exceeds 50% of the same designation for the global population, the subpopulation has a significant positive association with that parameter class designation. For example, Figure 11 shows that the broad shelf designation for the North Atlantic exceeds 50% of the same designation for the global population. (The 50% limit is noted by line A, Figure 11.) Conversely, where the percentage is 50% less than the global frequency, the subpopulation has a significant negative association (see line B, Figure 11A). A neutral association falls between in the 50-150% range. In summary, North Atlantic slopes have positive associations with broad shelves and rises, negative association with ocean plateaus, the no-top classification, and trenches and neutral associations with the remaining parameter class designations. Figure 11B shows the format for depicting associations on Plate II.

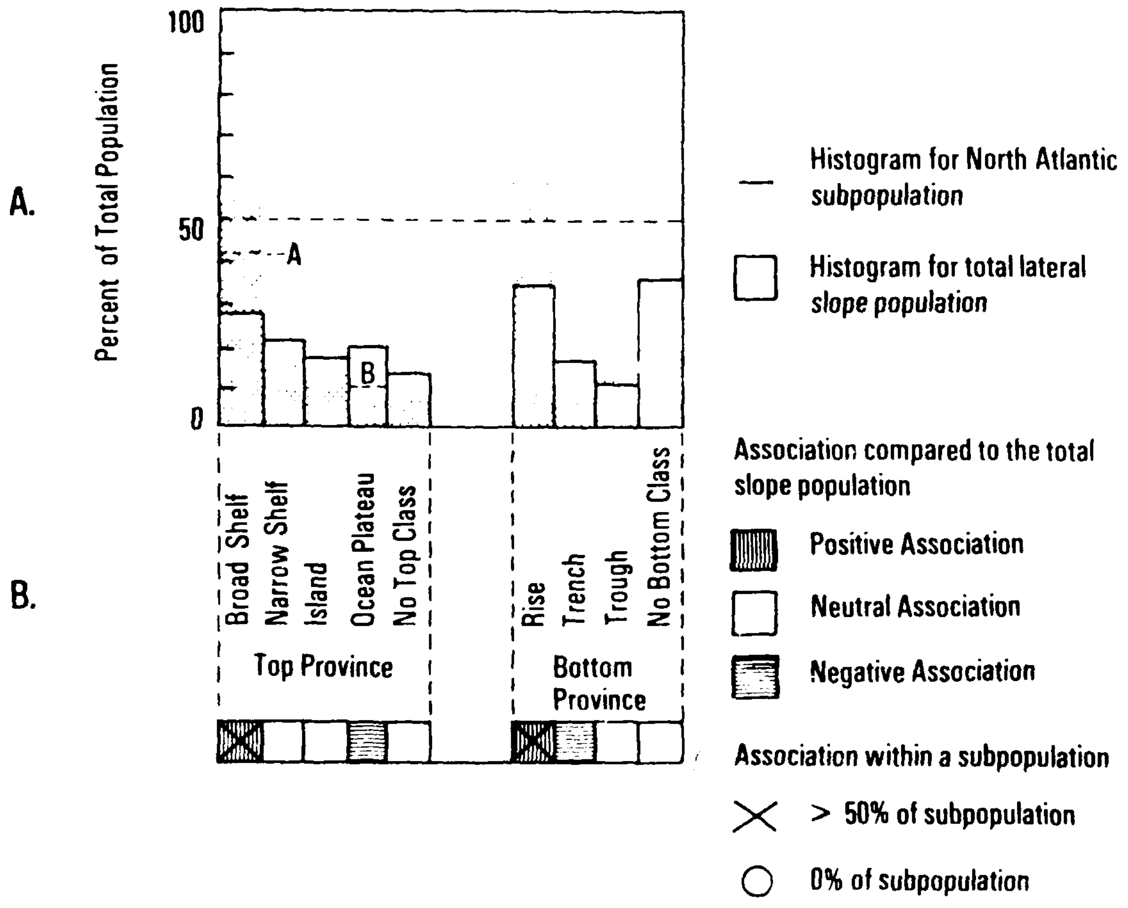
Absolute Associations

Absolute associations are a measure of extreme parameter-class percentages within a subpopulation. If an individual parameter-class

FIGURE 11. Comparison of North Atlantic slopes with global slopes. Comparison is shown for top and bottom provinces.

A. Derivation of relative and absolute associations.

B. Representation of associations for the Variation Matrix (Plate II).


A.
B.
Percent of Total Population
100
50
0
A
B
Broad Shelf
Narrow Shelf
Island
Ocean Plateau
No Top Class
Top Province
Rise
Trench
Trough
No Bottom Class
Bottom Province
Histogram for North Atlantic subpopulation
Histogram for total lateral slope population
Association compared to the total slope population
Positive Association
Neutral Association
Negative Association
Association within a subpopulation
> 50% of subpopulation
0% of subpopulation

designation represents 0% or greater than 50% of the total subpopulation, the occurrence is noted on Plate II by 0's and X's, respectively. The cut-off percentages enable the following statements to be made:

1. No stations of the subpopulation exhibit a certain parameter class designation.
2. The majority of the subpopulation stations exhibit a specific parameter-class designation.

On Plate II, absolute associations refer to parameter-class subpopulations listed on the B axis.

Supplemental Information

The following supplemental information is shown on Plate II for each parameter-class subpopulation:

1. the percent of the total lateral slope population which belongs to each subpopulation
2. a percent ratio of the number of profiles/number of stations to determine how representative the profile data base is
3. the slope-relief index
4. the difference of mean slope from the global mean of 3.8°
5. the difference of mean relief from the global mean of 3.04 km
6. the difference of mean outcrop percent from the global mean of 38%.

Interpretation

The variation matrix enables the formulation of a step-wise evaluation for each parameter-class subpopulation. Procedures for each evaluation are similar. Each subpopulation has a listing of positive, neutral, and negative associations which reveal its relationships with other parameters. The listing for the North Atlantic follows:

Positive	Neutral		Negative
broad shelf	narrow shelf	diapiric outcrop	ocean plateau
rise	trough	island	no top class.
active translation	all surface sediment types	no bottom class	fore-arc region
abrupt rough	back-arc	remnant arc	intra-oceanic
step	sigmoidal rough	sigmoidal smooth	crystalline outcrop
truncated sed.	abrupt rough	complex	acoustic basement
reef	prograded (no outcrop)		trench

Absolute Associations

X	O
broad shelf rise passive divergent	none

The listing provides a source to characterize the slopes of the North Atlantic. The positive associations reveal the characteristics which occur more frequently in the North Atlantic than in the world as a whole. The negative associations reveal the opposite. Neutral associations indicate similarities to the world as a whole. On the basis of absolute associations, it can be stated that the majority of North Atlantic slopes have broad shelves, rises and passive divergent tectonic association.

An interpretation of the North Atlantic association is offered. Top provinces are dominated by broad shelves. Ocean plateau and no top classification are less frequent than the world average. Passive divergent and active translation are preferred plate tectonic associations. Rises dominate as the bottom province largely due to absence of trenches. All surface sediment types are well represented. All shapes are represented but abrupt rough and step types are more common than the world average. Preference of outcrop type is for truncated sedimentary rocks at the expense of crystalline and acoustic basement. Slope angle, relief and outcrop percent are all similar to world averages.

The North Atlantic shows most variation for boundary provinces and tectonic association. Conversely, it shows conformity to global averages for surface sediment type, slope angle, relief and outcrop percent.

North Atlantic associations are very different from those of the South Pacific where most variation is caused by bottom province, surface sediment type, shape, outcrop type, and relief (Plate II). The South Pacific conforms to global averages for top province and slope angle.

Much interpretation can be derived from the variation matrix, and the potentially voluminous outpourings are beyond the scope of this thesis. The matrix is offered as a tool for defining relationships.

Natural Slope Groups

The concept of natural grouping is ambiguous. Ideally, an infinite amount of representative data which are accurately weighted are analyzed in a multidimensional fashion. For the present study, available data are not weighted, and analyses are restricted to two or three dimensions.

Consequently, the attempt at natural grouping for this study is far from complete.

The basis for natural grouping is depiction of positive associations derived from Plate II. The method is to plot parameter-class designations which exhibit significant positive associations and connect the designations to all other designations which have common associations. Single designations were plotted only once, and clustering was obvious by arranging the position of the designation in its most ordered position in relation to other designations.

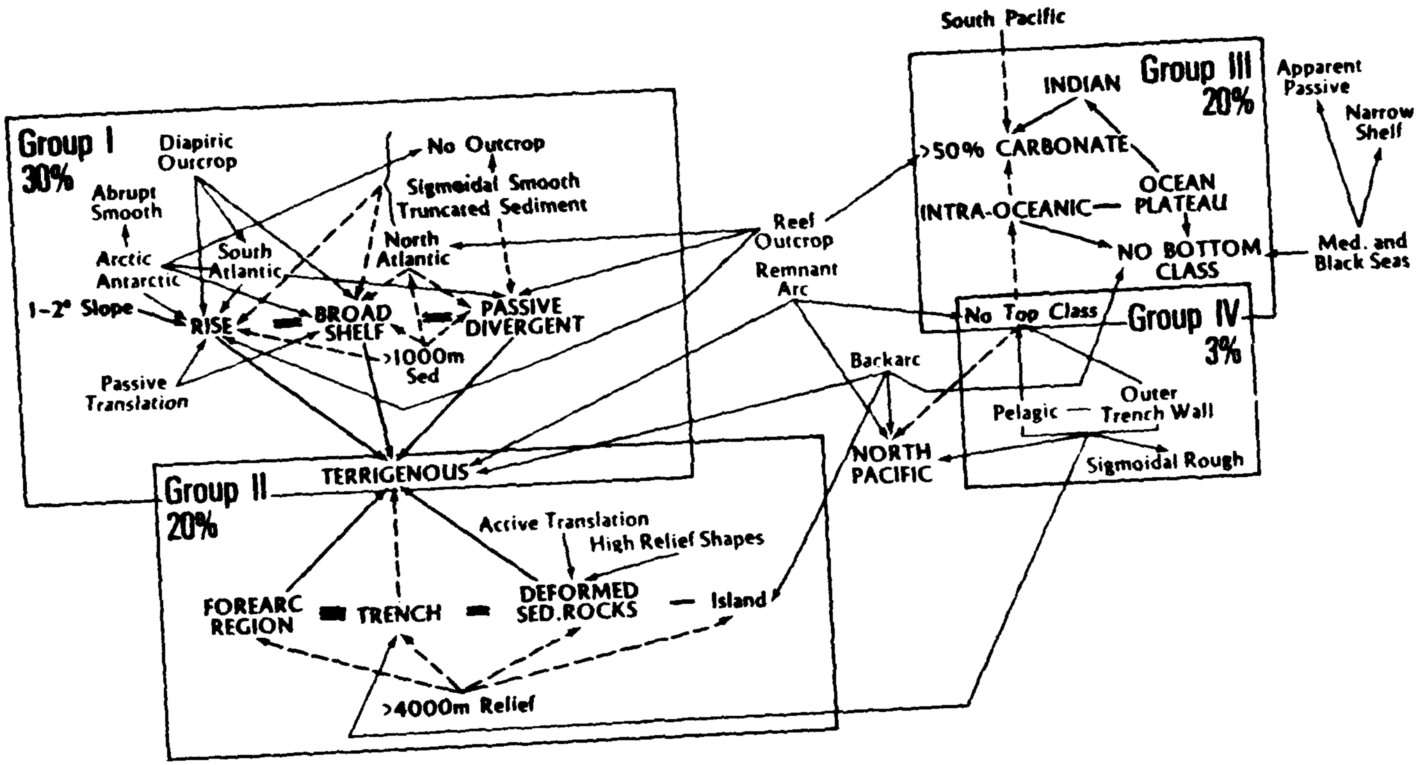
Figure 12 shows a hypothetical grouping of slopes. Only parameters 1-6 and 8-10 (Tables II and III) were used because other parameters have either incomplete or poor data sets. Plotted parameter classes have simultaneous occurrence of significant positive associations and positive absolute associations. Two strengths of association were noted. The stronger occurs when two or more parameter-class subpopulations share greater than 50% of each others' stations reciprocally. This relationship is the basis for the cores of each natural group (Figure 12). The weaker relationship occurs when one subpopulation shares over half its stations with another, but the sharing is not reciprocal. This relationship is often caused by the disparity of the subpopulation sizes.

Four clusters of parameter classes are obvious on Figure 12. Boundaries between the clusters take the form of single high population parameter classes which overlap two clustered groups. Terrigenous sediment is the overlap between Groups I and II, trench for groups II and IV, and no-top classification for Groups III and IV.

Approximate sizes assigned to the groups (Figure 12) were derived from frequencies of core parameter classes from the global distribution

FIGURE 12. Natural slope groups for the strongest associations. Groups are based upon clustering of strongest positive associations. Parameter class designations are weighted by size of subpopulations and strength of association. Arrows indicate direction of association. Four groups are indicated.

NATURAL SLOPE GROUPS FOR THE STRONGEST ASSOCIATIONS



Subpopulation involved with association is:

RISE ⟶ ≥20% total population

Island ⟶ 10-19% of total population

Backarc --→ ≤ 9% of total population

— Connects subpopulations which share ≥50% of same slope stations, links "Core" parameter class designations.

A ⟶ B Indicates that ≥50% of subpopulation A has stations shared with subpopulation B.

(Tables II and III). Actual size of each group is unknown; however, it can be assumed the minimum size of each group is at least half the average core frequency, as defined by absolute associations. The actual size should be significantly larger, depending upon the criteria used to define variation among the groups.

Group I centers around the rise- broad shelf -passive divergent core, and terrigenous surface sediment is dominant. Because all other associations are directed toward the core populations, each parameter class represents variation which is not necessarily true of the majority of Group I stations. The majority of stations for sigmoidal smooth, prograded sediment, truncated sediment, diapirs, Arctic, and Antarctic are contained in each of the core subpopulations. Truncated sediments are associated with the North Atlantic, whereas diapirs are most frequent in the South Atlantic. Stations with low slope angles are most frequent for rise stations, and passive translation stations are preferred for rise and broad shelf. The Arctic is best characterized by abrupt smooth shape and prograded sediments, whereas the strongest traits of the North Atlantic are broad shelves and passive divergent plate-tectonic association.

Group II's core consists of fore-arc region-trench-deformed sedimentary rocks-island. Terrigenous sediment dominates for all core parameter classes except island. The core classes have slope-relief indices in the high relief range. High relief is further supported by the strong association of the greater than 4000 m stations to the core parameter classes. Active translation occurs as a variation in Group II.

Group III centers around the intra-oceanic - ocean plateau cores which are associated with the no-bottom classification. The intra-oceanic subpopulation has dominance of greater than 50% carbonate surface sediment, and most ocean plateaus are found in the Indian Ocean.

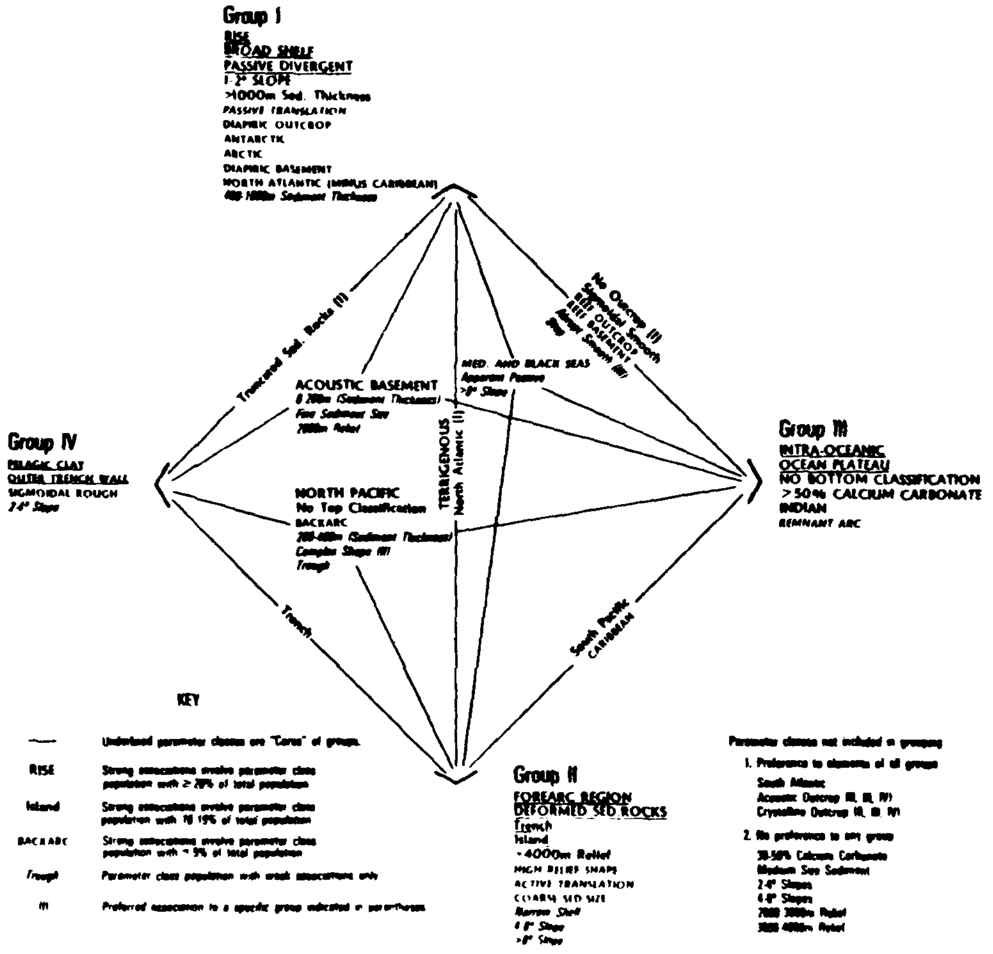
Group IV, the smallest group, clearly focuses on the outer trench wall which has dominance of pelagic clay sediment, sigmoidal rough shape, a no-top classification, a trench bottom, and a North Pacific location.

The natural grouping was expanded by including the remaining positive relative associations from Plate II. Three types of association are considered for the expanded grouping. The stronger two were used to derive Figure 12. The third consists of all the weakest positive associations which greatly outnumber the stronger ones. As with the first grouping, all parameter-class designations were plotted with lines drawn to represent association. Clustering for all associations is more complex than the clustering shown on Figure 12. Consequently, tie lines were generalized and arrows were omitted for depicting the grouping on Figure 13.

Four similar groups are apparent on Figure 13, but the additional parameter classes add a great deal of overlap. Parameter classes listed in a group have associations with others in the same group or with any of the overlap designations connected to the group by tie lines. Overlap designations have associations with any of the parameter classes connected to them by tie lines. Parameter-class designations listed in a group have the greatest preference to that group, and overlap designations are preferred to any number of groups.

FIGURE 13. Natural slope groups for all positive associations. Groups are based upon all positive associations indicated on Plate II. Parameter class designations are weighted by strength of association and size of subpopulations. Designations listed within a group can have associations with others in that group or with overlap designations tied to the group by arrows. Overlap designations can have associations with others in any group or overlap which connects with arrows.

NATURAL SLOPE GROUPS FOR ALL POSITIVE ASSOCIATIONS



KEY

___	Underlined parameter classes are "Cores" of groups.
RISE	Strong associations involve parameter class population with ≥ 20% of total population
Island	Strong associations involve parameter class population with 10-19% of total population
BACKARC	Strong associations involve parameter class population with < 5% of total population
Trough	Parameter class population with weak associations only
(I)	Preferred association to a specific group indicated in parentheses

Parameter classes not included in grouping

1. Preference to elements of all groups
   - South Atlantic
   - Acoustic Outcrop (II, III, IV)
   - Crystalline Outcrop (II, III, IV)
2. No preference to any group
   - 30-50% Calcium Carbonate
   - Medium Size Sediment
   - 2-4° Slopes
   - 4-8° Slopes
   - 2000-3000m Relief
   - 3000-4000m Relief

Although it is not obvious in Figure 13, the grouping scheme exhibits clustered ranges for average slope angle, relief and outcrop percent. Figure 14 is a plot of all mean slope and relief values for subpopulations of parameter classes of each natural group. Designations were weighted as to size of population and strength of association. Clustering of values is obvious for the four groups and no overlap values exist. Values of the strongest associations in each group were extracted from Plate I and listed as ranges for average values for each group on Table VII. Sequence of groups was established from the average values. By increasing slope angle, sequence is Group I, Group IV, Group III and Group II. By increasing relief, sequence is Group IV, Group I, Group III, and Group II; and by increasing outcrop percent, it is Group IV, Groups I/III, and Group II. Group II has consistently higher and further removed values for all three parameters. The other groups have more similar averages, but clustering still separates them into distinctive groups. No obvious clustering was noted for parameter classes which overlap natural groups.

FIGURE 14. Slope-relief means for natural groups. Average slope and relief are for parameter class subpopulations which compose each of the natural groups of Figure 13. Size of the symbol indicates the strength of association and relative size of populations involved. Largest symbols indicate populations greater than 20% of the total. Smallest symbols indicate populations which are less than 9% or associations which are weak. Groups are clustered on slope-relief axes with no overlap. The clustering indicates that slope and relief play a strong role in the natural grouping. Average values for "core" parameter classes are listed in Table VII. Also listed are parameter class designations which correspond to numbers on Figure 14.

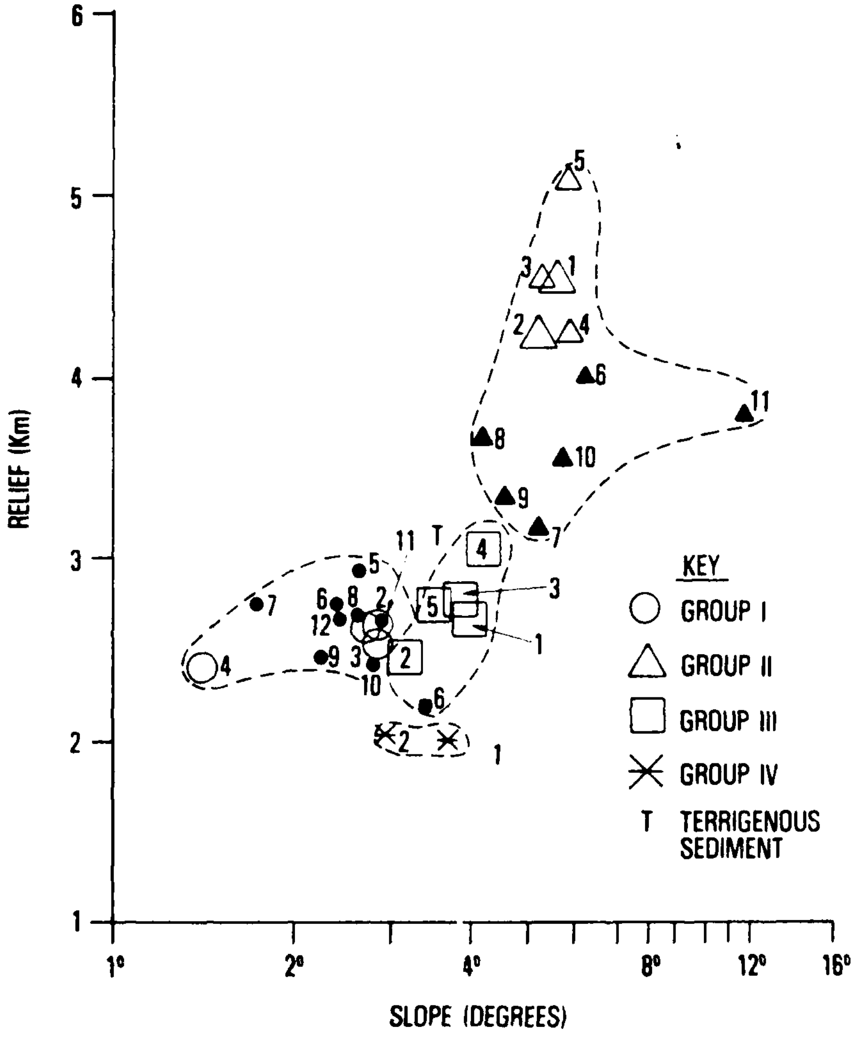

6
5
4
3
2
1
RELIEF (Km)
1°
2°
4°
8°
12°
16°
SLOPE (DEGREES)
KEY
GROUP I
GROUP II
GROUP III
GROUP IV
T TERRIGENOUS SEDIMENT
5
3
1
2
4
6
11
8
10
9
7
11
T
4
3
5
1
2
5
7
6
8
2
12
9
3
10
4
6
2
1

TABLE VII. NATURAL GROUP MEANS

KEY TO PARAMETER CLASSES ON FIGURE 14, AND AVERAGE VALUES FOR SLOPE, RELIEF, AND OUTCROP % FOR NATURAL GROUPS

	GROUP I Parameter Class	GROUP II Parameter Class	GROUP III Parameter Class	GROUP IV Parameter Class
	1 Rise	1 Forearc	1 Intra-oceanic	1 Pelagic clay
	2 Broad Shelf	2 Def. Sed. Rk.	2 Ocean Plateau	2 Outer Trench Wall
	3 Passive Div.	3 Trench	3 No-Bottom Class	
	4 1-2° Slope	4 Island	4 >50% Biogenic	
	5 >1000 m sed. Thickness	5 >4000 m Relief	5 Indian	
	6 Passive Trans.	6 High-Relief Shapes	6 Remnant Arc	
	7 Diapir Outcrop	7 Active Trans.		
	8 Antarctic	8 Silt		
	9 Arctic	9 Narrow Shelf		
	10 Diapir Bsm.	10 4-8° slope		
	11 North Atlantic (minus Caribbean)	11 >8° slope		
	12 400-1000 m Sed. Thickness			
Avg. Slope	2.7-2.9°	5.3-5.4°	3.0-4.0°	2.9-3.6°
Avg. Relief	2.5-2.6 km	4.1-4.5 km	2.5-3.1 km	2.0 km
Avg. Outcrop%	27-33%	50-64%	26-45%	18-27%

EVALUATION OF CONICAL SLOPES

For this study, conical slopes are the sides of ocean features that resemble circles or ellipses in map view and have a maximum top-of-slope dimension of less than 100 km. Approximately 25% of all large-scale ocean slopes are conical slopes; however, they are poorly studied and only a brief evaluation is offered in contrast to the extensive treatment of lateral slopes. In order to establish continuity between the two studies, discussion of conical slopes follows a similar outline as that used for lateral slopes.

The morphology of conical slopes was evaluated for slope angle, shape, and relief. Slope angles exceed 4° for nearly all conical slopes, as determined by measuring contour spacings of representative seamounts from unpublished NAVOCEANO bathymetry at a scale of 1"=1° longitude. Conical slopes are much steeper than lateral slopes, which have an average slope of 3.8°. The steepness is reflected in the high occurrence of abrupt type shapes as opposed to sigmoidal. Roughness was not evaluated. Average relief for North Pacific and North Atlantic conical slopes are 3412 m and 2901 m, respectively (Bracey, 1981). These values are remarkably similar to lateral slope averages of 3427 m and 2956 m for the same ocean sections. Consequently, no obvious variation was found for relief of conical slopes.

Definition of top and bottom provinces for conical slopes is fairly simple. Top provinces are analogous to the no-top classification or the island parameter classes. Bottom provinces are either the no-bottom classification, trough, or rise.

The scarcity of terrigenous input greatly influences sedimentation on conical slopes. By definition, the top-of-slope boundary province for conical slopes is extremely small and usually submerged so that fluvial or glacial input is negligible. Hemipelagic materials may occur on conical slopes, but sedimentation rates are much lower than for slopes with terrigenous sediment. Sediment is thin and mass movement of sedimentary strata, particularly slumping, is present on a much diminished scale. Modification of sediments by currents dominates on conical slopes, and effects are scouring of slope sediments and deposition of base-of-slope sediment wedges characterized by dunes and current structures (Taylor and others, 1975). Erosional canyons are also less common on conical slopes. Their absence can be attributed to lack of sediments; however, slope gullies are ubiquitous.

Biogenic sediments are significant on conical slopes. Pelagic carbonates are common to the carbonate compensation depth (CCD), and pelagic Foraminifera and nannoplankton dominate. In warm waters, carbonate reefs may grow in shallow depths on the tops of subsiding volcanoes (Menard, 1964). The shallow water carbonates accumulate at the base of the slopes, in erosional channels on slopes, or behind dam structures. Shallow water spillover carbonates are not common on intra-slope areas (Moore and others, 1976). For very thick carbonate caps, reef material forms the basement of the slope for depths less than 1400 m (Menard, 1964).

In the absence of carbonate sediments due to depth below the CCD or geography, various other types of sediment are possible. Biogenic silica may be significant on lower slopes in equatorial regions (radiolaria), or in high latitudes (diatoms) (Lisitzin, 1972). Amounts of hemipelagic sediments are determined by proximity to terrigenous sources or currents. If hemipelagic and biogenic sediments are absent, then sedimentation is likely to be extremely slow or absent, and red clay sediments may be present as thin patchy accumulations.

For the most part, sediment is very thin on conical slopes. Rarely should thickness approach the 200 m outcrop depth used for lateral slope characterization. Ponded or current modified sediments might reach up to 600 m (Taylor and others, 1975) on the lower flanks or behind dams, but such occurrences are not the rule. In most cases, conical slopes exhibit basaltic basement outcrop for the top 200 m of shallow structure.

CONCLUSIONS

Interpretation of Natural Groups

Conclusions are based upon natural slope groups for lateral slopes (Figure 13) and analogous information concerning conical slopes.

Group I slopes are continental slopes of passive rifted margins. They have broad shelves, rises, terrigenous surface sediments and complex sedimentary structure. Morphology is characterized by smooth shapes, a low average relief range (2.5-2.6 km), and the lowest average slope range of any natural group (2.7-2.9°). Most outcrops in the upper 200 m are sedimentary, and an average range of 27-37% of the slope has outcrops. Group I slopes are dominant in the North Atlantic (excluding the Caribbean), the Arctic, and the Antarctic Ocean sections. Only Group III slopes have ocean section preference as strong as those of Group I.

Group II slopes include the remaining continental slopes and island arc slopes. The only major link to Group I slopes is the presence of terrigenous surface sediments. Morphologically, the slopes have the highest averages for slope angle (5.3-5.4°) and relief (4.1-4.5 km). These extreme values are linked to plate tectonic association. Subduction related slopes have highest relief, whereas translation related slopes have comparable slope angles but lower average relief (3.1 km). The tops of slopes are islands and narrow shelves, and bottoms are trenches. Outcrop types are deformed sediments/sedimentary rocks and pinnacles of oceanic basement. Outcrop percent is the highest of all groups at 50-64%. Shapes generally exhibit greatest roughness of all groups, and a variety of forms are possible.

Group III slopes are intra-oceanic and lack terrigenous sediments. Surface sediments are >50% carbonate, and outcrop type is predominantly oceanic basement. Sediment is thinner than that of Group I slopes. However, despite thin sediments, outcrop percent is low (18-27%). Group III slopes are dominant for the Indian Ocean, and they are also common in the Caribbean and South Pacific. They have many similarities to Group I slopes. Relief values are similar (2.5-3.1 km) and slope angles are slightly higher for Group III slopes (3.0-4.0°). The steeper slopes are reflected in the higher occurrence of abrupt type shapes; however, slopes are as smooth as those of Group I. Reefs are present on both Group III and Group I slopes and they are not likely for other groups.

Group IV includes a small percent of all slopes. The slopes are a significant exception to those associated with active plate-tectonic association of Group II. Group IV slopes are outer trench walls which have a low average relief (2.0 km), a moderate slope angle range (2.9-3.6°), a low average outcrop-percent range (18-27%), acoustic basement for outcrop type, sigmoidal rough shape, and pelagic clay surface sediment.

Relationships among parameters are apparent in the natural grouping. Top province, bottom province, and plate-tectonic association have the strongest affinity for each other, and grouping is biased for these parameters. Surface sediment type clusters best with ocean sections (Plate II), and it contributes to grouping in ways different from the other three parameters. Although outcrop type best infers plate-tectonic association (Plate II), it is ambiguous in the natural grouping. Shapes cluster poorly with all parameters and have little influence in the grouping. Similarly, slope angle and relief have little influence in forming natural groups, but the results show outstanding clustering of mean values for parameters composing the groups (Figure 14).

Conical slopes resemble Group III slopes for top province, bottom province, plate-tectonic association, surface-sediment type, outcrop type and shapes. Both conical slopes and Group III slopes are oceanic features, and they lack terrigenous sediment sources. The major difference is that conical slopes are steeper.

Methods for Characterizing Specific Aspects of Slopes

The natural slope grouping is necessarily general, and it may be irrelevant to specific needs for slope classification. Consequently, methods were developed to characterize and classify specific aspects of slopes. These methods were drawn from the various data and the data base.

Plate I is a useful tool for generating classifications based upon two parameters. Matrices are illustrated for all combinations of two parameters and corresponding parameter classes. A global classification can be formed by noting all high frequency combinations and disregarding the less frequent ones. For example, 80% of all lateral slopes can be characterized by the following parameter-class combinations for top and bottom province:

Broad shelf-Rise (23%)
Ocean plateau-No Bottom Class.
Narrow shelf-Rise (8%)
Island-Trench (8%)
No Top Class.-No Bottom Class (7%)
Island-No Bottom Class (6%)
Narrow shelf-No Bottom Class (6%)
Narrow shelf-Trench (6%)

Sixty percent of the possible combinations are eliminated because they are not frequent. To apply this classification to global occurrence, one can use the data base to specify locations of the selected groups, and maps can be compiled to show the distribution of the classification scheme.

Another method was formulated to compare and characterize subpopulations of stations. Plate II shows relationships among parameters and parameter classes, and natural groups were based upon these relationships. As revealed in the analysis section, the matrix enables the formation of a detailed characterization of each parameter class subpopulation. Comparisons were made to the global distribution of slopes.

The methods used for the variation matrix and natural grouping can be used with the data base in expanded analyses. For example, geographic areas can be specified as subpopulations, and their data distributions can be retrieved from the data base. The resulting subpopulations can be incorporated into the variation matrix, and they can be characterized by other parameters in relation to the global distribution. An alternative is to establish other mean population distributions and construct a variation matrix based upon them.

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APPENDIX I

Bibliographies

Two bibliographies are offered. First is a bibliography for general slope topics which are not directed toward specific geographic areas. The second bibliography presents slope studies that deal with specific locations. Fourteen ocean quadrants are outlined on an index map, and a separate bibliography corresponds to each quadrant.

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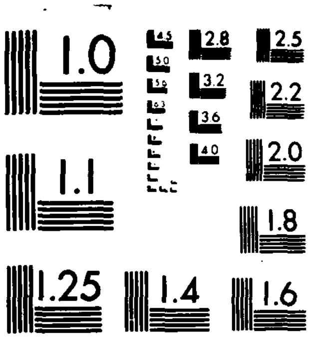

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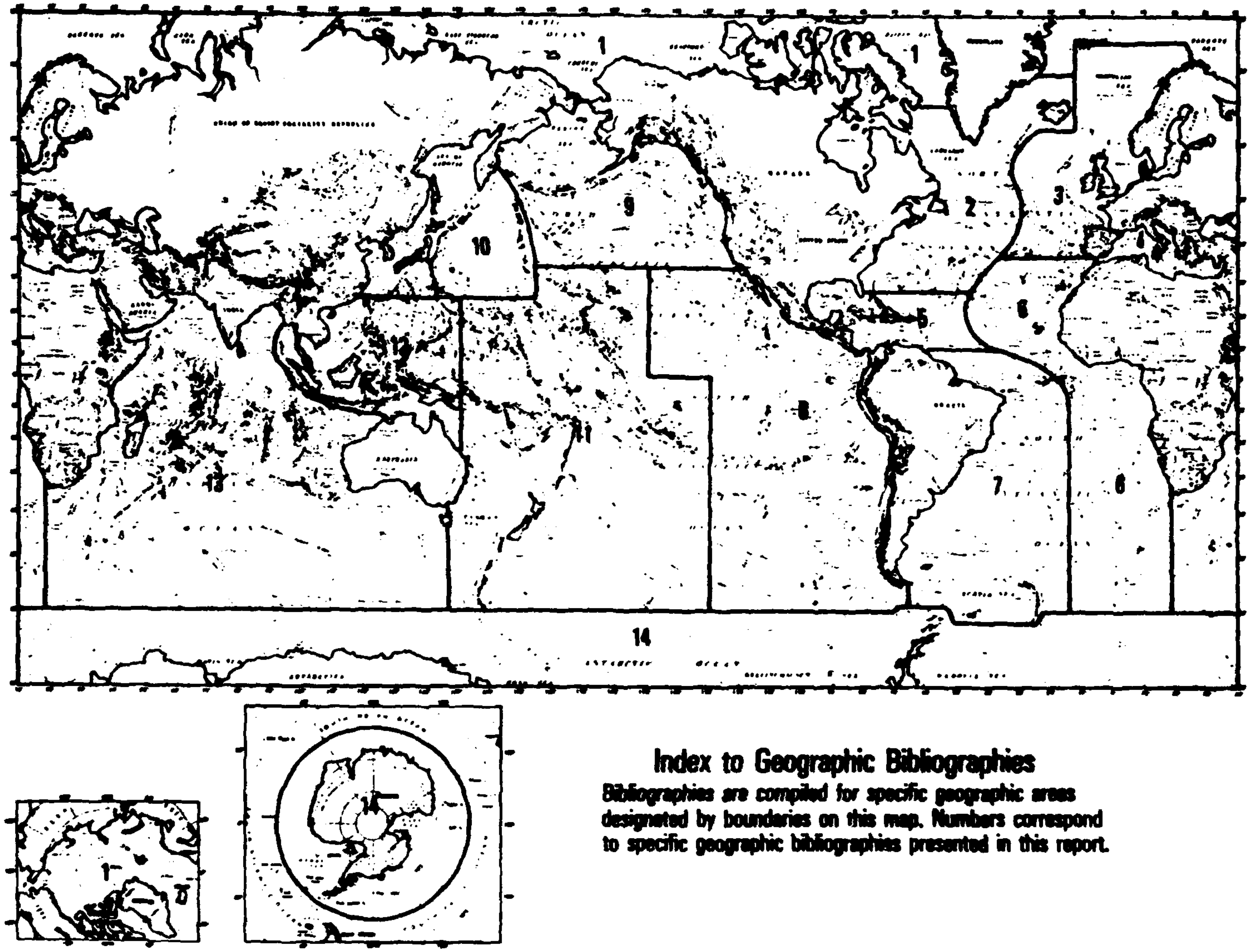

Index to Geographic Bibliographies

Bibliographies are compiled for specific geographic areas designated by boundaries on this map. Numbers correspond to specific geographic bibliographies presented in this report.

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APPENDIX II

Line Drawings of Seismic and Bathymetric Profiles

Profiles are adjusted to uniform scale with a vertical exaggeration of 10:1. Traces of the sediment-water interface and selected horizons were digitized from published studies. A digitized data base for the profiles was formed. Results are the profiles of this appendix. Sources for profiles are given at the end of the appendix. Order of profiles corresponds to the index map (Map IV).

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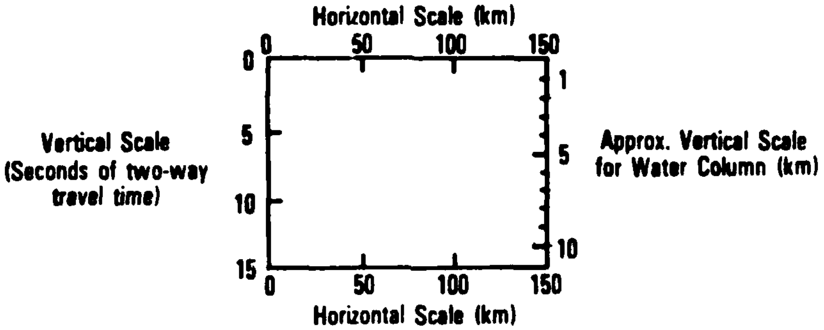
*See Map IV for locations.

Scale

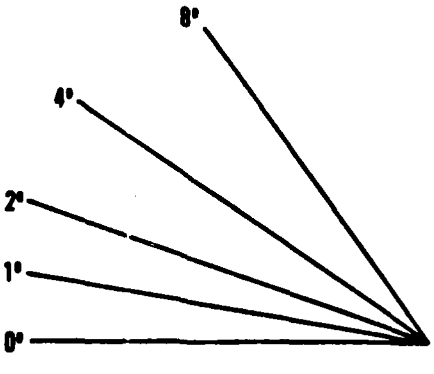
Horizontal scale is in kilometers.

Vertical scale is in seconds of two-way travel time.

Vertical exaggeration to the sediment-water interface is X10 assuming an average water velocity of 1500 m/sec.



Slope Scale for the Sea Bottom



Key to Slope Profiles

—— **Sea Level**

—— **Water-Sediment Interface (Sea Bottom)**

══ **Diagramatic interpretation of seismic structures** *(Note: The position of the lines do not necessarily represent actual seismic structure except for deepest reflector)*

⋯ **Actual seismic structure interpreted to be diapiric salt or shale.**

Actual seismic structure interpreted to be reef material.

– – **Actual seismic reflection planes interpreted to be time boundaries between sedimentary units.**

Abbreviated age levels are:

Q	Quaternary (end of)	Pe	Paleocene
T	Tertiary (end of)	K	Cretaceous
N	*Neogene*	*Ku*	*Upper Cretaceous*
Pl	Pleistocene	Kl	Lower Cretaceous
P	Pliocene	Mz	Mesozoic
M	Miocene	Pz	Paleozoic
E	Eocene	A	A Horizon
O	Oligocene		

(Note: Age abbreviation labels represent the age of sedimentary units when located between reflection planes.)

Where two labels are hyphenated (i.e. M-E), the time boundary dates between the two ages.

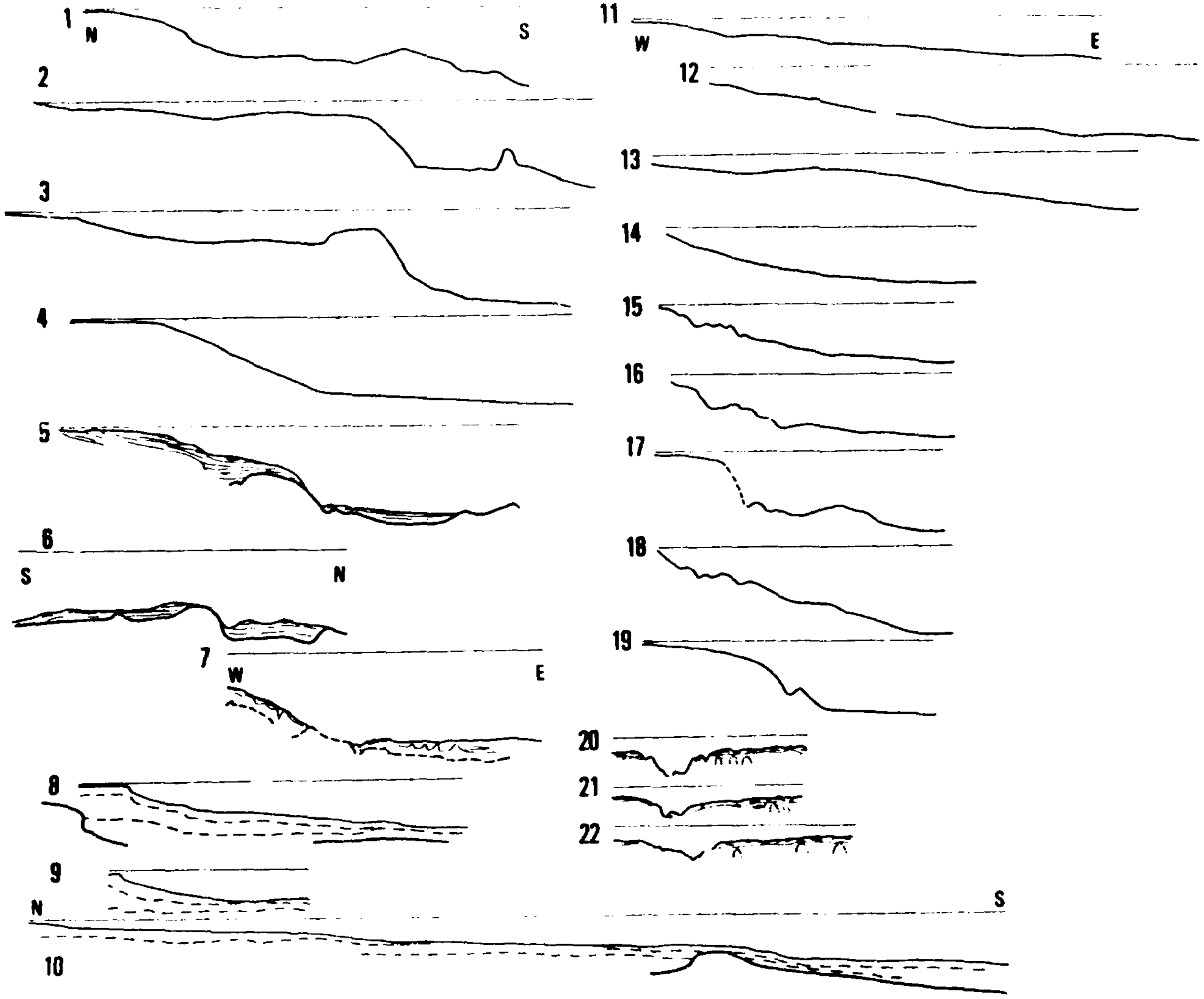
━━ **Acoustic Basement- deepest actual acoustic reflector interpreted to be acoustic basement**

━━ **Crystalline basement- Acoustic reflector interpreted to be either oceanic or continental crystalline material**

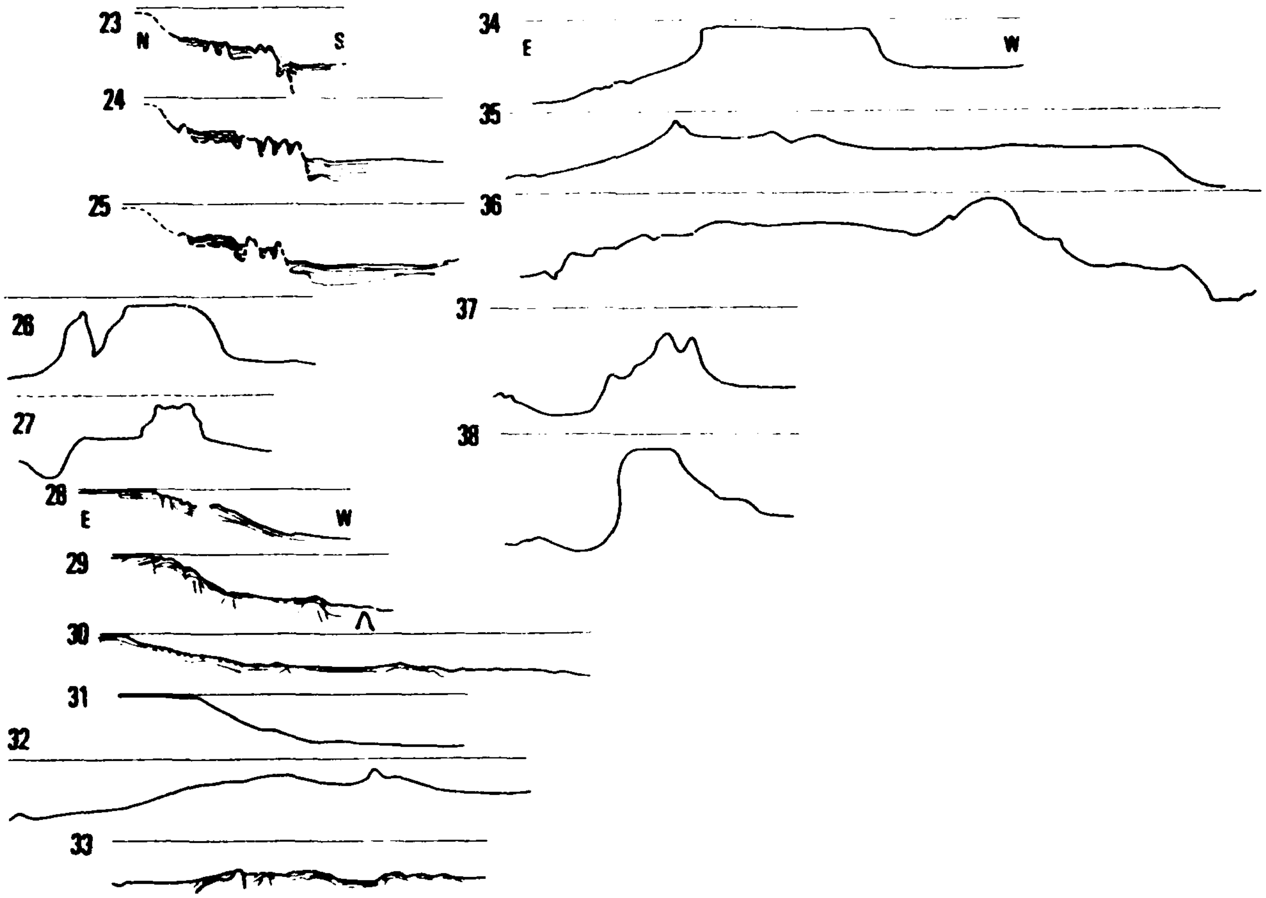
1.91 **Interval velocity in km/sec.**

$\boxed{1.91}$ **Average acoustic velocity (km/sec) for a designated unit.**

INDIAN (1-105)   1-22 Africa

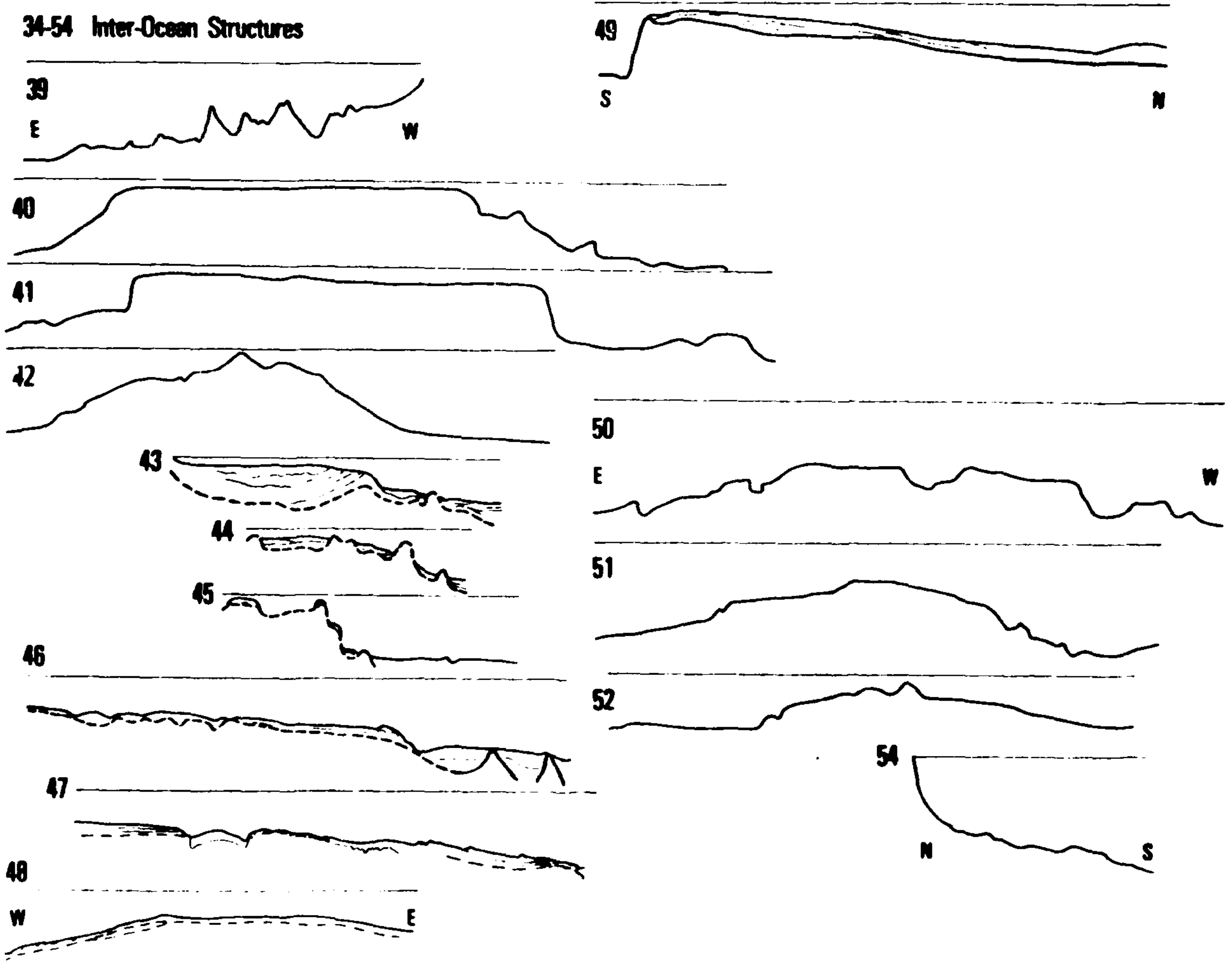


INDIAN (Continued) 23-33 Iran to Western India 34-54 Inter-Ocean Structures



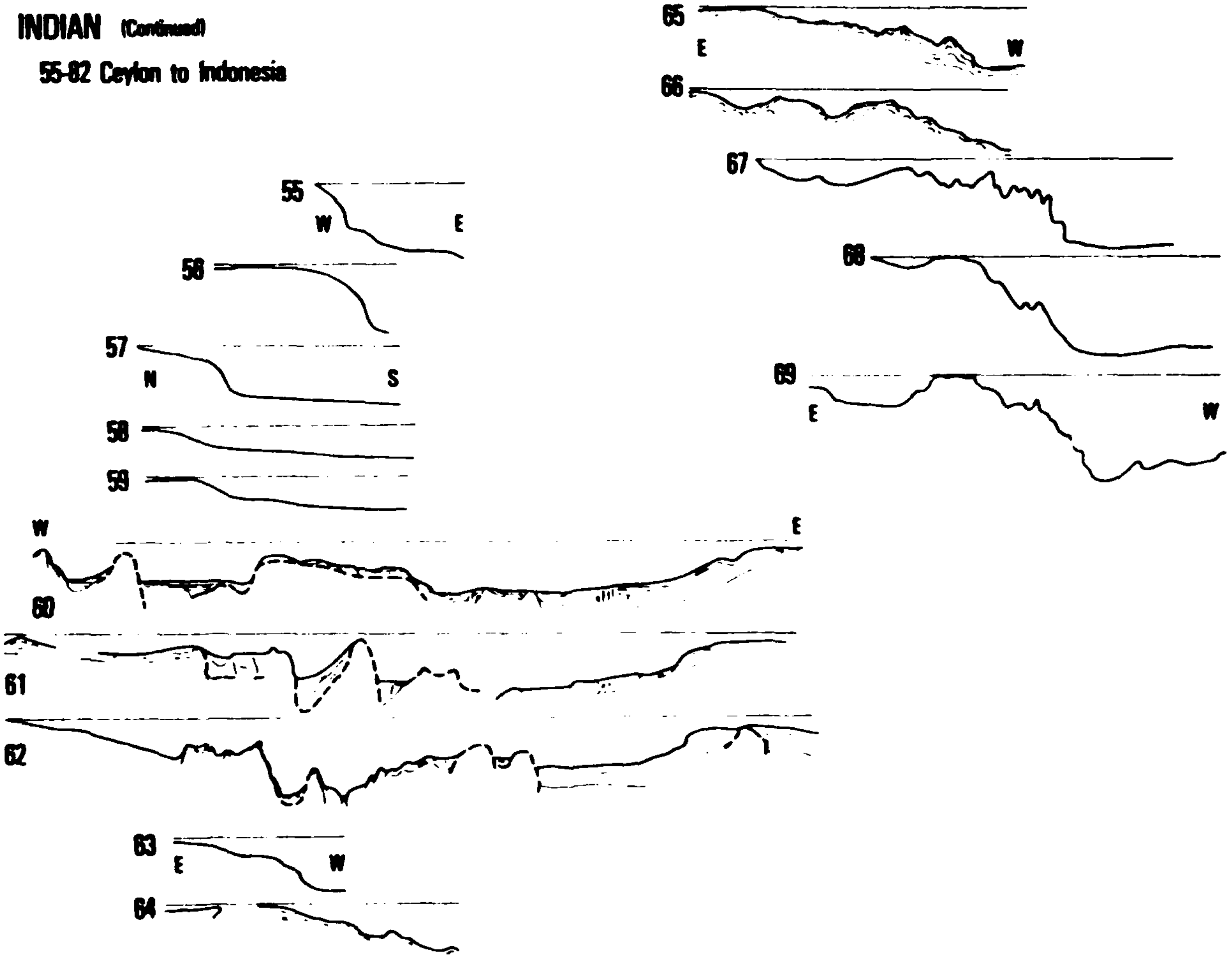
INDIAN (Continued)

34-54 Inter-Ocean Structures



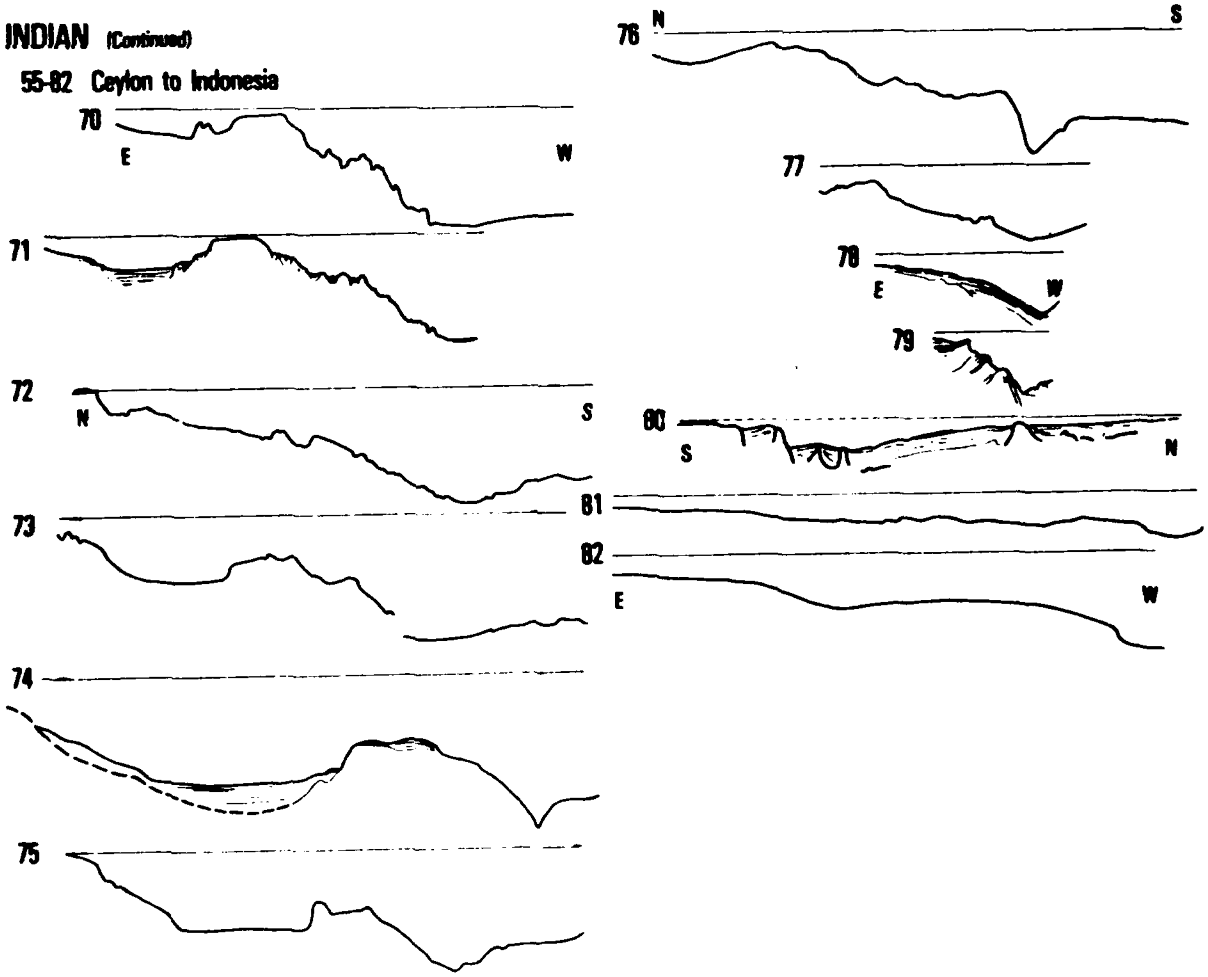
INDIAN (Continued)

55-82 Ceylon to Indonesia



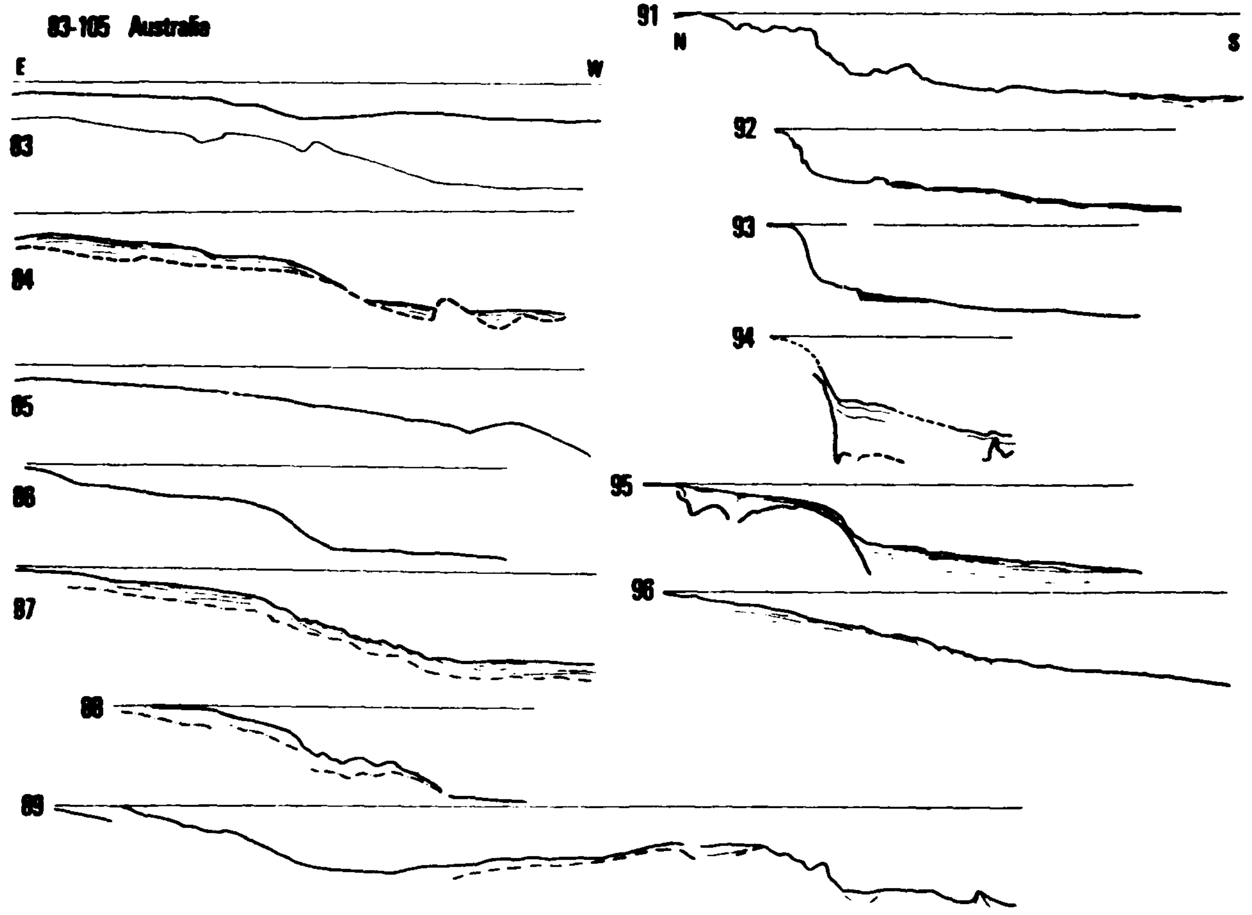
INDIAN (Continued)

55-82 Ceylon to Indonesia



INDIAN (Continued)

83-105 Australia



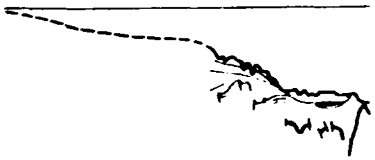
INDIAN (Continued)

83-105 Australia

97

98

99



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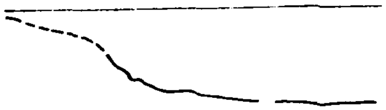

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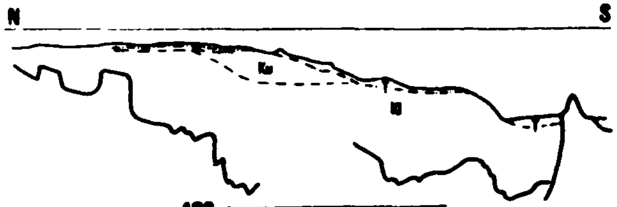

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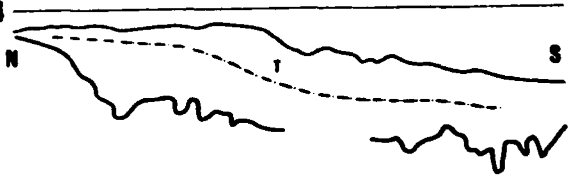

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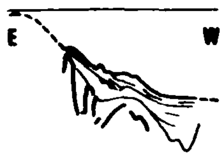
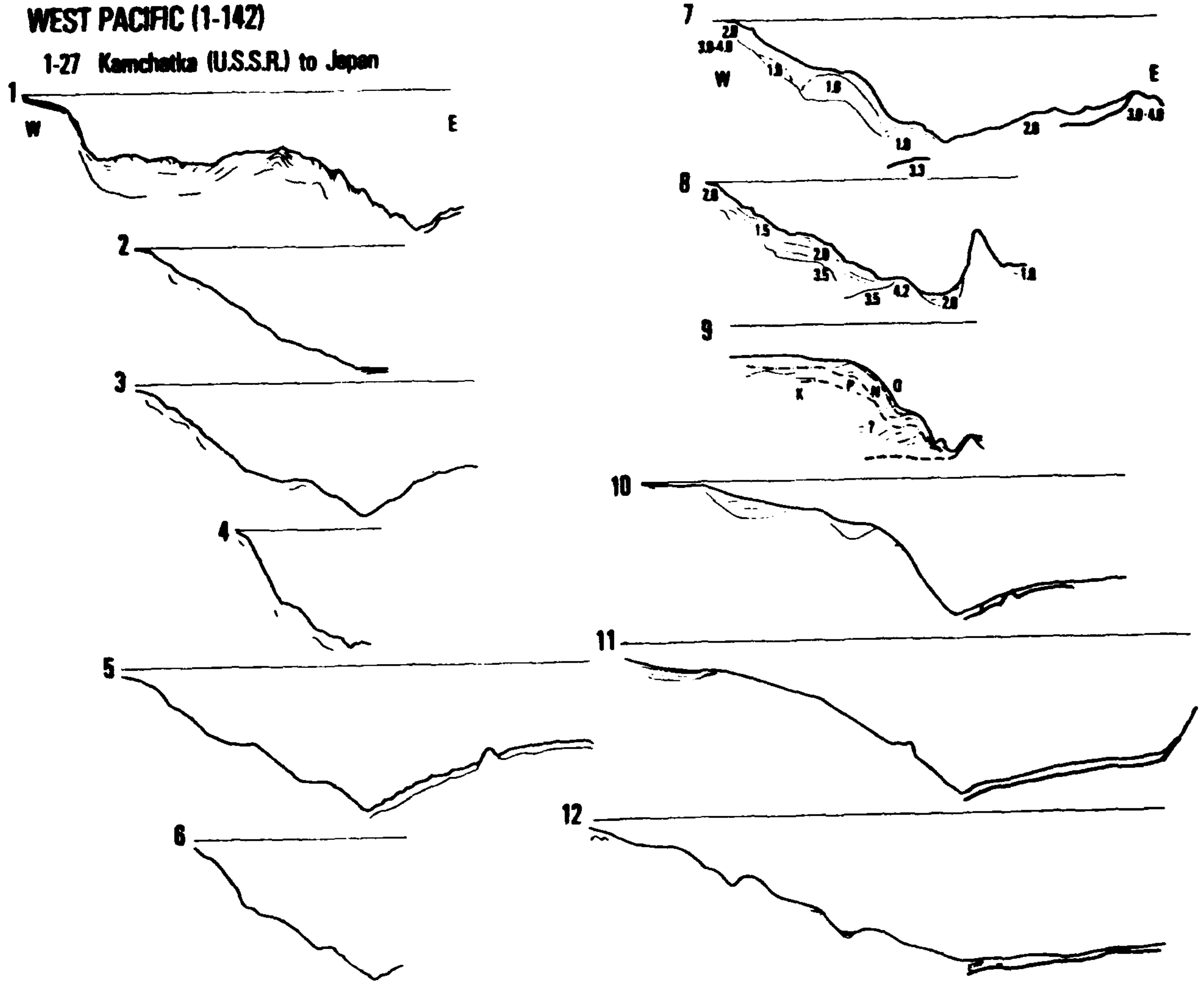


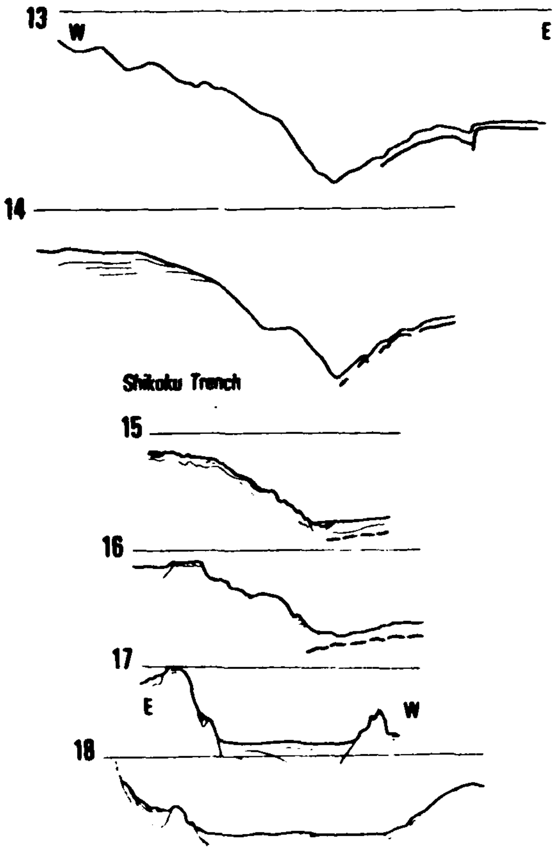
WEST PACIFIC (1-142)

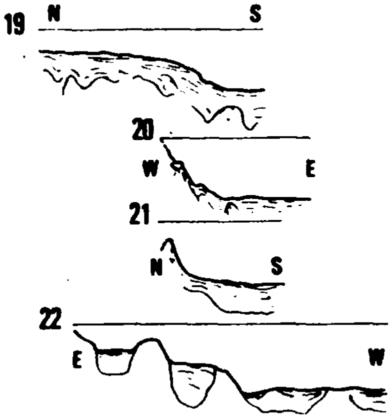
1-27 Kamchatka (U.S.S.R.) to Japan



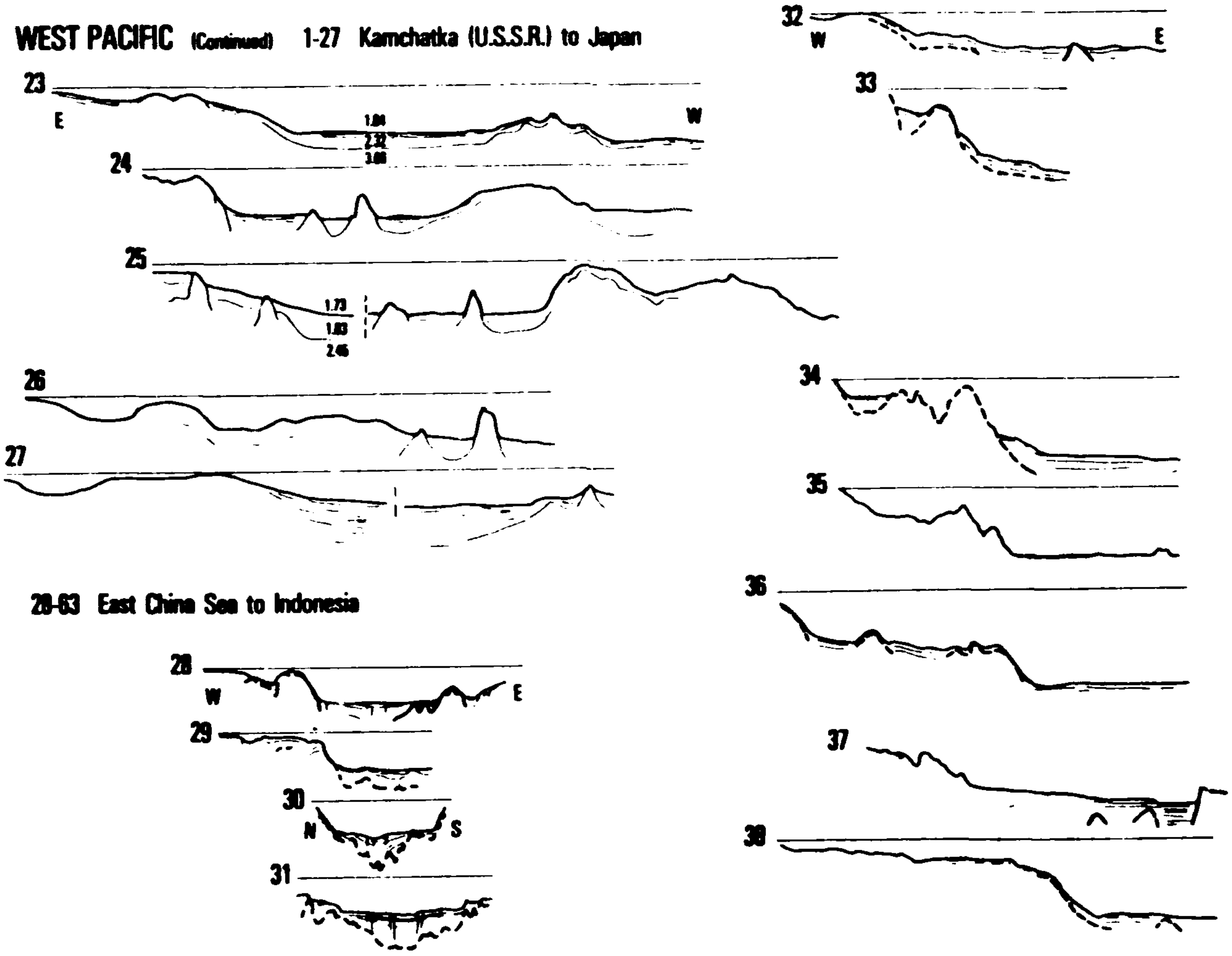
WEST PACIFIC (Continued)

1-27 Kamchatka (U.S.S.R.) to Japan





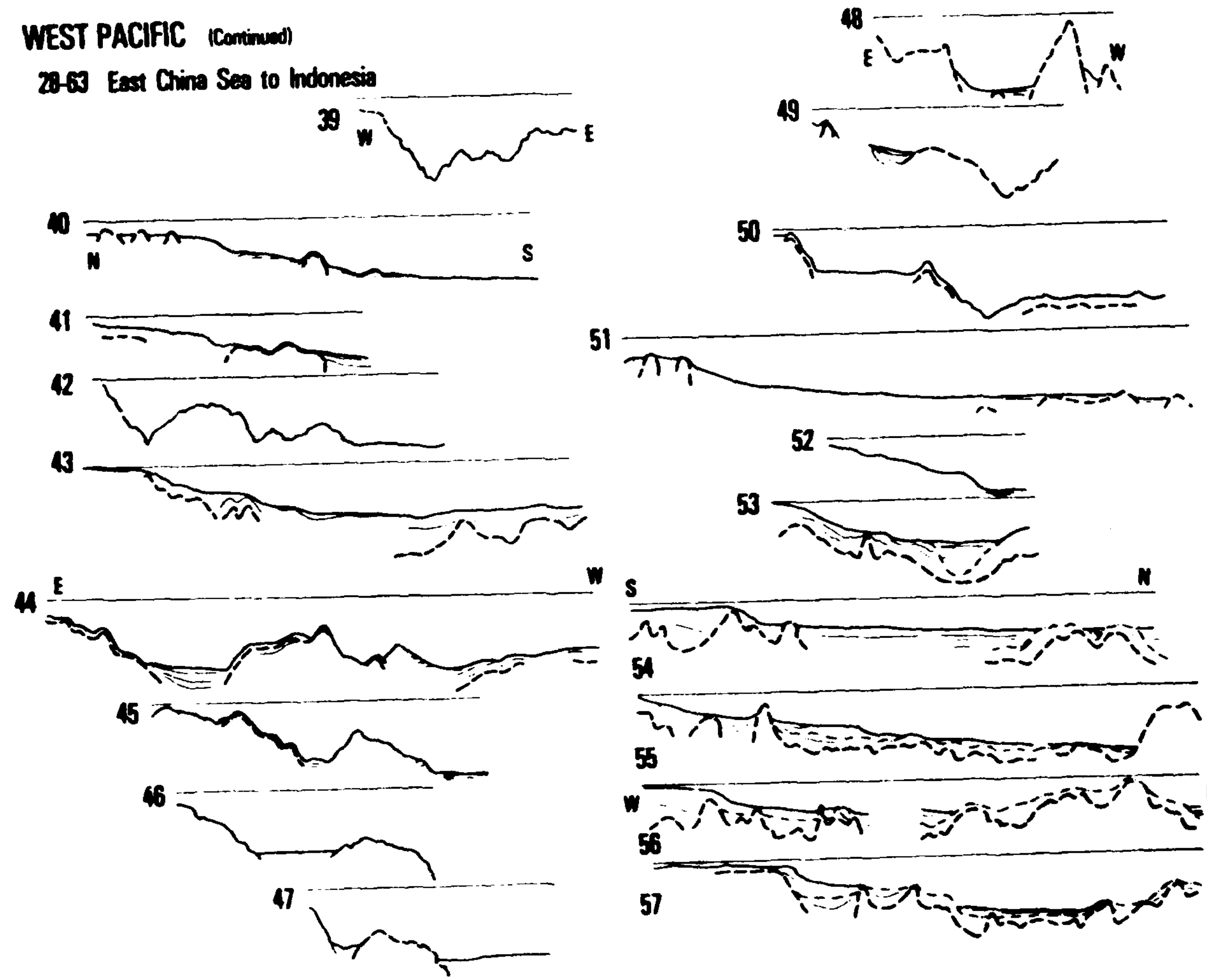
WEST PACIFIC (Continued) 1-27 Kamchatka (U.S.S.R.) to Japan



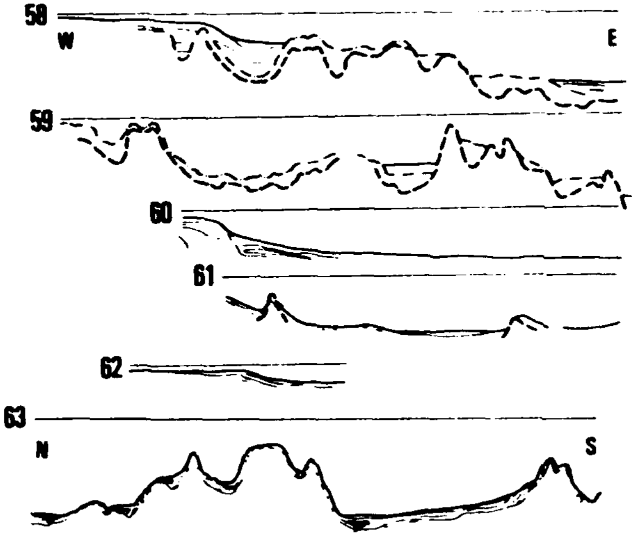
28-63 East China Sea to Indonesia

WEST PACIFIC (Continued)

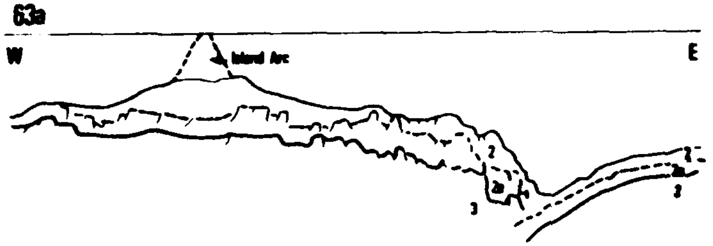
28-63 East China Sea to Indonesia

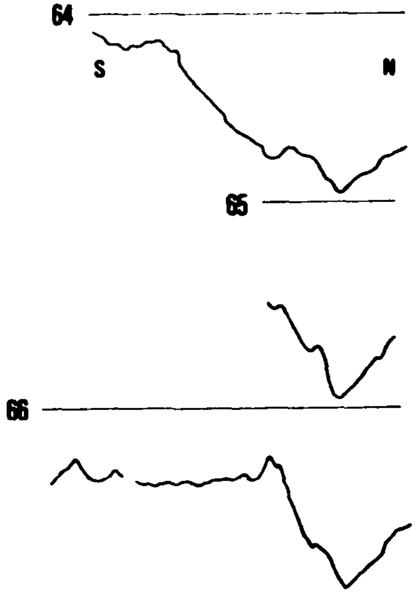


WEST PACIFIC (Continued) 28-63 East China Sea to Indonesia

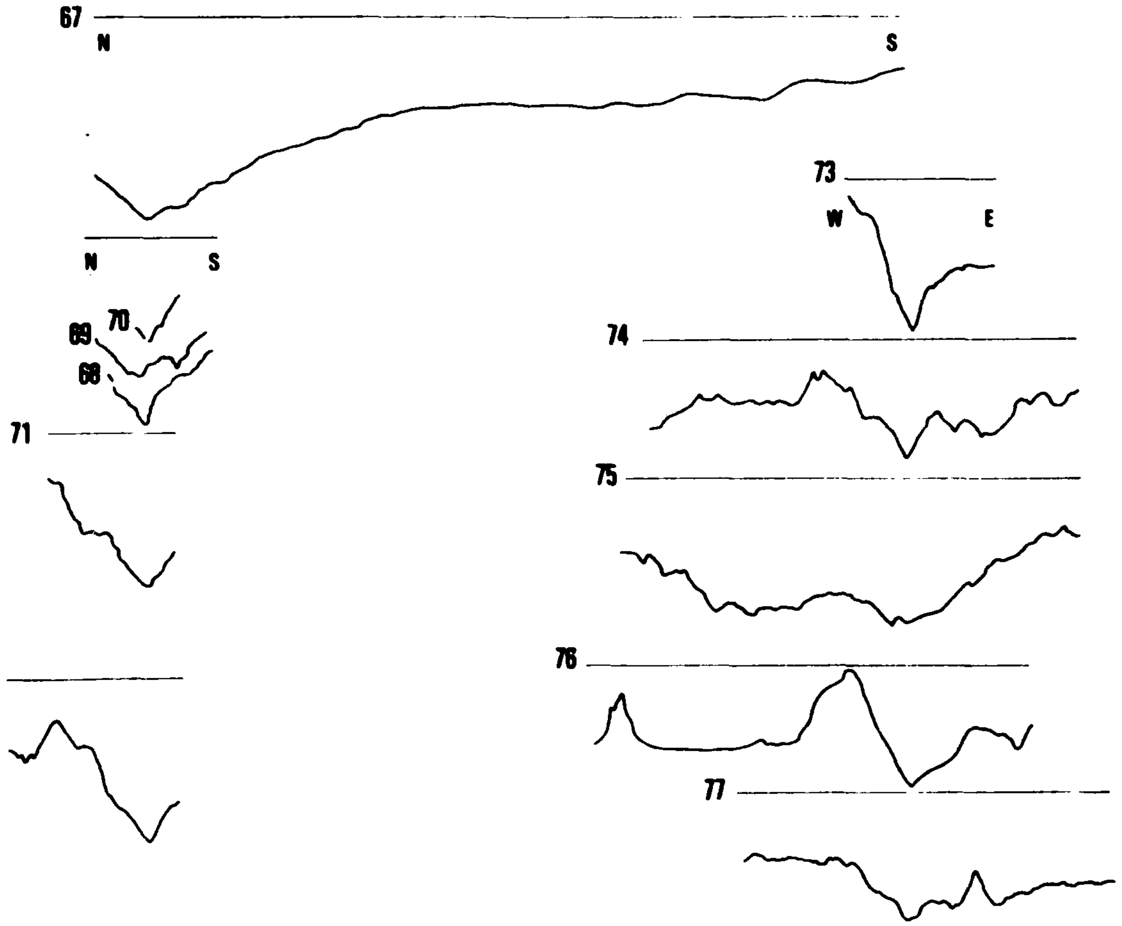


63a-77 Marianas Islands to Yap Island

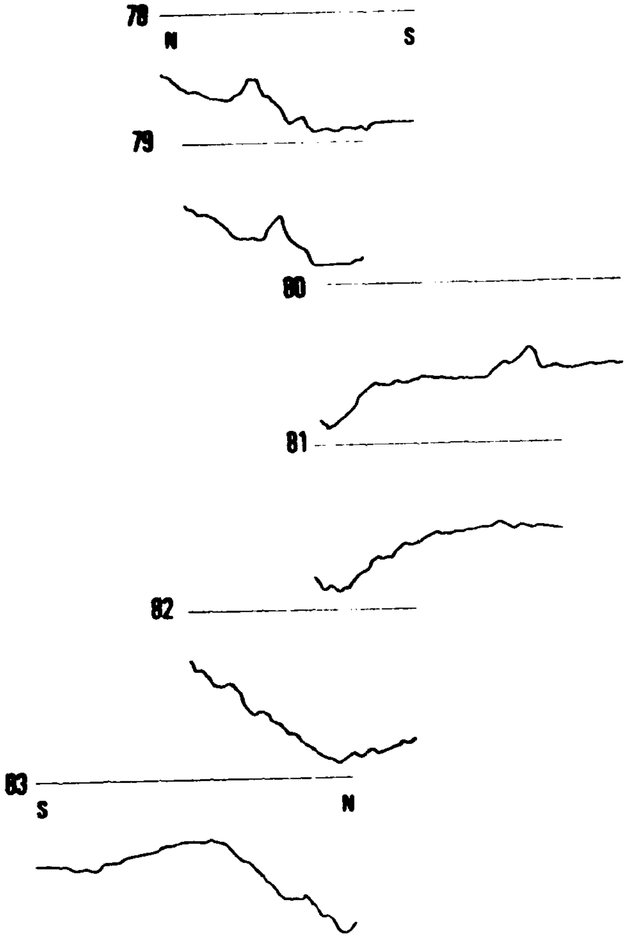


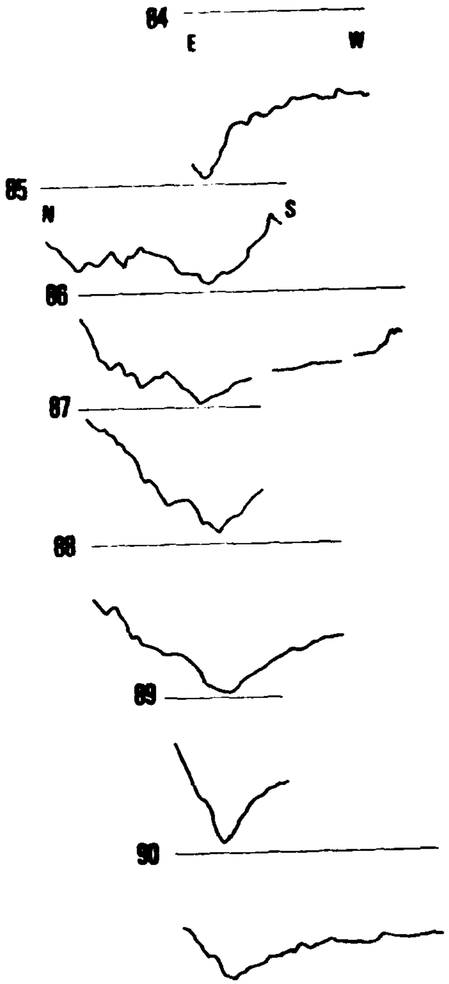


WEST PACIFIC (Continued) 63a-77 Marianas Islands to Yap Island



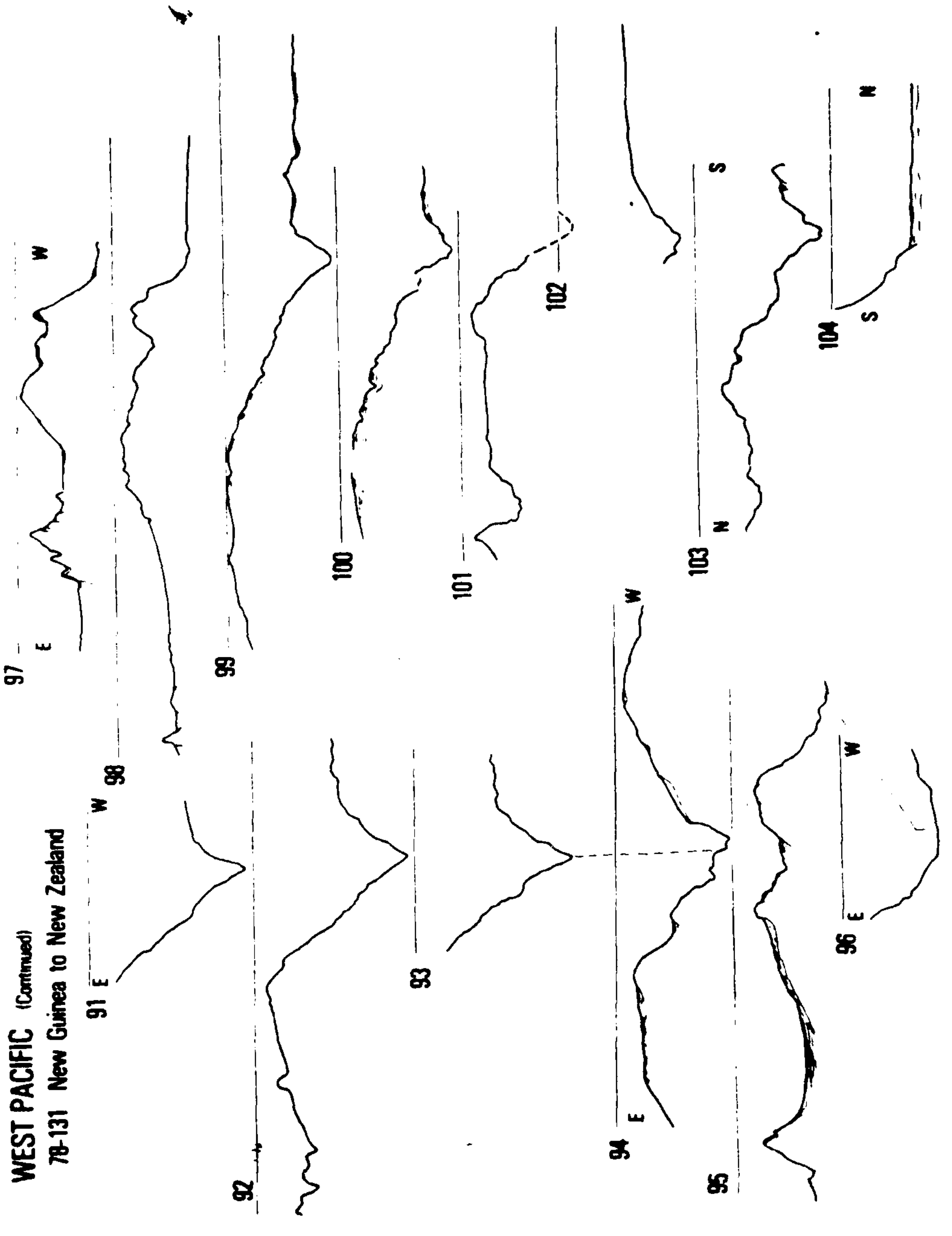
WEST PACIFIC (Continued) 78-131 New Guinea to New Zealand





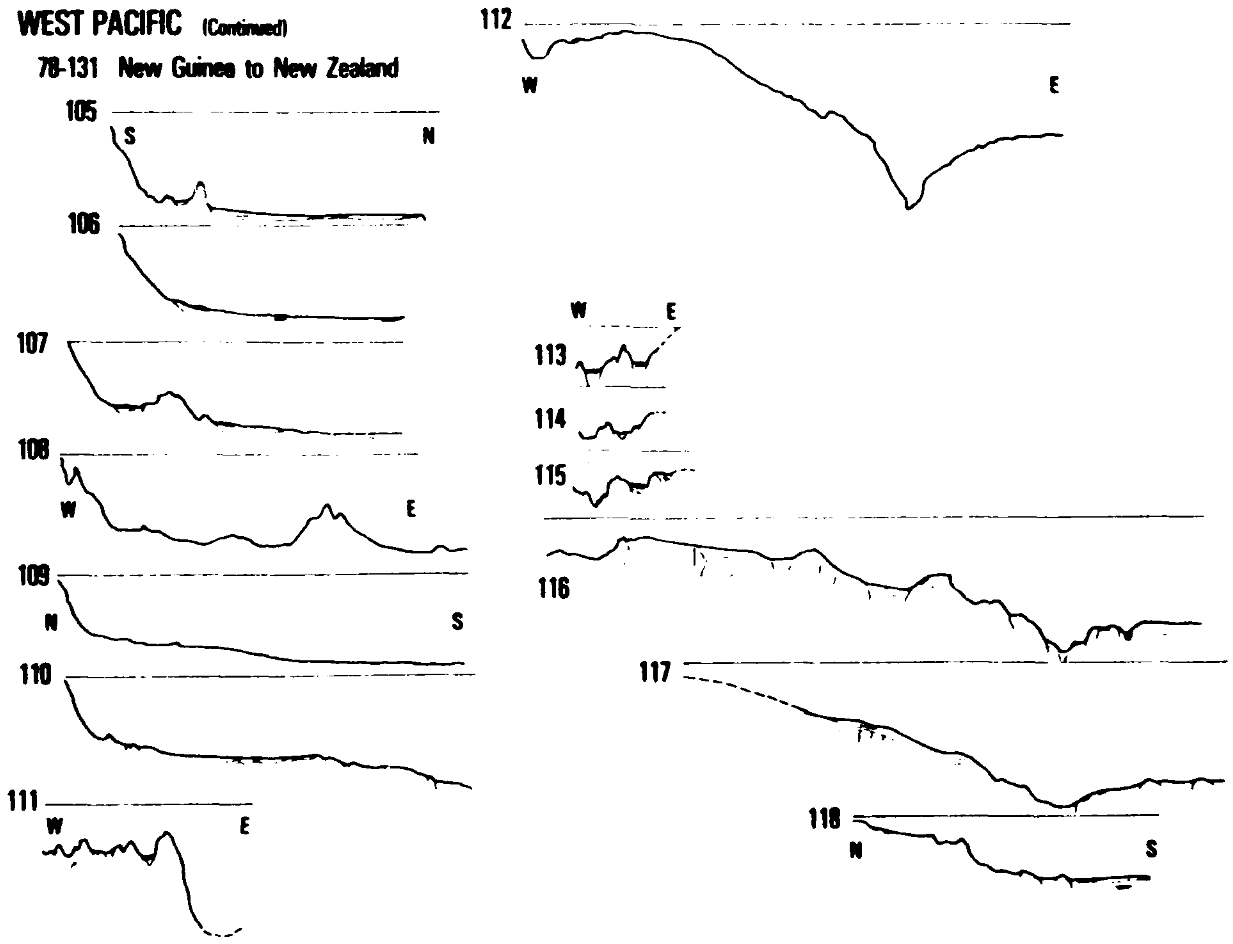
WEST PACIFIC (Continued)

78-131 New Guinea to New Zealand

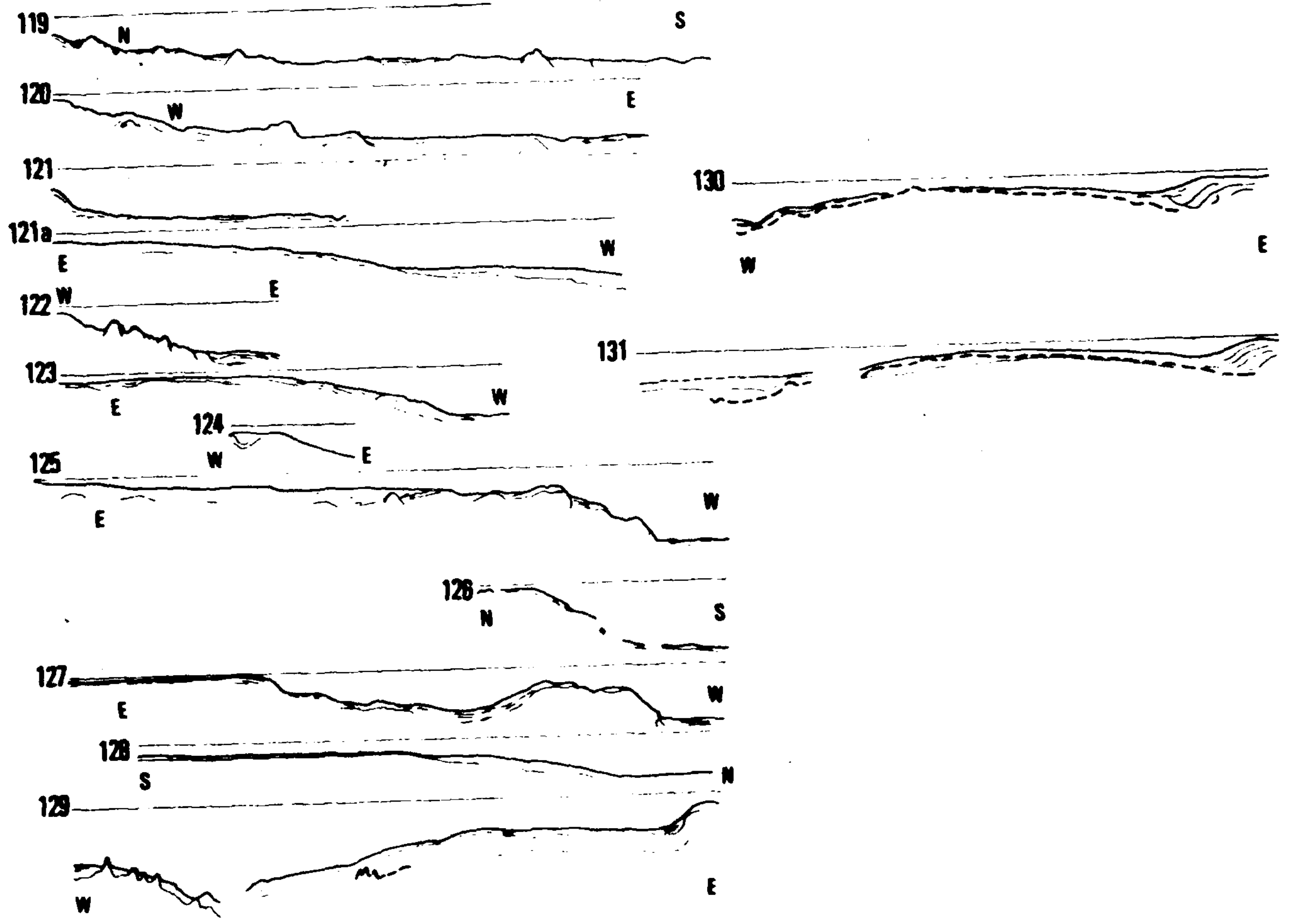


WEST PACIFIC (Continued)

78-131 New Guinea to New Zealand

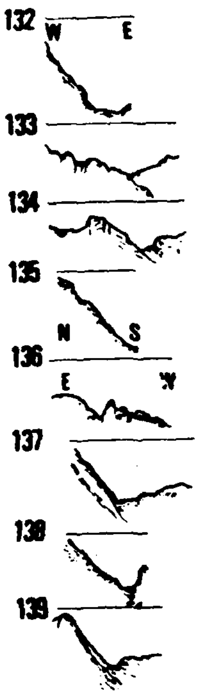


WEST PACIFIC (Continued) 78-130 New Guinea to New Zealand



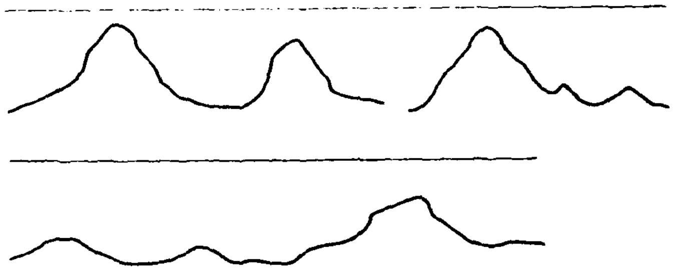
WEST PACIFIC (Continued)

132-139 Molucca Sea

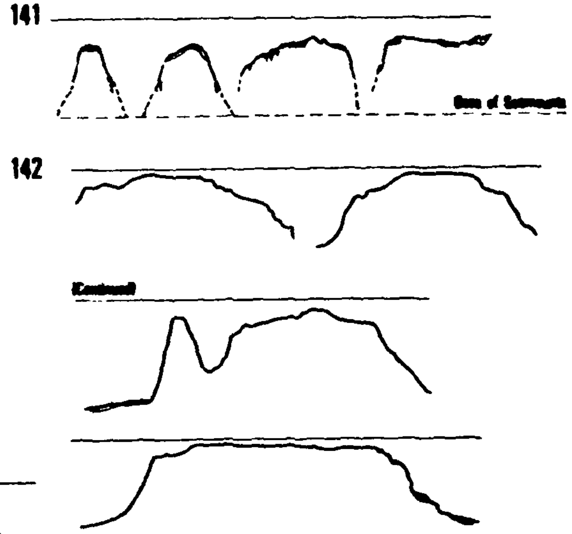


140 Musician Seamounts

140 (Continued)

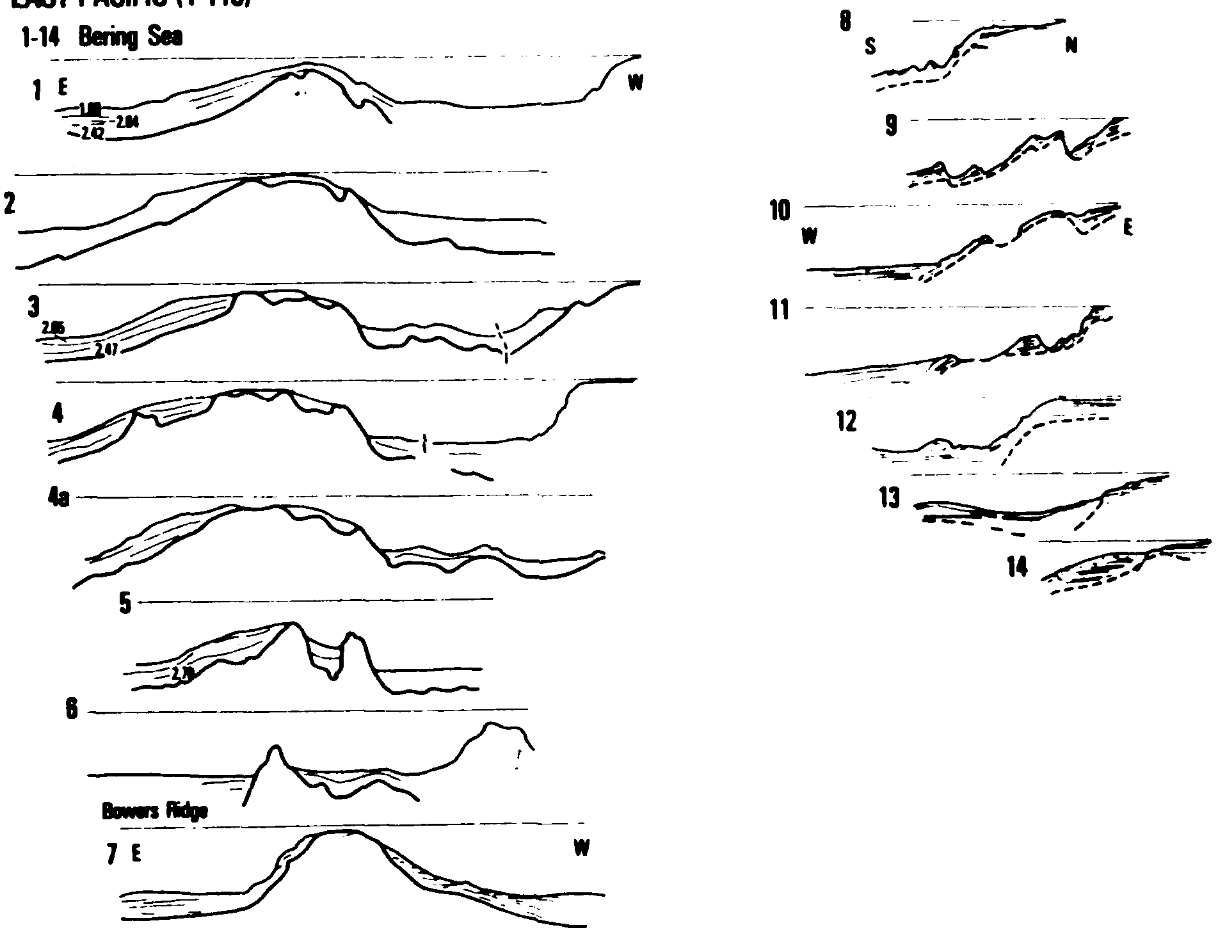


141-142 Emperor Seamounts



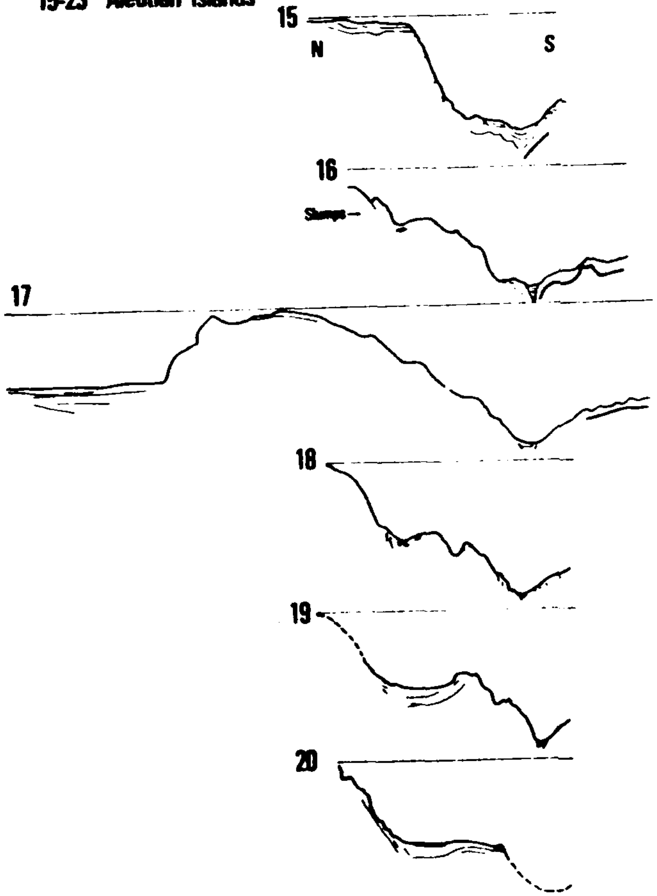
EAST PACIFIC (1-113)

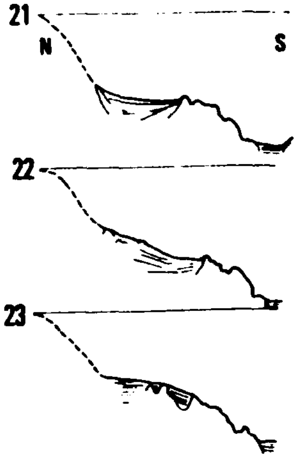
1-14 Bering Sea



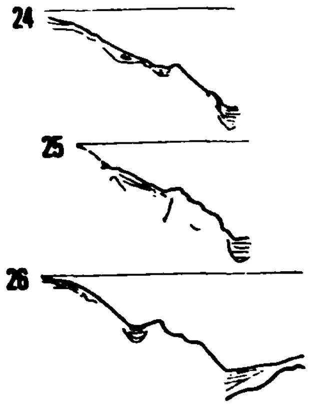
EAST PACIFIC (Continued)

15-23 Aleutian Islands

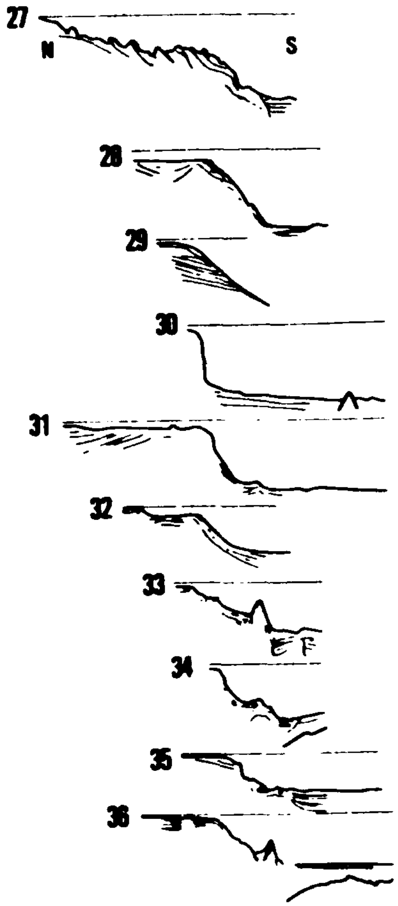


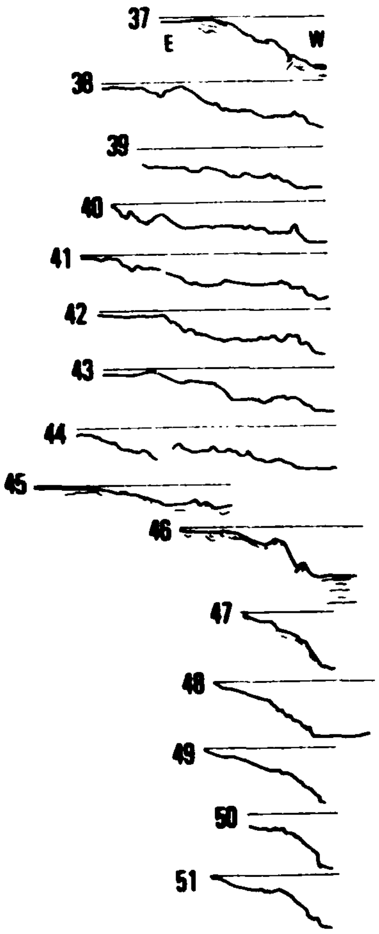


24-71 Alaska, Canada, U.S.

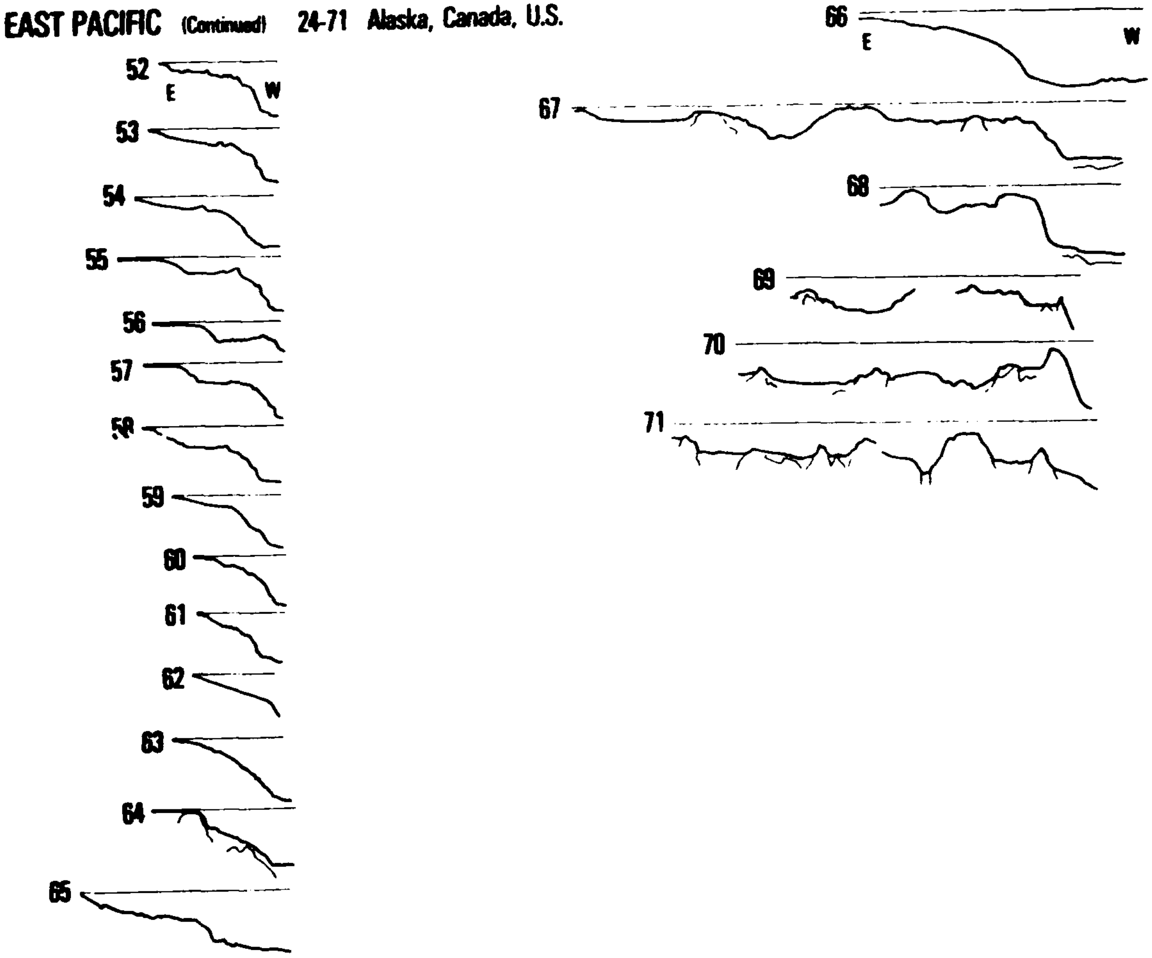


EAST PACIFIC (Continued) 24-71 Alaska, Canada, U.S.



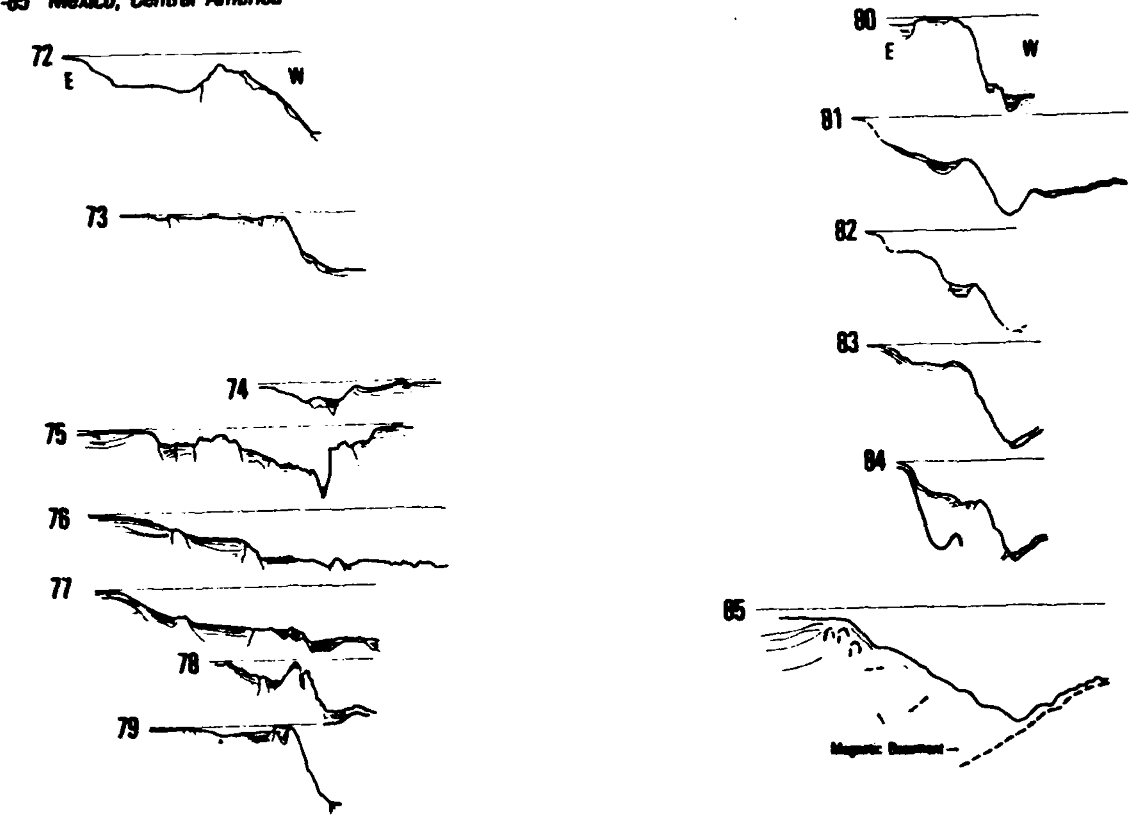


EAST PACIFIC (Continued) 24-71 Alaska, Canada, U.S.

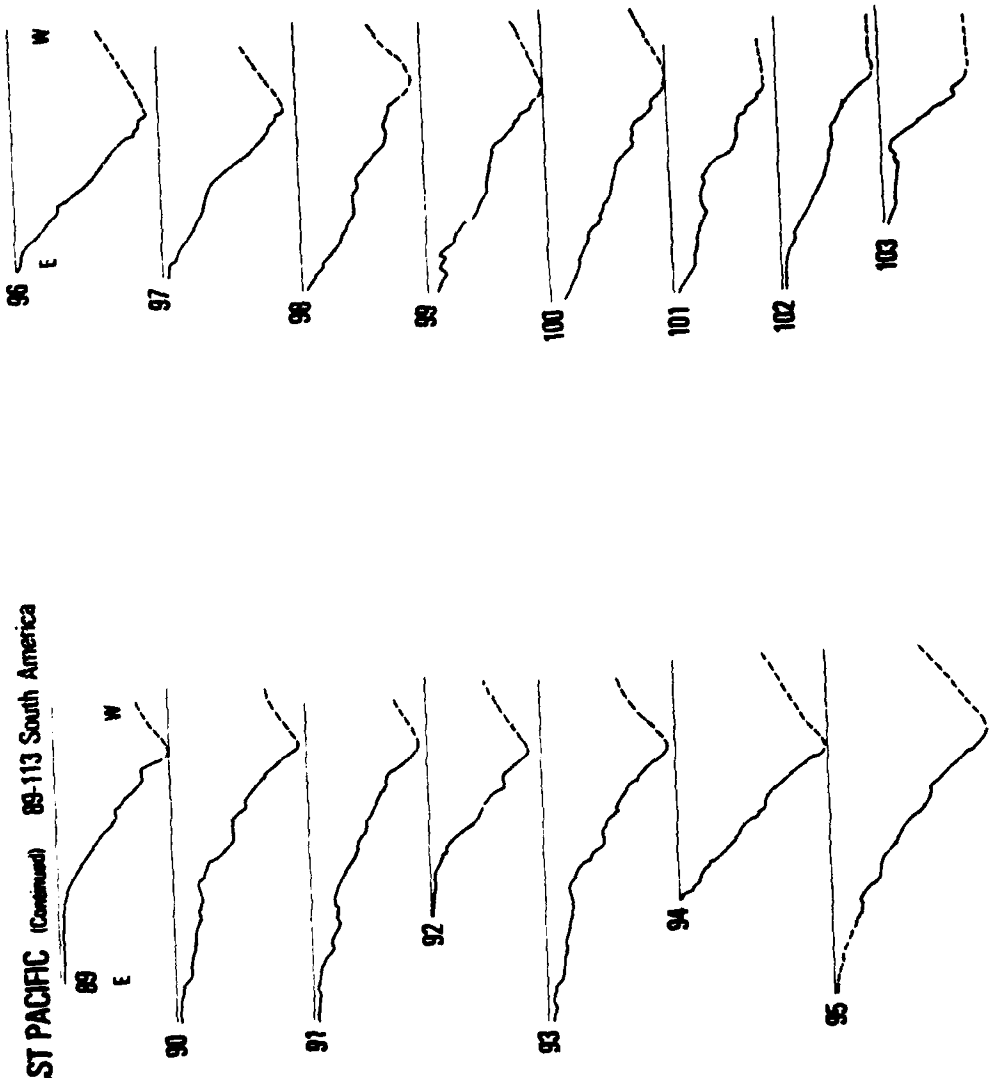


EAST PACIFIC (Continued)

72-85 Mexico, Central America

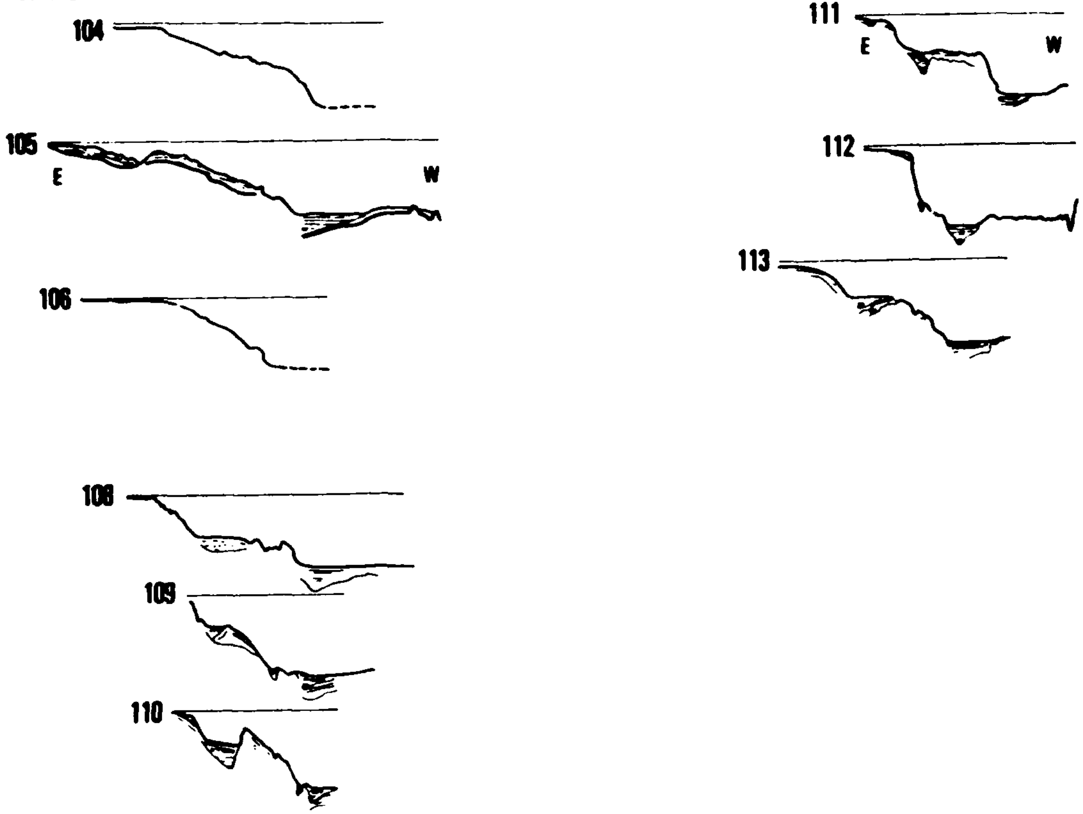


EAST PACIFIC (Continued) 89-113 South America



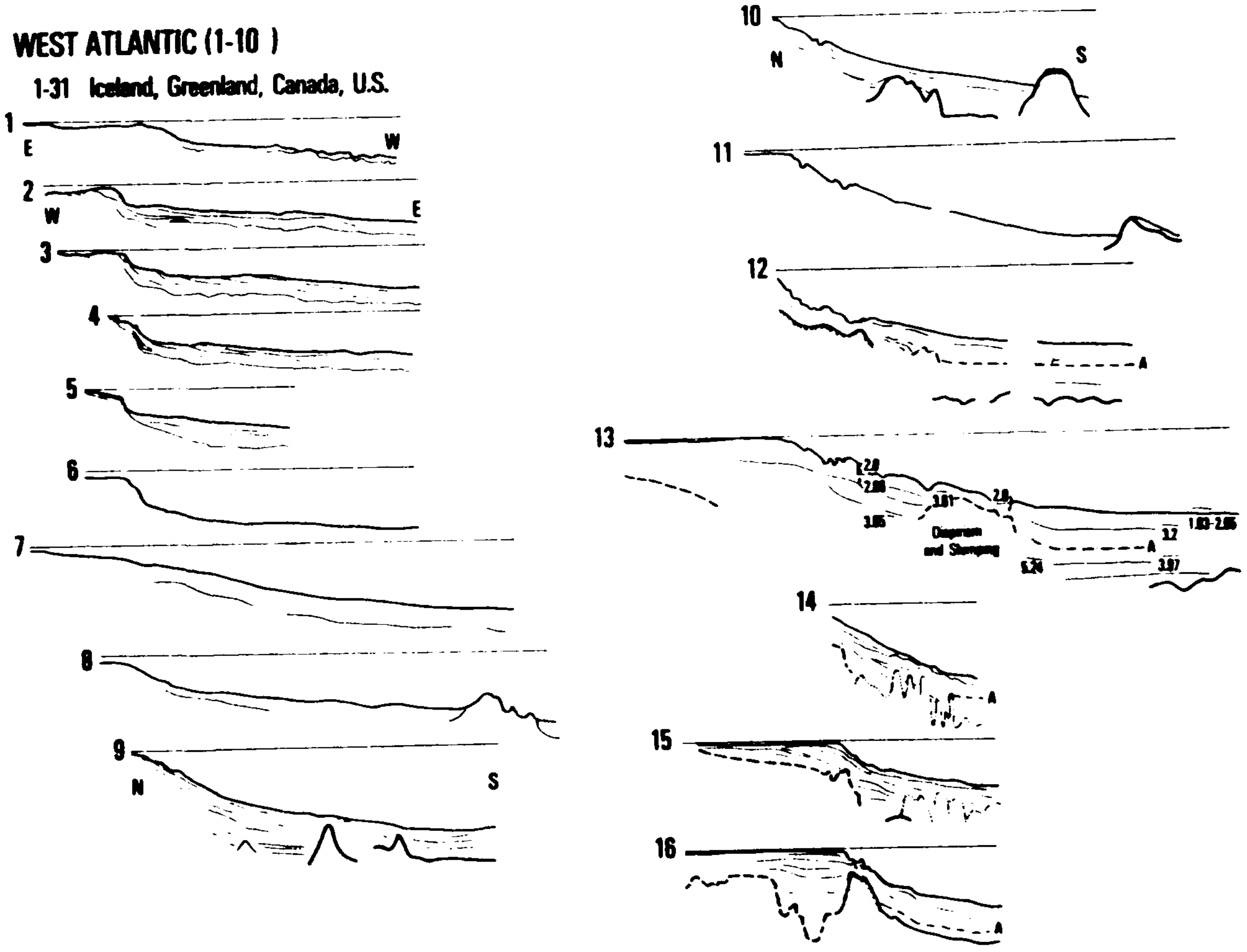
EAST PACIFIC (Continued)

89-113 South America



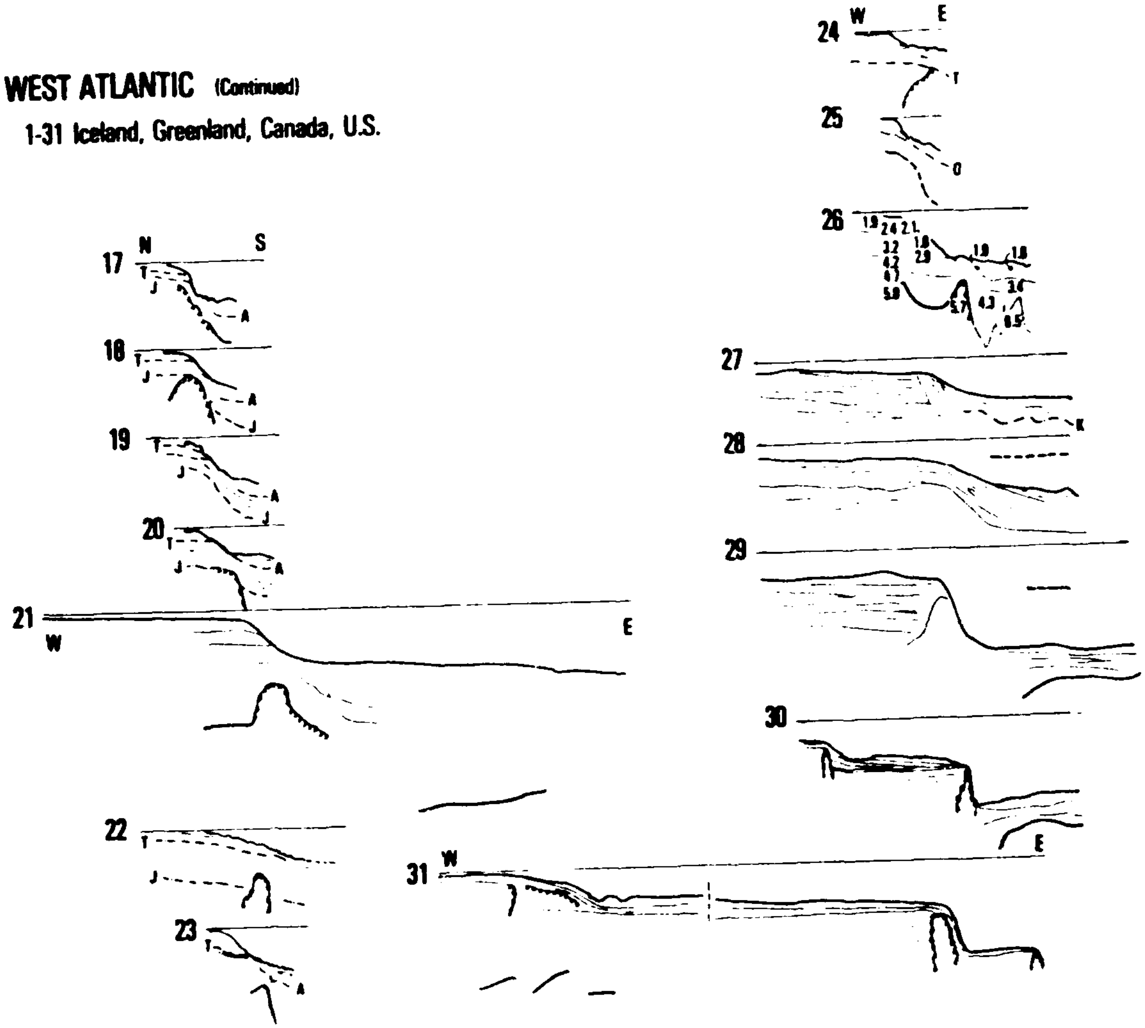
WEST ATLANTIC (1-10)

1-31 Iceland, Greenland, Canada, U.S.



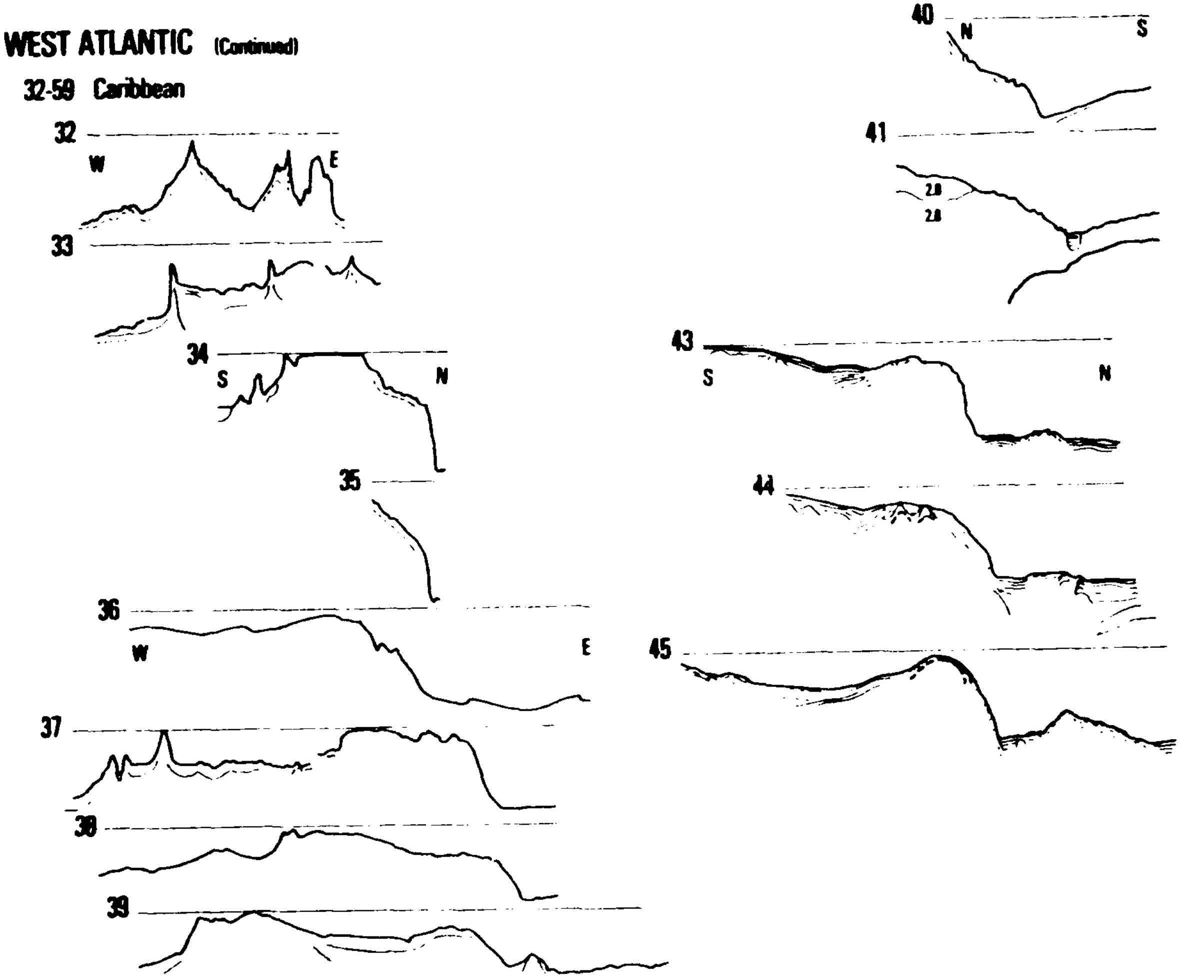
WEST ATLANTIC (Continued)

1-31 Iceland, Greenland, Canada, U.S.



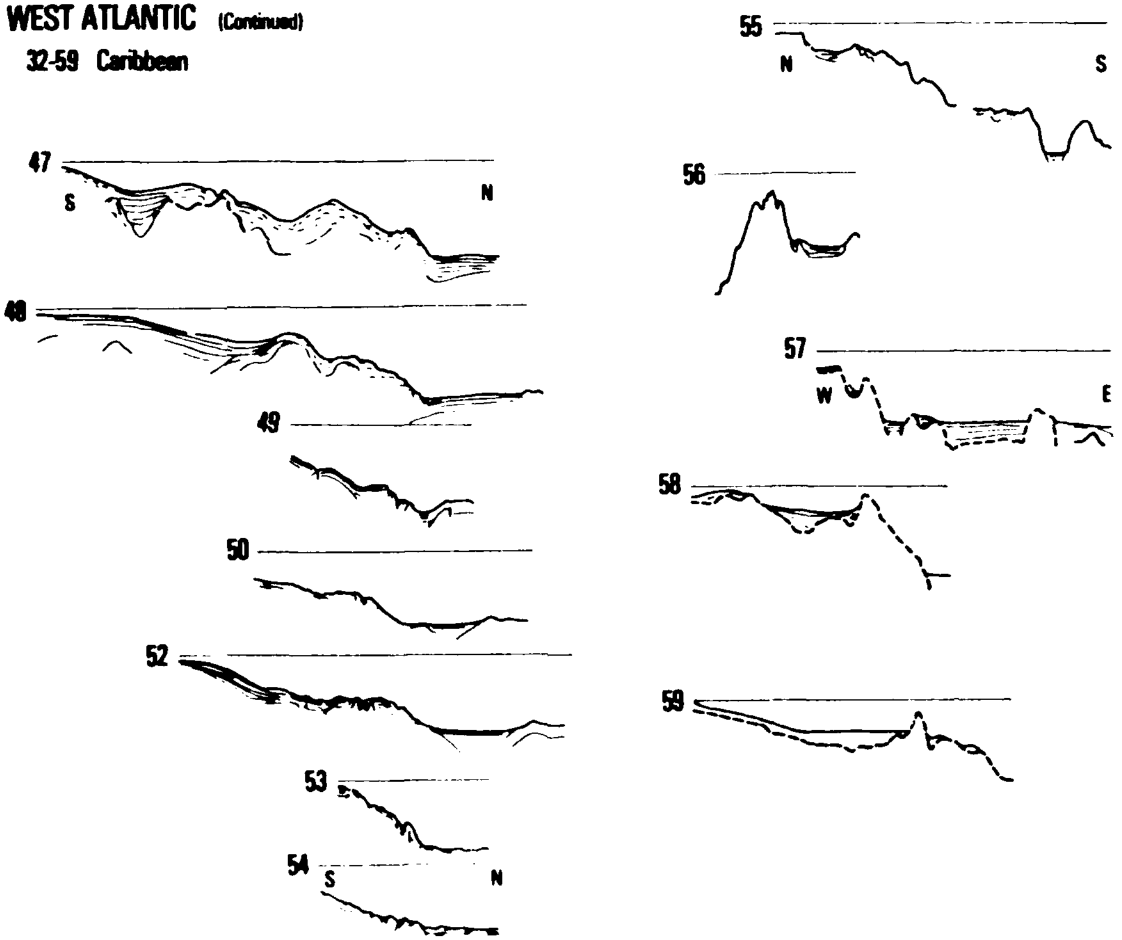
WEST ATLANTIC (Continued)

32-59 Caribbean



WEST ATLANTIC (Continued)

32-59 Caribbean



WEST ATLANTIC (Continued)

59-67 Gulf of Mexico

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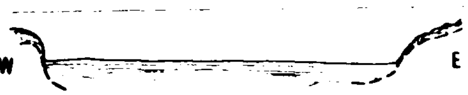

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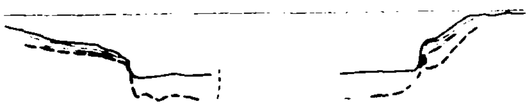

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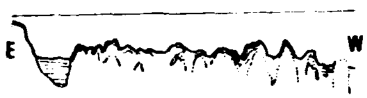

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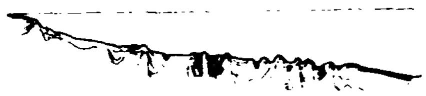
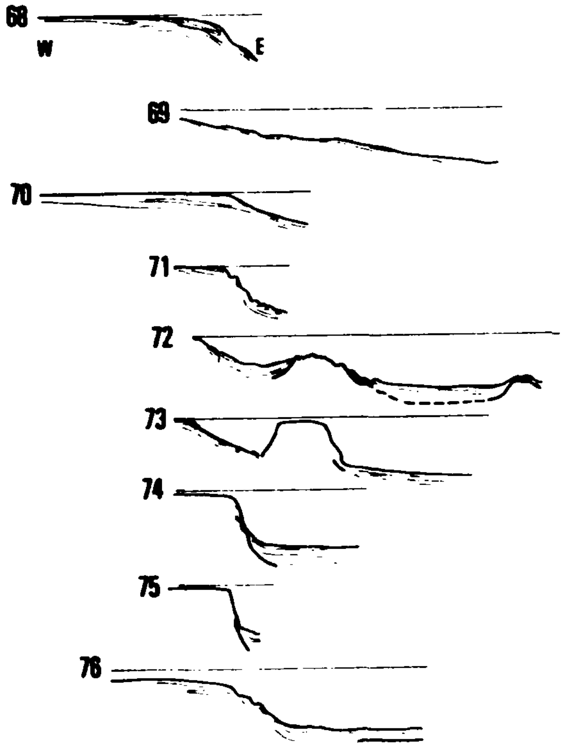
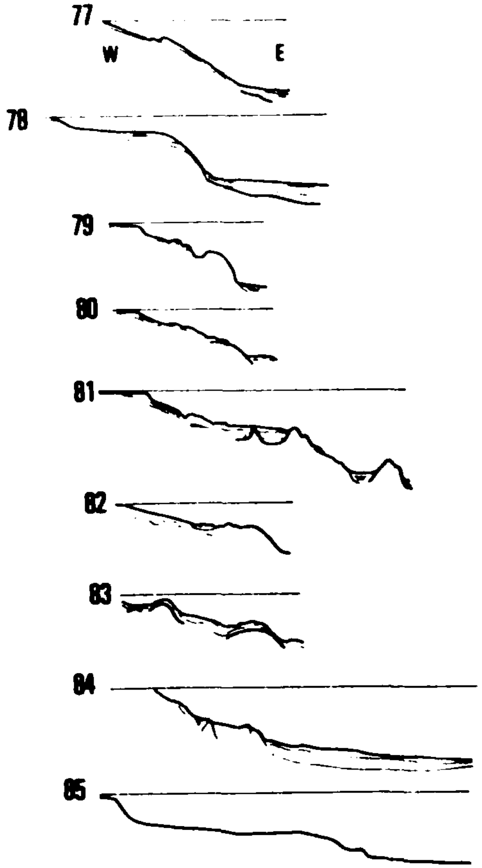


67


WEST ATLANTIC (Continued)

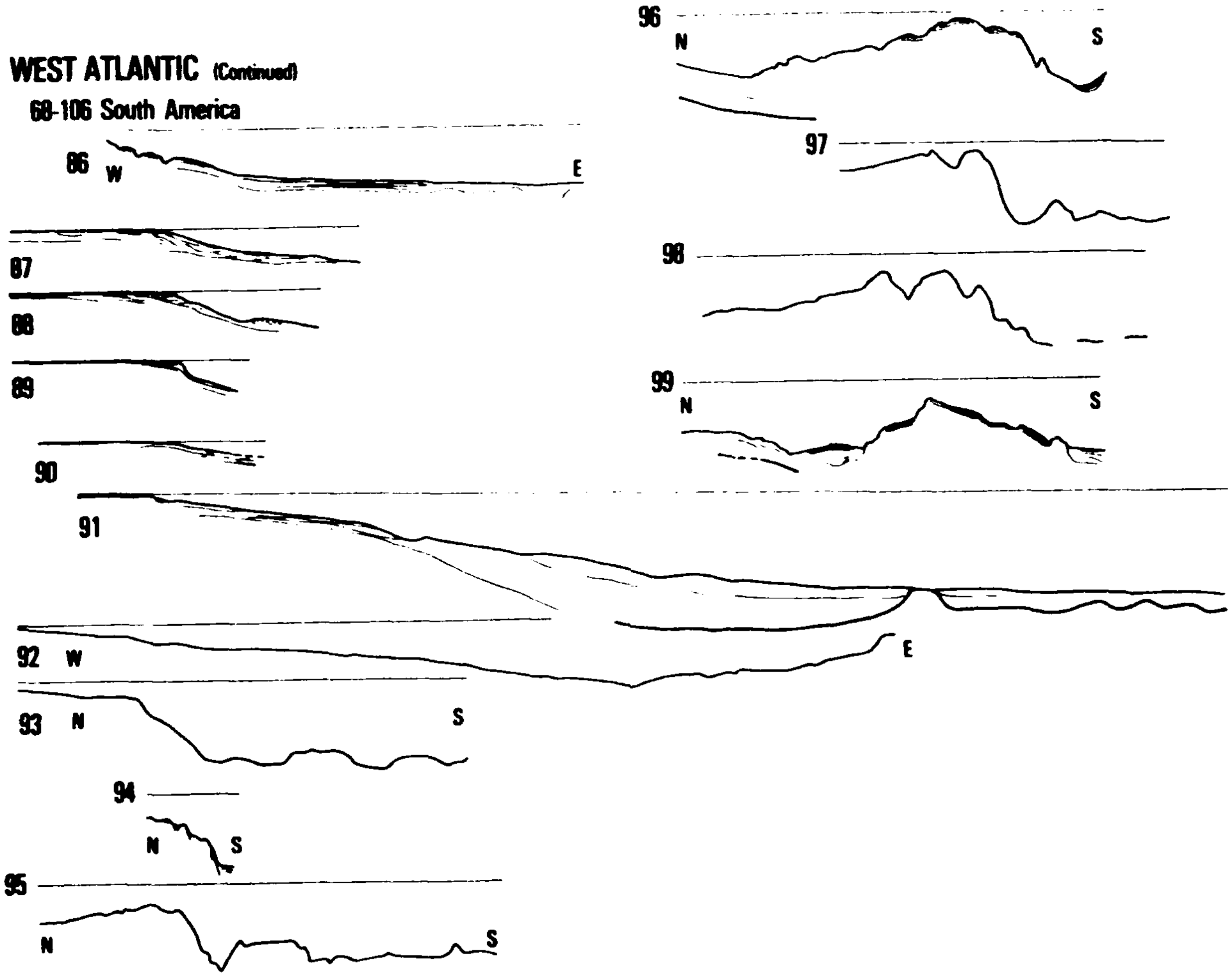
68-106 South America



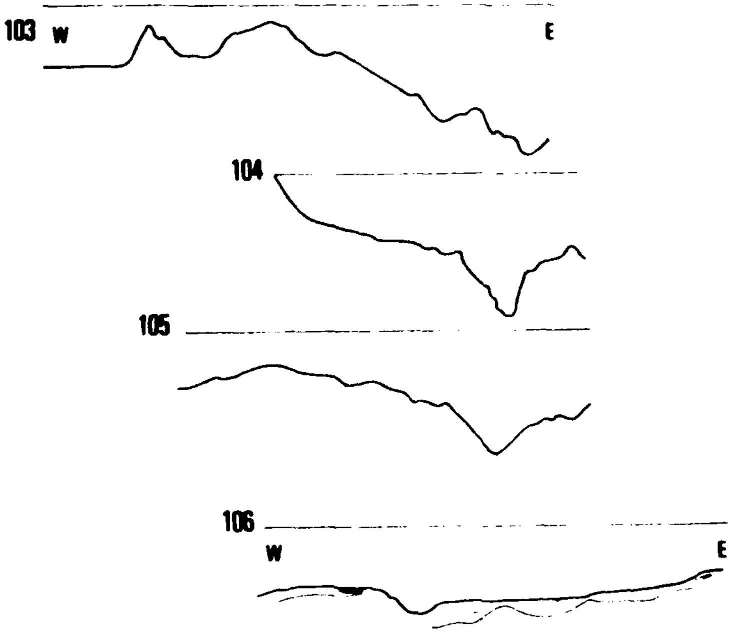


WEST ATLANTIC (Continued)

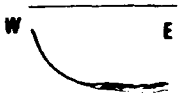
68-106 South America



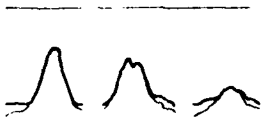
WEST ATLANTIC (Continued) 68-106 South America



107 Bermuda

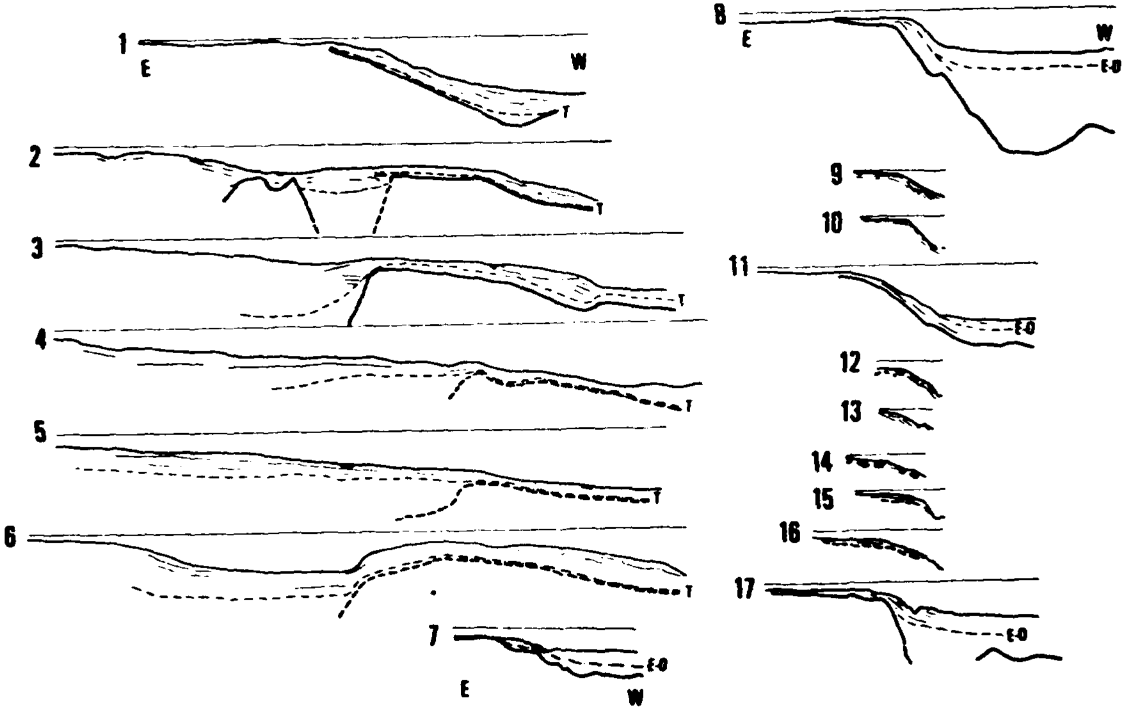


108 Gilliss Seamount



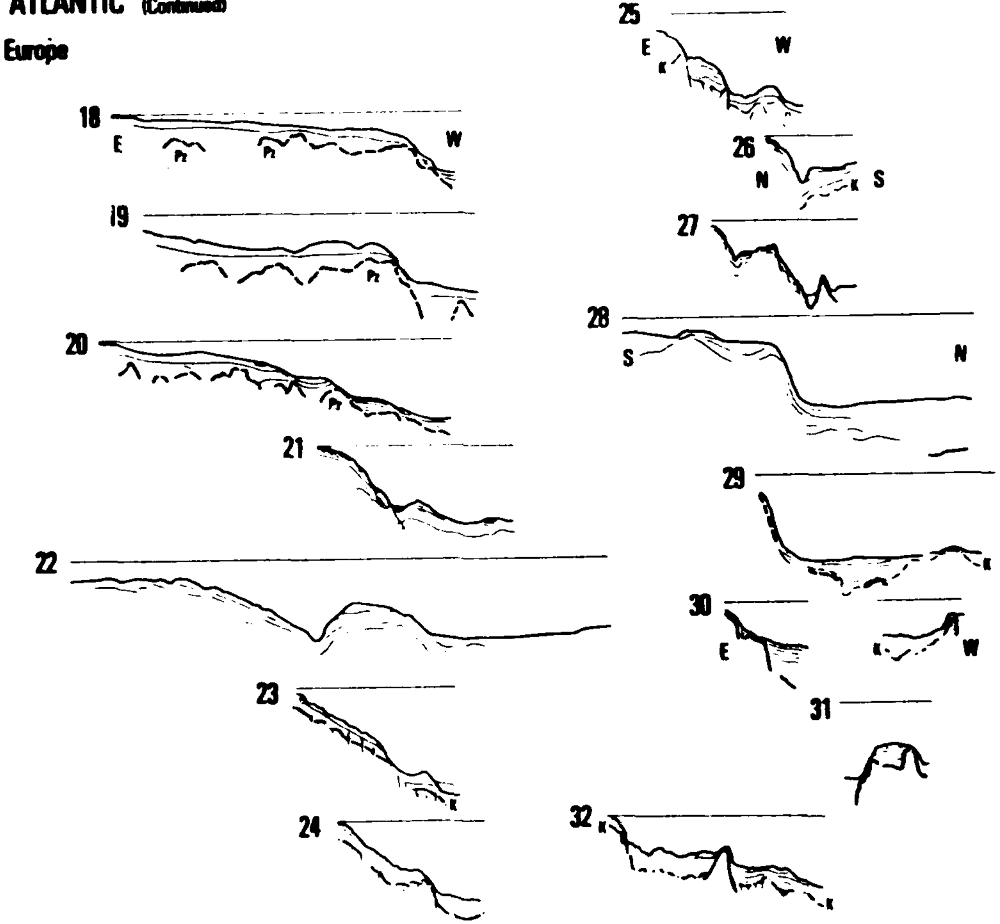
EAST ATLANTIC (1-112)

1-36 Europe

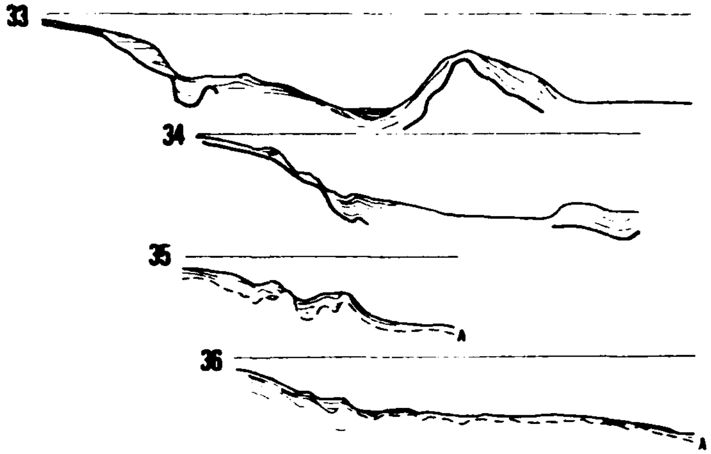


EAST ATLANTIC (Continued)

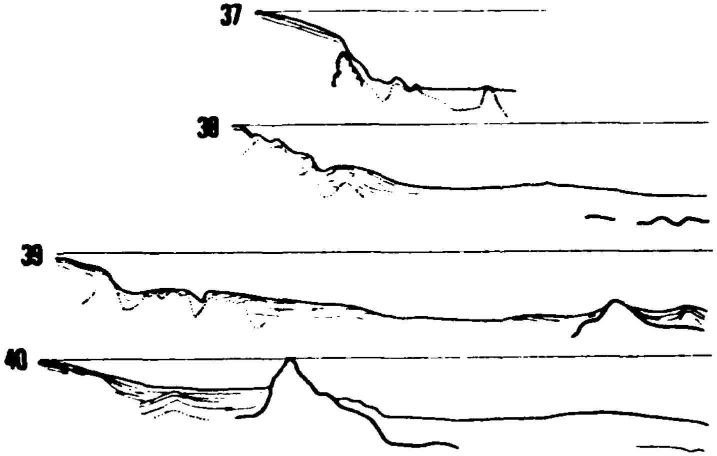
1-38 Europe

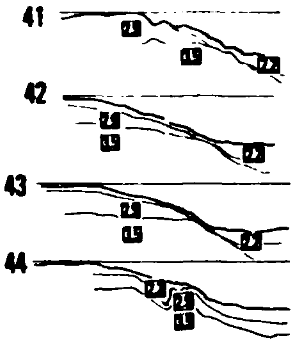


EAST ATLANTIC (Continued) 1-36 EUROPE



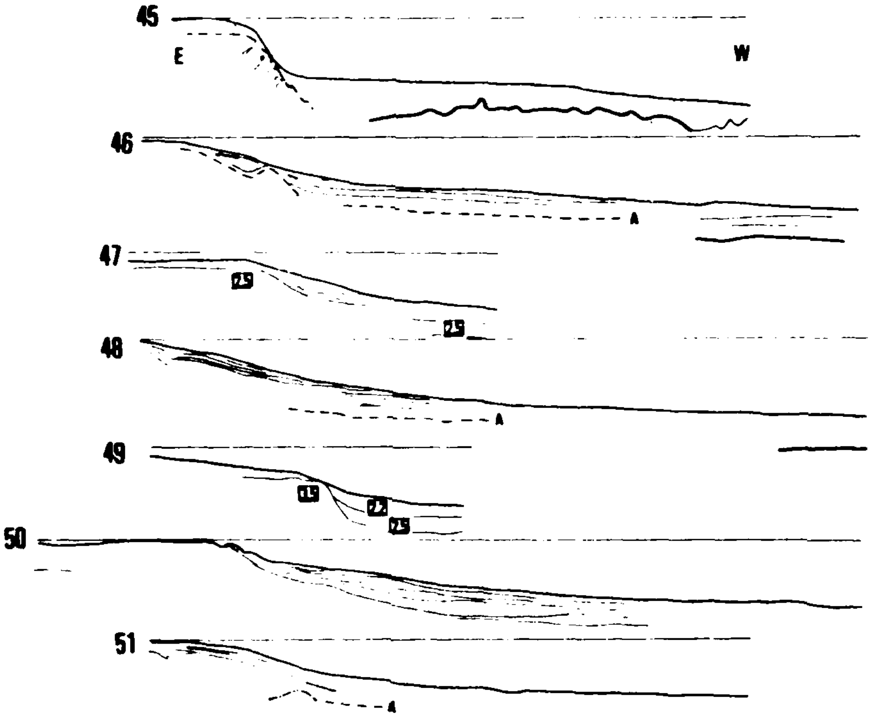
37-112 Africa





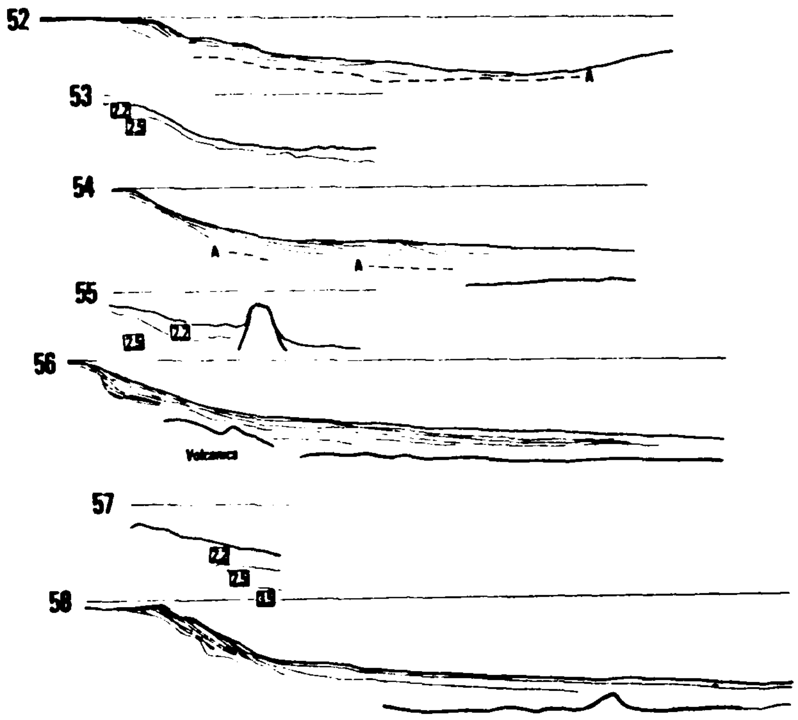
EAST ATLANTIC

37-112 Africa



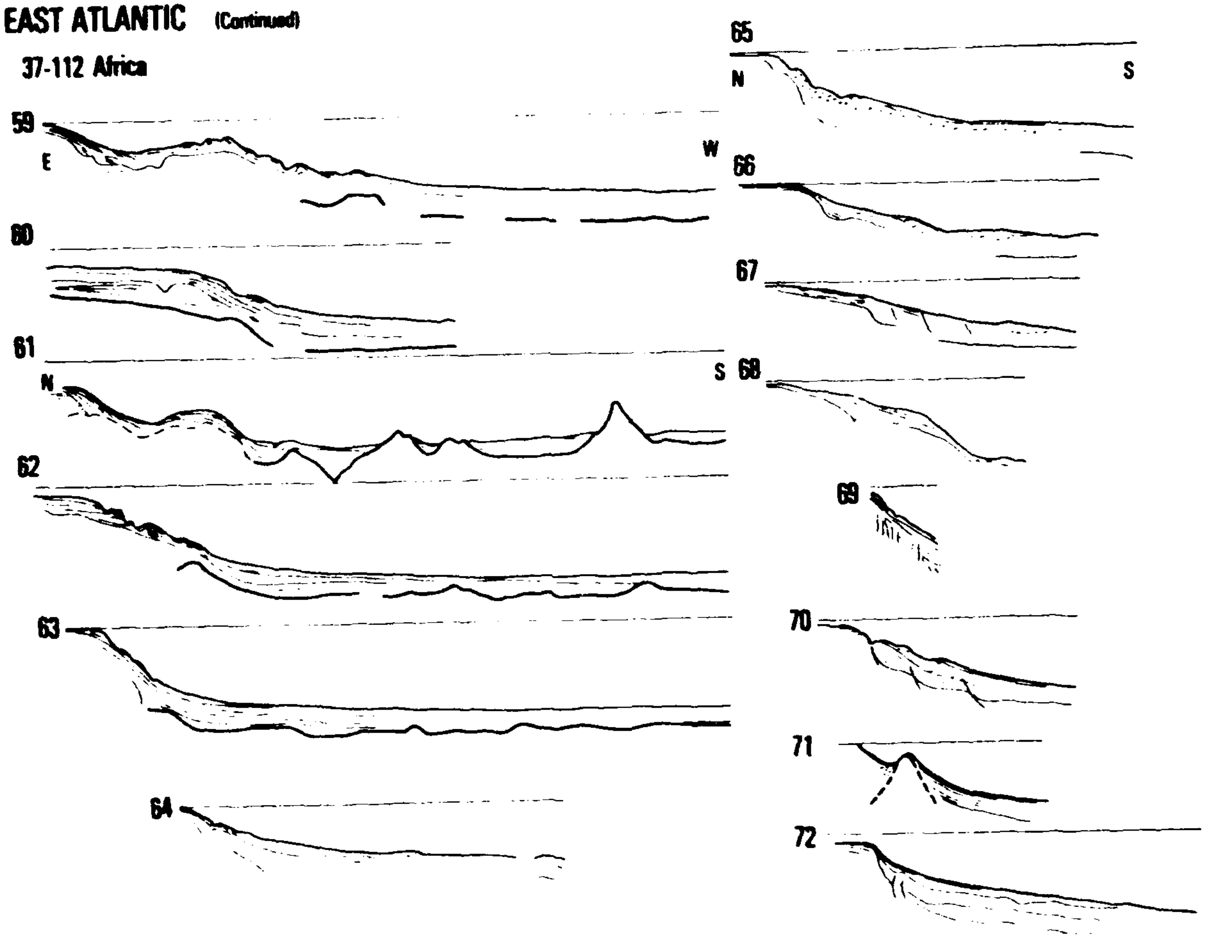
EAST ATLANTIC (Continued)

37-112 Africa



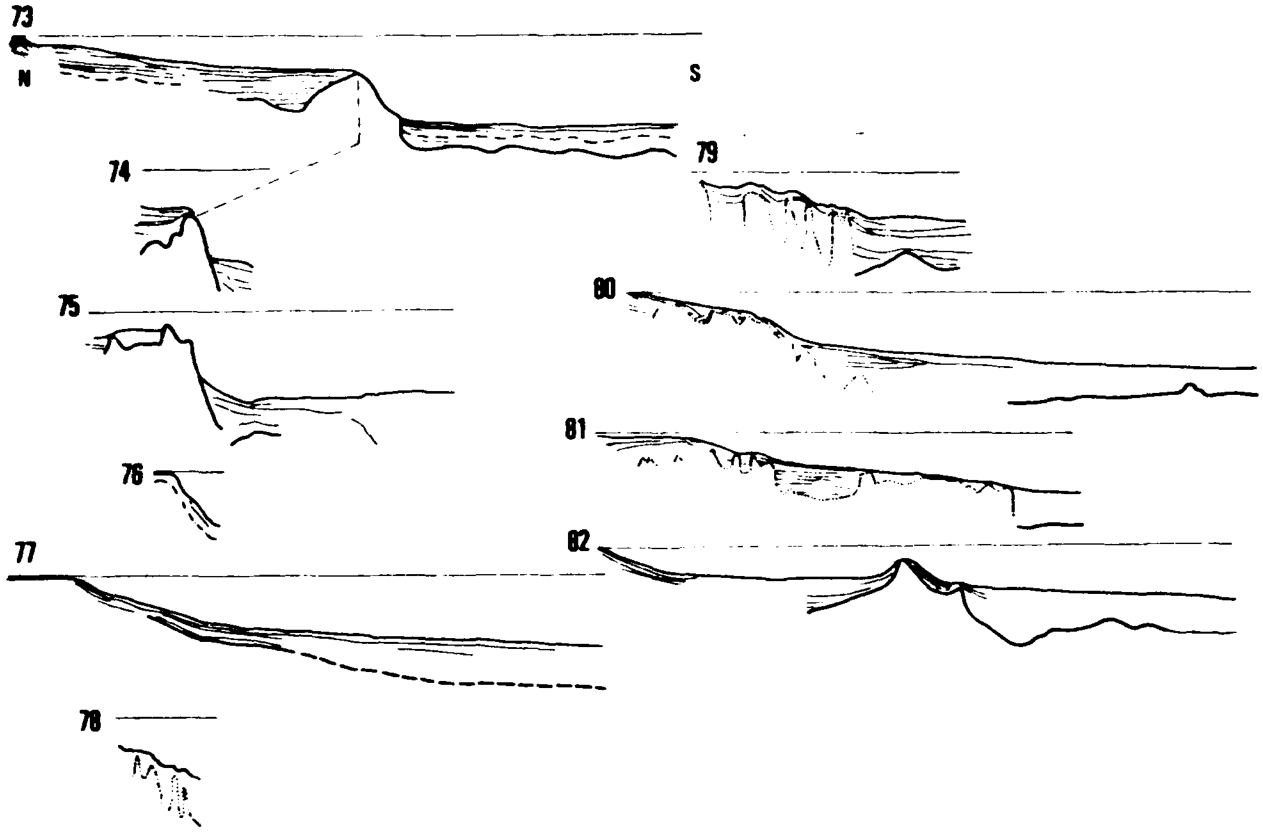
EAST ATLANTIC (Continued)

37-112 Africa



EAST ATLANTIC (Continued)

37-112 Africa

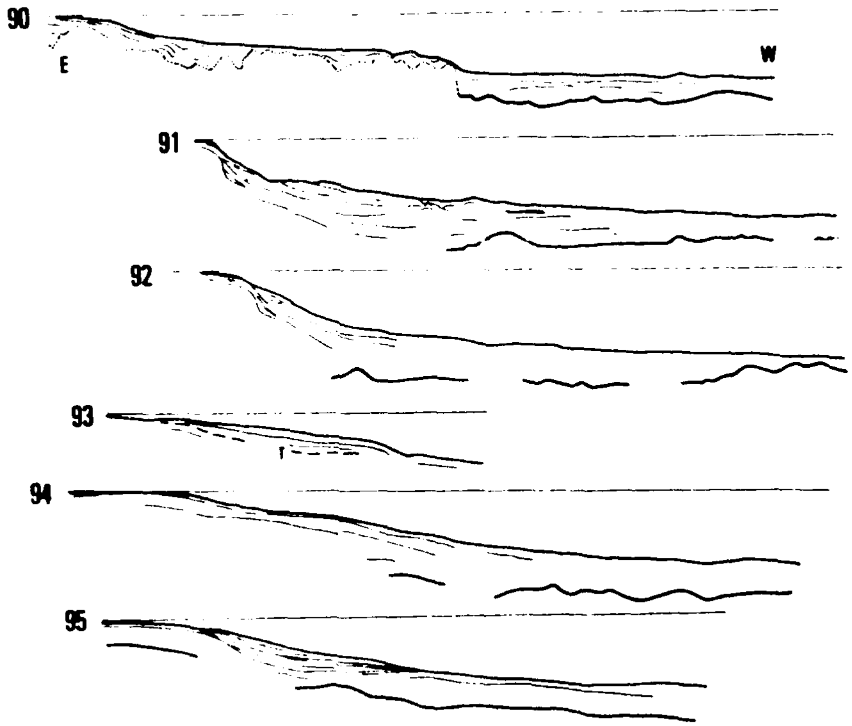


EAST ATLANTIC (Continued)

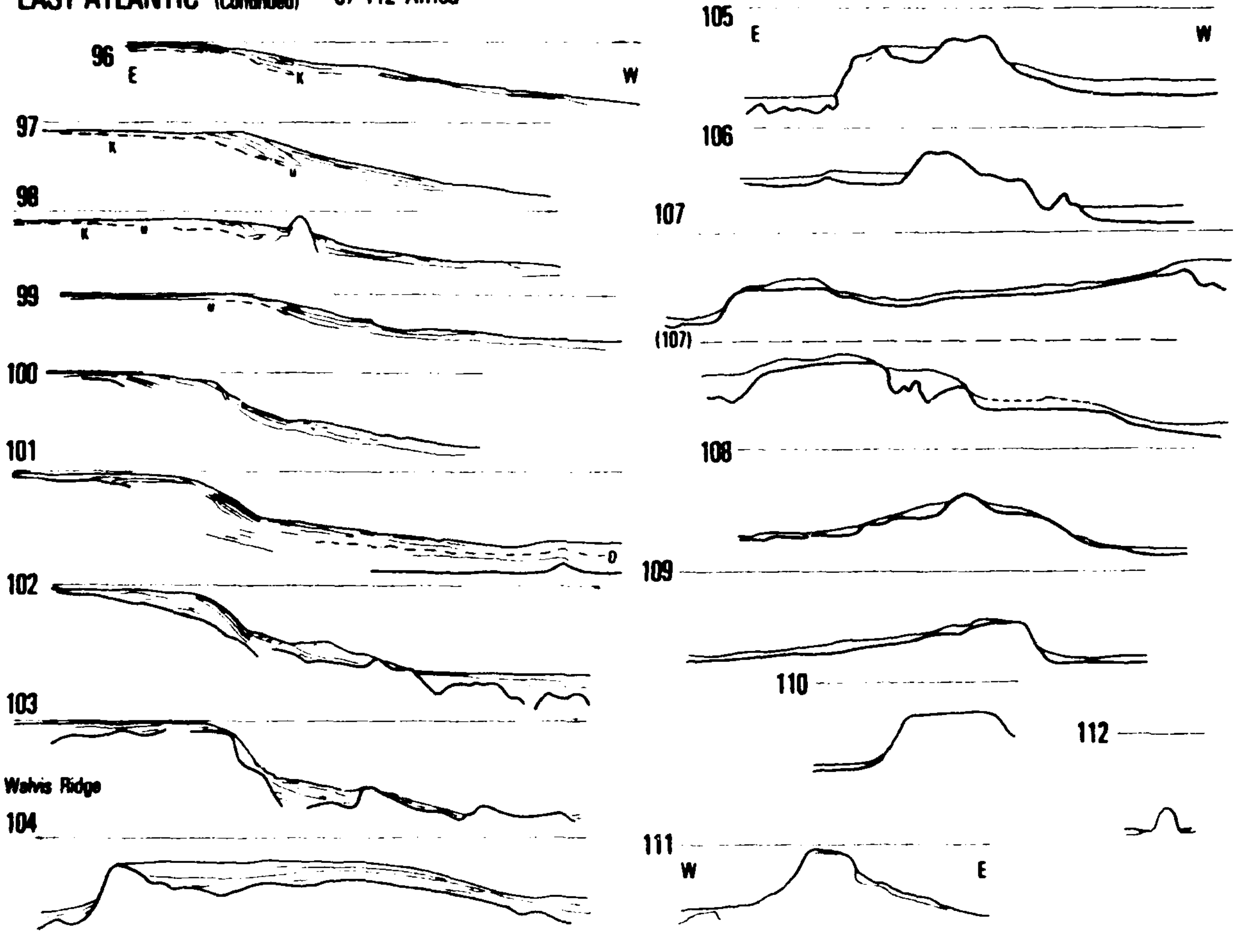
37-112 Africa

EAST ATLANTIC

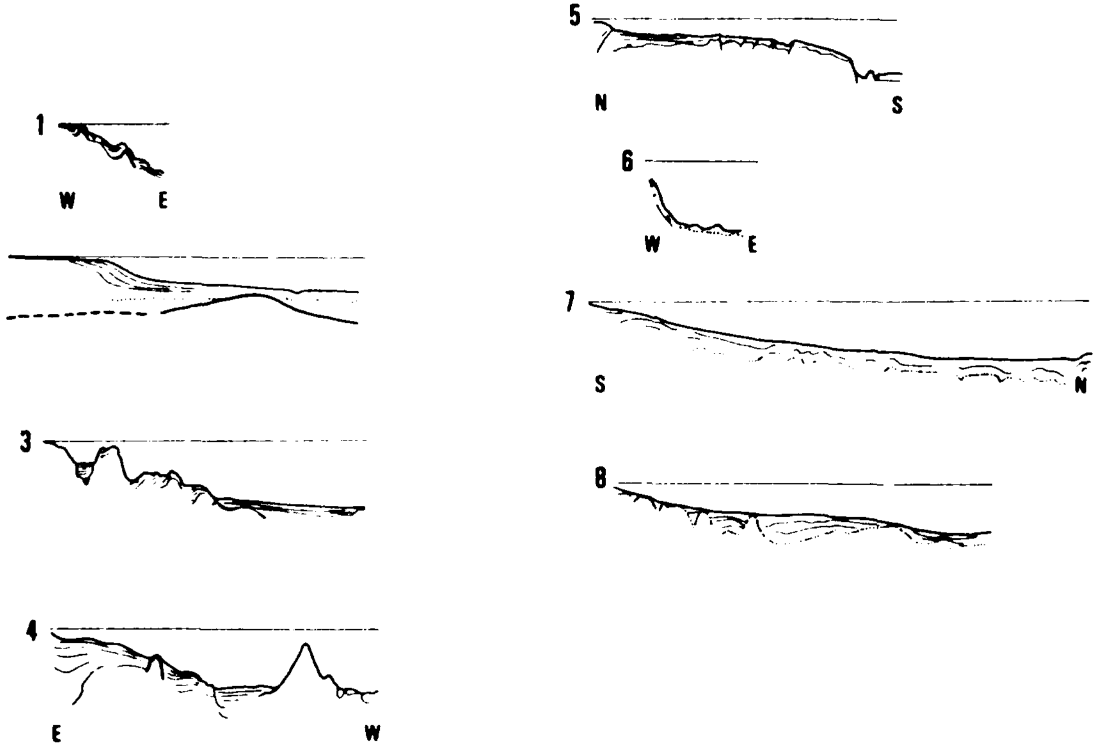
37-112 Africa



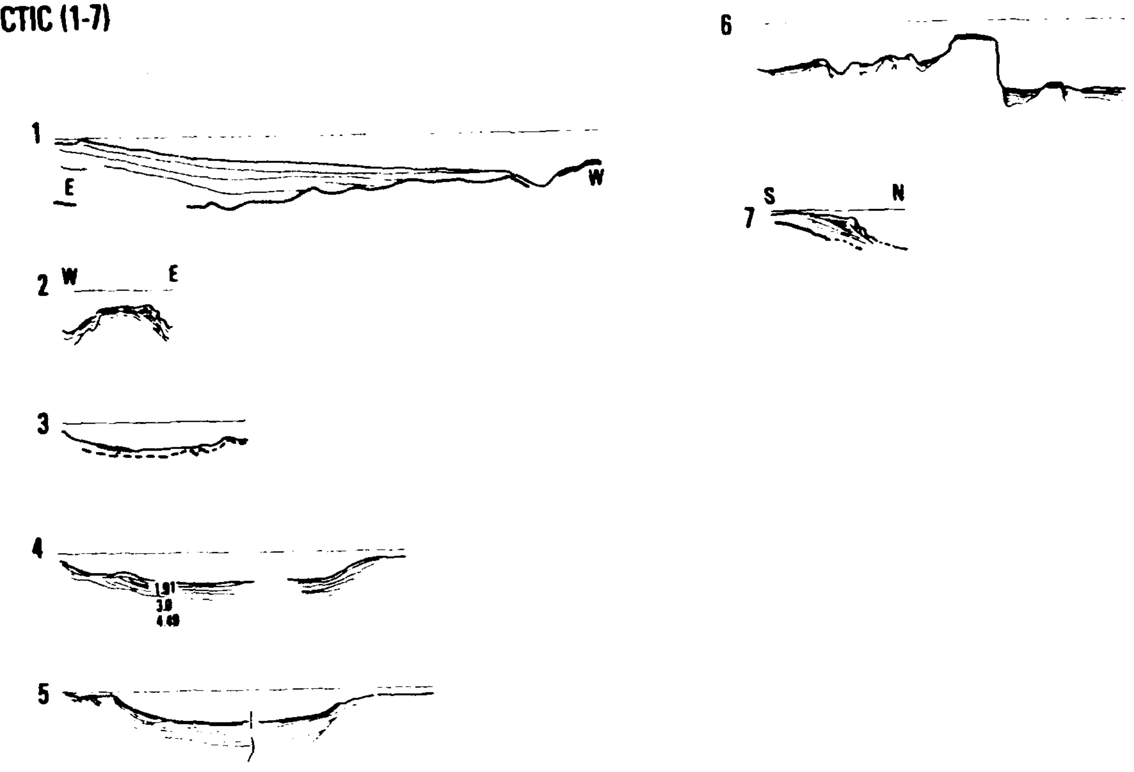
EAST ATLANTIC (Continued) 37-112 Africa



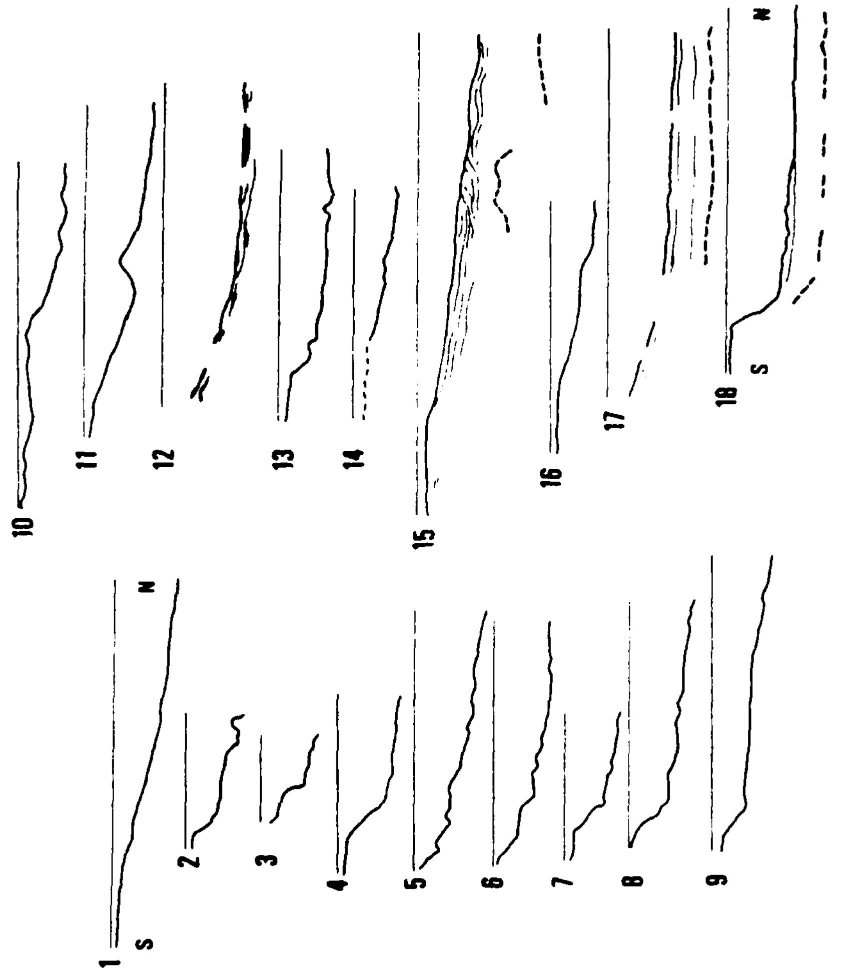
MEDITERRANEAN (1-8)



ARCTIC (1-7)



ANTARCTIC (1-18)



PROFILE SOURCES

Profile #	Source
I. ARCTIC	
1	Renard and Mascle (1974)
2	Johnson (1975)
3	Johnson and others (1975)
4-5	Grant (1975)
6	Ostenso (1974)
7	Grantz and others (1975)
II. ANTARCTIC	
1-3	Anderson and others (1979)
4-11	Anonymous (1975)
12	Houtz and others (1972)
13-14	Anderson and Markl (1972)
15	Houtz (1974)
16	Anderson and others (1979)
17-18	Houtz (1974)
III. MEDITERRANEAN	
1	Nairn and others (1975) p.101
2	Ryan and Cita (1978)
3-6	Biju-Duval and others (1974)
7-8	Maldanado and Stanley (1979)
IV. EAST ATLANTIC	
1-6	Talwani and Eldholm (1974)
7-8	Roberts (1974)
9-10	Baily (1975)
11	Roberts (1974)
12-16	Baily (1975)
17	Roberts (1974)
18-20	Dingle and Scrutton (1979)
21	Blundell (1975)
22	Renard and Mascle (1974)
23-27	Montadert and others (1974)
28	Renard and Mascle (1974)
29-32	Montadert and others (1974)
33-40	Uchupi and others (1976)
41-44	Seibold and Minz (1974)
45-46	Uchupi and others (1976)

Profile #	Source
47	Seibold and Minz (1974)
48	Uchupi and others (1976)
49	Seibold and Minz (1974)
50-52	Uchupi and others (1976)
53	Seibold and Minz (1974)
54	Uchupi and others (1976)
55	Seibold and Minz (1974)
56	Uchupi and others (1976)
57	Seibold and Minz (1974)
58-60	Uchupi and others (1976)
61-63	Emery and others (1975a)
64-48	Schlee and others (1974)
69	Delteil and others (1974)
70-71	Schlee and others (1974)
72	Delteil and others (1974)
73	Emery and others (1975a)
74	Delteil and others (1974)
75	Renard and others (1974)
76	Delteil and others (1974)
77	Emery and others (1975a)
78	Mascle and others (1974)
79	Renard and Mascle (1974)
80-84	Emery and others (1975a)
85	Driver and others (1974)
86-88	Emery and others (1975a)
89	Renard and Mascle (1974)
90-92	Emery and others (1975a)
93	DuPlessis and others (1972)
94	Renard and Mascle (1974)
95	Emery and others (1975)
96-100	DuPlessis and others (1972)
101-103	Emery and others (1975)
104-110	Emery and others (1975a)
111	Uchupi and others (1975)
112	Lowrie and others (1978)

V. WEST ATLANTIC

1	Talwani (1974)
2-5	Featherstone and others (1977)
6-8	Talwani (1974)
9-10	Keen and Keen (1974)
11	Talwani (1974)
12	Keen and Keen (1974)
13	Watts and Steckler (1979)
14	Jansa and Wade (1975)
15-16	Austin and others (1980)
17-20	Schlee and others (1979)
21	Watts and Steckler (1979)
22-29	Schlee and others (1979)
30-31	Sheridan and others (1979)
32-35	Talwani (1974)

Profile #	Source
36	Fink (1972)
37	Talwani (1974)
38	Fink (1972)
39	Peter and Westbrook (1976)
40	Talwani (1974)
41	Ladd and others (1977)
42	No profile
43	Silver and others (1975)
44	Case (1974)
45-46	Silver and others (1975)
47-54	Case (1974)
55-56	Talwani (1974)
57-59	Dillon and Vedder (1973)
60	Worzel and Burk (1979)
61	Garrison and Martin (1973)
62-63	Worzel and Burk (1979)
64-67	Garrison and Martin (1973)
68-71	Milliman (1979)
72-83	Fainstein and Milliman (1979)
84-86	Leyden and others (1976)
87-90	Milliman (1978)
91	Lonardi and Ewing (1971)
92-93	Barker (1972)
94	Ludwig and others (1979a)
95	Barker (1972)
96	Ludwig and others (1979a)
97-98	Barker (1972)
99-102	Ludwig and others (1979a)
103-105	Heezen and Johnson (1965)
106	Johnson and others (1977)
107	Tucholke and Mountain (1979)
108	Taylor and others (1975)

VI. EAST PACIFIC

Profile #	Source
1-7	Rabinowitz and Cooper (1977)
8	Sychev and Snegovsky (1976)
8a-14	Scholl and others (1968)
15-16	Buffington (1973)
17	Sychev and Snegovsky (1976)
18-22	Grow (1973)
23	No profile
24-25	Von Heune (1979a)
26	Seely (1979)
27	Seely (1977)
28-32	Von Heune and others (1979)
33-36	Chase and others (1975)
37-44	Barnard (1979)
45-47	Kulm and Fowler (1974)
48-61	Silver (1971)
62	Curray (1965)
63	Blake and others (1978)

Profile #	Source
64	Blake and others (1978)
65-66	Curray (1965)
67-72	Moore (1972)
73	Blake and others (1978)
74-80	Moore (1973)
81-83	Karig and others (1978)
84	Karig (1977)
85	Seely (1979)
86-88	No profiles
89-104	Kulm and others (1977)
105	Scholl and others (1977)
106	Kulm and others (1977)
107	No profile
108-113	Herron and others (1977)
VII. WEST PACIFIC	
1	Buffington (1973)
2-6	Unpub. LDGO data, R/V ROBERT CONRAD 14
7-8	Minayev and Suvorov (1974)
9	Scientific Party (1980)
9-14	Ludwig and others (1966)
15	Moore and others (1976)
16	Hilde and others (1969)
17-18	Jacobi and Mrozowski (1979)
19-21	Sychev and Snegovsky (1976)
22-27	Ludwig and others (1975)
28-31	Herman and others (1979)
32-34	Bowin and others (1978)
35	Karig (1973)
36	Bowin and others (1978)
37	Karig (1973)
38	Bowin and others (1978)
39	Karig (1973)
40-41	Emery and Ben-Avraham (1972)
42	Karig (1973)
43	Emery and Ben-Avraham (1972)
44-46	Karig (1973)
47-49	Emery and Ben-Avraham (1972)
50	Bowin and others (1978)
51-58	Emery and Ben-Avraham (1972)
59	Parke and others (1971)
60-62	Emery and Ben-Avraham (1972)
63	Mizano and others (1979)
64-91	Fisher (1974)
92	Karig and Mammerickz (1972)
93	Fisher (1974)
94-95	Luyendyk and others (1974)
96	Fisher (1974)
97	Luyendyk and others (1974)
98	Karig and Mammerickz (1972)

Profile #	Source
99	Luyendyk and others (1974)
100-101	Karig and Mammerickz (1972)
102	Fisher (1974)
103	Karig and Mammerickz (1972)
104-110	Lonsdale (1975)
111	Hawkins (1974)
112	Fisher (1974)
113-115	Hawkins (1974)
116-117	Katz (1974)
118-127	Houtz and others (1967)
128	Bentz (1974)
129-131	Andrews and Eade (1973)
132-139	Silver and Moore (1978)
140	Rea and Naugler (1971)
141	Greene and others (1978)
142	Davies and othere (1972)

VIII. INDIAN

1-4	Anonymous (1975)
5-6	Emery and others (1975)
7	Kolla and others (1980)
8-10	Dingle and others (1978)
11	Anonymous (1975)
12	Bunce and others (1967)
13-19	Anonymous (1975)
20-22	Ross and Schlee (1973)
23-25	White and Klitgord (1976)
26-27	Anonymous (1975)
28-30	Harbinger and Bassinger (1973)
31-32	Anonymous (1975)
34-38	Anonymous (1975)
39	Bunce and others (1967)
40-42	Anonymous (1975)
43-48	Houtz and others (1977)
49-53	Anonymous (1975)
54	No profile
55-59	Anonymous (1975)
60-62	Curray and others (1979)
63	Anonymous (1975)
64-66	Curray and others (1979)
67-70	Anonymous (1975)
71	Karig (1977)
72-77	Anonymous (1975)
78-79	Jacobson and others (1979)
80-82	Anonymous (1975)
84-86	Anonymous (1975)
87-89	Veevers (1974)
90	No profile
91-93	Talwani and othes (1979)
94	Anonymous (1975)
95-96	Talwani and others (1979)

Profile #	Source
97	Boeuf and Doust (1975)
98	Talwani and others (1979)
99	Boeuf and Doust (1975)
100	Houtz and Markl (1972)
101-105	Boeuf and Doust (1975)

VITA

James Andrew Green was born January 18, 1952, in Athol, Massachusetts. In 1974, he received a Bachelor of Science Degree in Geology from the University of Massachusetts. From 1974 to 1976, he was employed by the National Oceanic and Atmospheric Administration in Rockville, Maryland, and in Kings Point, New York. He has been employed since 1976 as a marine geologist for the Naval Ocean Research and Development Activity in Bay St. Louis, Mississippi.

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18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

ocean slopes
lateral slope parameters
global data distributions
plate-tectonics
boundary province
sediment type

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

Large-scale ocean slopes have continental-slope dimensions (e.g., slope inclinations exceeding 1° for relief of 2000 m). Approximately 40% are related to continental margins, 40% to features with oceanic crust, and 20% to unknown origins or overlap with the first two groups. Of the slopes, 75% are laterally continuous (lateral slopes), and the remaining 25% form the sides of conical shaped features.

Groupings and ranges have been established for the following lateral slope parameters; ocean section, top boundary province, bottom boundary province,

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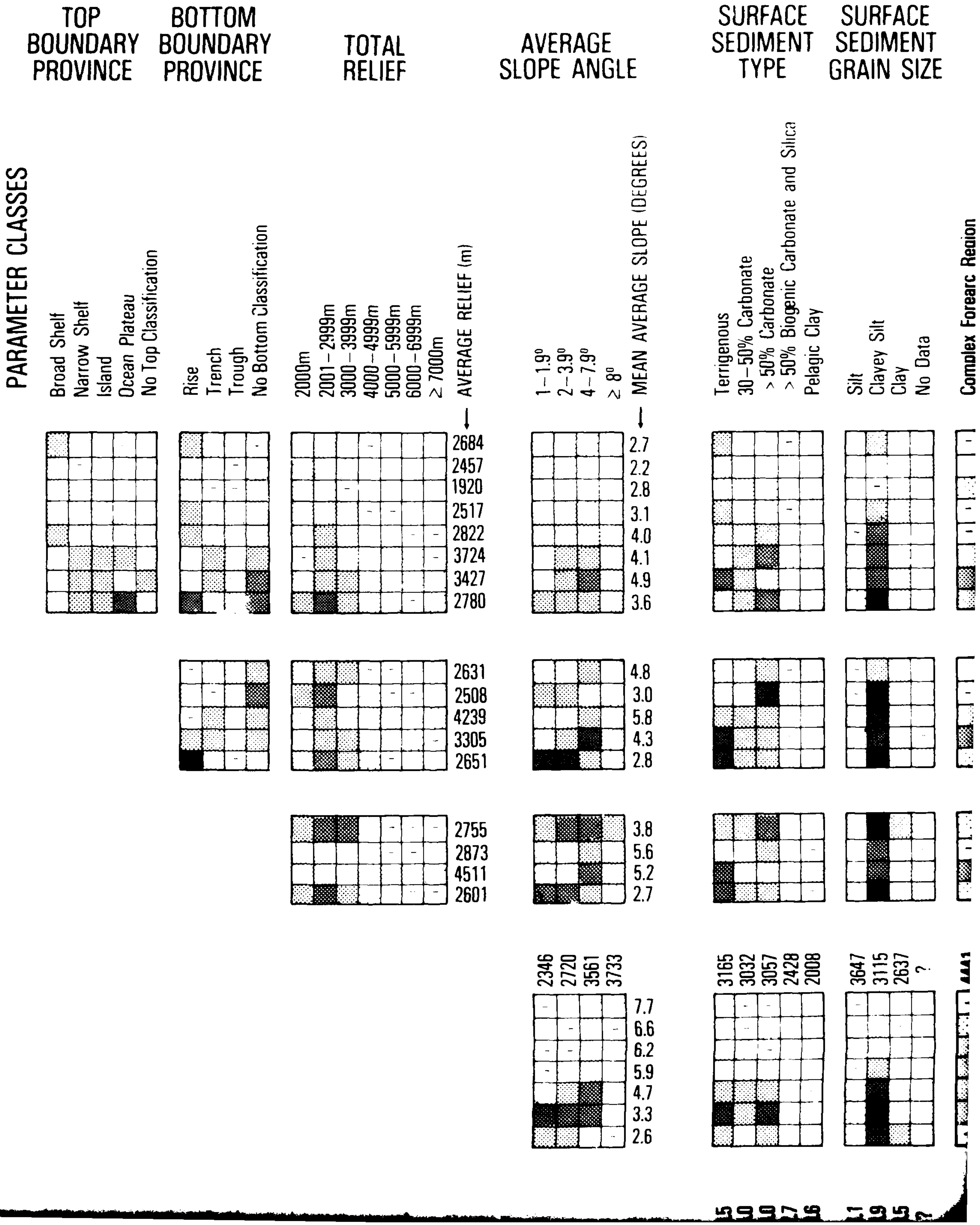
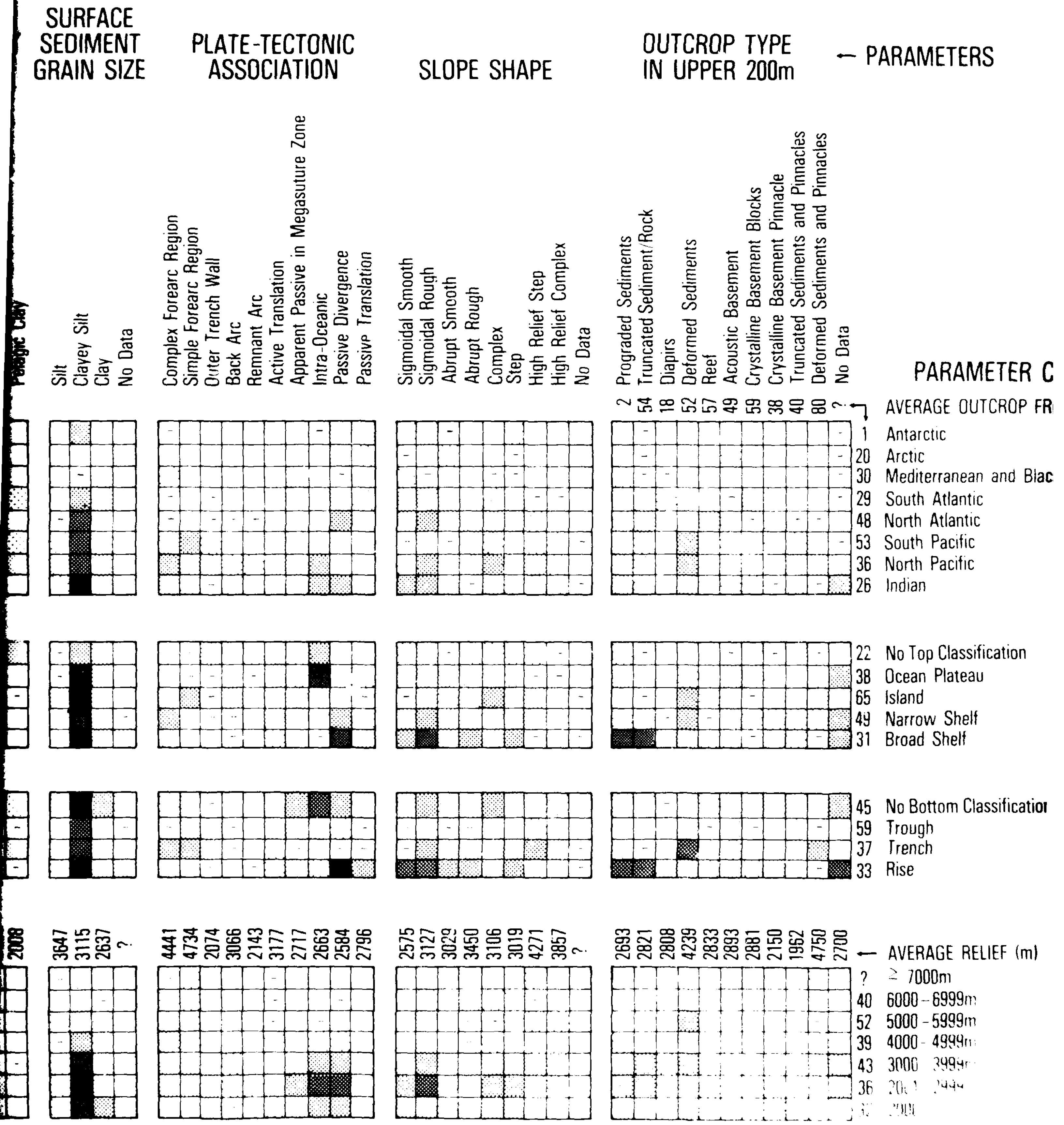
relief, slope angle, surface-sediment grain size, plate-tectonic association, shape, outcrop type in the upper 200 m, percent of slope with outcrop, sediment thickness, and basement type. Mapping and computer adaption of parameter compilations reveal global data distributions, global averages, parameter relationships, and applied classification methods. Global averages are 3.8° for slope angle, 3035 m for relief, and 38% for percent of slope with outcrop. Strongest relationships occur among top boundary province, bottom boundary province, plate-tectonic association, and surface-sediment type.

Preferred clustering of parameter relationships reveal four model groups for lateral slopes. Group I center around strong association of broad shelves, rises, and divergent plate-tectonic association. Group II includes high-relief slopes associated with subduction and high-angle slopes associated with translation. Group III contains the slopes of oceanic features and carbonate surface sediments. Group IV, the smallest group, includes outer trench walls.


TOP BOUNDARY PROVINCE
BOTTOM BOUNDARY PROVINCE
TOTAL RELIEF
AVERAGE SLOPE ANGLE
SURFACE SEDIMENT TYPE
SURFACE SEDIMENT GRAIN SIZE
PARAMETER CLASSES
Broad Shelf
Narrow Shelf
Island
Ocean Plateau
No Top Classification
Rise
Trench
Trough
No Bottom Classification
2000m
2001–2999m
3000–3999m
4000–4999m
5000–5999m
6000–6999m
≥ 7000m
AVERAGE RELIEF (m)
1–1.9°
2–3.9°
4–7.9°
≥ 8°
MEAN AVERAGE SLOPE (DEGREES)
Terrigenous
30–50% Carbonate
> 50% Carbonate
> 50% Biogenic Carbonate and Silica
Pelagic Clay
Silt
Clayey Silt
Clay
No Data
Complex Forearc Region
2684
2457
1920
2517
2822
3724
3427
2780
2.7
2.2
2.8
3.1
4.0
4.1
4.9
3.6
2631
2508
4239
3305
2651
4.8
3.0
5.8
4.3
2.8
2755
2873
4511
2601
3.8
5.6
5.2
2.7
2346
2720
3561
3733
7.7
6.6
6.2
5.9
4.7
3.3
2.6
3165
3032
3057
2428
2008
3647
3115
2637
?

1 /2



SURFACE SEDIMENT GRAIN SIZE
PLATE-TECTONIC ASSOCIATION
SLOPE SHAPE
OUTCROP TYPE IN UPPER 200m
← PARAMETERS
Pelagic Clay
Silt
Clayey Silt
Clay
No Data
Complex Forearc Region
Simple Forearc Region
Outer Trench Wall
Back Arc
Remnant Arc
Active Translation
Apparent Passive in Megasuture Zone
Intra-Oceanic
Passive Divergence
Passive Translation
Sigmoidal Smooth
Sigmoidal Rough
Abrupt Smooth
Abrupt Rough
Complex
Step
High Relief Step
High Relief Complex
No Data
Prograded Sediments
Truncated Sediment/Rock
Diapirs
Deformed Sediments
Reef
Acoustic Basement
Crystalline Basement Blocks
Crystalline Basement Pinnacle
Truncated Sediments and Pinnacles
Deformed Sediments and Pinnacles
No Data
PARAMETER C
2 54 18 52 57 49 59 38 40 80 ?
AVERAGE OUTCROP FR
1 Antarctic
20 Arctic
30 Mediterranean and Blac
29 South Atlantic
48 North Atlantic
53 South Pacific
36 North Pacific
26 Indian
22 No Top Classification
38 Ocean Plateau
65 Island
49 Narrow Shelf
31 Broad Shelf
45 No Bottom Classificatio
59 Trough
37 Trench
33 Rise
2008 3647 3115 2637 ?
4441 4734 2074 3066 2143 3177 2717 2663 2584 2796
2575 3127 3029 3450 3106 3019 4271 3857 ?
2693 2821 2808 4239 2833 2893 2881 2150 1962 4750 2700
← AVERAGE RELIEF (m)
? ≥ 7000m
40 6000 - 6999m
52 5000 - 5999m
39 4000 - 4999m
43 3000 - 3999m
36 2000 - 2999
2000

AD-A128 208 GLOBAL ANALYSIS OF THE SHALLOW GEOLOGY OF LARGE-SCALE 3/3
OCEAN SLOPES(U) NAVAL OCEAN RESEARCH AND DEVELOPMENT
ACTIVITY NSTL STATION MS J A GREEN ET AL. MAY 83
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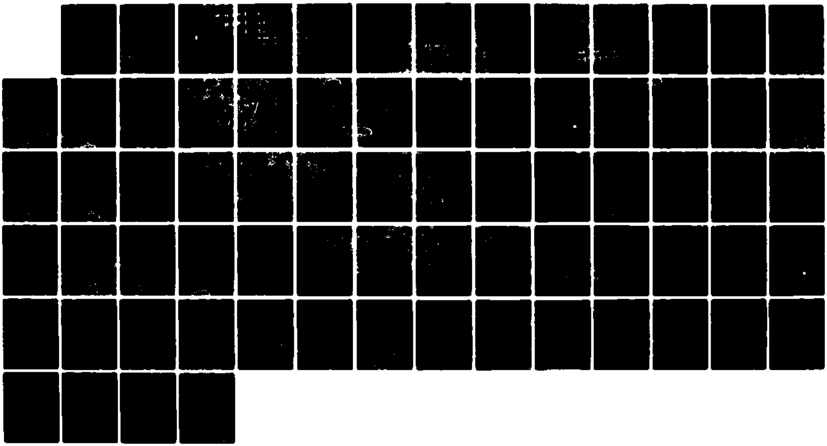
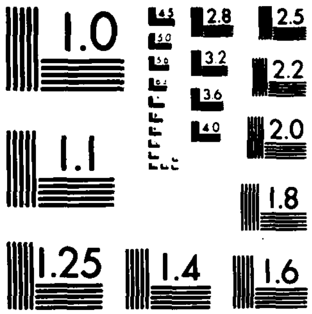
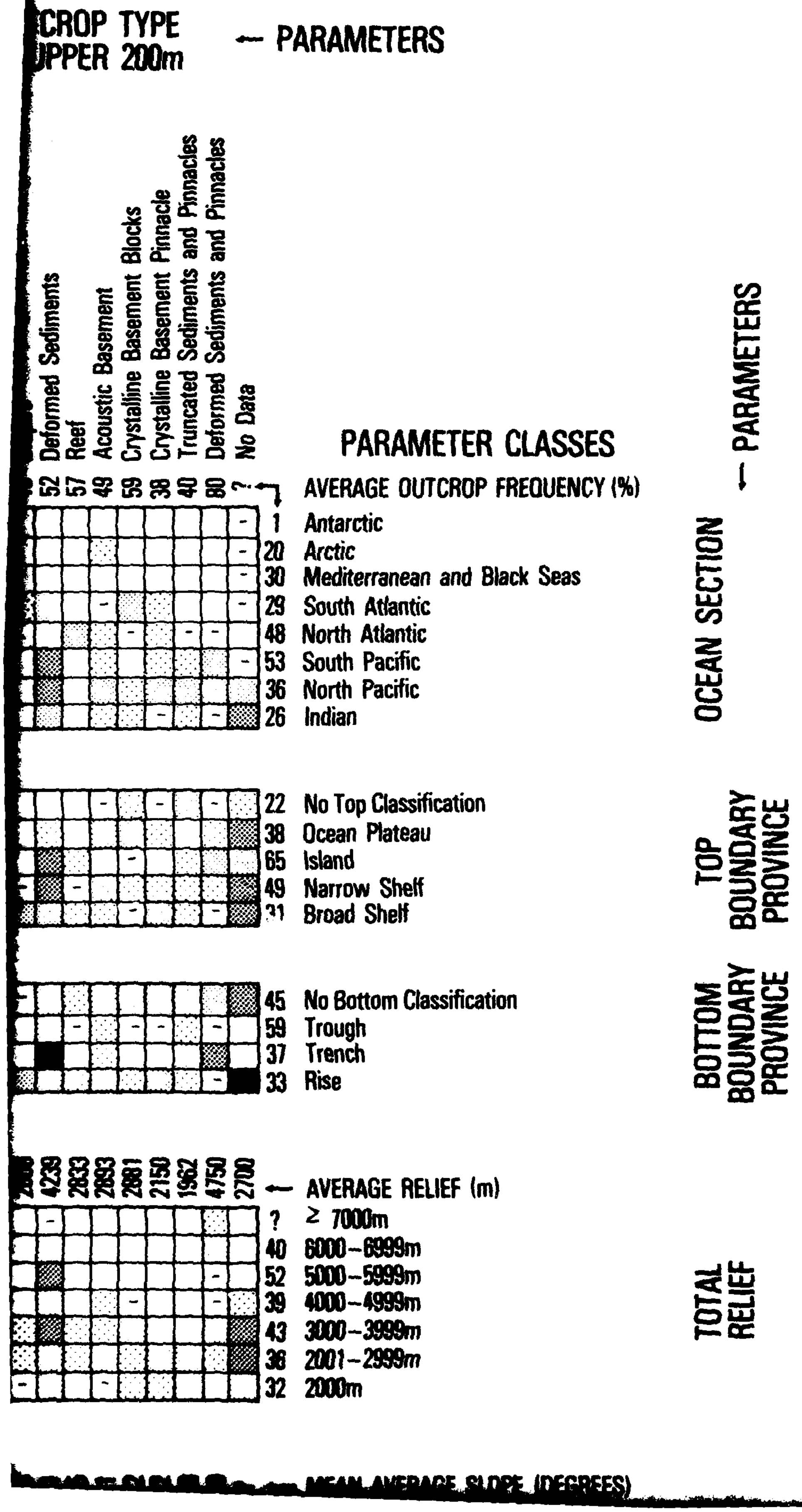
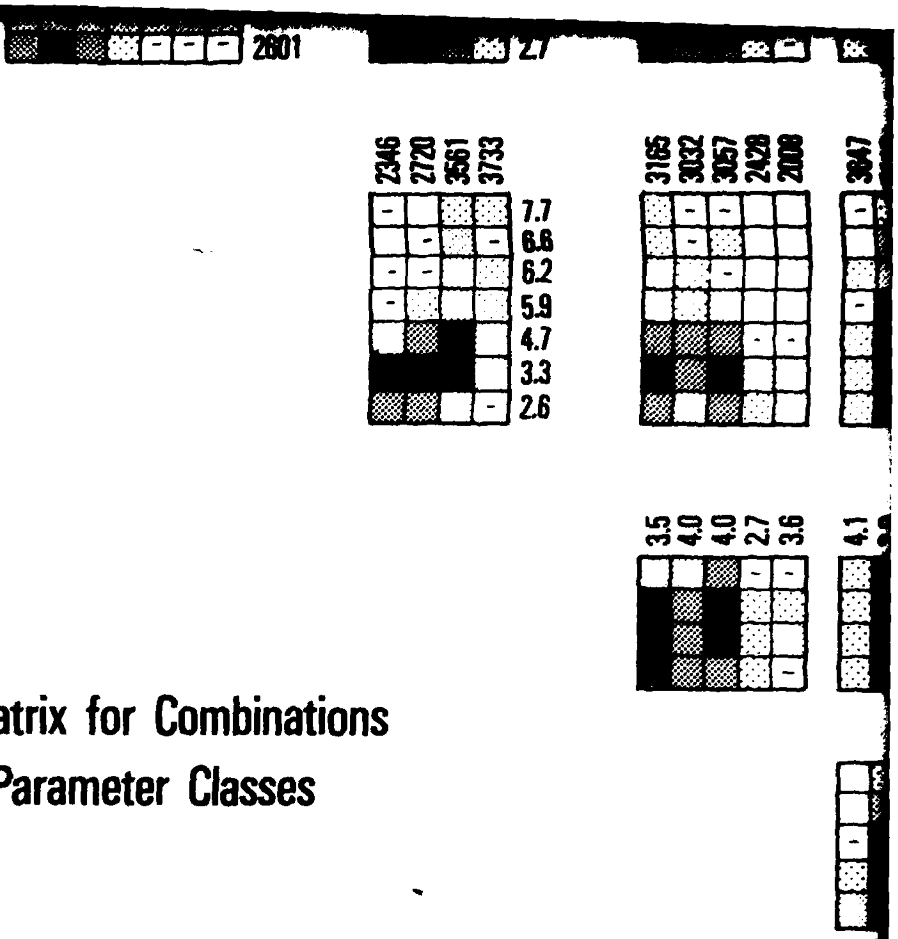




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

3


CROP TYPE
PPER 200m
← PARAMETERS
Deformed Sediments
Reef
Acoustic Basement
Crystalline Basement Blocks
Crystalline Basement Pinnacle
Truncated Sediments and Pinnacles
Deformed Sediments and Pinnacles
No Data
52
57
49
59
38
40
80
?
PARAMETER CLASSES
AVERAGE OUTCROP FREQUENCY (%)
1 Antarctic
20 Arctic
30 Mediterranean and Black Seas
29 South Atlantic
48 North Atlantic
53 South Pacific
36 North Pacific
26 Indian
OCEAN SECTION
← PARAMETERS
22 No Top Classification
38 Ocean Plateau
65 Island
49 Narrow Shelf
31 Broad Shelf
TOP BOUNDARY PROVINCE
45 No Bottom Classification
59 Trough
37 Trench
33 Rise
BOTTOM BOUNDARY PROVINCE
4239
2833
2893
2881
2150
1962
4750
2700
← AVERAGE RELIEF (m)
? ≥ 7000m
40 6000–6999m
52 5000–5999m
39 4000–4999m
43 3000–3999m
36 2001–2999m
32 2000m
TOTAL RELIEF
MEAN AVERAGE SLOPE (DEGREES)



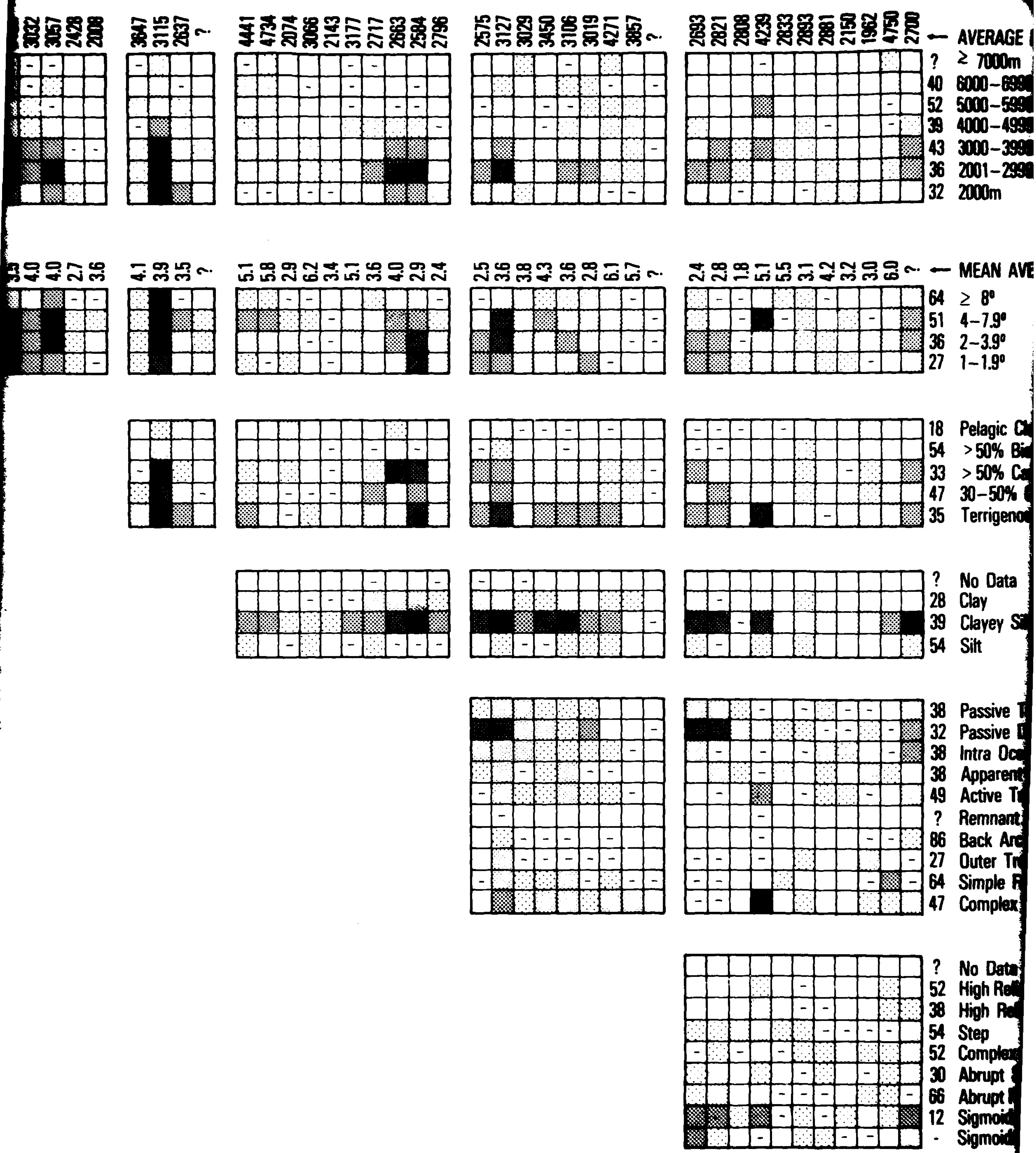
Frequency Matrix for Combinations of Two Parameter Classes

KEY

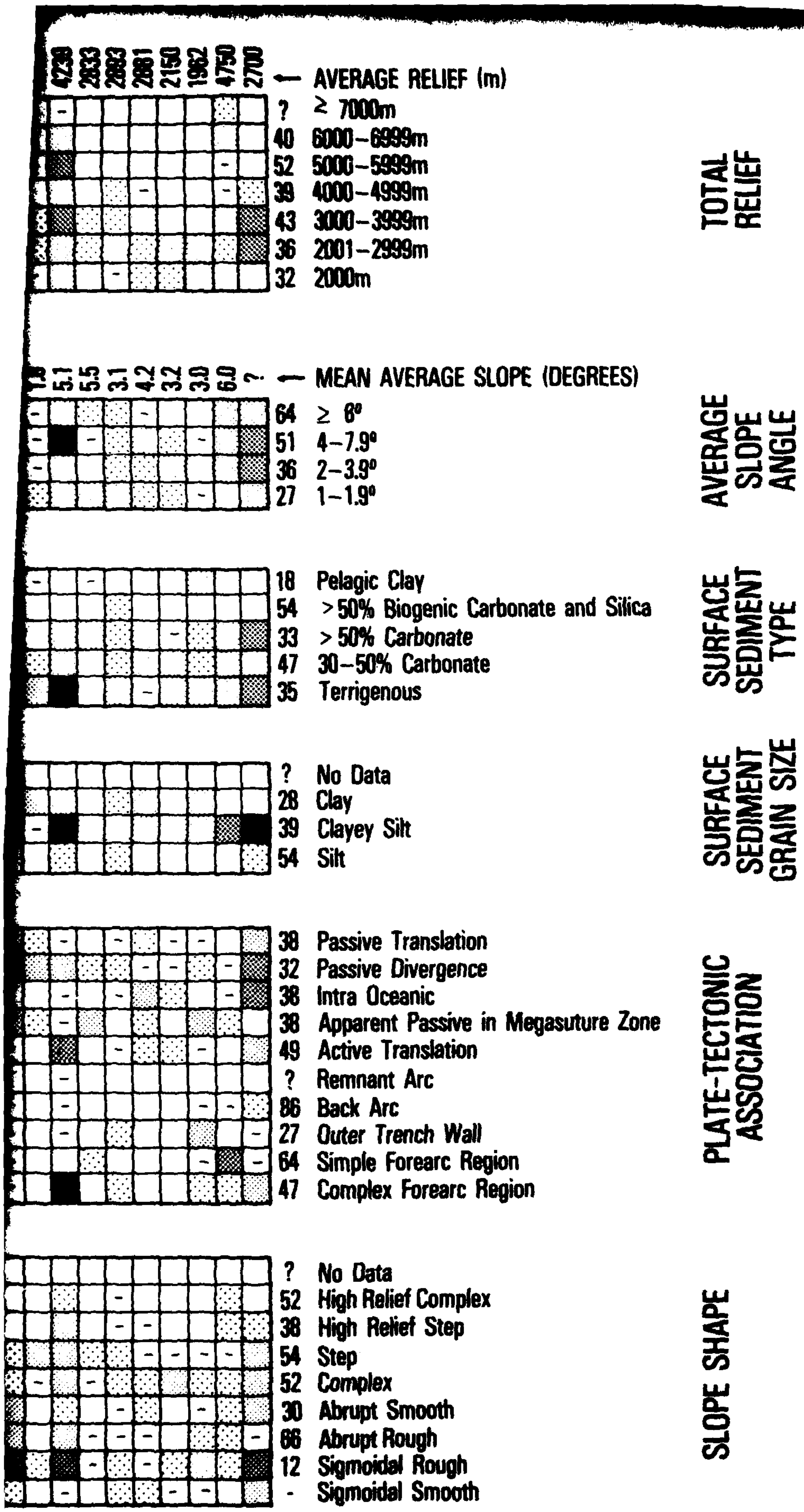
■ 20%
■ 10–19%
▨ 5–9%
□ 2–4%
░ 1%
⊟ Fraction

Percent of Total
Population of Slopes

Plate I


3032 3057 2428 2008
3647 3115 2637 ?
4441 4734 2074 3066 2143 3177 2717 2663 2584 2796
2575 3127 3029 3450 3106 3019 4271 3857 ?
2693 2821 2808 4239 2833 2893 2881 2150 1962 4750 2700
← AVERAGE
? ≥ 7000m
40 6000-699
52 5000-599
39 4000-499
43 3000-399
36 2001-299
32 2000m
3.3 4.0 4.0 2.7 3.6
4.1 3.9 3.5 ?
5.1 5.8 2.9 6.2 3.4 5.1 3.6 4.0 2.9 2.4
2.5 3.6 3.8 4.3 3.6 2.8 6.1 5.7 ?
2.4 2.8 1.8 5.1 5.5 3.1 4.2 3.2 3.0 6.0 ?
← MEAN AVE
64 ≥ 8°
51 4-7.9°
36 2-3.9°
27 1-1.9°
18 Pelagic C
54 >50% Bi
33 >50% Ca
47 30-50%
35 Terrigeno
? No Data
28 Clay
39 Clayey Si
54 Silt
38 Passive T
32 Passive D
38 Intra Oce
38 Apparent
49 Active T
? Remnant
86 Back Arc
27 Outer Tr
64 Simple R
47 Complex
? No Data
52 High Rel
38 High Rel
54 Step
52 Complex
30 Abrupt
66 Abrupt
12 Sigmoid
- Sigmoid

1 5


4238 2833 2863 2081 2150 1962 4750 2700 ← AVERAGE RELIEF (m)
? ≥ 7000m
40 6000–6999m
52 5000–5999m
39 4000–4999m
43 3000–3999m
36 2001–2999m
32 2000m
TOTAL RELIEF
1.8 5.1 5.5 3.1 4.2 3.2 3.0 6.0 ? ← MEAN AVERAGE SLOPE (DEGREES)
64 ≥ 8°
51 4–7.9°
36 2–3.9°
27 1–1.9°
AVERAGE SLOPE ANGLE
18 Pelagic Clay
54 >50% Biogenic Carbonate and Silica
33 >50% Carbonate
47 30–50% Carbonate
35 Terrigenous
SURFACE SEDIMENT TYPE
? No Data
28 Clay
39 Clayey Silt
54 Silt
SURFACE SEDIMENT GRAIN SIZE
38 Passive Translation
32 Passive Divergence
38 Intra Oceanic
38 Apparent Passive in Megasuture Zone
49 Active Translation
? Remnant Arc
86 Back Arc
27 Outer Trench Wall
64 Simple Forearc Region
47 Complex Forearc Region
PLATE-TECTONIC ASSOCIATION
? No Data
52 High Relief Complex
38 High Relief Step
54 Step
52 Complex
30 Abrupt Smooth
66 Abrupt Rough
12 Sigmoidal Rough
- Sigmoidal Smooth
SLOPE SHAPE

6

VARIATION MATR

Variation of Each Parameter Class Subpopulation to the Distrib

PARAMETER →

← PARAMETER

A PARAMETER CLASS

B

← PARAMETER	A PARAMETER CLASS	Percent of Total Lateral Slope Population	No. of Profiles / No. of Stations %[1]	Slope/Relief Index[2]	Average Slope Variation (Degrees)[3]	Average Relief Variation (KM)[4]	Average Outcrop Variation (%)[5]	OCEAN SECTION Indian	North Pacific	South Pacific	North Atlantic	South Atlantic	Mediterranean and Black Seas	Arctic	Antarctic	TOP PROVIN Broad Shelf	Narrow Shelf	Island
OCEAN SECTION	Indian	26	14	LS,LR	−0.2	−0.3	−12									▤		
	North Pacific	22	19	HS,HR	+1.1	+0.4	−2									▤		
	South Pacific	19	11	HR	+0.3	+0.8	+15									▤		
	North Atlantic	11	30	N	+0.2	−0.2	+10									☒		
	South Atlantic	9	25	LS,LR	−0.7	−0.5	−9									▥	▤	▤
	Mediterranean and Black Seas	3	8	LS,LR	−1.0	−1.1	−8									▥	☒	⊖
	Arctic	4	5	LS,LR	−1.6	−0.6	−16									☒	⊖	⊖
	Antarctic	6	10	LS,LR	−1.1	−0.4	−37									☒	⊖	⊖
	Caribbean	6	20	HS	+1.6	−0.1	+18										▥	▥
	North Atlantic (minus Caribbean)	6	41	LS,LR	−0.9	−0.4	+8									☒	⊖	⊖
TOP PROVINCE	Broad Shelf	27	24	LS,LR	−1.0	−0.4	−7	▤	▤	▤	▥	▥	▥	▥	▥	░	░	░
	Narrow Shelf	22	18	HS,HR	+0.5	+0.9	+11					▤	▥	▤	▤	░	░	░
	Island	17	16	HR	+2.0	+1.2	+27					▤	▤	▤	▤	░	░	░
	Ocean Plateau	20	12	LS,LR	−0.8	−0.5	0	☒	▤		▤	▥	▤		▤	░	░	░
	No Top Classification	14	7	LR	−1.0	−0.4	−16	▤	☒		▤		▤	▤	▤	░	░	░
BOTTOM PROVINCE	Rise	34	23	LS,LR	−1.1	−0.4	−5		▤	▤	▥	▥	▤	▥	▥	☒		▤
	Trench	18	21	HR	+1.4	+1.5	−1	▤	▥	▥	▤	▤	▤	▤	▤	▤	▥	▥
	Trough	11	5	HS	+1.8	−0.2	+21		▤	▥			▤	▤	▤	▤	▤	▥
	No Bottom Classification	37	12	LS,LR	0	−0.3	+7				▤	▤	▥		▤	▤		
TOTAL RELIEF(m)	2000m	17	13	–	−1.2	−1.5	−6			⊖	▥		▥		▤			▤
	2001–2999m	44	16	–	−0.5	−0.5	−2								▥			
	3000–3999m	23	20	–	+0.9	+0.5	+5						⊖		▤			
	> 4000m	15	18	–	+2.3	+2.6	+6		▥	▥	▤	▤	▤	▤	▤	▤	▥	☒
SLOPE (DEGREES)	1–1.9°	24	17	–	−2.3	−0.7	−11		▤					▥		▥		▤
	2–3.9°	31	19	–	−0.8	−0.3	−2											
	4–7.9°	35	15	–	+2.2	+0.5	+13						▤	▤	▤			
	> 8°	11	14	–	+8.2	+0.7	+26		▥					▤	▤	▤		▥
SURFACE SEDIMENT TYPE	Terrigenous	38	22	N	−0.3	+0.1	−3	▤	▥	▤				▥	▥	▥		
	30–50% Carbonate	22	17	N	+0.2	0	+9						▥	⊖	⊖			
	> 50% Biogenic Carbonate and Silica	34	12	N	+0.2	0	−5	▥	▤	▥		▤	▤	⊖	⊖	▤		
	Pelagic	4	11	LR	−0.2	−1.0	−20	⊖	☒			▥	▤	▤	▤	⊖	⊖	▤

1 2

1

VARIATION MATRIX

opulation to the Distribution of the Total Lateral Slope Population

OCEAN SECTION: North Pacific, South Pacific, North Atlantic, South Atlantic, Mediterranean and Black Seas, Arctic, Antarctic

TOP PROVINCE: Broad Shelf, Narrow Shelf, Island, Ocean Plateau, No Top Classification

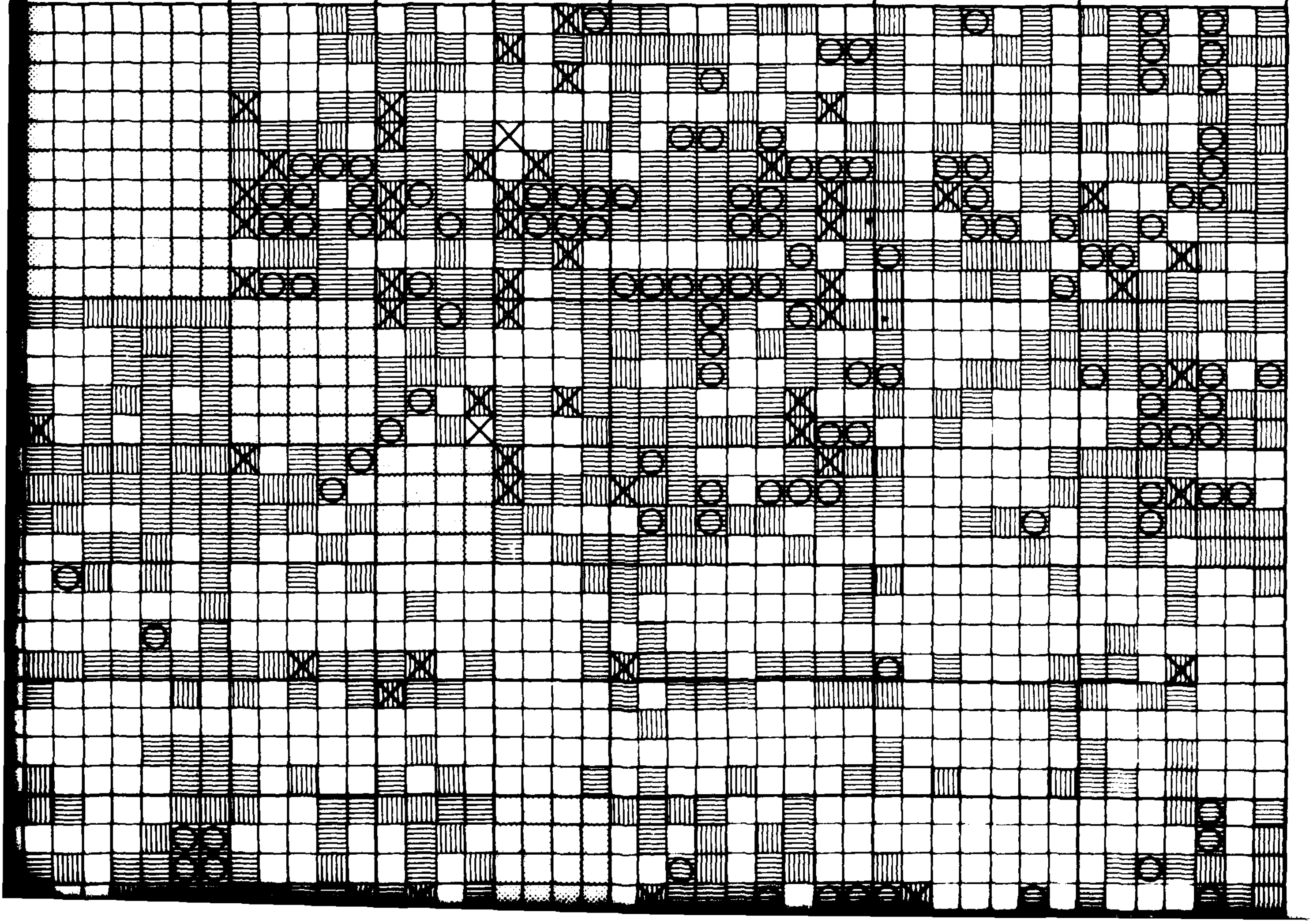
BOTTOM PROVINCE: Rise, Trench, Trough, No Bottom Classification

SURFACE SEDIMENT TYPE: Terrigenous, 30–50% Carbonate, >50% *Biogenic Carbonate and Silica*, Pelagic

PLATE-TECTONIC ASSOCIATION: Forearc Region, Outer Trench Wall, Backarc Wall, Remnant Arc, Active Translation, Apparent Passive in Megasuture Zone, Intra–Oceanic, Passive Divergent, Passive Translation

SHAPE: Sigmiodal Smooth, Sigmiodal Rough, Abrupt Smooth, Abrupt Rough, Complex, Step, High Relief

OUTCROP TYPE: Prograded Sediment (No Outcrop), Truncated Sediment/Rock, Diapirs, Deformed Sediment/Rock, Reef, Acoustic Basement, Crystalline Block



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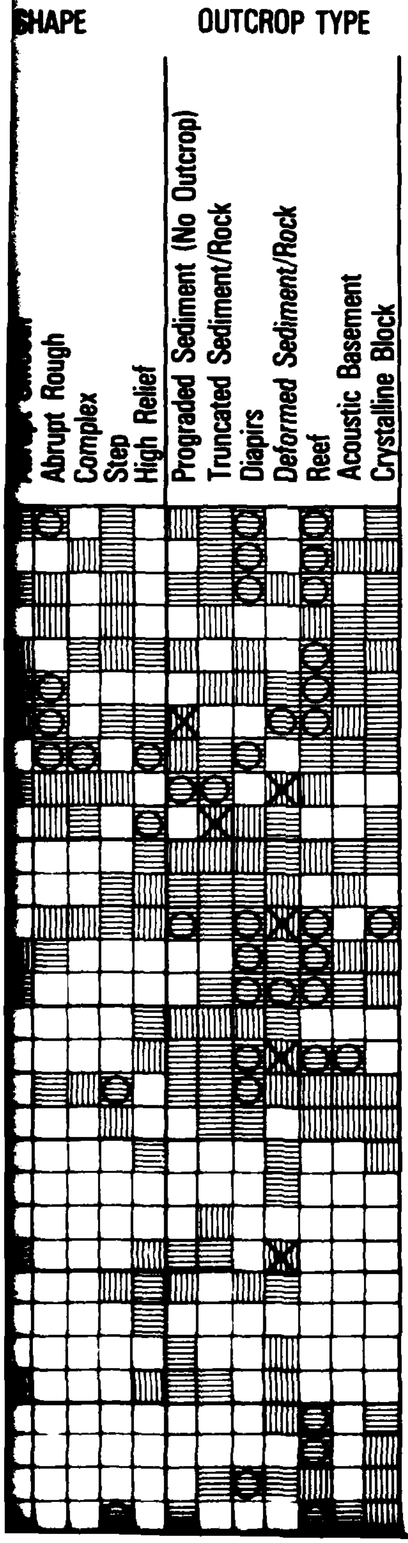


Key

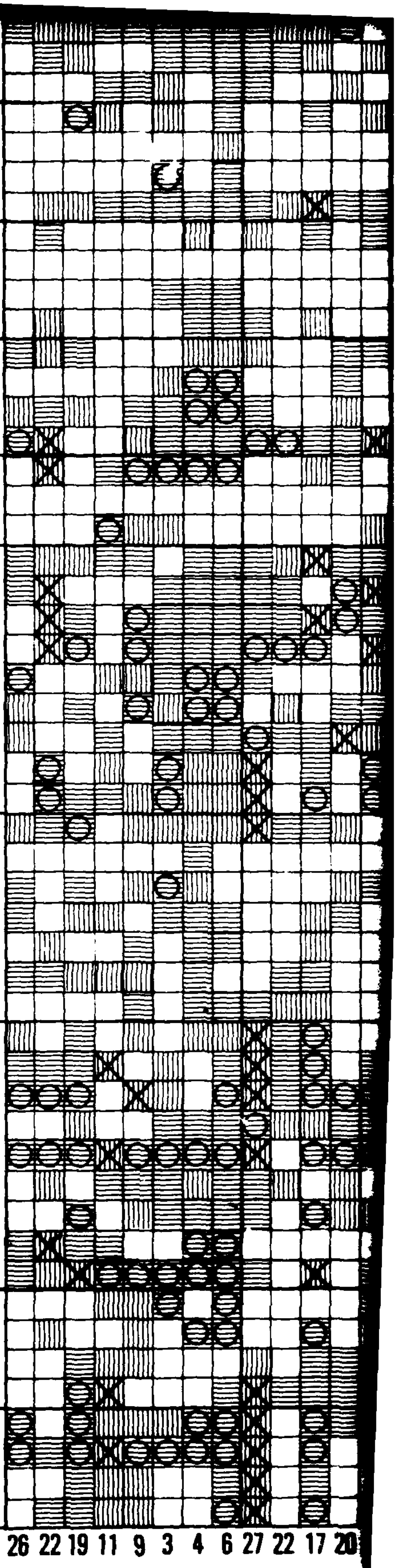
▥	Frequency of subpopulation exceeds 150% of frequency for total lateral slope population.
☐	Frequency of subpopulation is 50–150% of frequency for total lateral slope population.
▤	Frequency of subpopulation is less than 50% of frequency for total lateral slope population.
☐	No comparison made.
×	50% of subpopulation (indicated by parameter classes in column A) coincides with subpopulation indicated by parameter classes in column B.
○	No stations exhibit parameter class designations.

Note: *The first three key designations indicate relative comparisons of subpopulations to the total lateral slope population. The final two designations are absolute and specify strongest or weakest associations between parameter class topics.*

[1] No value given where only profile stations were used.

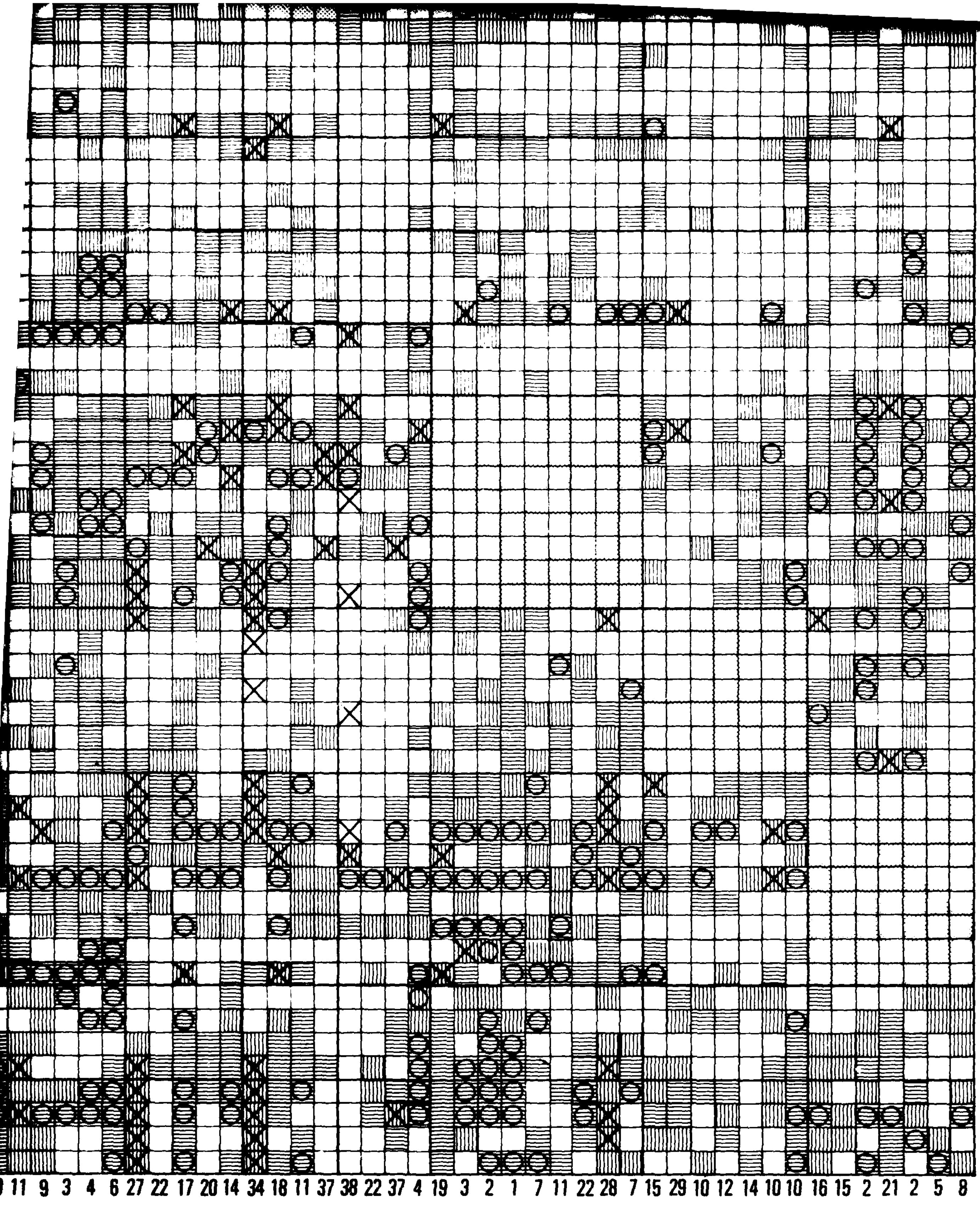
[2] Characterization of average slope and relief values in relation to average values for all lateral slopes. N–normal slope relief values, LS– low slope values, HS– high slope values, LR– low relief values, HR– high relief values.

BOTTOM PROVINCE	Rise						
	Trench	18	21	HR	+1.4	+1.5	−1
	Trough	11	5	HS	+1.8	−0.2	+21
	No Bottom Classification	37	12	LS,LR	0	−0.3	+7
TOTAL RELIEF(m)	2000m	17	13	−	−1.2	−1.5	−6
	2001−2999m	44	16	−	−0.5	−0.5	−2
	3000−3999m	23	20	−	+0.9	+0.5	+5
	> 4000m	15	18	−	+2.3	+2.6	+6
SLOPE (DEGREES)	1−1.9°	24	17	−	−2.3	−0.7	−11
	2−3.9°	31	19	−	−0.8	−0.3	−2
	4−7.9°	35	15	−	+2.2	+0.5	+13
	> 8°	11	14	−	+8.2	+0.7	+26
SURFACE SEDIMENT TYPE	Terrigenous	38	22	N	−0.3	+0.1	−3
	30−50% Carbonate	22	17	N	+0.2	0	+9
	> 50% Biogenic Carbonate and Silica	34	12	N	+0.2	0	−5
	Pelagic	4	11	LR	−0.2	−1.0	−20
SURFACE SEDIMENT SIZE	Silt	4	17	HR	+0.3	+0.5	+16
	Clay−Silt	79	17	N	+0.1	+0.1	+1
	Clay	13	24	LR	−0.3	−0.6	−10
PLATE-TECTONIC ASSOCIATION	Forearc Region	25	21	HR	+1.6	+1.5	+12
	Outer Trench Wall	3	15	LS,LR	−0.9	−1.0	−11
	Backarc Wall	2	17	HS	+2.4	0	+48
	Remnant Arc	1	4	LR	−0.4	−0.9	N.D.
	Active Translation	7	22	HS,HR	+1.3	+0.1	+11
	Apparent Passive in Megasuture Zone	11	13	LS,LR	−0.2	−0.3	0
	Intra−Oceanic	22	8	LR	+0.2	−0.4	0
	Passive Divergent	28	21	LS,LR	−0.9	−0.5	−6
	Passive Translation	7	21	LS	−1.4	−0.2	0
SHAPE	Sigmoidal Smooth	15	−	LS,LR	−.1.1	−0.6	−26
	Sigmoidal Rough	29	−	N	0	0	−8
	Abrupt Smooth	10	−	N	+0.2	−0.1	+14
	Abrupt Rough	12	−	HS,HR	+0.7	+0.3	+23
	Complex	14	−	N	0	−0.1	+16
	Step	10	−	LS	−0.8	−0.1	0
	High Relief	6	−	HS,HR	+2.4	+0.9	+14
OUTCROP TYPE	Prograded Sediment (No Outcrop)	14	−	LS,LR	−1.2	−0.5	−38
	Truncated Sediment/Rock	15	−	LS,LR	−0.8	−0.3	−16
	Diapirs	3	−	LS	−1.8	−0.4	−20
	Deformed Sediment/Rock	21	−	HR	+1.5	+1.1	+14
	Reef	2	−	HS	+2.3	−0.3	+19
	Acoustic Basement	5	−	LS,LR	−1.5	−0.3	+11
	Crystalline Block	4	−	N	+0.6	−0.3	+21
	Crystalline Pinnacle/Ridge	9	−	LS,LR	−0.7	−1.0	0
	Crystalline Pinnacle/Ridge Def. Sed.	7	−	HS	+2.0	+1.7	+40
SEDIMENT THICKNESS	0−200m	10	−	LS,LR	−0.2	−0.3	+21
	201−400m	7	−	LS,LR	−1.4	−0.7	−14
	401−999m	21	−	LS	−1.2	−0.3	−13
	>1000m	12	−	LS	−1.2	−0.1	−5
BASEMENT OF SEDIMENTARY STRATA	Diapiric	5	−	LS,LR	−1.1	−0.5	−1
	Reef	3	−	N	+1.2	−0.2	+26
	Acoustic Basement	32	−	LS,LR	−1.2	−0.4	−7
	Crystalline	8	−	LS	−0.3	0	−4



Percent of Total Lateral Slope Population →

4



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[1] No value gi

[2] Characterizatio
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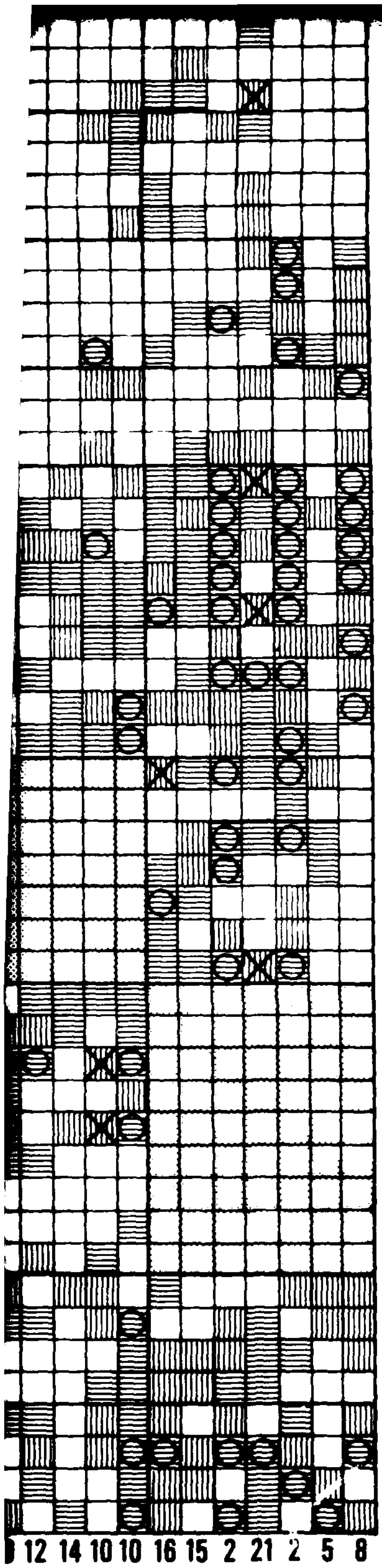
[3] Average slope
for the total l

[4] Average relief
for the total l

[5] Average outcr
for the total l



Note: The first three key designations indicate relative comparisons of subpopulations to the total lateral slope population. The final two designations are absolute and specify strongest or weakest associations between parameter class topics.

[1] No value given where only profile stations were used.

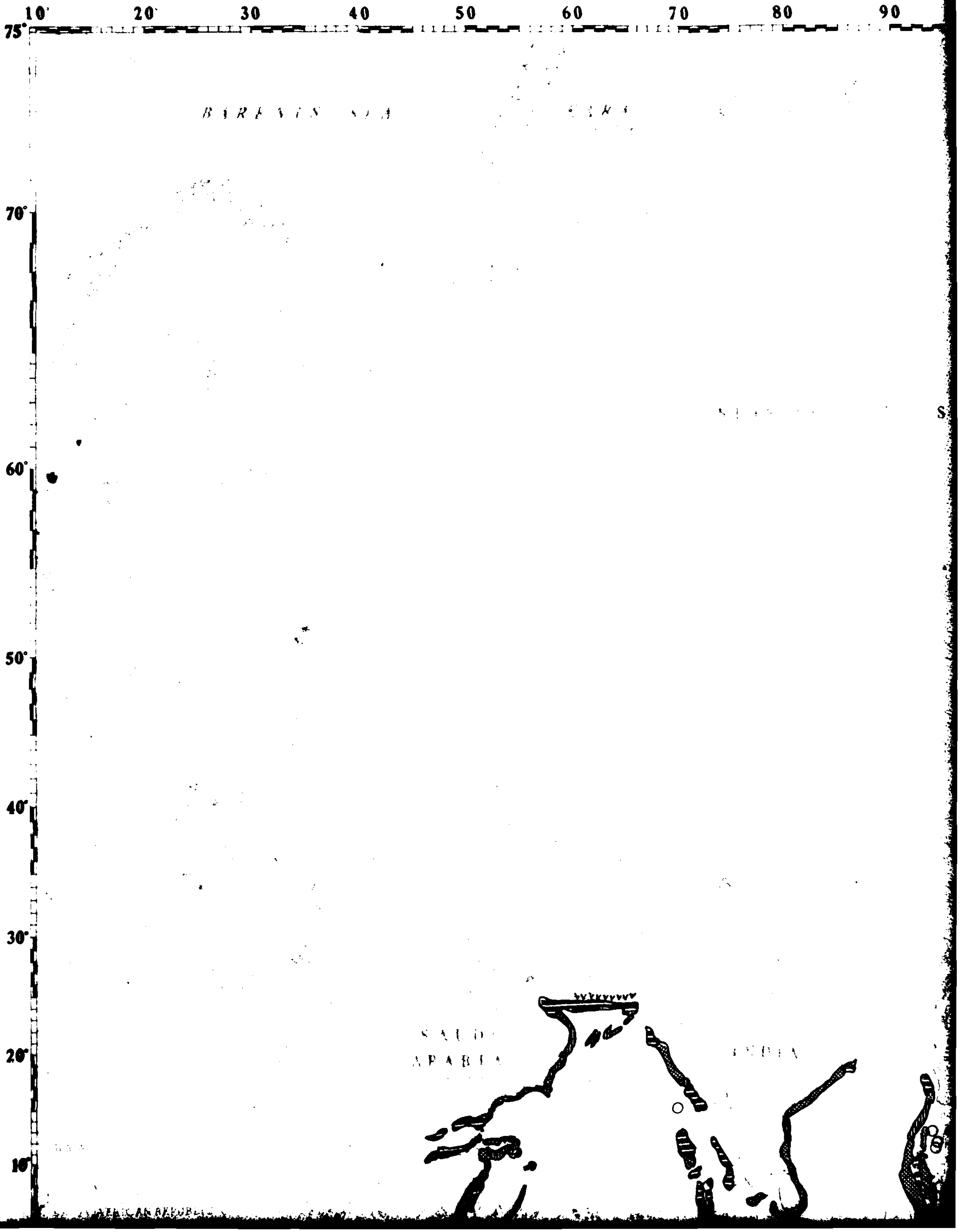
[2] Characterization of average slope and relief values in relation to average values for all lateral slopes. N–normal slope relief values, LS– low slope values, HS– high slope values, LR– low relief values, HR– high relief values.

[3] Average slope value for a subpopulation minus the average value for the total lateral slope population (3.8°).

[4] Average relief value for a subpopulation minus the average value for the total lateral slope population (3.035KM).

[5] Average outcrop percent for a subpopulation minus the average value for the total lateral slope population (38%).

Plate II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BARENTS SEA
KARA
SAUDI ARABIA
INDIA
AFRICAN REPUBLIC

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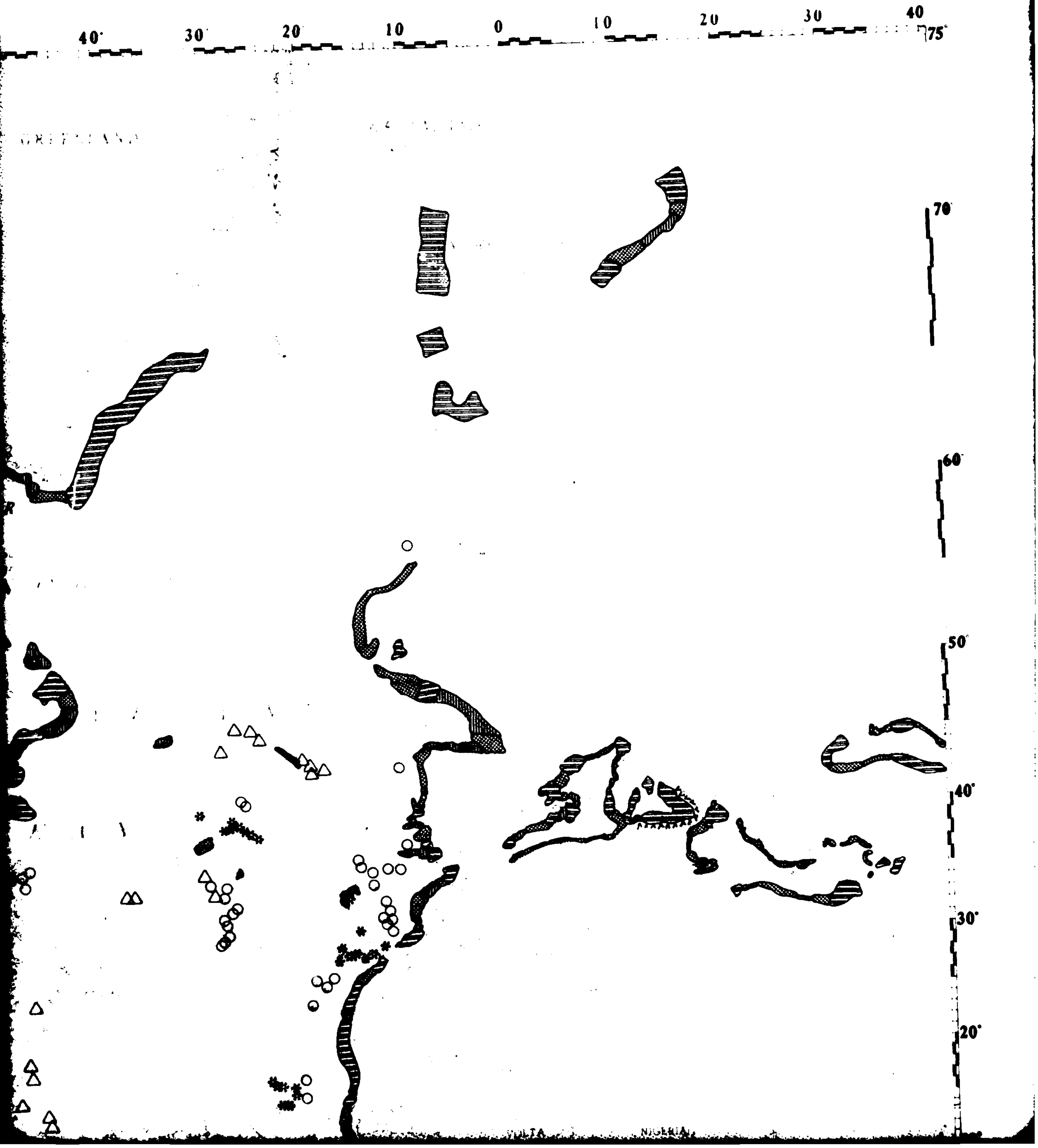
GREENLAND
UNITED STATES
MEXICO
OCEAN
CARIBBEAN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NDIA
ANTARCTICA

TASMAN SEA
OCEAN
ANTARCTIC OCEAN


Plate 9
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PACIFIC
OCEAN
BRAZIL
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OCEAN
BELLINGHAUSEN SEA
WEDDELL SEA
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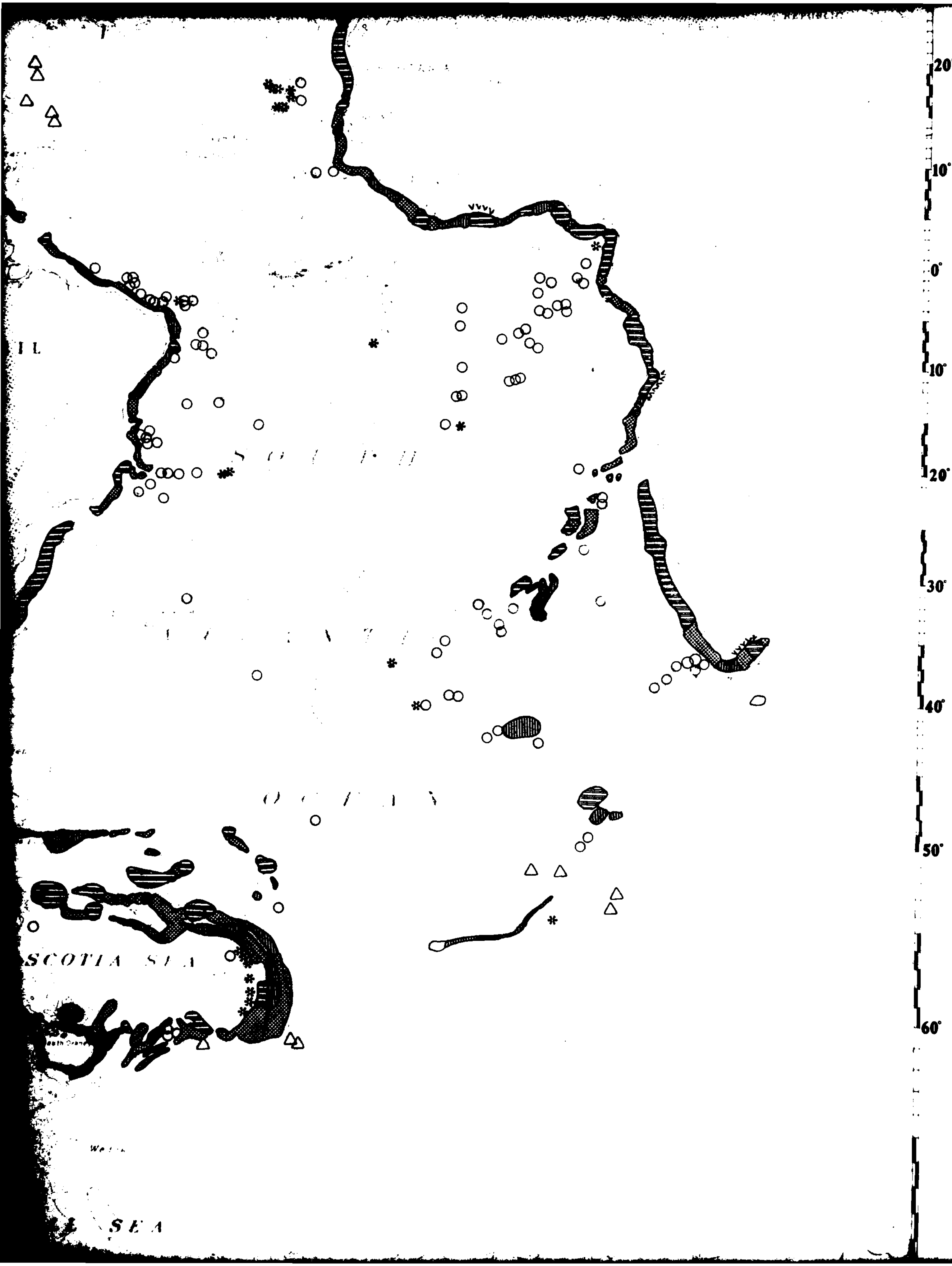
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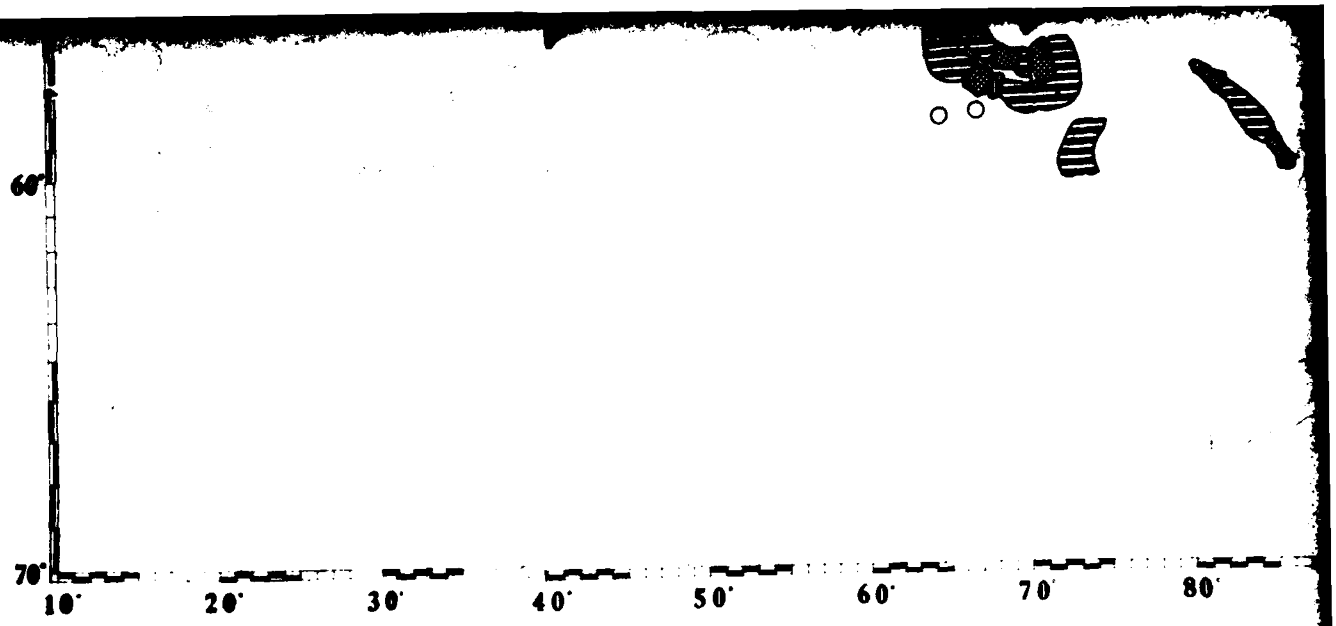

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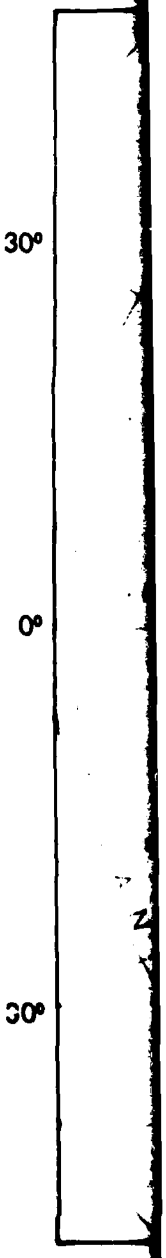

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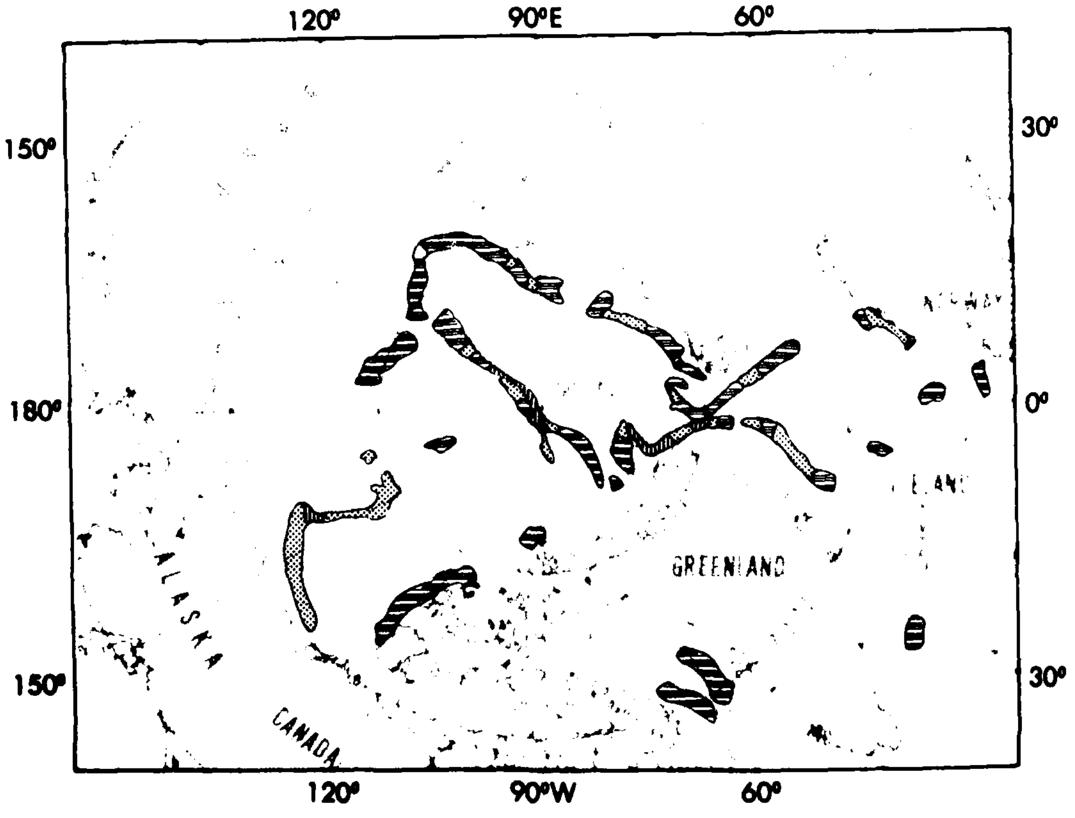

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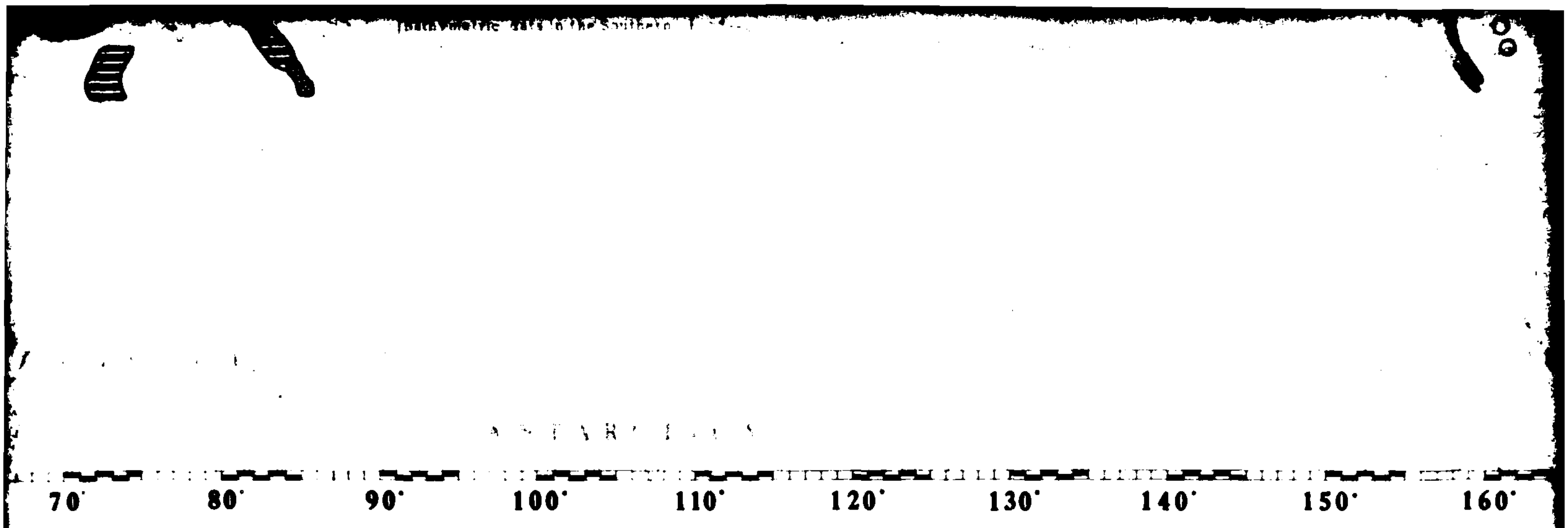

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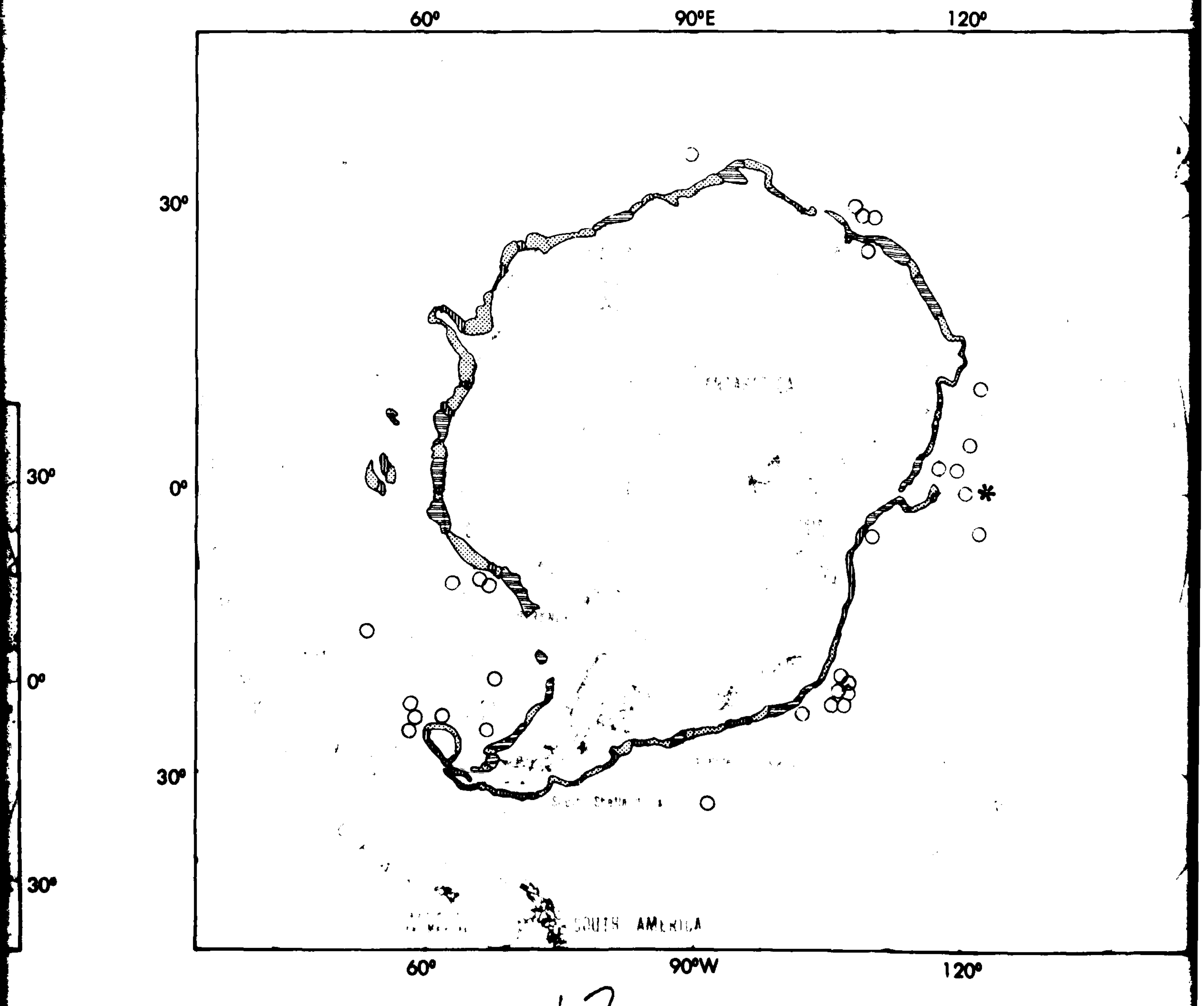

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ANTARCTICA
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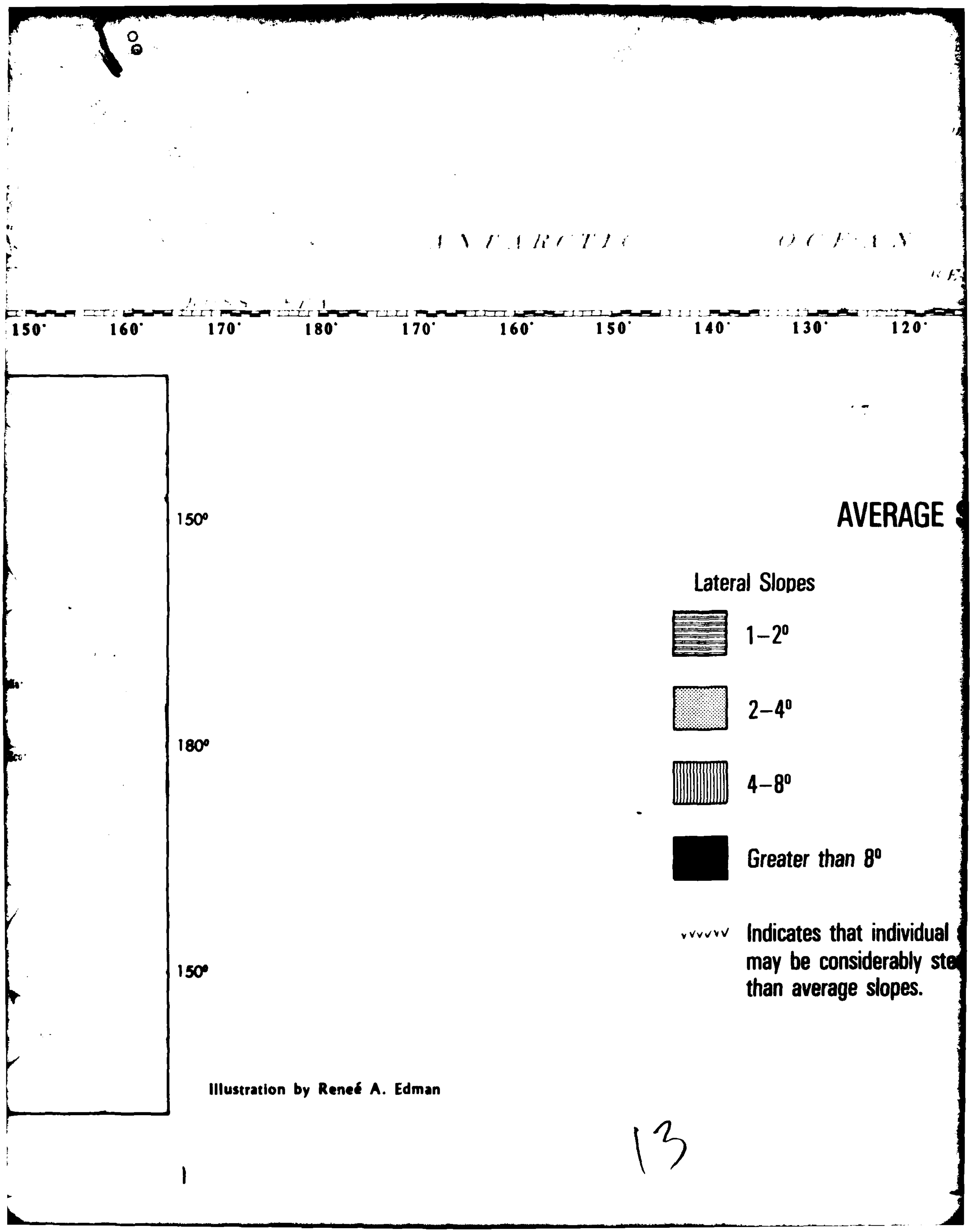
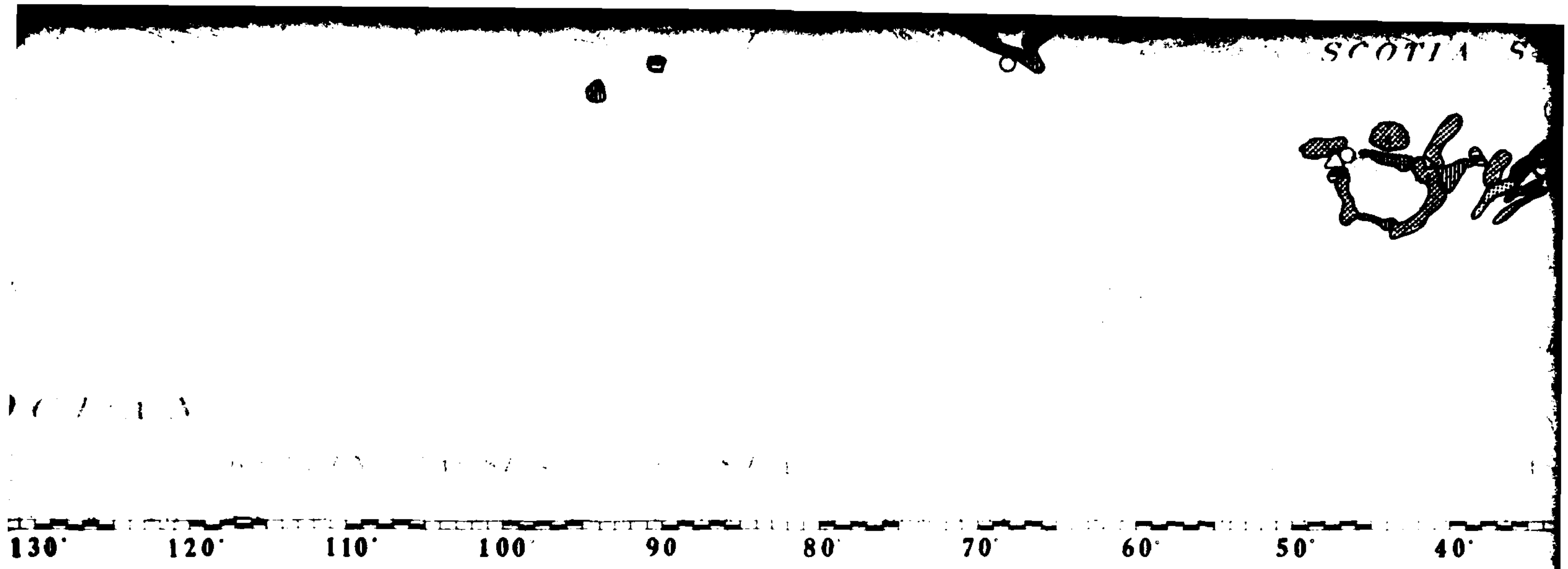


Illustration by Reneé A. Edman



AVERAGE SLOPE INCLINATION

pes

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tes that individual slopes
be considerably steeper
average slopes.

Conical and Discrete Slopes

○ Seamounts

✲ Islands

△ Discrete slopes

⊛ Island which does not exhibit relief of 2000m or average slope of 1°.

All outlined slo
of relief. Slope
Lateral slopes
sides of conica
slopes are insi
features. Slope
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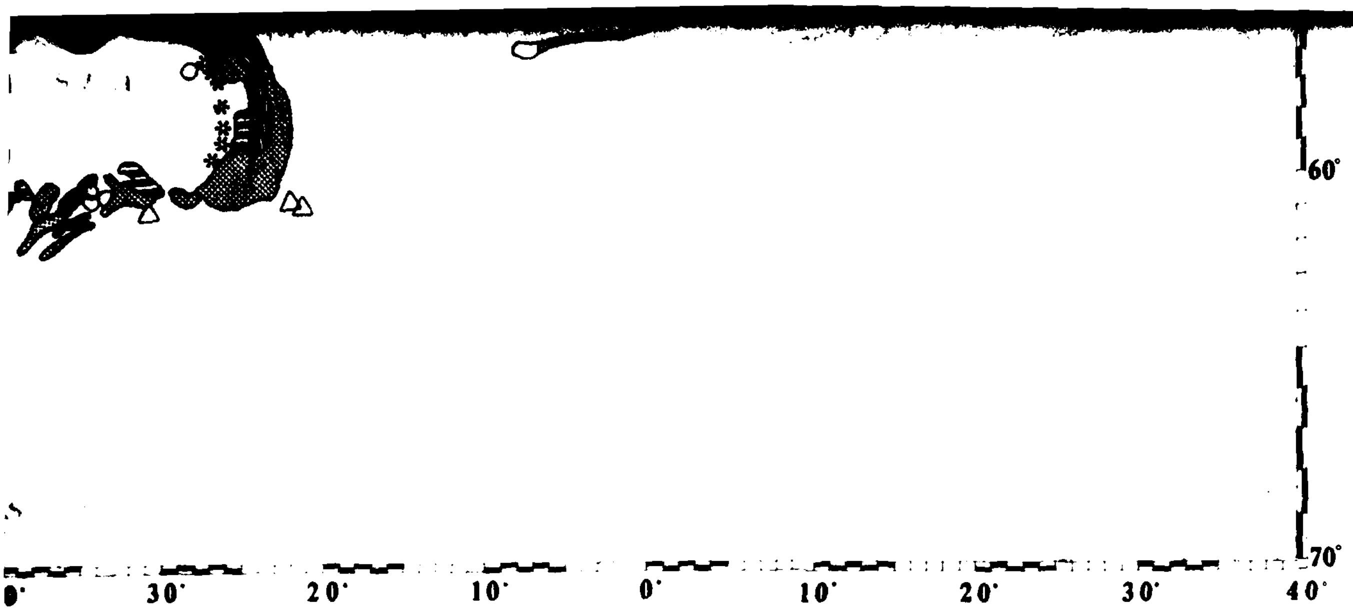
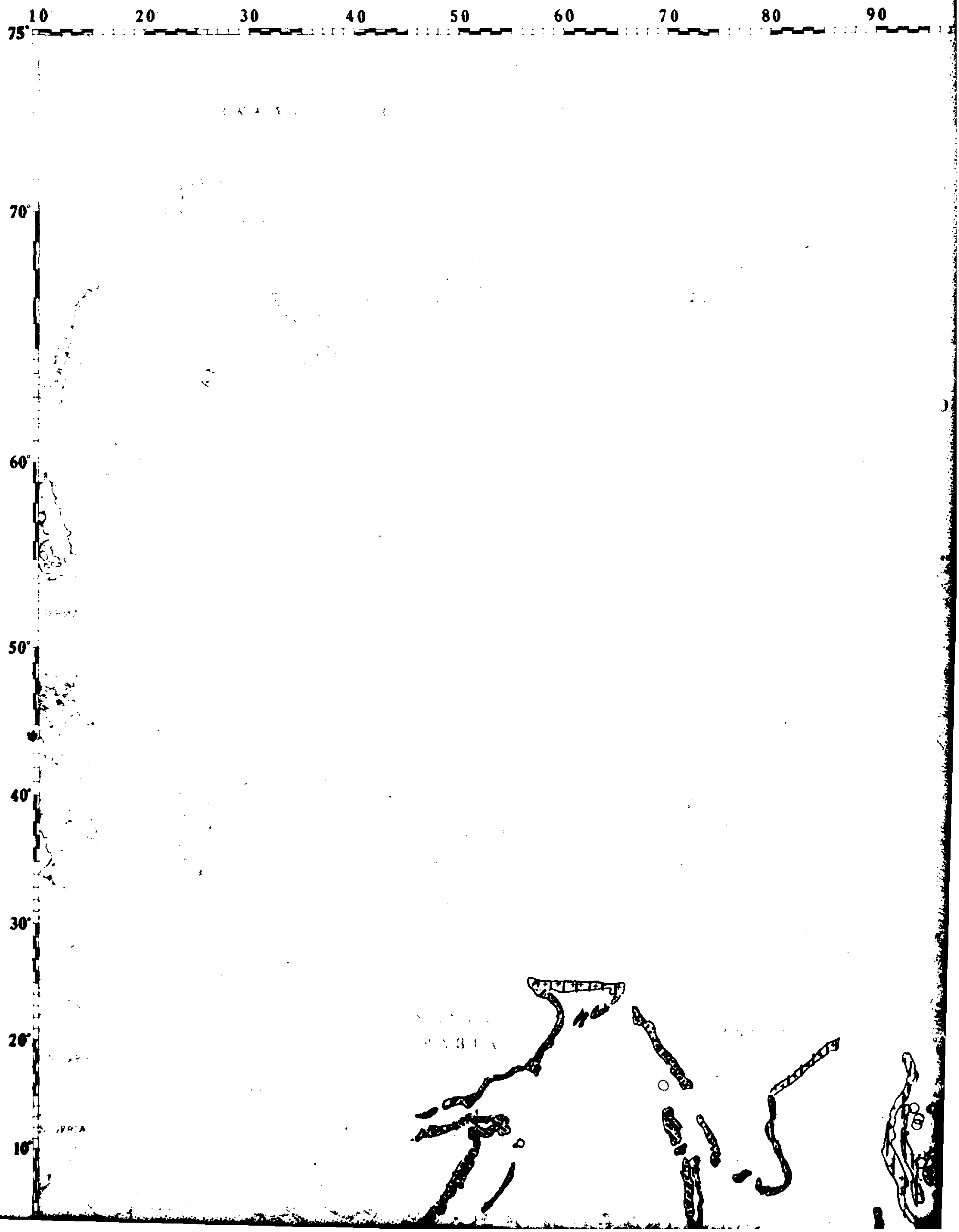
14



ned slope areas have average slope inclinations exceeding 1° for a 2000m range
Slope ranges indicate average inclination for the steepest 2000m relief range.
slopes resemble walls and continue for great lengths. Conical slopes form the
conical features which have a maximum top dimension of 100km. Discrete
re insignificant and extend for less than 100km along sides of various oceanic
Slopes were determined from unpublished Naval Oceanographic Office
try maps, scale: 1"= 1°.

Map I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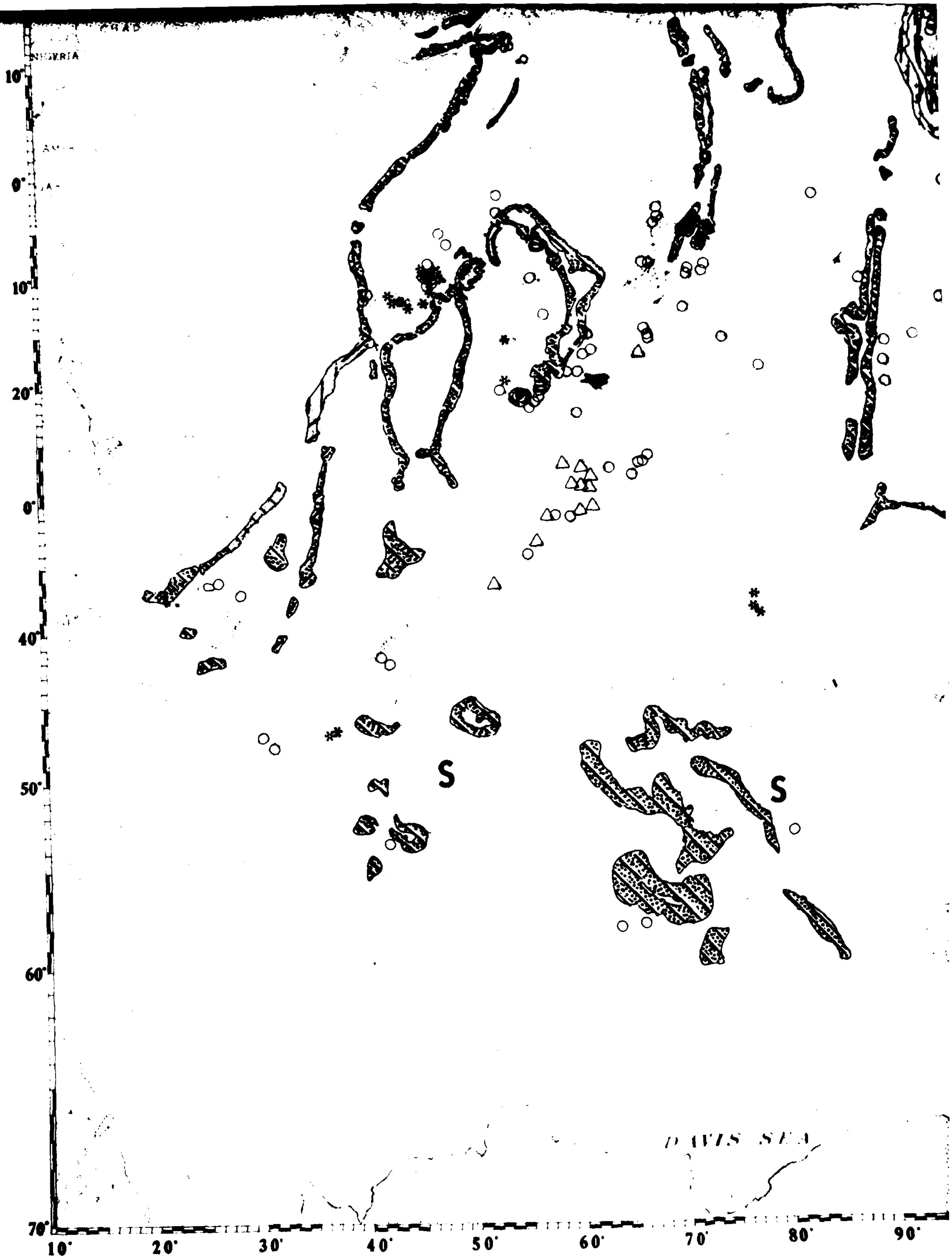

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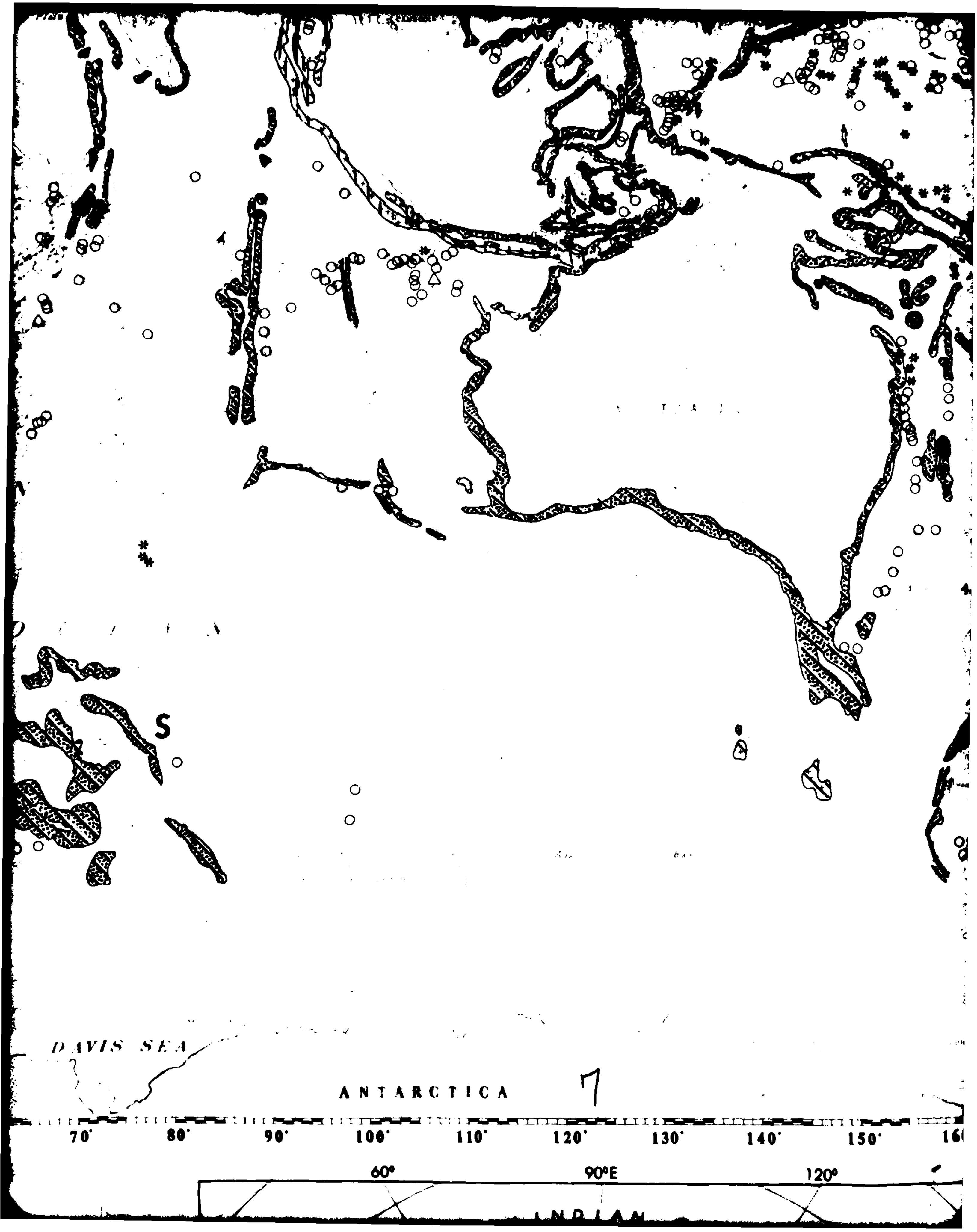
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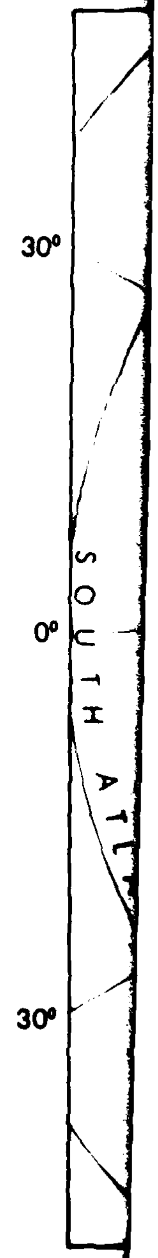
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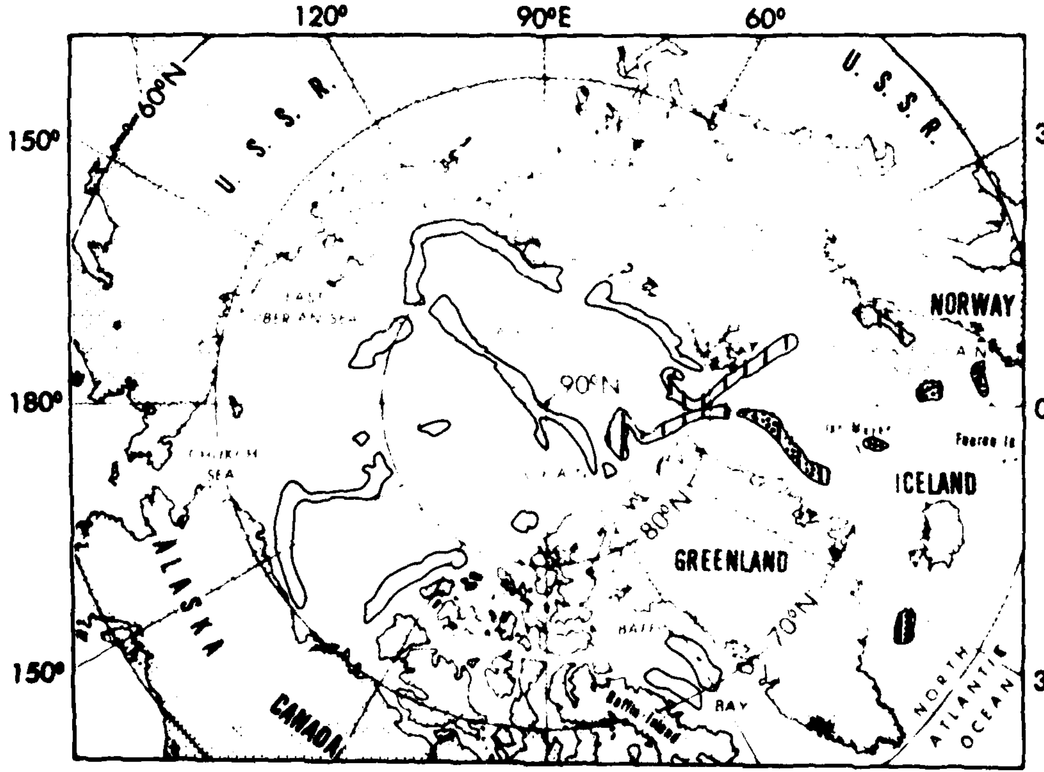
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CHUKCHI SEA
ALASKA
CANADA
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80°N
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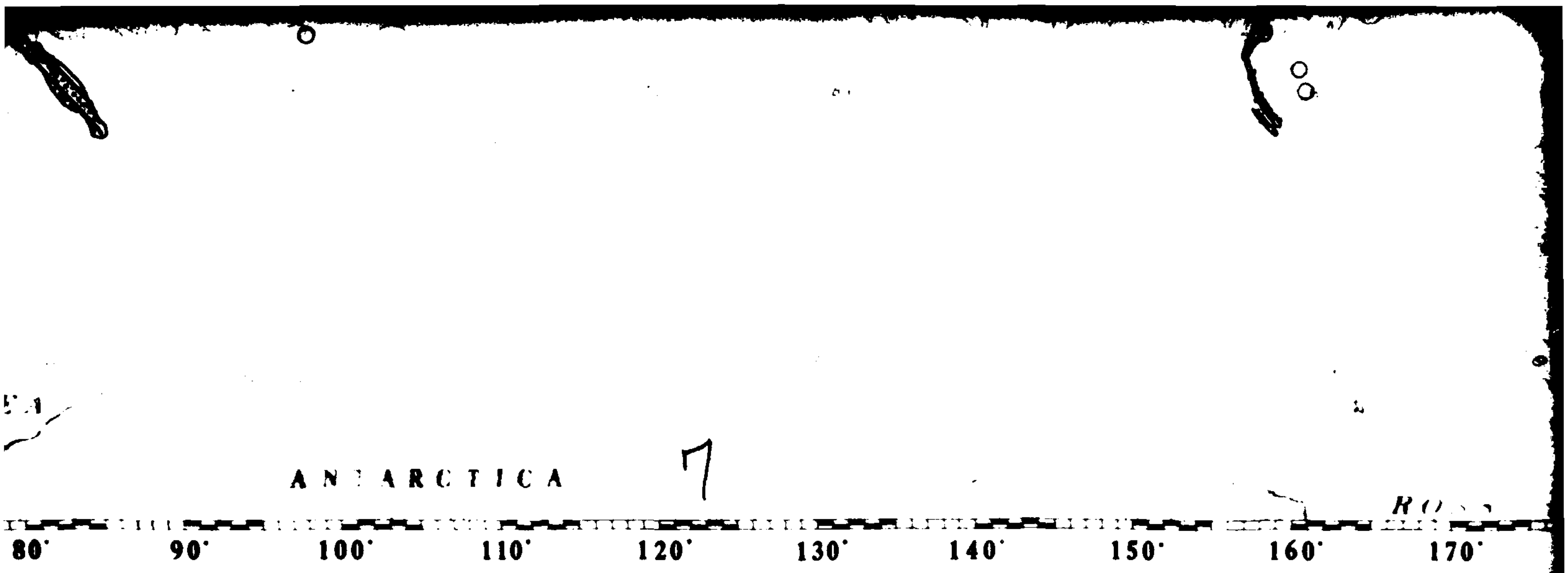
NORWAY
ICELAND
Jan Mayen
Faeroe Is
BAFFIN BAY
Baffin Island
NORTH ATLANTIC OCEAN



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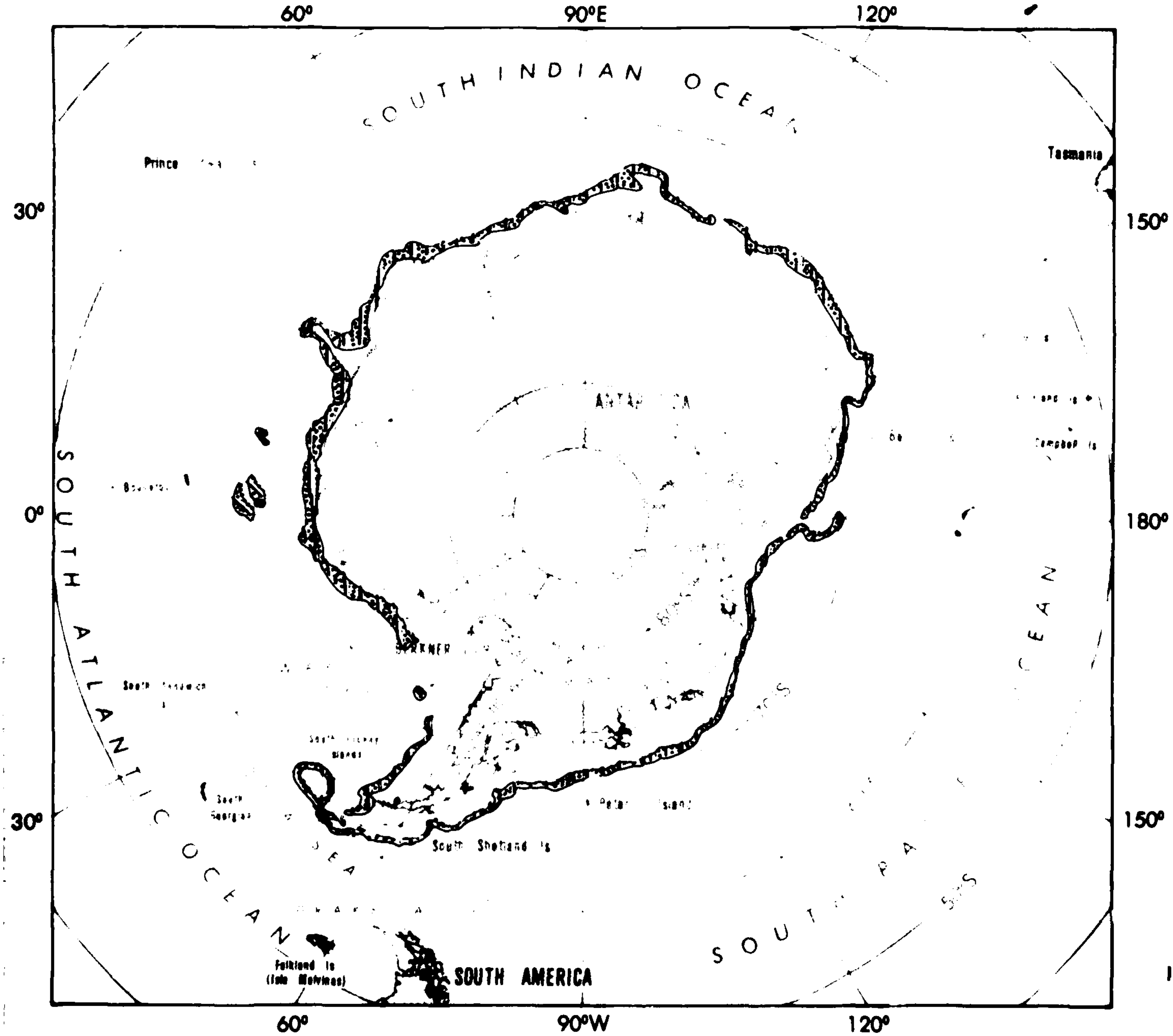

Illustration

13

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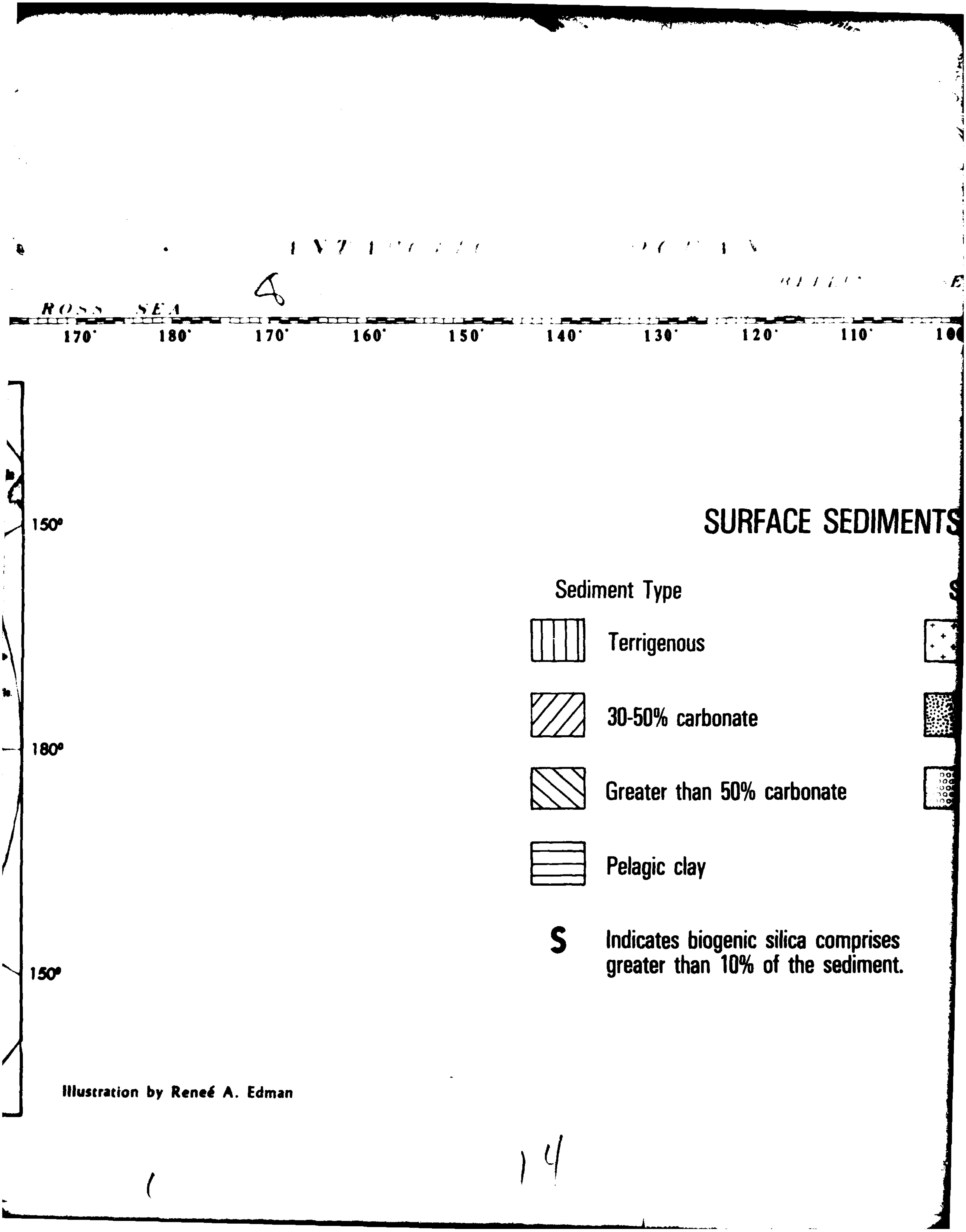

Illustration by Reneé A. Edman

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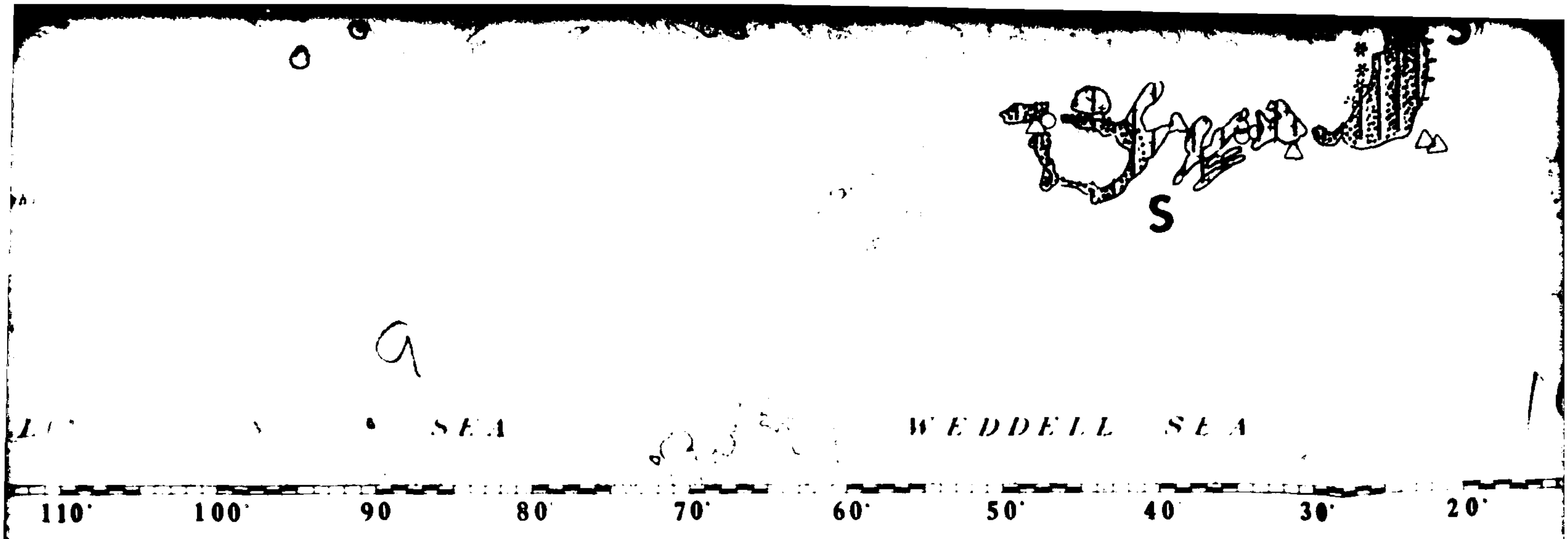


SEDIMENTS

Sediment Size

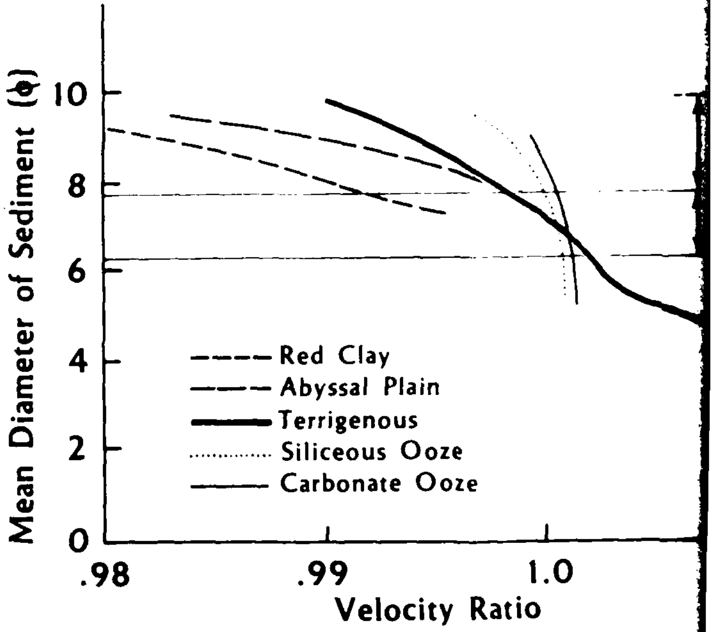
⁘ Clay

▨ Fine silt

☐ Silt

ate

comprises
sediment.



Major Sources:

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Exped., Akad Nauk, SSR, 151p.
Frazer, J. and others (1972) Surface Sediments and Topograp
IMR-TRI-10. maps
Kort, V. (1970) Sedimentation in the Pacific Ocean, Books I a
of the USSR, Moscow, 419 and 427p.
Lisitzyn, A. (1975) Sedimentation in the Atlantic Ocean, Acade
USSR, Soviet Geophysical Committee, 402p.

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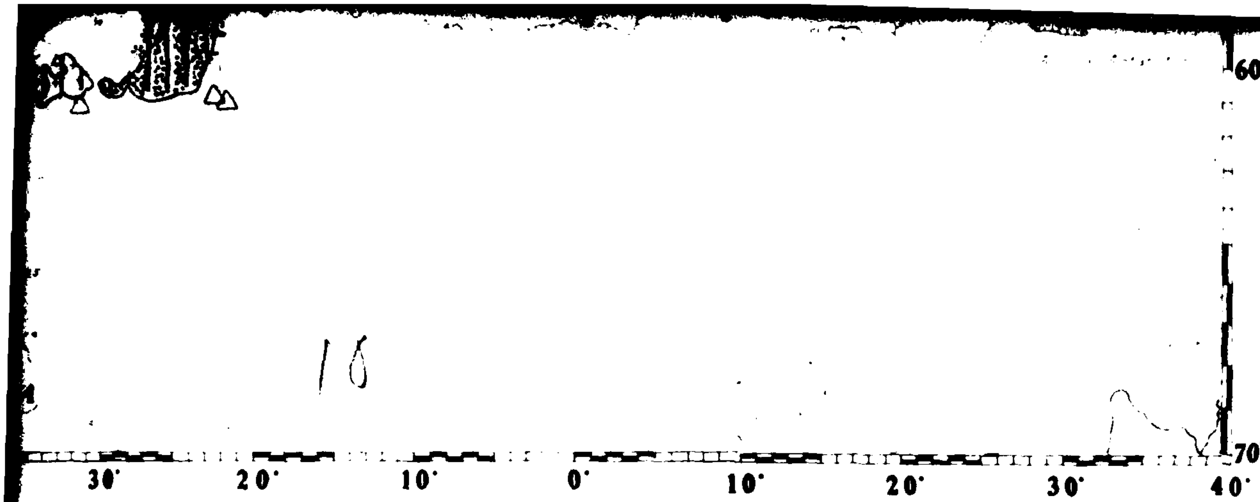

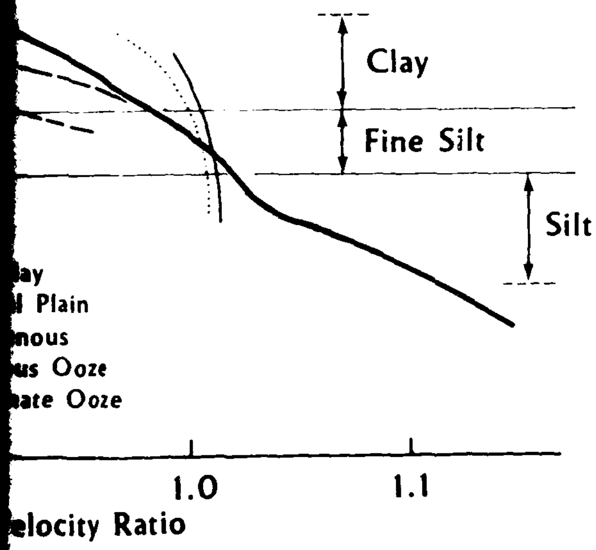

ophysical Atlas of the Indian Ocean, Int. Indian Ocean

ce Sediments and Topography of the North Pacific,

he Pacific Ocean, Books I and II, Academy of Sciences
27p.
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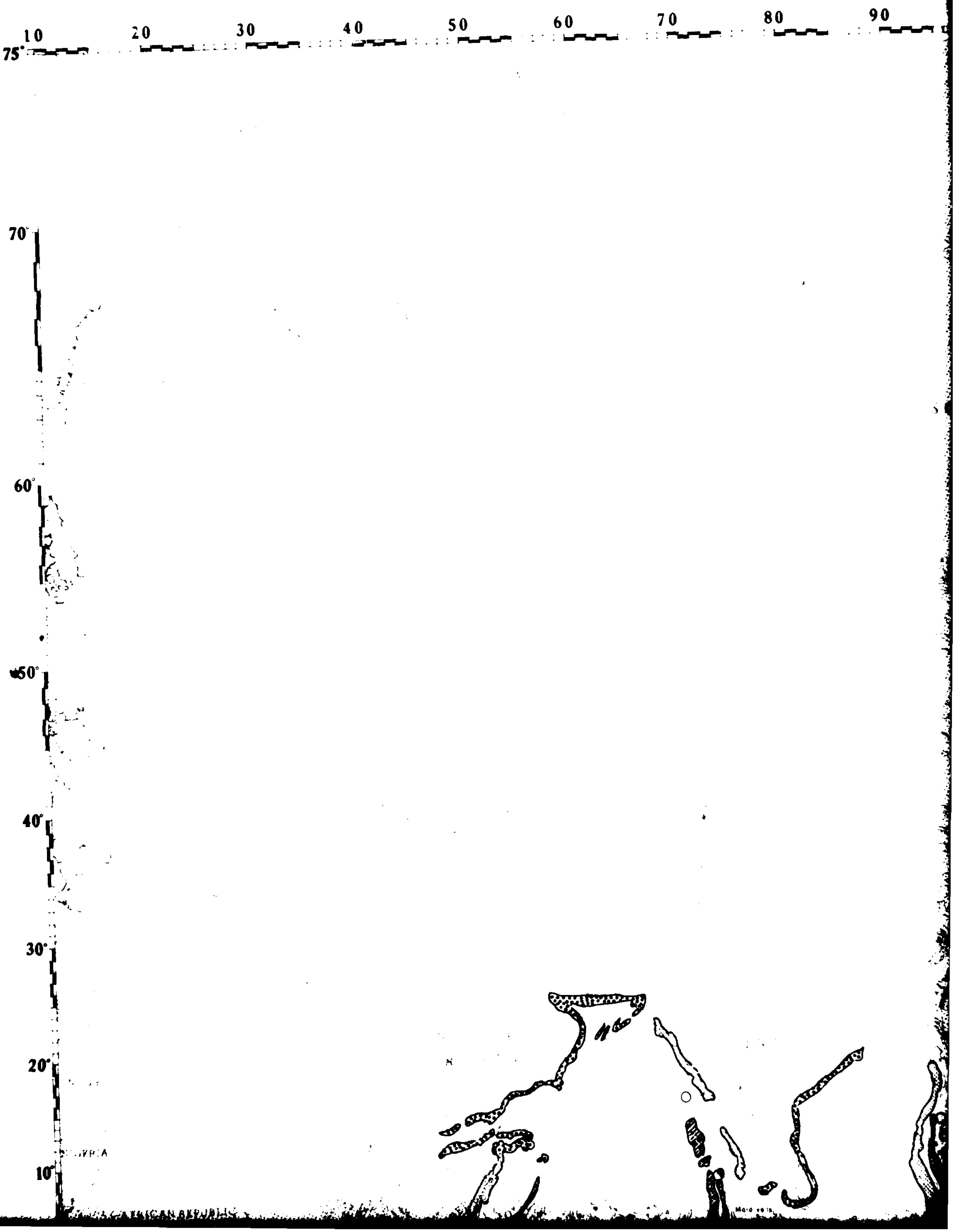
tee, 402p.

Map II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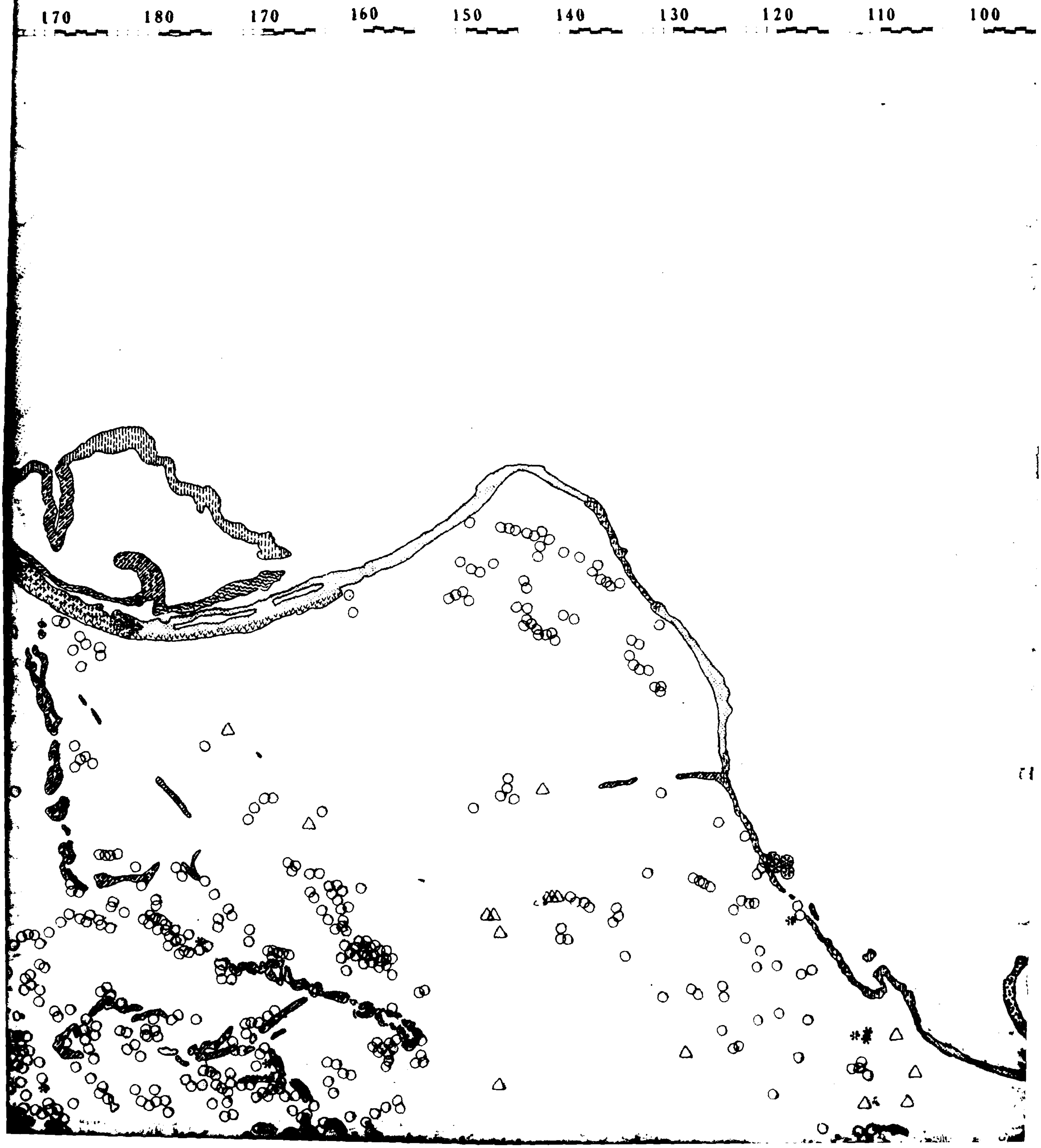

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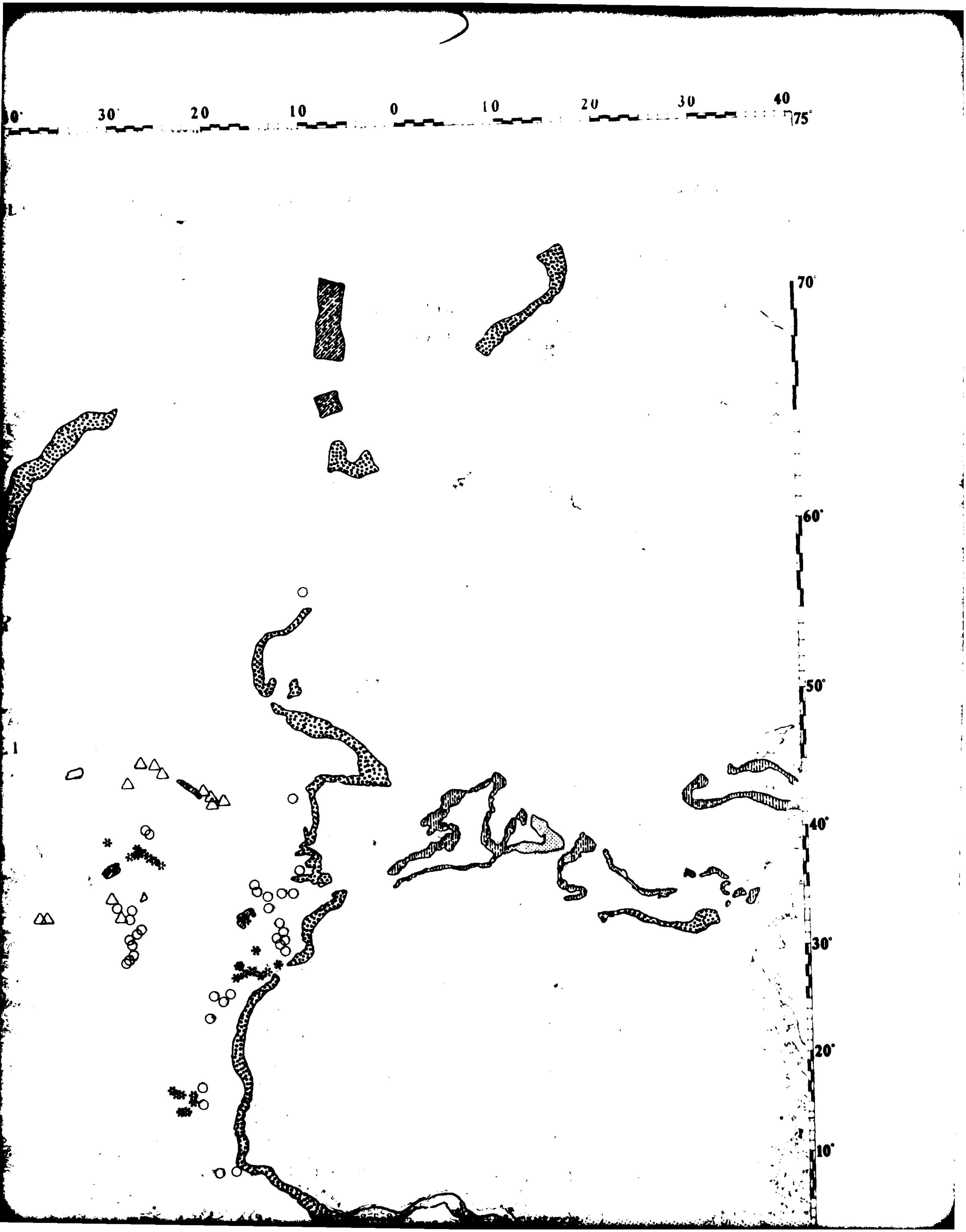
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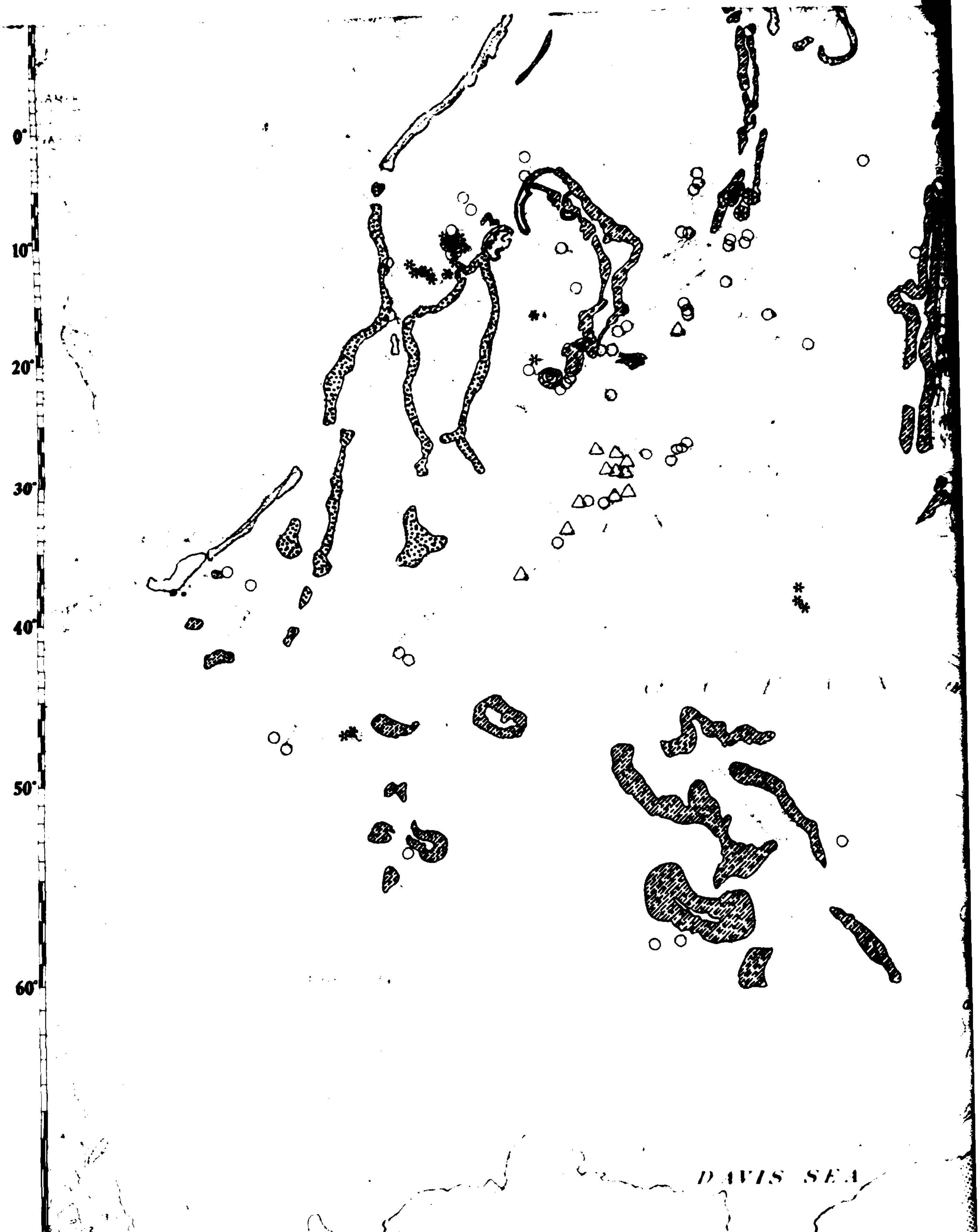

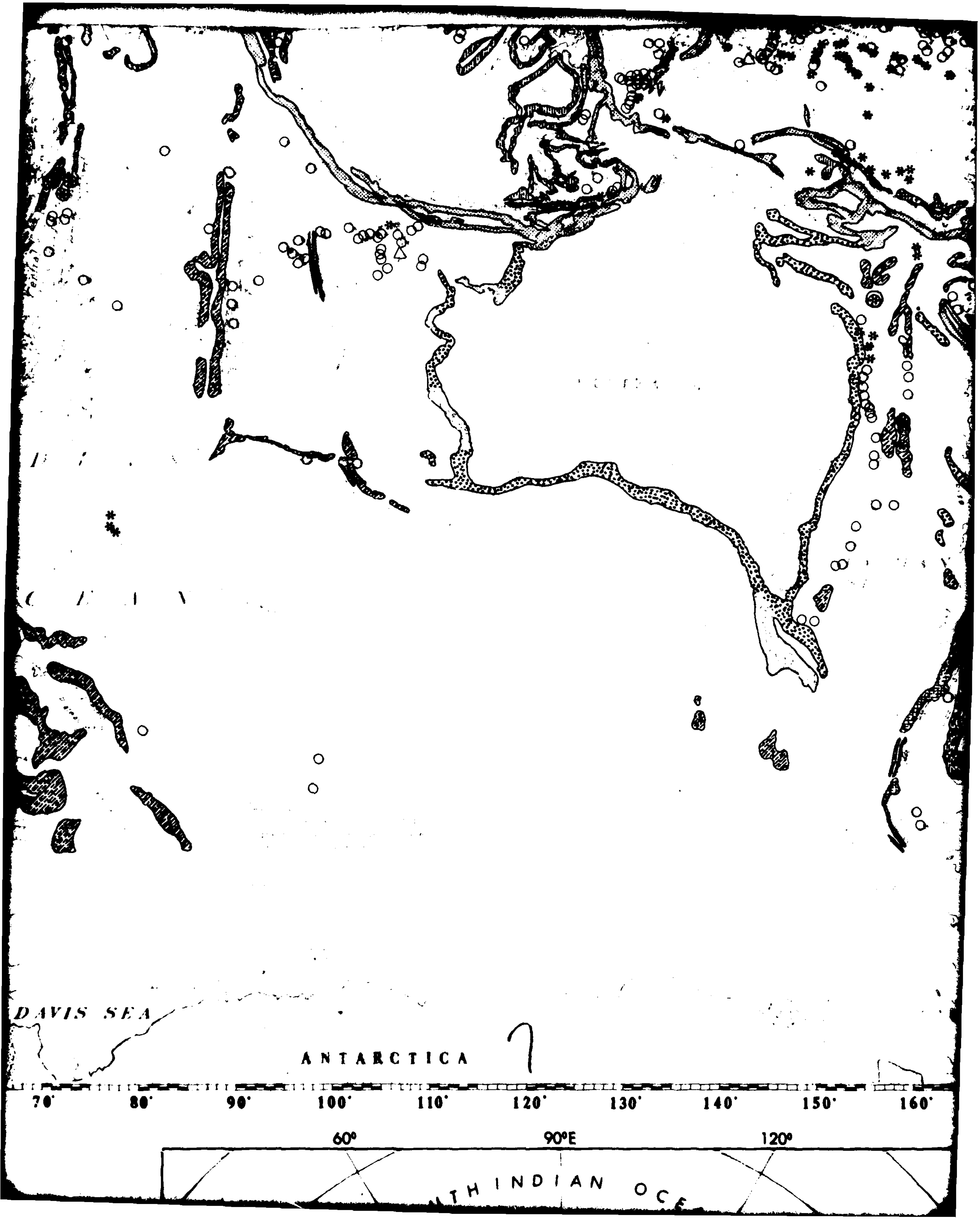
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150°
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90°E
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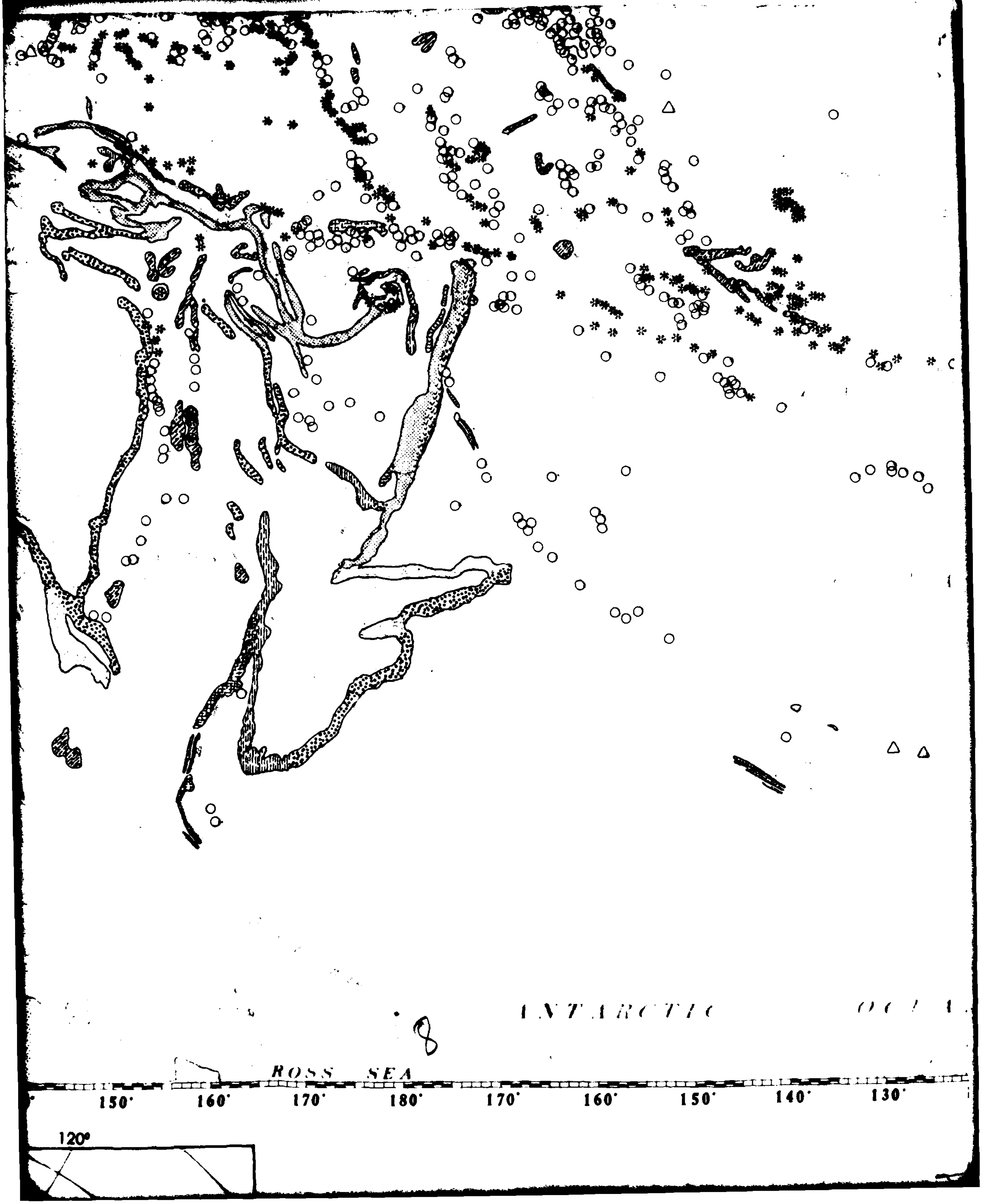
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OCEA
ROSS SEA
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160°
170°
180°
170°
160°
150°
140°
130°
120°


OCEAN
NTARCTIC
OCEAN
BELLINGHAUSEN
SEA
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110°
100°
90°
80°
70°

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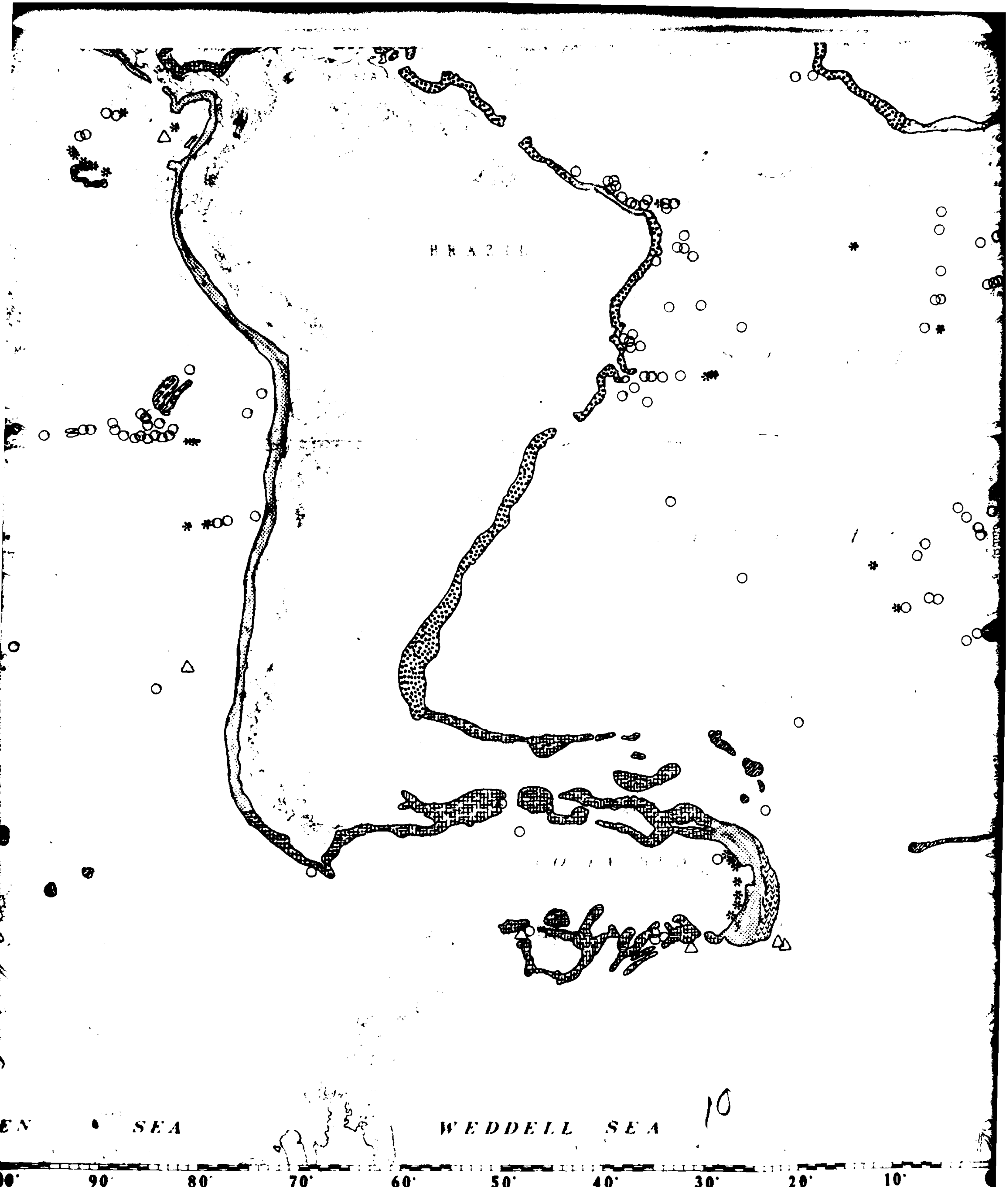

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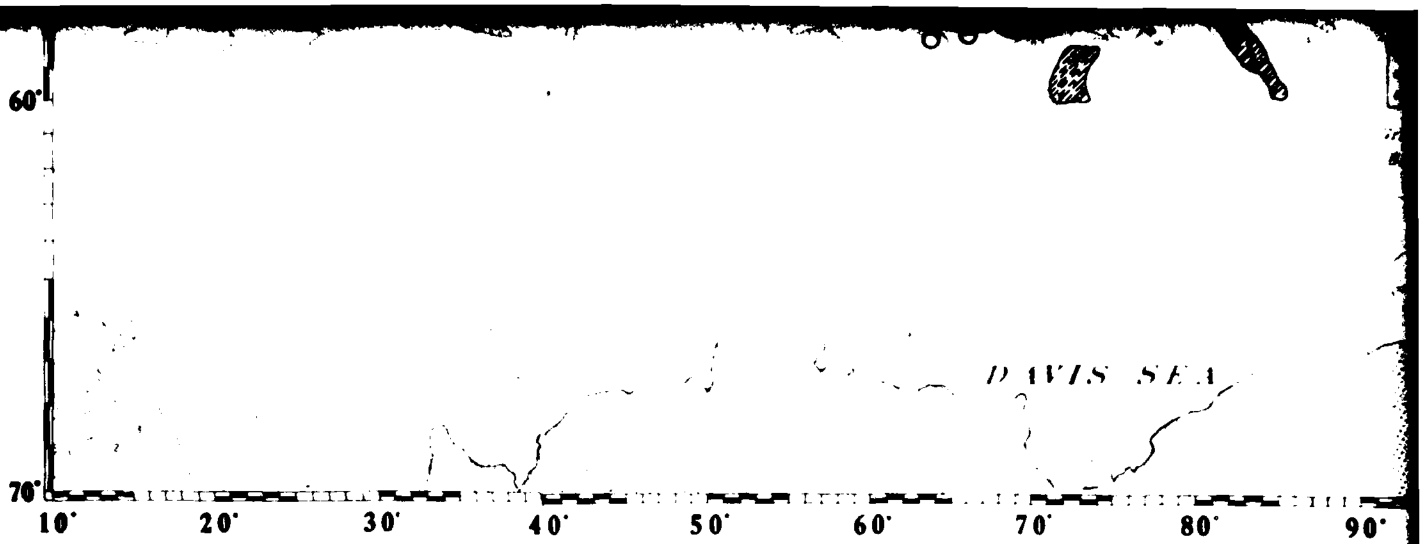
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DAVIS SEA
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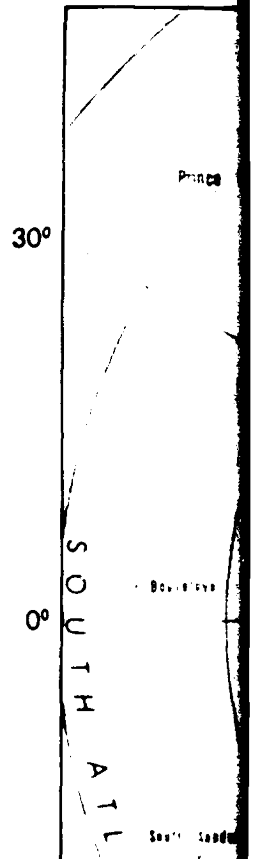
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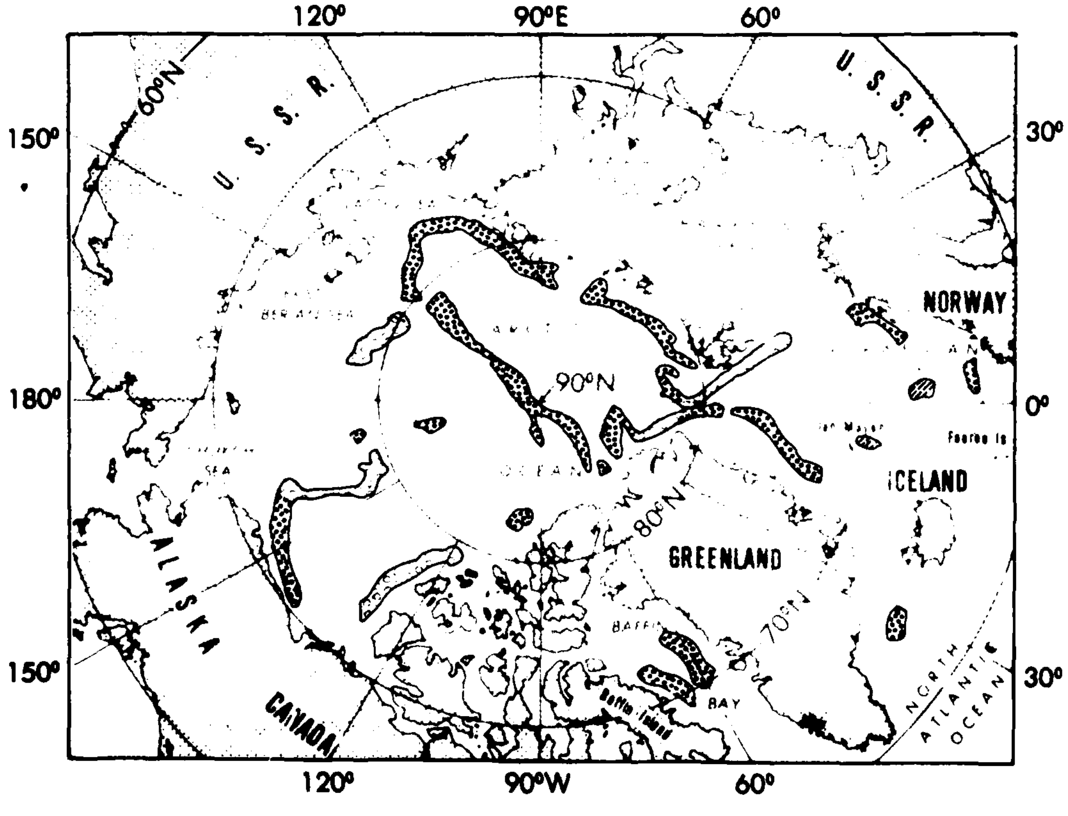
0°
Bouvetøya
SOUTH ATLANTIC
30°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180°
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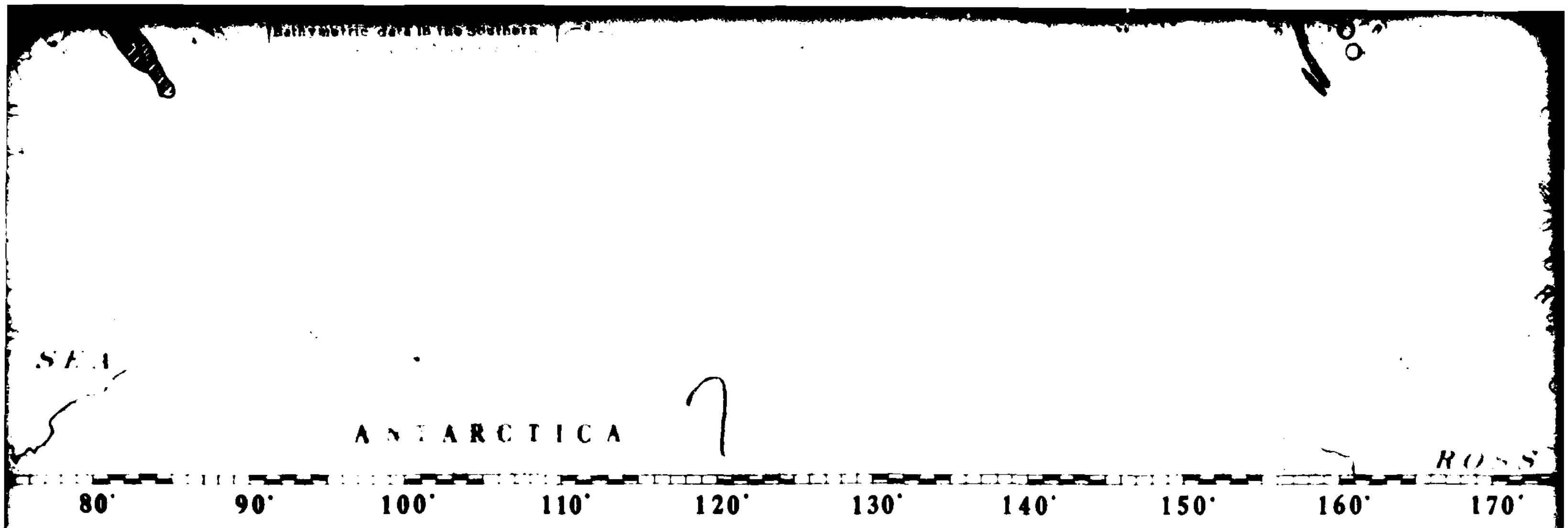
60°N
U. S. S. R.
U. S. S. R.
NORWAY
ICELAND
GREENLAND
ALASKA
CANADA
90°N
80°N
70°N
Jan Mayen
Faeroe Is
BAFFIN
BAY
Baffin Island
NORTH ATLANTIC OCEAN
OCEAN
SEA

12



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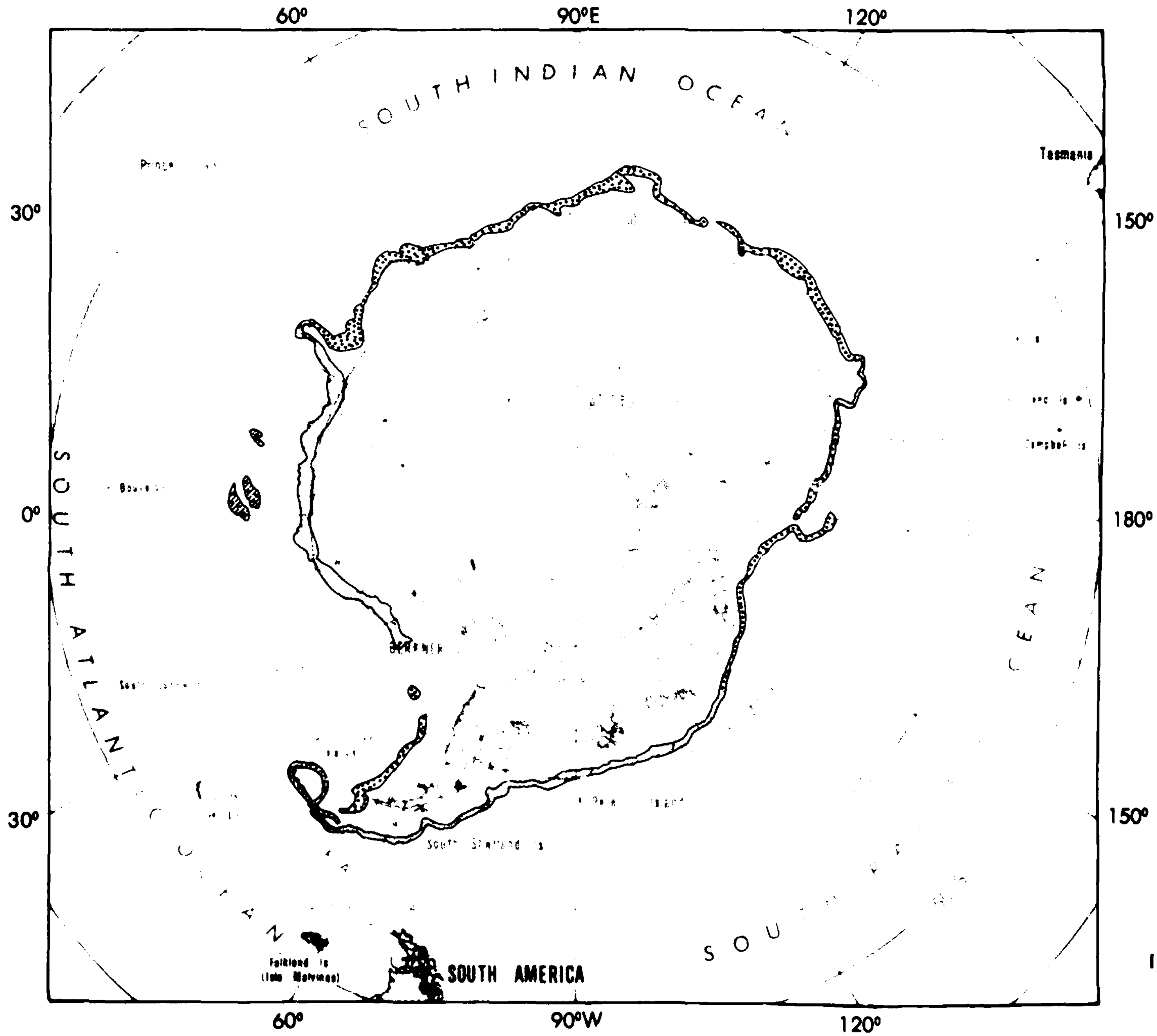

Illustrat

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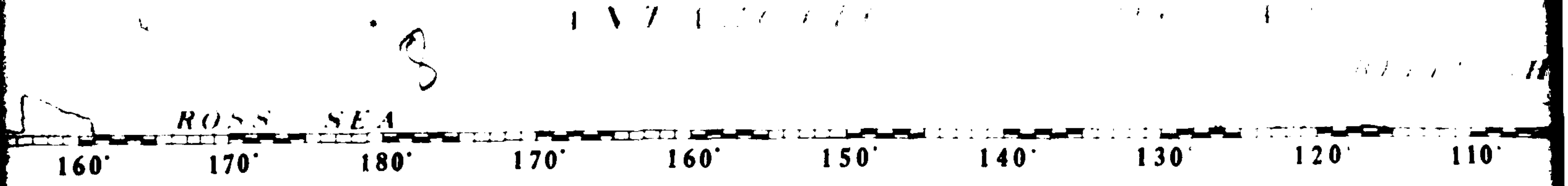


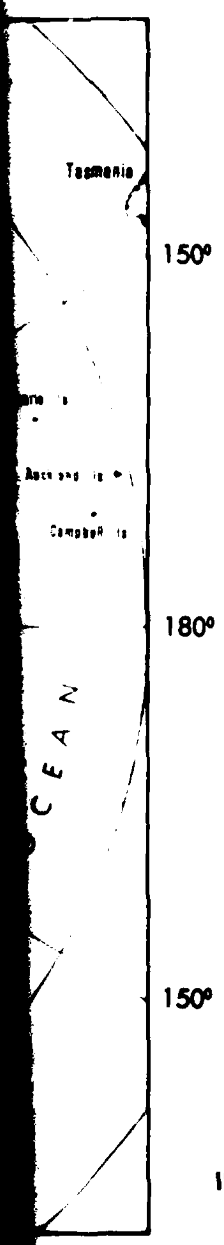


PLATE-TECTONIC ASSOC

Slopes in Megasuture Zone

☐ 1 Forearc region

▨ 2 Outer trench wall

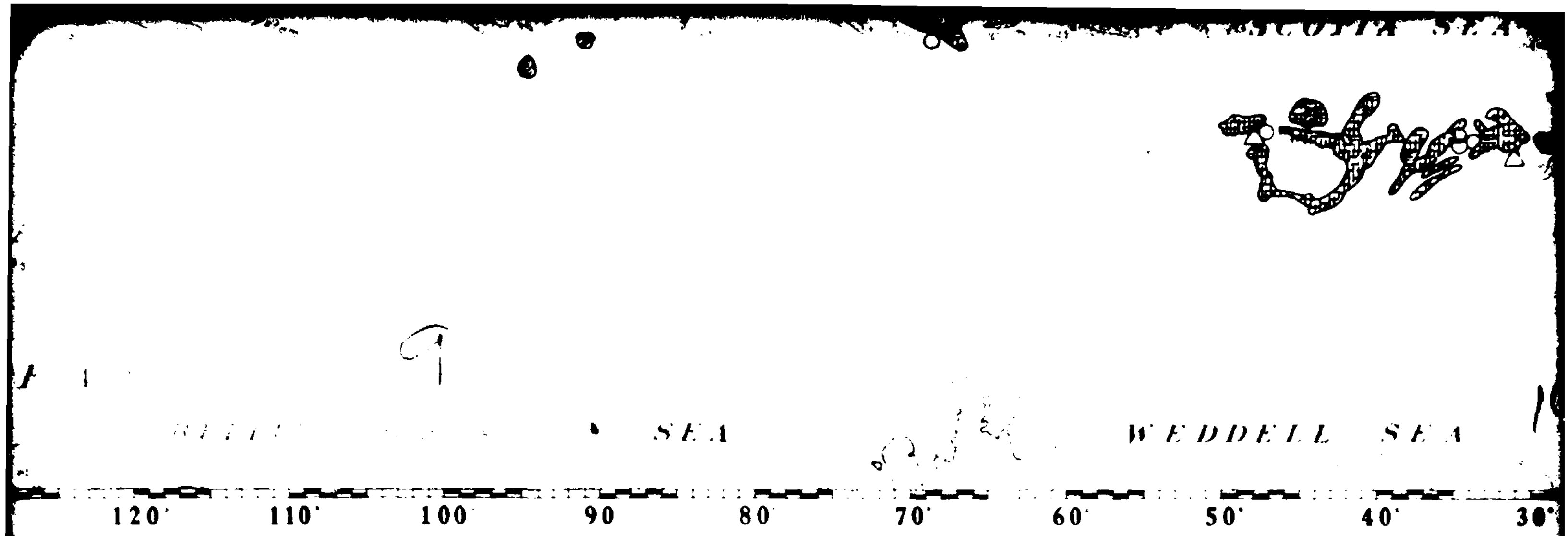
▨ 3 Backarc wall

■ 4 Remnant arc

▦ 5 Associated with active translation

▥ 6 Apparent passive margin slope in

Illustration by Reneé A. Edman



-TECTONIC ASSOCIATION OF SLOPES

suture Zone

region

rench wall

wall

t arc

ted with active translation

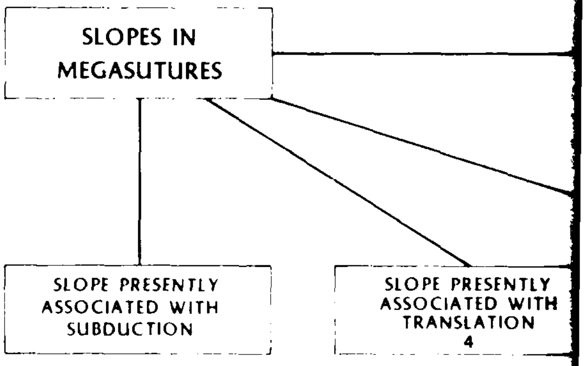
t passive margin slope in a megasuture

Slopes not in Megasuture Zone

▨ 7 Intra-oceanic

░ 8 Passive divergent

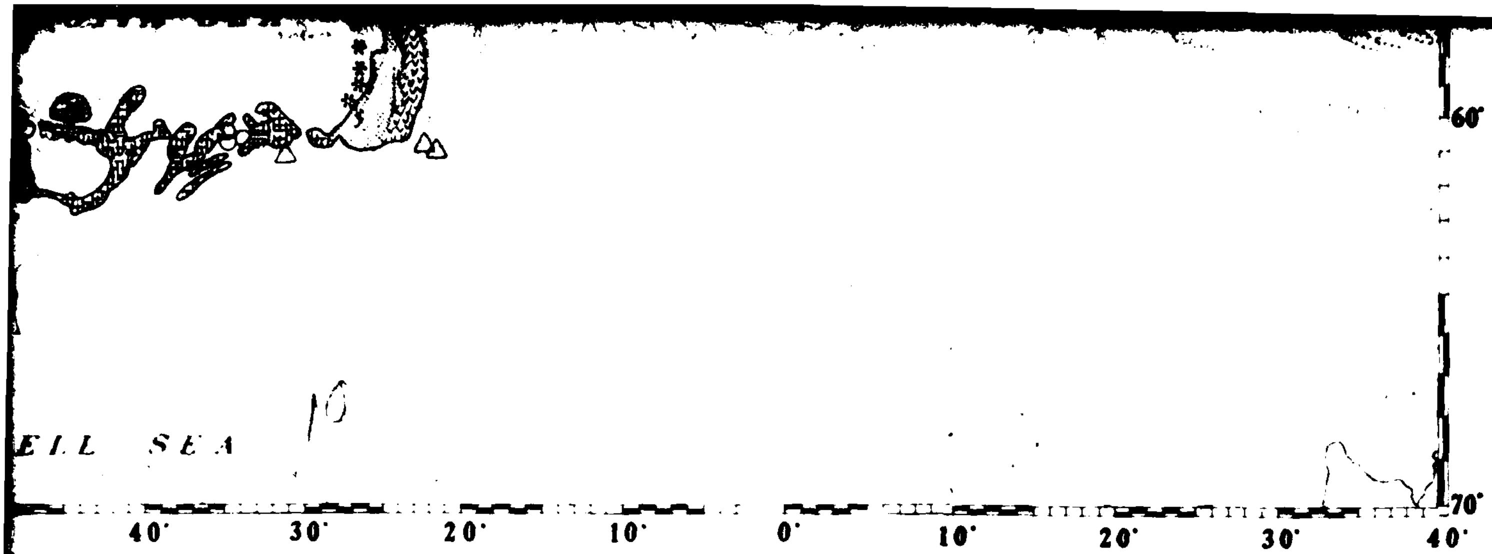
□ 9 Passive translation



*1 FOREARC REGION
2 OUTER TRENCH WALL
3 BACK ARC WALL

* Numbers correspond to Parameter Classes

19



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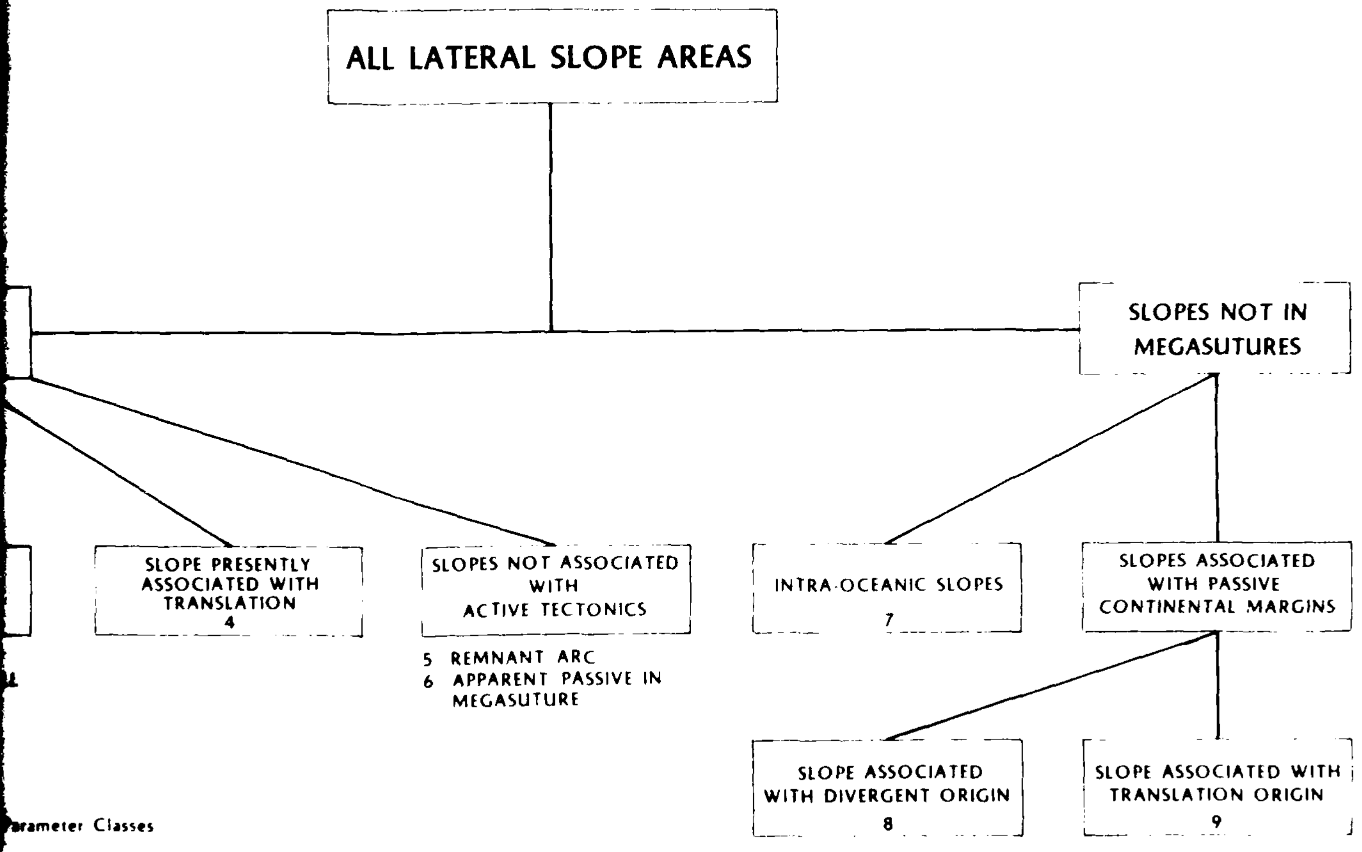
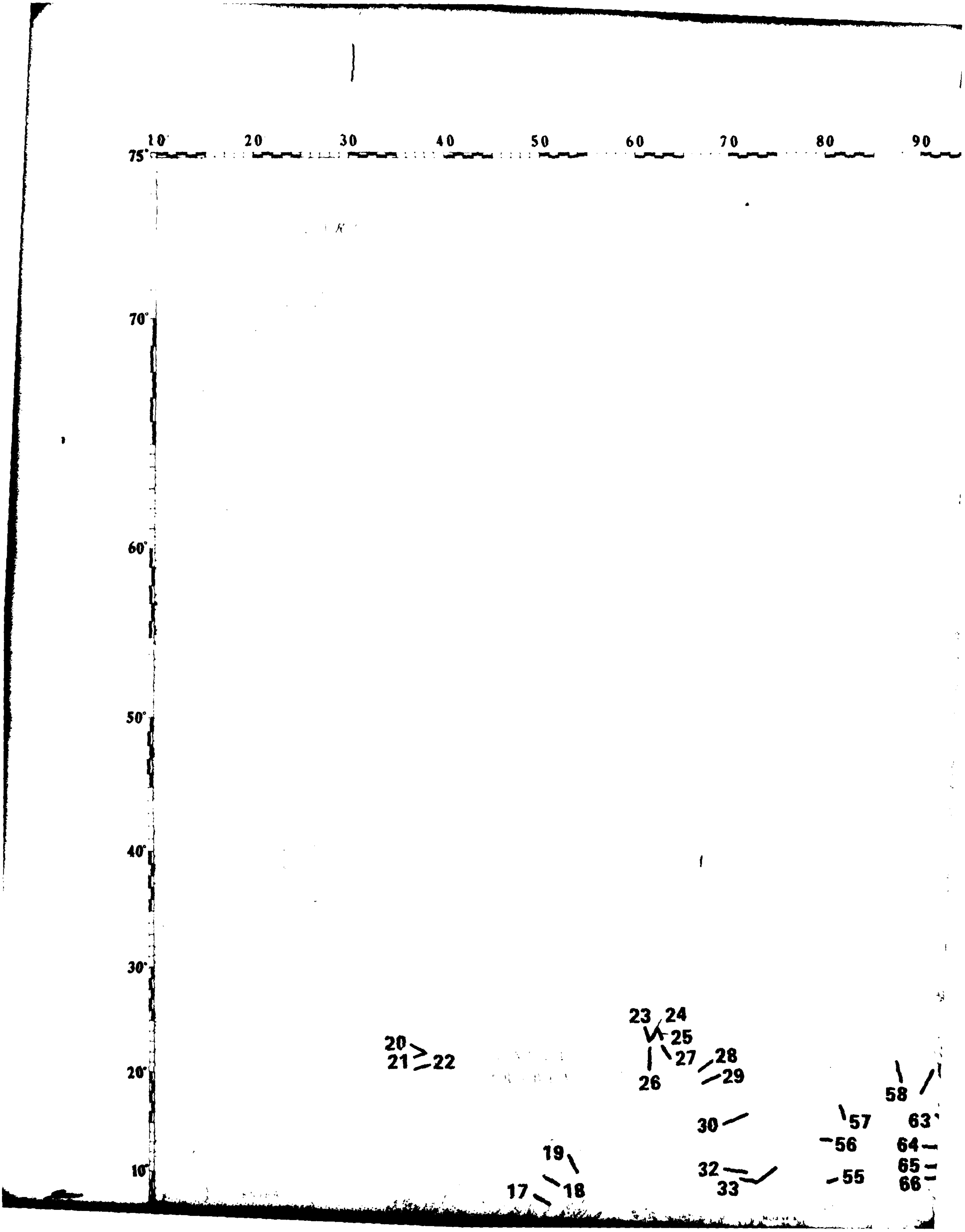


arameter Classes

Map III

12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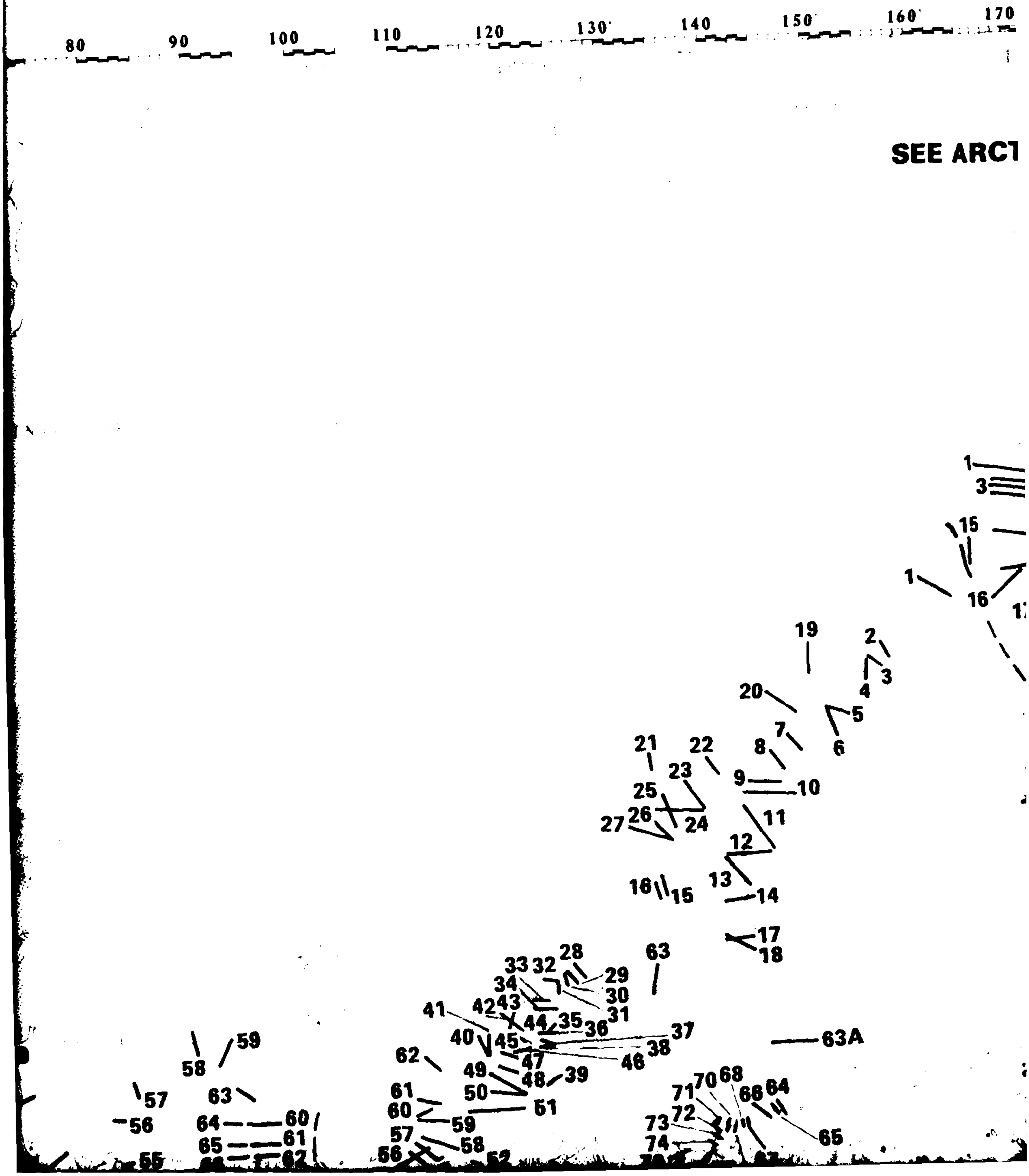
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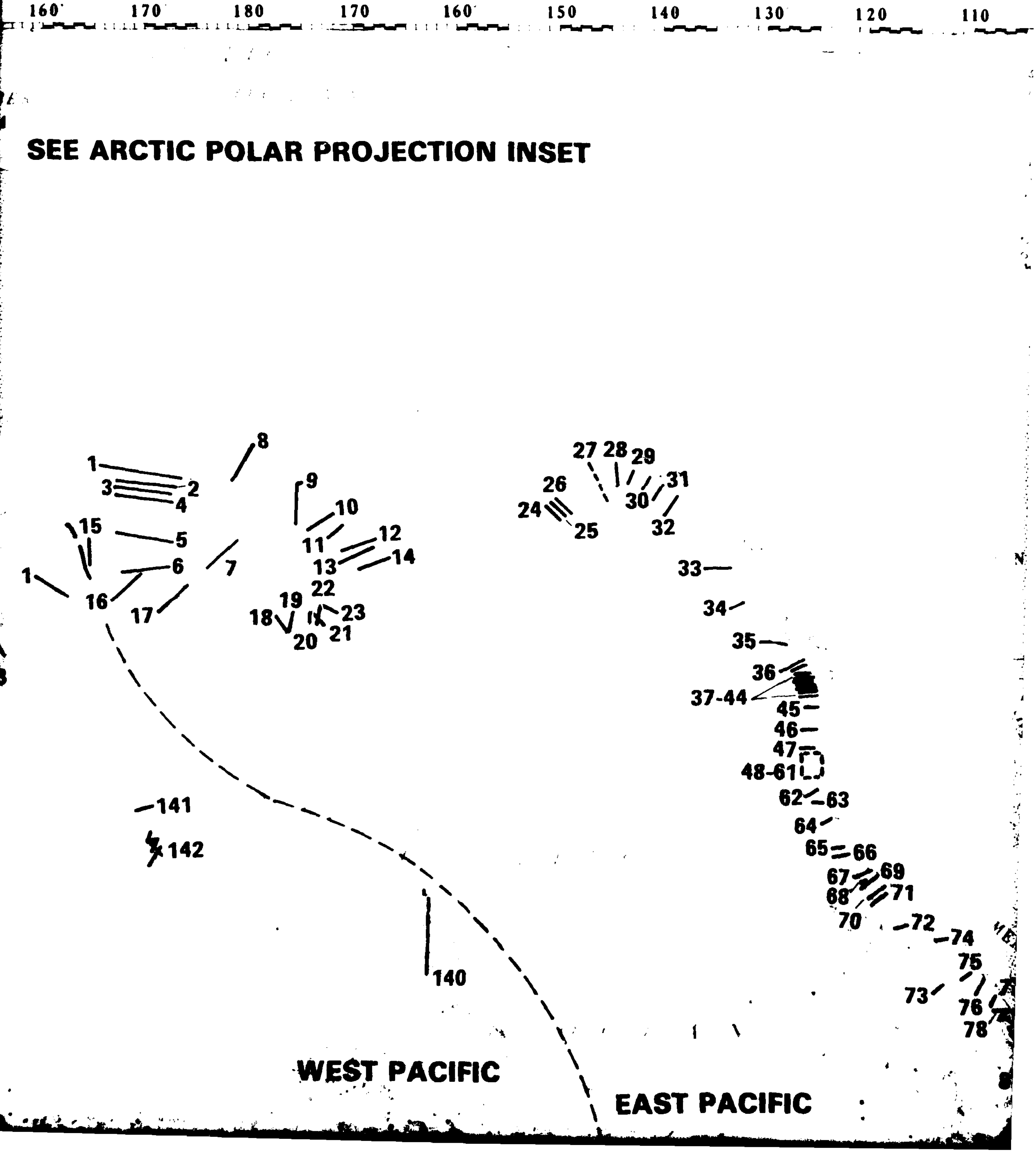

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SEE ARCTIC POLAR PROJECTION INSET
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48-61
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WEST PACIFIC
EAST PACIFIC

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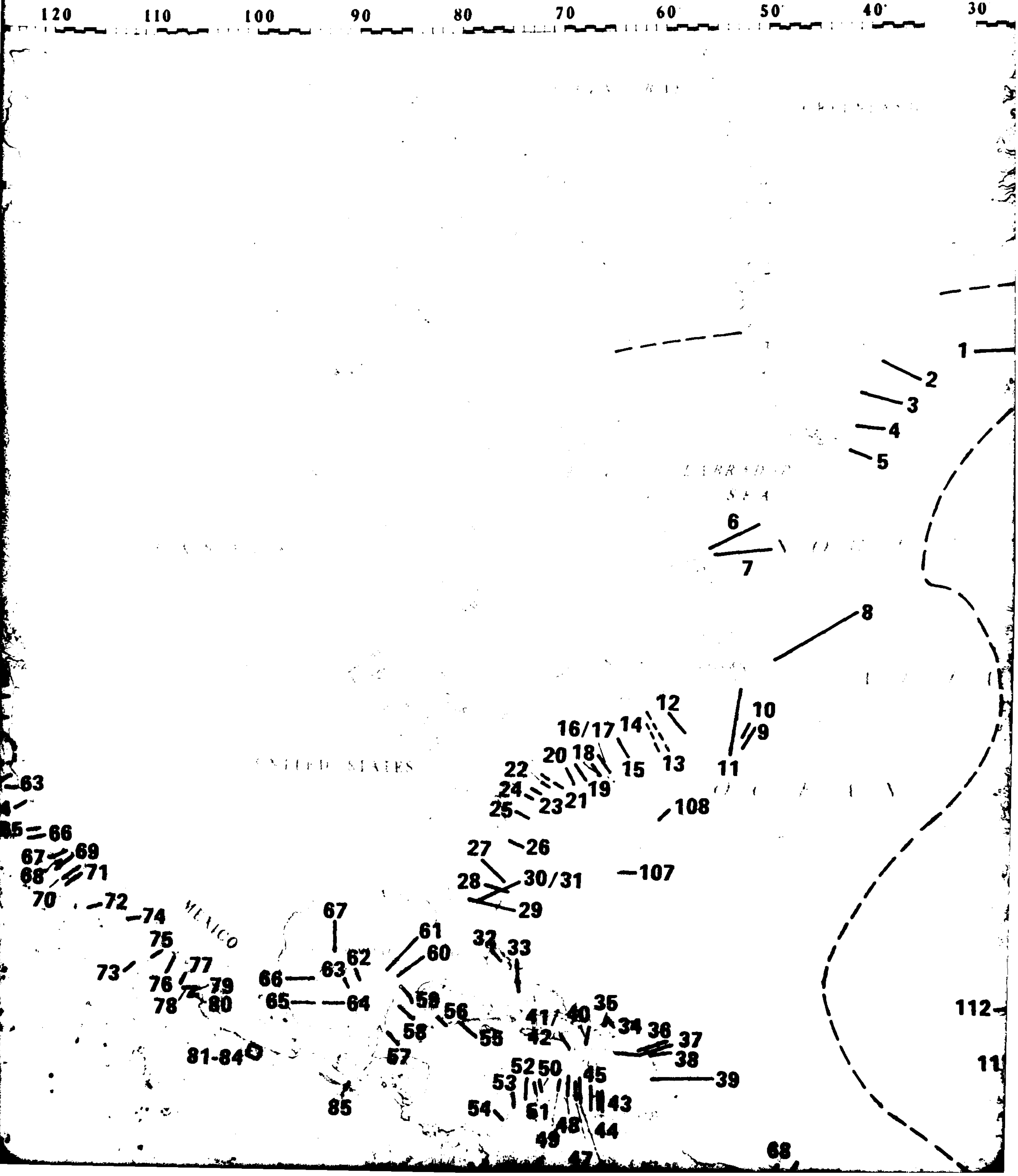
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MEXICO
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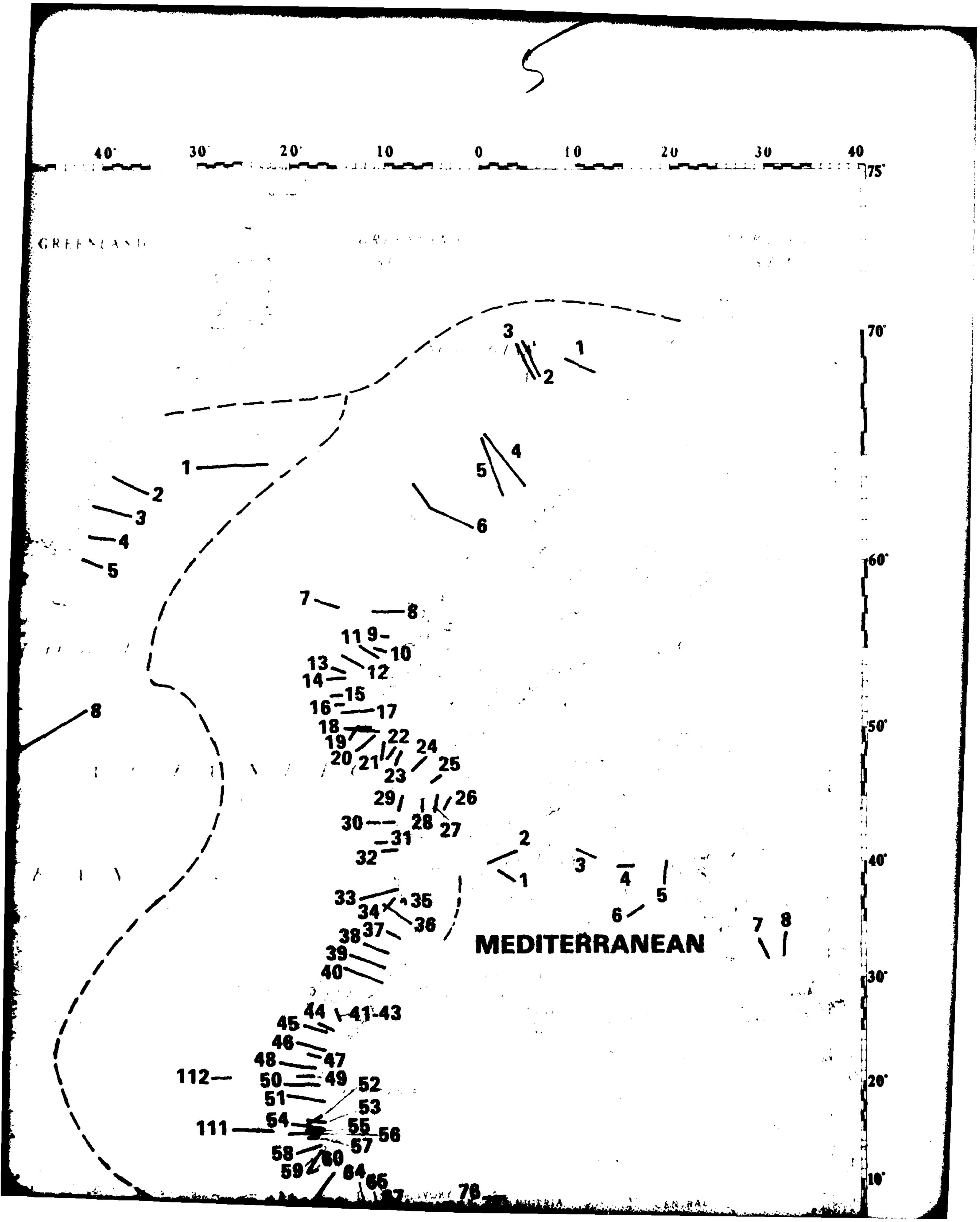
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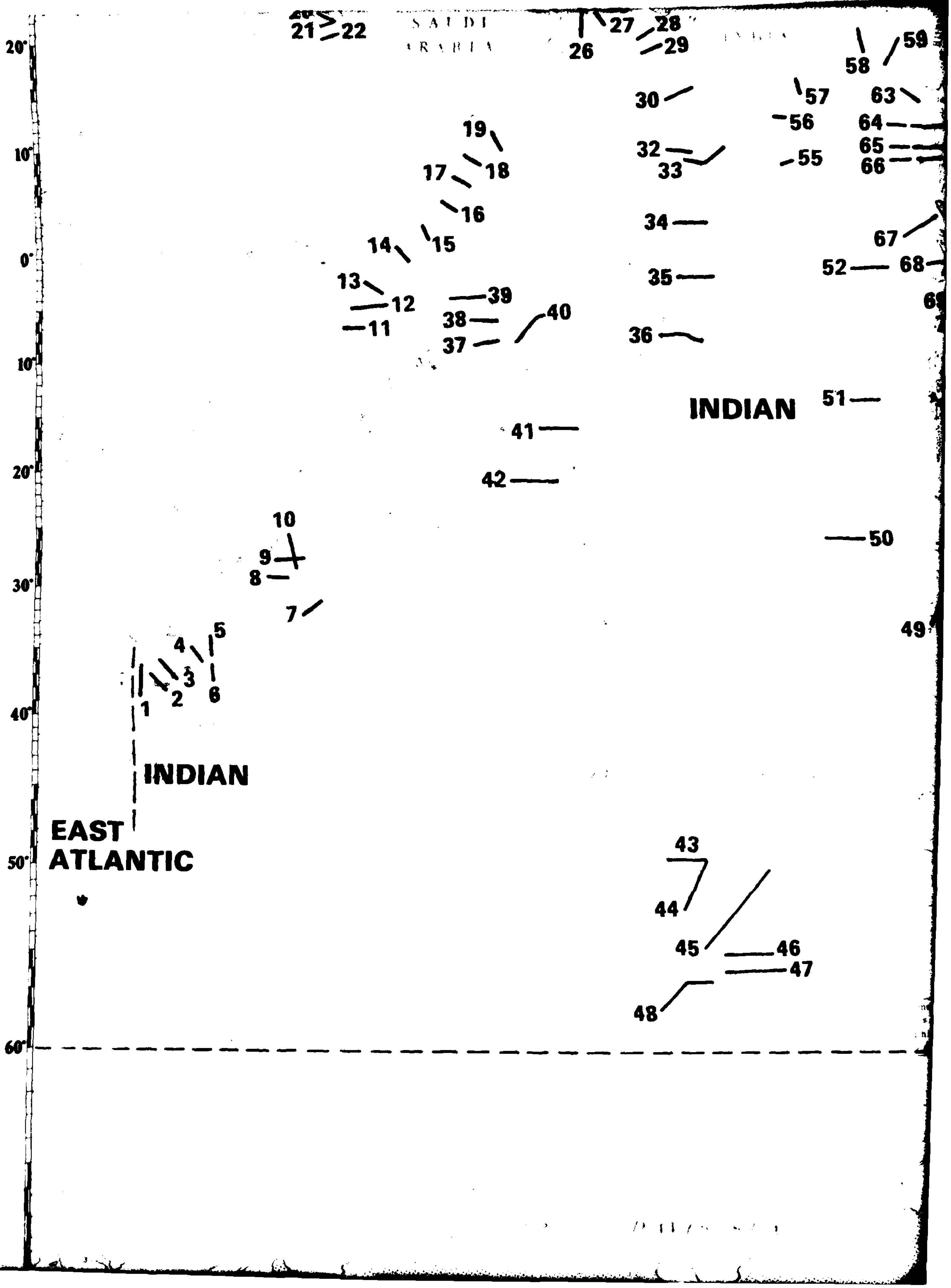
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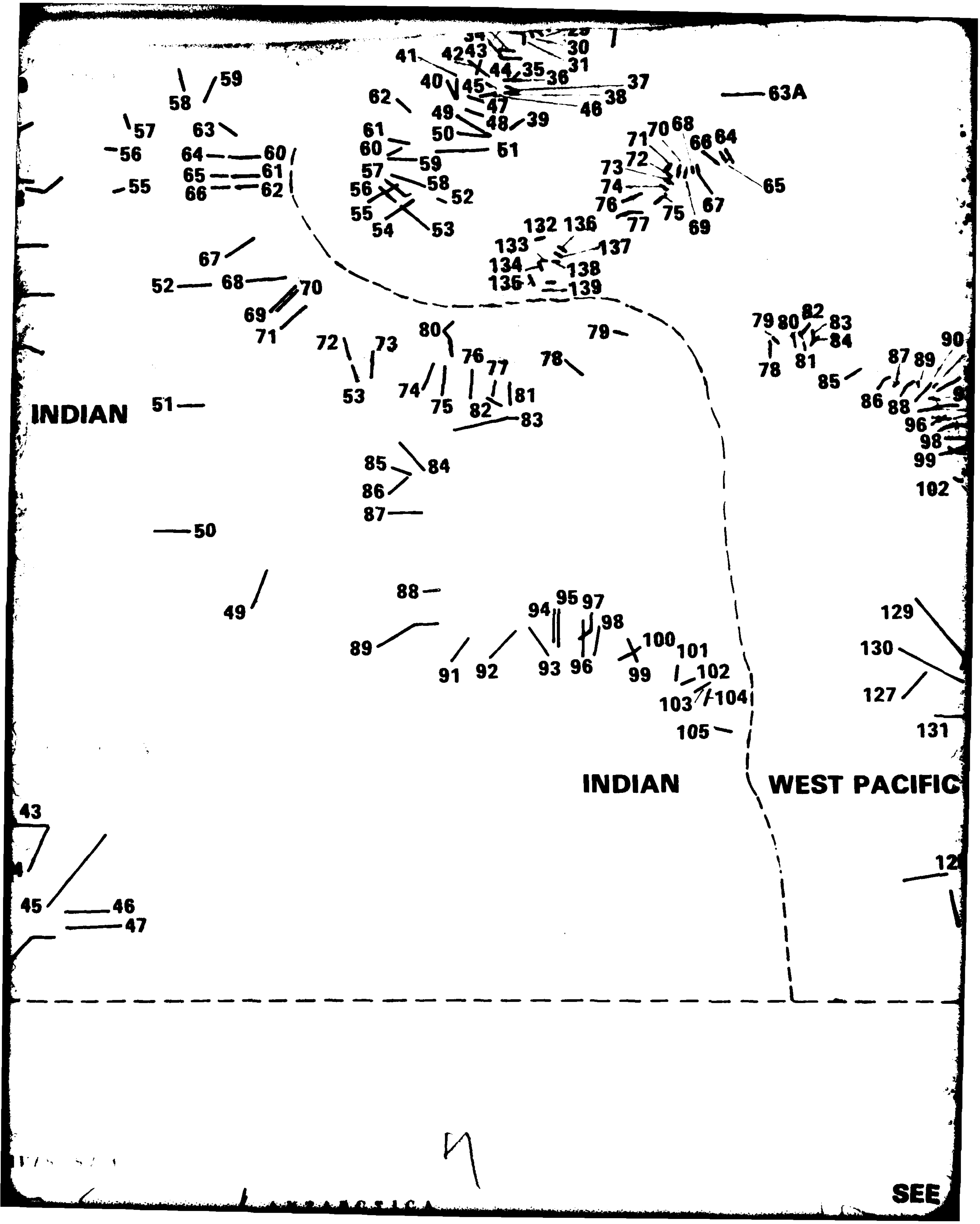

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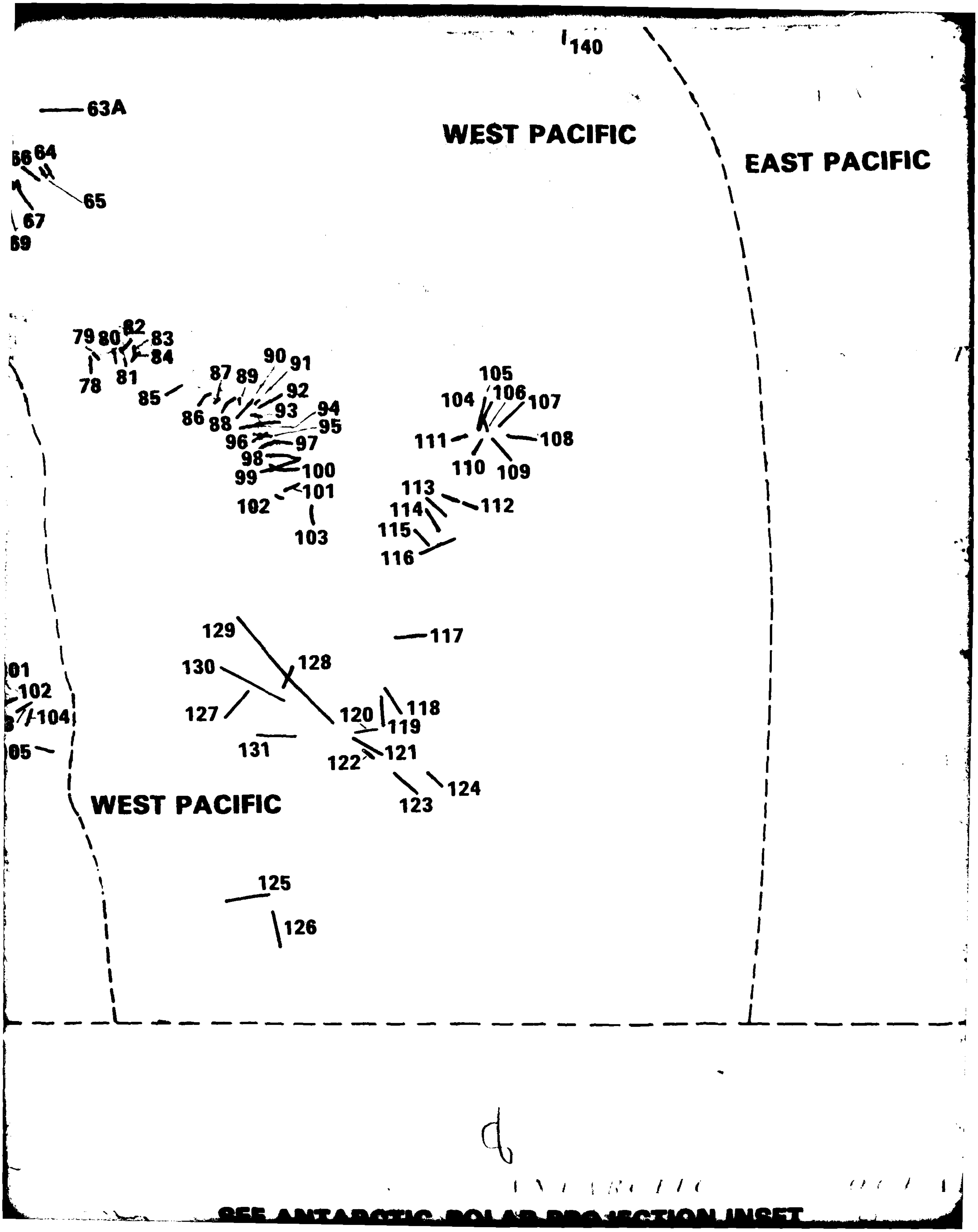

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WEST PACIFIC
EAST PACIFIC
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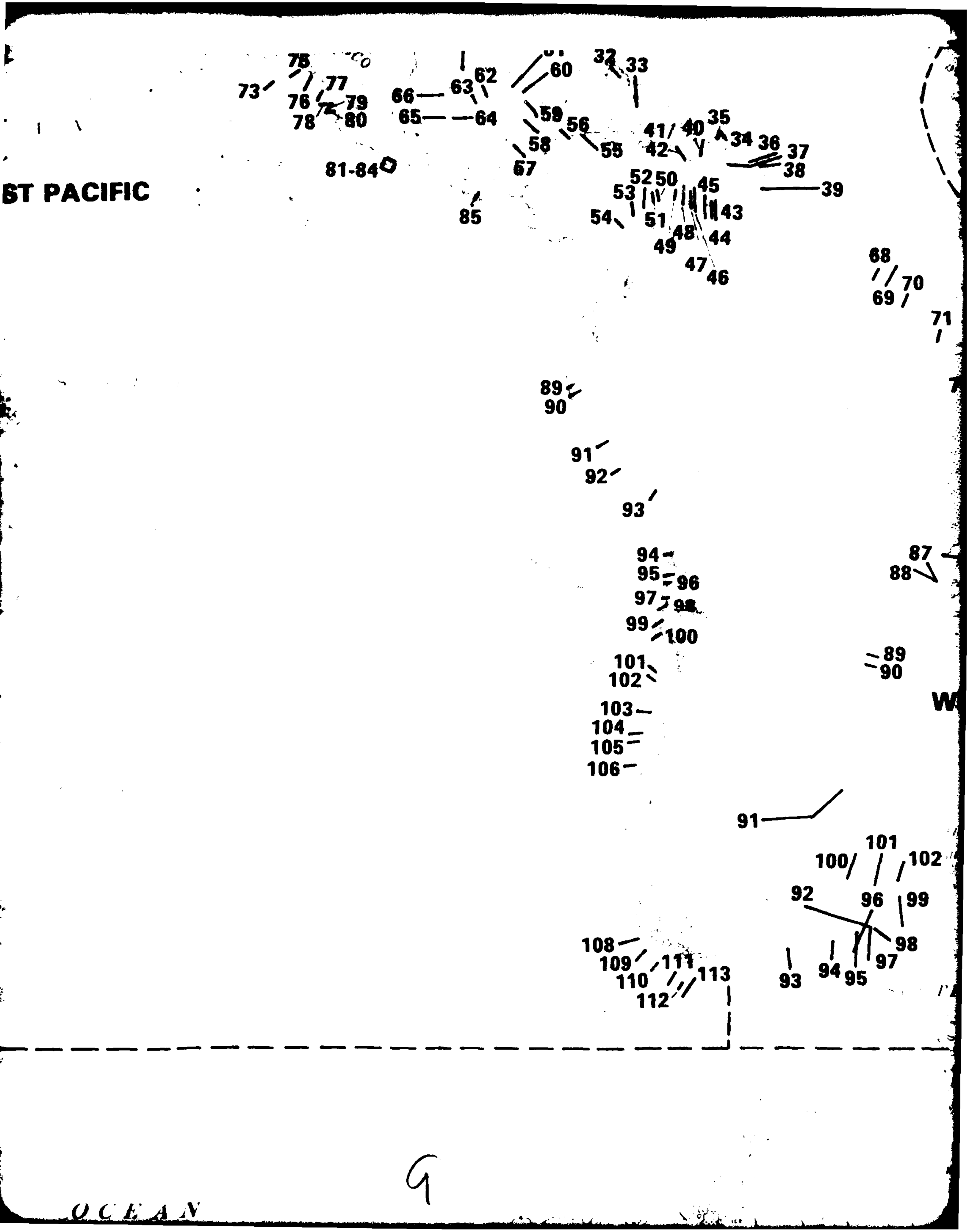
WEST PACIFIC
SEE ANTARCTIC POLAR PROJECTION INSET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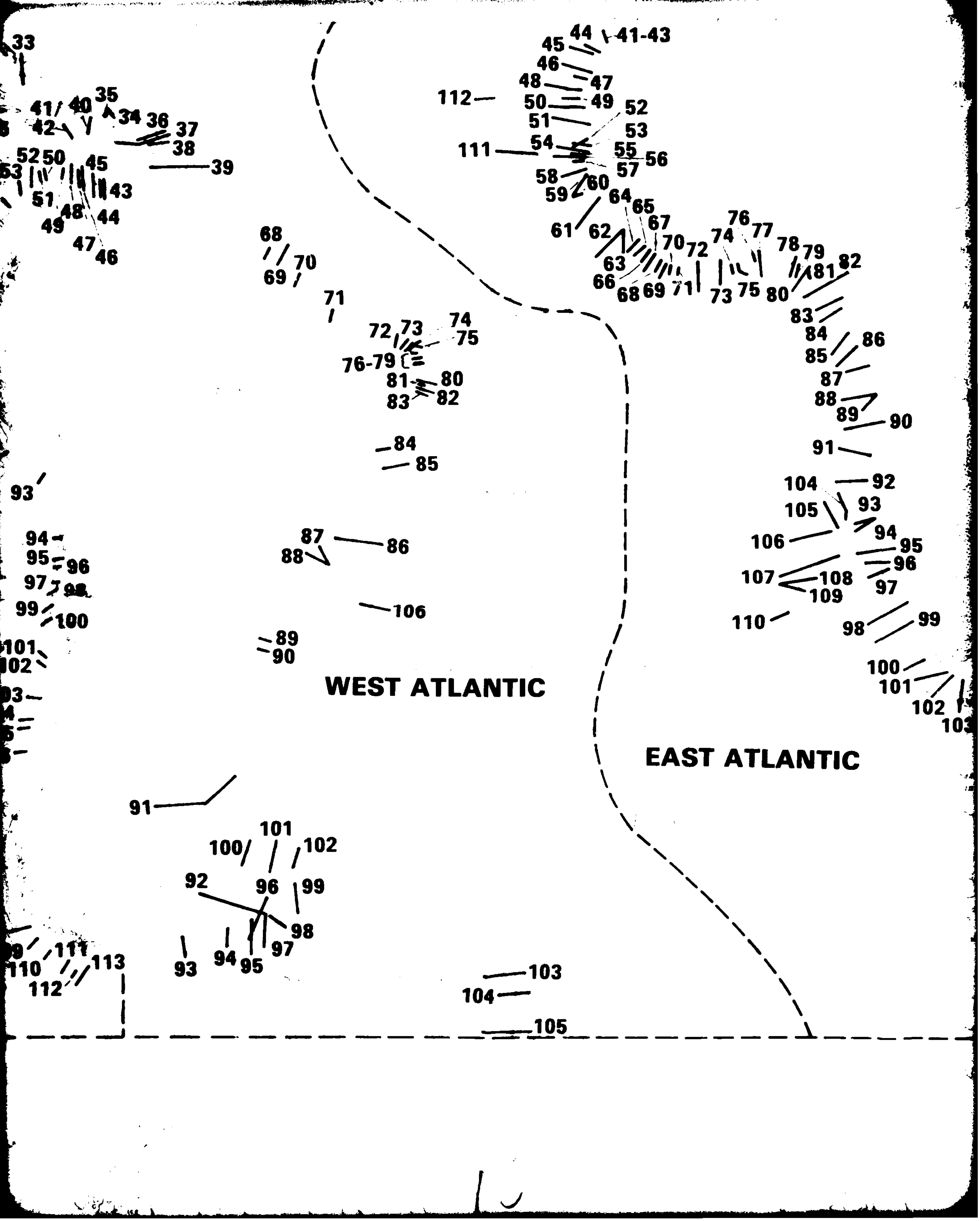

WEST ATLANTIC
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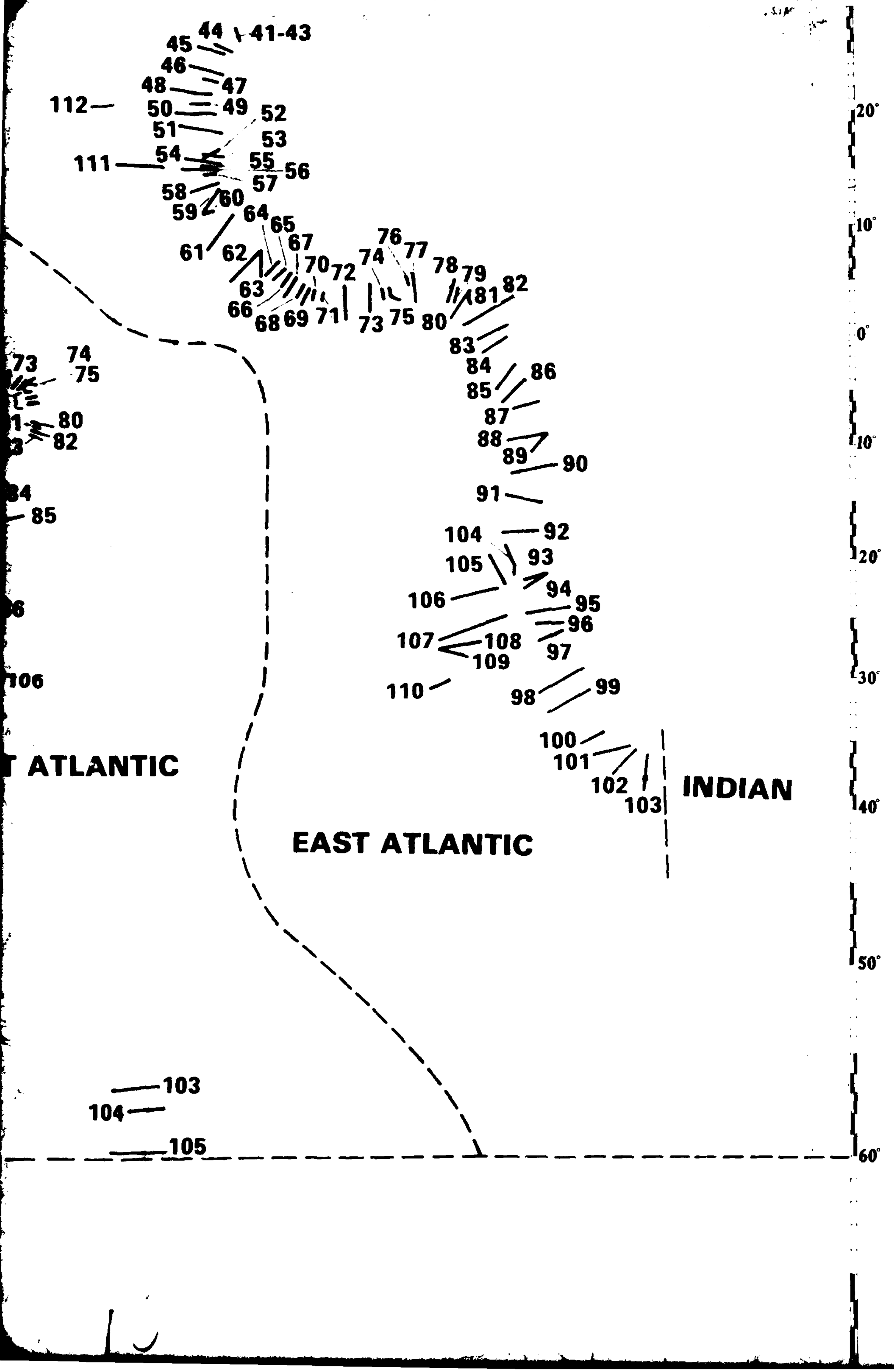
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INDIAN
EAST ATLANTIC
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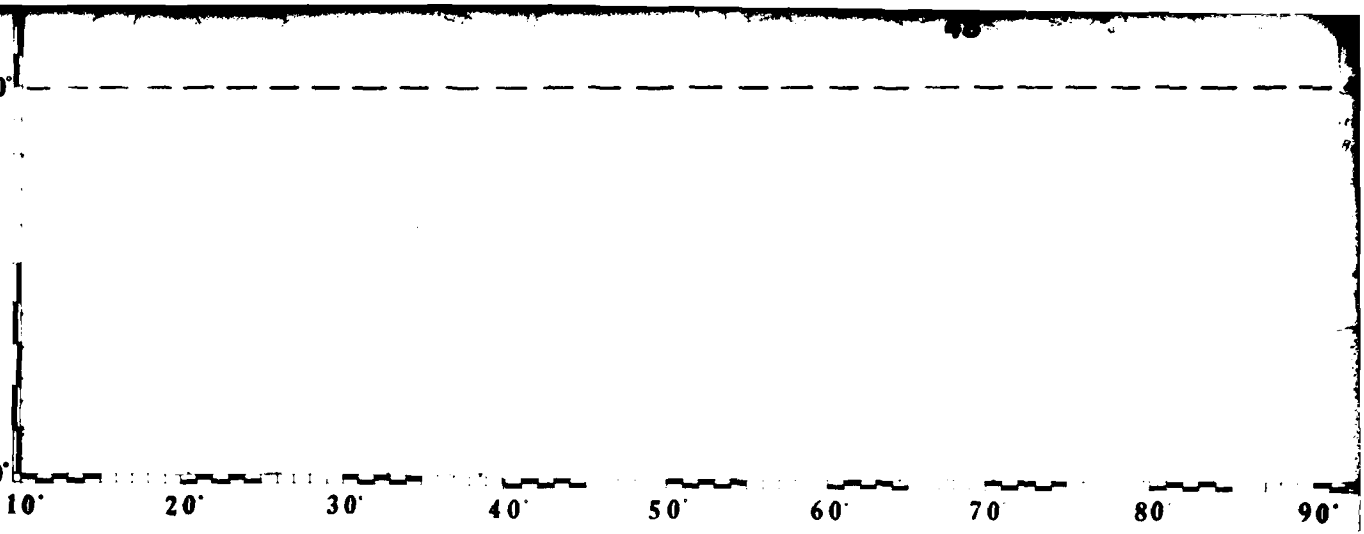
60°



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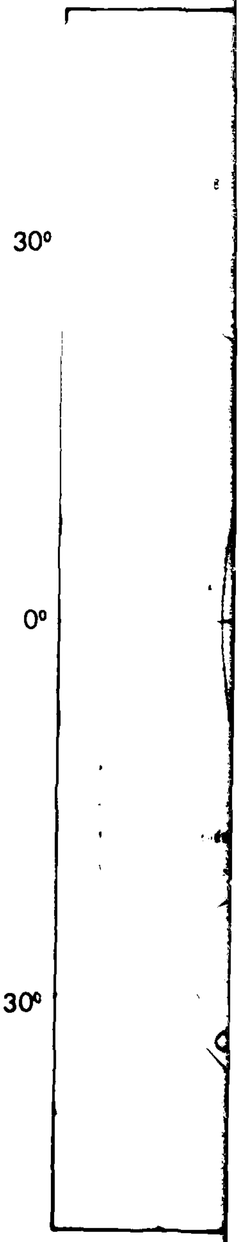

30°
0°
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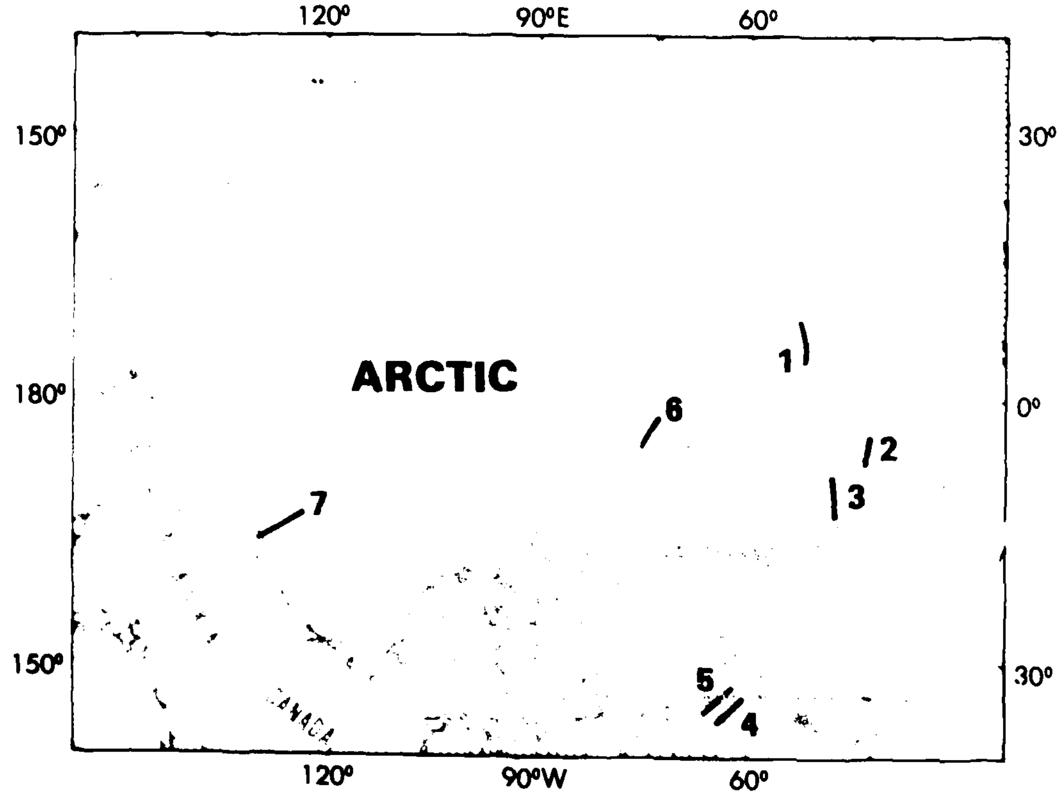

120°
90°E
60°
150°
180°
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30°
ARCTIC
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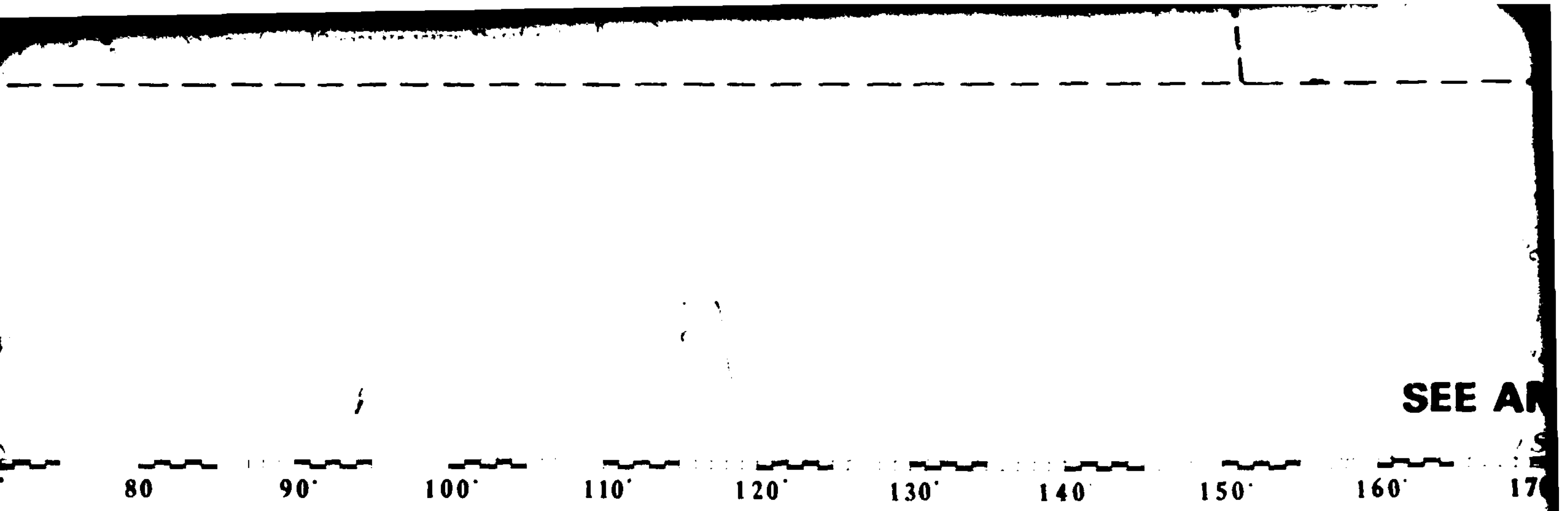
CANADA
120°
90°W
60°

17


SEE A
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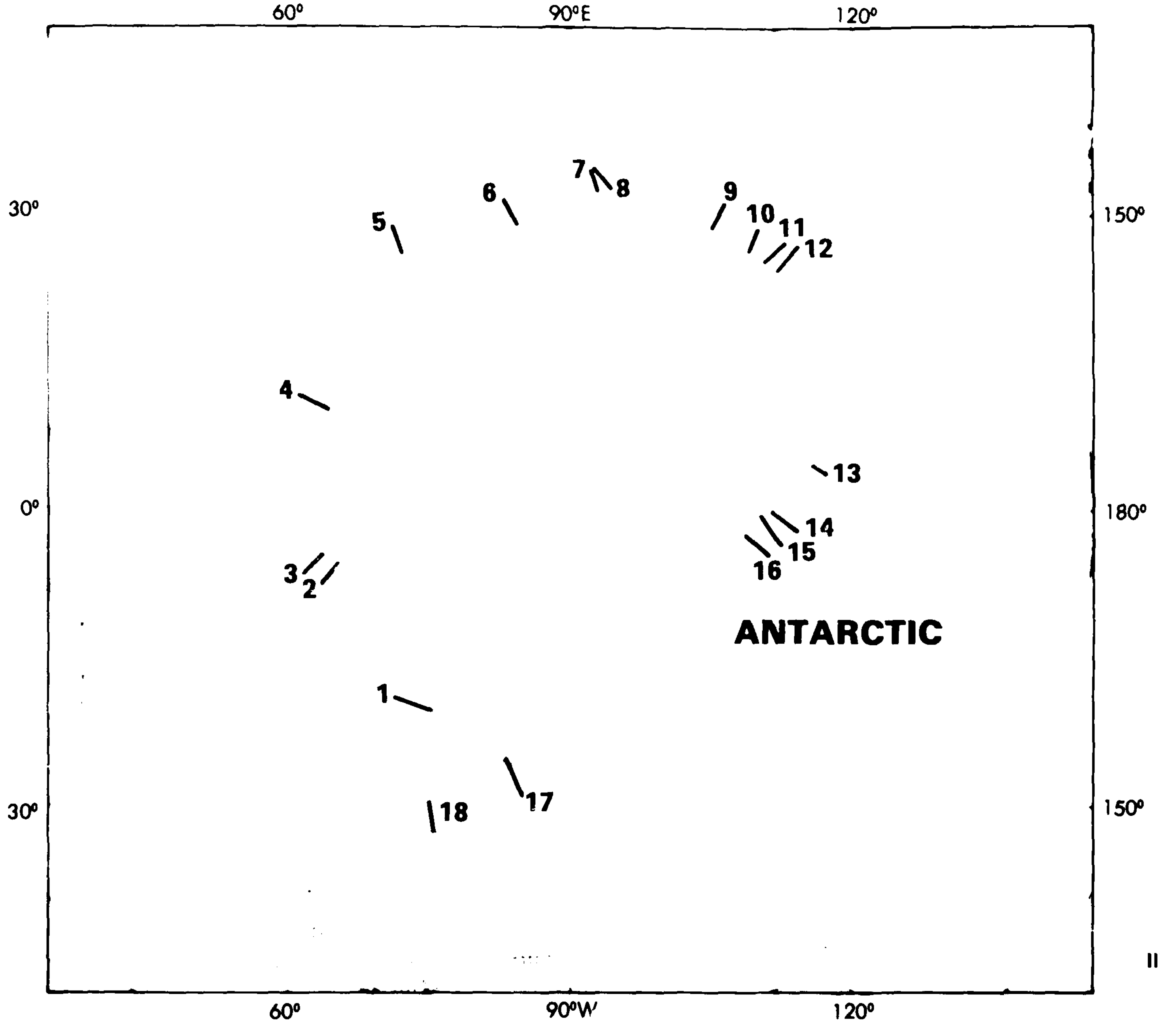
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ANTARCTIC

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13

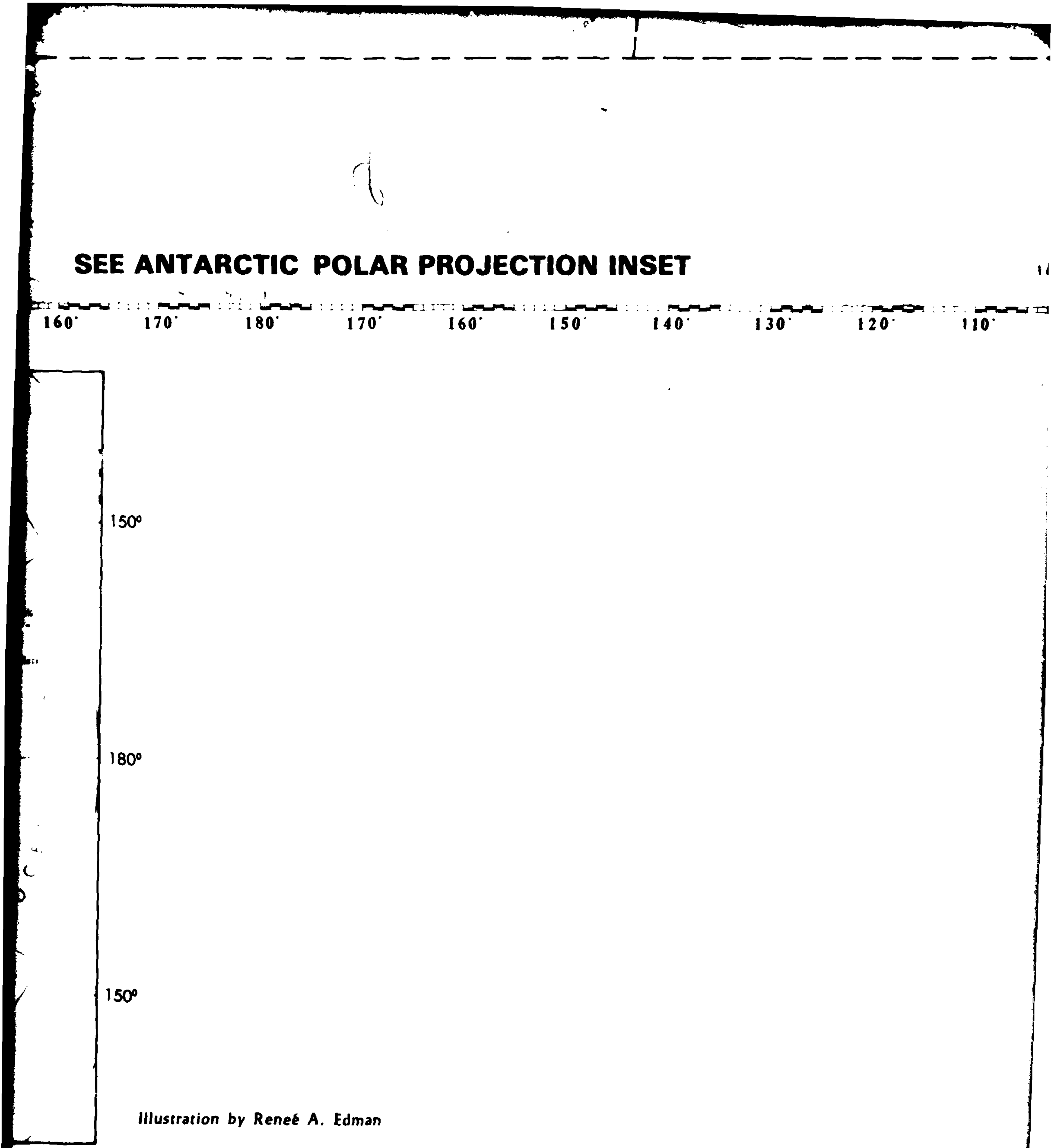


Illustration by Reneé A. Edman

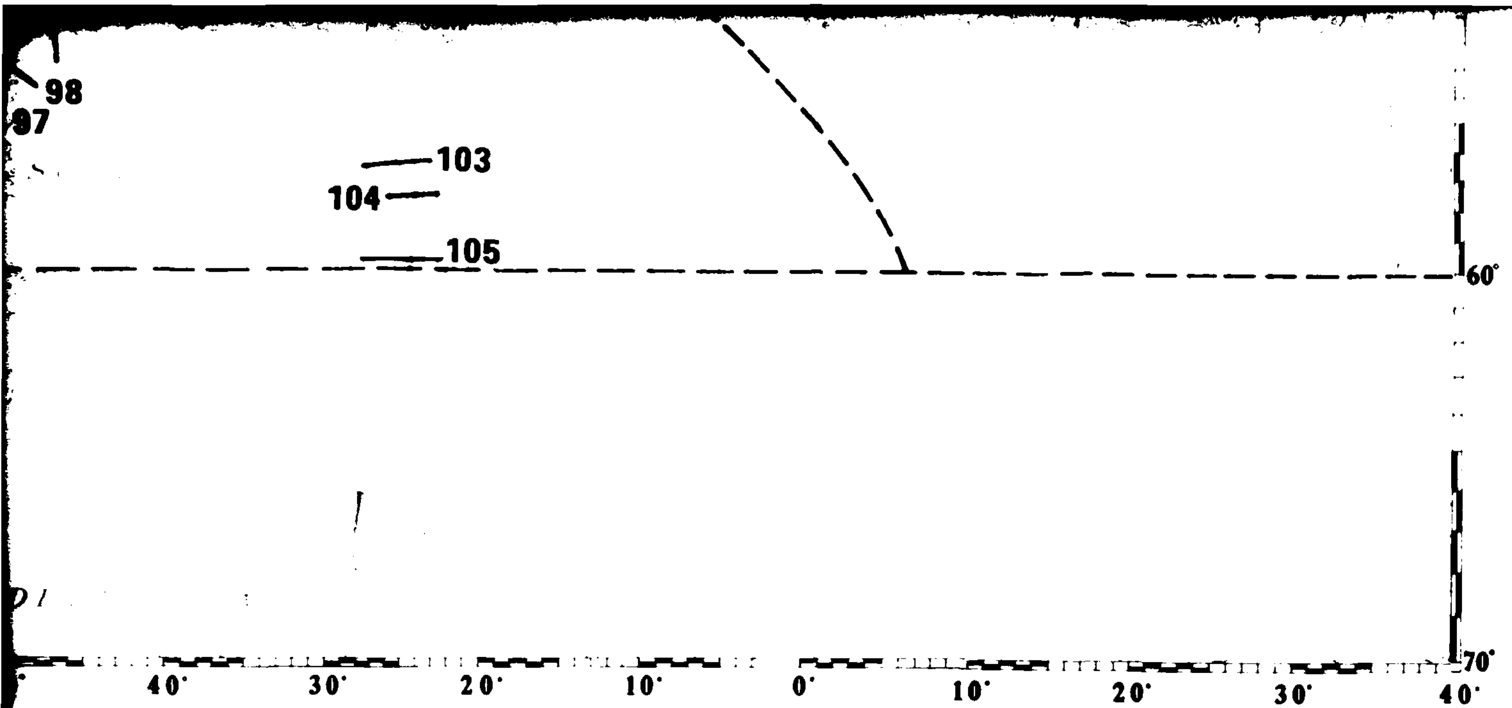
9

130° 120° 110° 100 90 80° 70° 60° 50° 40°

INDEX TO SLOPE PROFILES

(See Appendix II for profiles)

15



Map IV