AD-A061 312 MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF EARTH A--ETC F/G 8/6
PALEOBATHYMETRY AND SEDIMENTS OF THE INDIAN OCEAN, CHAPTER 2,(U)
1977 J G SCLATER, D ABBOTT, J THIEDE N00014-75-C-0291

UNCLASSIFIED NL

1 OF 1
AD
A061312

END
DATE
FILMED
2 - 79
DDC

[redacted]

(15)

Contract N00014-75-C-0291

(12)

(6)

CHAPTER 2. PALEOBATHYMETRY AND SEDIMENTS OF THE INDIAN OCEAN

(10) Chapter 2,

John G. Sclater

Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dallas Abbott[1]

Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Jörn Thiede
School of Oceanography, Oregon State University
Corvallis, Oregon 97331

(11) 1977

(12) 35p.

DDC FILE COPY AD A061312

DDC NOV 16 1978 F

Abstract. We establish a simple relation between subsidence and age for both normal ocean floor and the aseismic ridges in the Indian Ocean. This subsidence is accounted for by the cooling and contraction of the lithospheric plate as it moves away from a center of spreading. We use the relation between subsidence and age to construct paleobathymetric charts of the ocean for the early Oligocene (36 m.y.b.p.), the early Eocene (53 m.y.b.p.) and the late Cretaceous (70 m.y.b.p.). We conclude from these charts that the Indian Ocean between the middle Cretaceous and the Oligocene may have been separated by the Ninetyeast Ridge/Kerguelen Plateau complex and the Madagascar, Amirantes, Mascarene, Chagos complex into three basins which were not connected at depths below 2,000 m. We discuss the implications these complexes and the active mid-ocean ridge axis may have had for deep water circulation patterns in the Indian Ocean.

As an example of the application of these charts we use 19 drill sites to reconstruct the past history of the Calcite Compensation Depth (CCD) in the Indian Ocean. The average depth of this boundary shallows from more than 4,500 m at present to 4,000 m in the Oligocene and remains approximately constant till the Campanian. In the Wharton Basin it shallows in the Albian and Aptian. Major differences from the average in the Northern Arabian Sea and the Australia and Antarctic Basins can be accounted for by proximity to the continental shelf and the presence of bottom water in the Antarctic Circumpolar Current. We assume a constant CCD of 4,000 m for the rest of the Indian Ocean and compute the surface distribution of carbonate and clay sediments in the Oligocene. The shallowing of the CCD results in a marked reduction in the surface distribution of calcareous sediments between the present and

[1]Currently at Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964.

78 07 31 181

78 10 23 062

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

404 784

the Oligocene. The reason for such a dramatic diminution of carbonate sediments is not known.

Introduction

In the plate theory of tectonics, oceanic crust is created at a spreading center by the intrusion of hot magma. As this magma moves away from the spreading center it loses heat, cools and contracts. Plate models based on these simple concepts give an excellent match to the observed increase in depth with age of the oceanic crust (Parsons and Sclater, 1977). In general, the depth of the ocean floor increases from 2,700 ± 300 m at a spreading center to 5,800 ± 300 m in oceanic crust of early Cretaceous to late Jurassic age. The depth versus age relationship is a simple consequence of plate creation and there is no reason to believe that plate creation was any different in the late Cretaceous than now. Thus, if the past motions of the plates are known from mapping fracture zones, identifying magnetic lineations and DSDP site information, it is possible to predict the past bathymetry of the ocean floor as a function of time (Sclater and McKenzie, 1973; Berger and von Rad, 1972).

Unfortunately not all of the ocean floor has been created by the simple sea floor spreading process. There are major structural units called aseismic ridges some of which have not been created in this fashion. Further, many of these ridges have been found to have been topped by shallow water sediments early in their history. These structural units, of which the Chagos-Laccadive and Ninetyeast Ridges are the most prominent, abound in the Indian Ocean. A model for their subsidence history has to be developed before quantitative paleobathymetric charts can be constructed. The analysis of sediments recovered in DSDP holes has been invaluable in resolving the past history of these ridges. For example, sediments recovered from the Ninetyeast Ridge in the Indian Ocean are evidence that this feature was formed at sea level close to an active spreading center and that it has subsided at exactly the same rate as the oceanic crust to which it is attached (Sclater and Fisher, 1974; Pimm et al., 1974). This also holds true for ancient ridges from other oceans (Thiede, 1977; Detrick et al., 1977). If information is available, it is possible to predict in a quantitative fashion the past subsidence history of aseismic ridges.

To construct a series of paleobathymetric charts and then to use them to examine sediment facies changes through time it is necessary first to establish a consistent magnetic and biostratigraphic time scale. We start this paper by establishing such a time scale and follow by justifying the depth versus age relation we propose to use for normal ocean crust and the aseismic ridges. Then we present the tectonic history we propose to follow and from this history and the depth versus age relation we produce paleobathymetric charts for the Indian Ocean at 36, 53 and 70 m.y.b.p. As an example of the possible application of the relation between depth and age and these charts we examine the past history of the Calcite Compensation Depth (CCD) in the Indian Ocean as a function of time. We use this curve and the paleobathymetry to examine the variation with time of the surface distribution of calcareous and clayey sediments.

The tectonic history of the Indian Ocean is not well understood (see also Johnson et al., 1976). Many of the aseismic features of the ocean floor are as yet undrilled. Thus, the present study is mainly a semi-quantitative attempt to determine the depth of the major topographic features of the Indian Ocean with time followed by a speculative use of the CCD and these charts to predict past surface sediment distributions.

As the paper is mainly speculative we have concentrated in the text on the major points and have left the details of how the various charts were constructed to the appendices.

There are other major sedimentary problems in the Indian Ocean upon which the paleobathymetry will have some effect. Such problems include the explanation of the deep and shallow water Oligocene hiatus (Davies, et al., 1974) and the influence the past topography has upon the terrigenous input to the major basins. These specific questions are tackled by Davies and Kidd (this volume) in the following paper in this volume and only briefly alluded to in this manuscript.

Justification of the Chosen Time Scale

Sediments recovered in DSDP holes give information concerning the past history of the site. To relate this information to the general tectonics of the area it is necessary to have a biostratigraphic time scale and to know the relationship between this time scale and the ages predicted by the magnetic anomalies on the sea floor. For the biostratigraphic information we have used the Berggren and van Couvering (1974) time scale for the Tertiary and the preliminary time scale of Thierstein (1977) for the Cretaceous/Jurassic. Relating the biostratigraphic time scale to the magnetic anomaly information is more difficult. It is clear from deep sea drilling data in the Indian Ocean that the original Heirtzler et al. (1968) scale as modified by Larson and Pitman (1972) is inadequate due to large discrepancy in the Eocene and Paleocene (Site 213 from Sclater et al., 1974; Site 236 from Vincent, 1974; Vincent et al., 1974; and Sites 239 and 245 from Schlich et al., 1974a).

Sclater et al. (1974) have proposed a modification to the Heirtzler et al. (1968) magnetic scale which brings the age of the distinctive magnetic anomalies into better agreement with the sediment information from the DSDP holes. This modification has been questioned by both Larson and Pitman (1975) and Schlich (1975). Larson and Pitman (1975) argue in particular that Sites 239 and 10 in the South Atlantic indicate an older age for anomalies 31 through 34 than given by Sclater et al. (1974). However, at Site 239 the lowermost distinctive nannofossil horizon is Micula mura (Latest Maastrichtian) and not Tetralithus aculeus as cited in the original report (Larson and Thierstein, personal communication). Also we consider the location of Site 10 with respect to magnetic anomalies to be too poorly known to be considered as a basis for a time scale. Further, Site 211, which may well be on the quiet zone attributed to anomaly 33, has a basal sediment age of early to middle Campanian. This is significantly younger than that predicted by Larson and Pitman (1975, Figure 1). Clearly the relation between the magnetic and the late Cretaceous biostratigraphic time scales is still controversial. For the sake of consistency we have decided to use the Sciater et al. (1974) modification of the Heirtzler et al. (1968) scale because it involves no dramatic spreading rate change in the South Atlantic in the late Cretaceous.

ACCESSION for
NTIS White Section
DDC Buff Section
UNANNOUNCED
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. SPECIAL
A

The Depth of the Ocean Floor as a Function of Age

To determine the past bathymetry of the ocean floor it is necessary to establish a relation between depth and age for all portions of the ocean crust. To a first approximation the floor of the Indian Ocean can be separated into typical ocean crust and aseismic ridges (Figure 1). In this section we compare the depth versus age data for the Indian Ocean with that found in other oceans and we develop a subsidence model for the aseismic ridges.

78 07 31 181
78 10 23 060

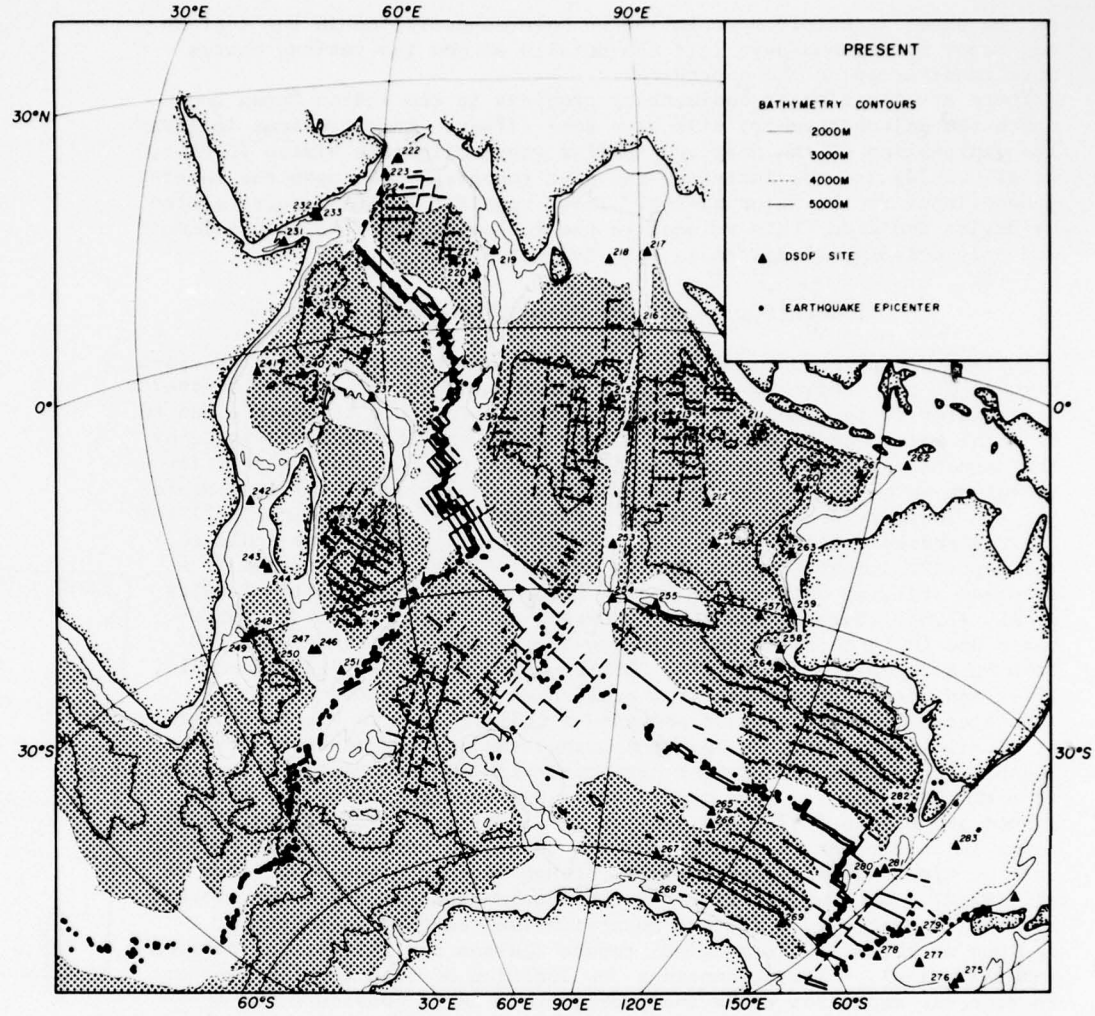

Fig. 1. A plot of JOIDES Deep Sea Drilling Sites on a bathymetric and tectonic chart of the Indian Ocean. Bathymetric contours from the new Russian Atlas of the Indian Ocean. Magnetic lineations are from McKenzie and Sclater (1971); Weissel and Hayes (1972); Sclater and Fisher (1974); and Schlich (1975). The shaded areas represent depths greater than 4000 m.

Typical Ocean Crust

We have defined typical oceanic crust as that produced by the normal sea floor spreading process. In the Indian Ocean we contrast it with the aseismic ridges which show up as distinct regions of shallow topography on the bathymetric chart (Figure 1). We have listed all the sites on normal ocean floor which penetrated basement (Table 1) and computed the isostatically corrected depth and biostratigraphic age of the basal sediments. We plotted the depths as a function of age and compared these depths with that expected for normal ocean crust (Figure

TABLE 1. Depth and Age Relation for Sites on Normal Ocean Crust

Site	Latitude	Longitude	Depth (m)	Sediment Thickness	Sediment Correction* (m)	Topographic Relief Correction	Mean corrected Depth+ (m)	Contact	Fossil Zones
211	09°46.53'S	102°41.95'S	5528	428.5	259	-	5787	excellent	Eiffellithus augustus zone
212	19°11.34'S	99°17.84'E	6240	516	287	-240	∿6287	excellent	Nephrolithus frequens zone [0] in lowermost chalk
213	10°12.71'S	93°53.77'E	5609	154	97	-100	5606	excellent	Discoaster mohleri zone [0], not older than Planorotalites pseudomenardii zone (P4)
215	8°07.30'S	86°74.50'E	5319	155.5	99	-	5428	excellent	Fasciculithus tympaniformis zone; Morozovella pusilla, M. angulata (P3), Planorotalites pseudomenardii (P4) zone
220	6°30.97'N	70°59.02'E	4036	329	210	-	4246	excellent	Morozovella aragonensis (P8) zone, Discoaster lodoensis zone
221	7°58.18'N	68°24.37'E	4650	261	170	-	4820	excellent	Chiasmolithus grandis (13-P14) ? zone
231	11°53.41'N	48°14.71'E	2152	566.5	357	-	2509	excellent	Discoaster exilis-Sphenolithus heteromorphus zone, Globorotalia fohsi (N12) zone
235	03°14.06'N	52°41.64'E	5130	651.5	450	-	5580	poor but sediment in basalt	Micula mura zone
236	01°40.62'S	57°38.85'E	4487	306	198	-	4685	excellent	Discoaster mohleri zone, Planorotalites pseudomenardii (P4) zone
238	11°09.21'S	70°31.56'E	2832	506	310	+700	3842	excellent	Sphenolithus predistentus zone, Pseudohastigerina barbadoensis (P19) zone
239	21°17.67'S	51°40.73'E	4971	320	223	-	5194	excellent contact poor fossils	Tetralithus aculeus zone
240	03°29.28'S	50°03.42'E	5082	190	126	-	5208	fair	Discoaster multiradiatus zone, Morozovella subbotinae - M. wilcoxensis (P16) zone
245	31°32.02'S	52°18.11'E	4857	389	245	-	5102	excellent	Chiasmolithus danicua (NP3) zone, Globoconusa daubjergensis (P1) zone)
248	29°31.78'S	37°28.48'E	4994	422	273	-	5267	excellent	Cyclococcolithus formosus, probably somewhat older than NP12
250	33°27.74'S	39°22.15'E	5119	725	498	-	5617	excellent contact but fossils 15m above basalt	Marthasterites furcatus zone, Inoceramus sp.
251	36°30.26'S	49°29.08'E	3489	487	296	-	3785	excellent contact	Sphenolithus heteromorphus (NN5) zone, Globorotalia peripheroroda (N4-N8) zone
256	23°27.35'S	100°46.46'E	5361	251	172	-350m*	∿5700	excellent contact	Eiffellithus turriseiffeli zone
257	30°59.16'S	108°20.00'E	5278	262	186	-	5464	excellent contact but fossils 15m above basalt	Prediscosphaera cretacea zone
259	29°37.05'S	112°41.78'E	4696	304.3	200	-	4896	excellent contact	Crybelosphirites stylosus zone
260	16°08.67'S	110°17.92'E	5702	323.0	219	-	5921	excellent contact	Prediscosphaera cretacea zone
261	12°56.83'S	117°53.56'E	5667	542.0	353	-	6020	excellent contact	Stephanolithion bigoti zone
265	53°32.45'S	109°56.74'E	3582	444.5	324.5		3906	excellent contact	Denticula hustedtii/C. lanta zone
266	56°24.13'S	110°06.70'E	4167	370	291		4358	excellent contact	Discoaster deflandrei, Sphenolithus moriformis zone, Catapsydrax unicavus zone
267	59°14.55'S	104.29.94'E	4495	314	229		4724	excellent contact	Globigerina linaperta (P15-P16) zone

* Topography correction dominant. + The isostatic loading of the sediments is corrected for by the method of Sclater et al., 1971, Appendix III, $\rho s = 1.8$ g/cm^3

TABLE 1. Depth and Age Relation for Sites on Normal Ocean Crust (Cont.)

Fossil Zones	Extrapolated age (Relative)	Numerical m.y.b.p.	Magnetics Anomaly No.	Magnetics Age m.y.b.p.	Comments
Eiffellithus augustus zone	Early-Middle Campanian	74-82	>33b	?	Wharton Basin 120 km southeast of anomaly 33b
Nephrolithus frequens zone [0] in lowermost chalk	Late Cretaceous	84-110	>33b	?	On extension of Investigator Fracture Zone
Discoaster mohleri zone [0], not older than Planorotalites pseudomenardii zone (P4)	Late Paleocene	55-58	25-26	59	East of Ninetyeast Ridge
Fasciculithus tympaniformis zone; Morozovella pusilla, M. angulata (P3), Planorotalites pseudomenardii (P4) zone	Late Paleocene	58-60	-	-	West of Ninetyeast Ridge
Morozovella aragonensis (P8) zone, Discoaster lodoensis zone	Early Eocene	50-52	-	-	Western Flank of Chagos Laccadive Ridge
Chiasmolithus grandis (13-P14) ? zone	Middle Eocene	43-51	19-20?	44-46?	Arabian Abyssal Plain
Discoaster exilis-Sphenolithus heteromorphus zone, Globorotalia fohsi (N12) zone	Middle Miocene	14-17	-	-	Arabian Sea
Micula mura zone	Late Maastrichtian	65-68	-	-	50 km east of Chain Ridge
Discoaster mohleri zone, Planorotalites pseudomenardii (P4) zone	Late Paleocene	56-58	26-27	-	North of Seychelles
Sphenolithus predistentus zone, Pseudohastigerina barbadoensis (P19) zone	Early Oligocene	30-35	-	-	Northeast end of Argo Fracture Zone
Tetralithus aculeus zone	Maastrichtian to Late Campanian	65-76	end of 31	69	Mascarene Basin
Discoaster multiradiatus zone, Morozovella subbotinae - M. wilcoxensis (P16) zone	Late Paleocene	53-57	-	-	Somali Basin
Chiasmolithus danicus (NP3) zone, Globoconusa daubjergensis (P1) zone	Early Paleocene	59-64	29-30	64-66	Mascarene Basin
Cyclococcolithus formosus, probably somehwat older than NP12	Late Paleocene to Early Eocene	50-60	-	-	In Madagascar Basin 50 km east of Mozambique Ridge
Marthasterites furcatus zone, Inoceramus sp.	Santonian-Coniacian	>82-87	-	-	In Madagascar Basin
Sphenolithus heteromorphus (NN5) zone, Globorotalia peripheroroda (N4-N8) zone	Early Miocene	16-22	-	-	North flank of Southwest Indian Ridge
Eiffellithus turriseiffeli zone	Late Albian	95-98	-	-	South Wharton Basin near tongue of Broken Ridge
Prediscosphaera cretacea zone	Middle Albian	94-102	-	-	Southeast Wharton Basin, N.G. of Naturaliste Plateau
Crybelosphirites stylosus zone	Aptian	102-107	-	-	Off westcoast of Australia
Prediscosphaera cretacea zone	Albian	94-102	-	-	Gascoyne Abyssal Plain
Stephanolithion bigoti zone	Late Oxfordian	151-155	M23	150	Argo Abyssal Plain
Denticula hustedtii/C. lanta zone	Late to Middle Miocene	10-22-5	5-5b	10-15	Australia Antarctic Ridge (Area C)
Discoaster deflandrei, Sphenolithus moriformis zone, Catapsydrax unicavus zone	Early Miocene	16-23	6-7	20-5-26	Australia Antarctic Ridge (Area C)
Globigerina linaperta (P15-P16) zone	Late Eocene	38-44	?	?	Australia Antarctic Ridge (Area C)

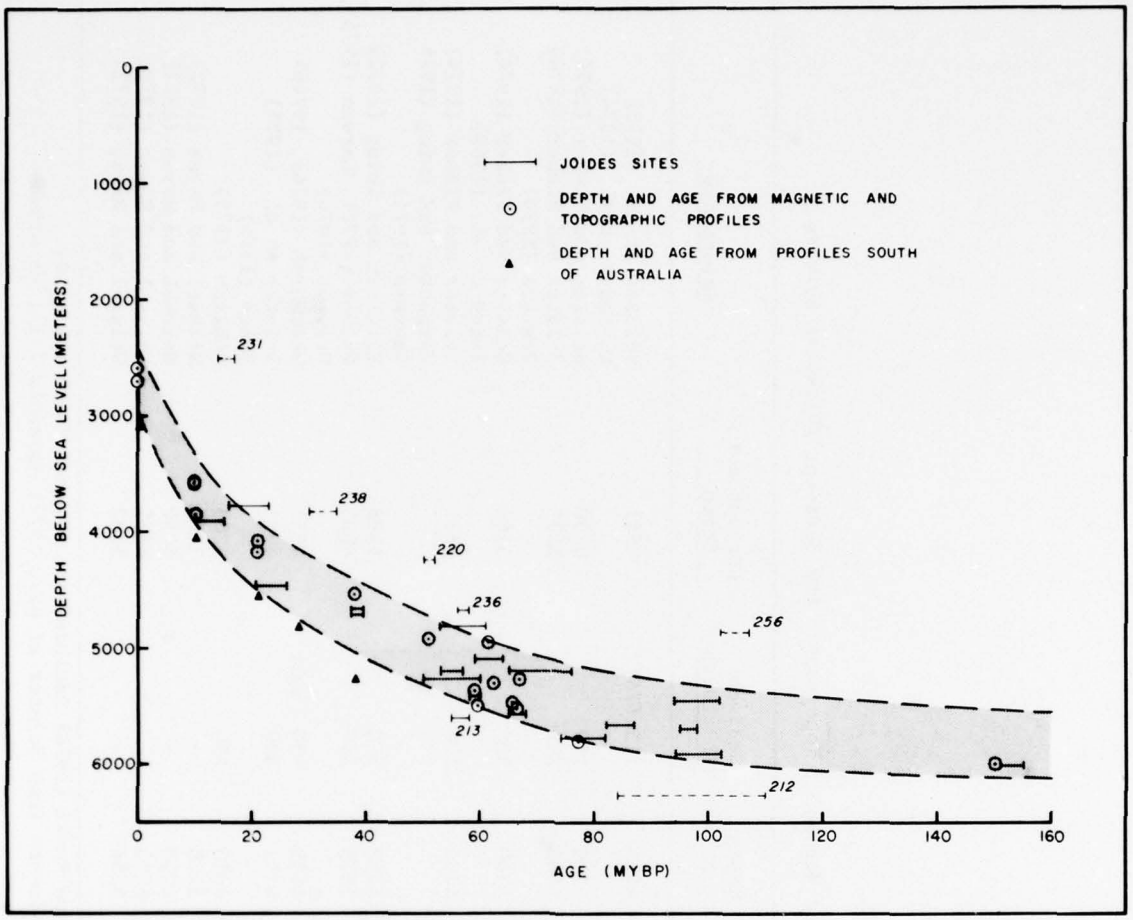

Fig. 2. The relationship between depth and age in the Indian Ocean for topographic profiles over oceanic crust with identified magnetic lineations and for JOIDES Sites on normal ocean crust. The two dashed lines are 600 m apart and represent the scatter in the data for the depth versus age relation shown by most oceanic crust (Parsons and Sclater, 1977). Sites which do not fall within these lines have been identified.

2). We also superimposed upon this plot the depth versus age data for the spreading center crests and anomalies 5, 6, and 25 from Sclater et al., 1971. Further, on the basis of topographic and seismic information collected along the track of the GLOMAR CHALLENGER and published topographic, magnetic, and seismic surveys, we added fourteen depth/age points to those originally computed by Sclater et al. (1971) (Table 2). These depths, except for one point south of Australia, all fall within the depth versus age relationship expected for normal ocean crust. Only 7 out of 43 DSDP holes do not fall within the expected relationship for depth and age. Of these 7 there are excellent reasons why 5 fall out of the range. Starting with the younger of these anomalous sites, Site 231 is in the Gulf of Aden and close to the African continental margin. Site 238 is virtually on a fracture zone close to the foot of the Chagos-

TABLE 2. Depth and Age from Magnetic, Topographic and Sediment Thickness Surveys.

Region	Anom. No.	Age m.y.	Depth m	Sediment Thickness	Corrected + Depth	References
Southeast Indian Ridge	14-16	36-40	4465	115 (76)	4541	Sclater et al. (1976) Luyendyk et al. (1974)
Wharton Basin (22-3)	27	62.5	5200	150	5300	Sclater and Fisher (1974)
Wharton Basin (22-4)	30	66.5	5400	200	5533	Sclater and Fisher (1974) Veevers (1974)
Wharton Basin (22-3a)	25-26	59-60	5300	300	5500	Sclater and Fisher (1974) Ewing et al. (1969)
Wharton Basin	33	76	5750	100	5816	Sclater and Fisher (1974) Carpenter and Ewing (1974 Veevers (1974)
Central Indian Basin	31	67	5168	500	5498	Eittreim and Ewing (1972)
Argo Abyssal Plain	M-23	150	5675	550	6005	Falvey (1972), Larson (1975), Veevers (1974)
Arabian Sea	21	51	4635	450 (300)	4935	Whitmarsh (1974a, 1974b)
North of the Seychelles	26-27	60-63	4751	300	4951	Sclater et al. (1971) Bunce (1974)
Mascarene Basin	30	67	4983	450	5283	Schlich (1975)
Australia-Antarctic Ridge	0	0	3100	-	3100	Weissel and Hayes (1972)
	5	9-10	4050	-	4050	Weissel and Hayes (1972)
	8	27-29	4835	-	4835	Weissel and Hayes (1972)
	13	37-39	5280*	-*	5280	Weissel and Hayes (1972)

* Sediment thickness from figure 5 of Houtz and Markl (1972) included in original depth estimate.
\+ Depth adjusted for isostatic loading of sediments (see Sclater et al., 1971; Appendix III), ρs assumed $= 1.8\ g/cm^3$.

Laccadive Ridge. Site 220 is on the western flank of the same ridge. Site 212 is too deep because it is located in an extension of the Investigator Fracture Zone (Sclater and Fisher, 1974; Figure 1). Site 256 lies on a topographic spur which trends in a northeasterly direction away from Broken Ridge. It is not surprising that it is too shallow (Sclater and Fisher, 1974; Figure 1). Support for the anomalous nature of this site comes from the chemical composition and concentration of rare earth elements which suggest the basalt has more affinities to Sites 214 and 216 on the Ninetyeast Ridge than other sites in the Wharton Basin (Frey et al., this volume). There are two sites which are unexpectedly different from normal ocean crust. Site 236 is on a topographic bulge north of the Seychelles, which shows up very clearly on the 1964 Russian chart of the Indian Ocean (Anonymous, 1964). Site 213 which is located in a wide northeast-southwest trough between the Ninetyeast Ridge and the Cocos-Keeling Island complex (Figure 1 from Sclater and Fisher, 1974) is too deep. The explanation of these troughs which trend in a different direction to the other prominent features in the Wharton Basin is unknown.

In general the depth versus age data from the Indian Ocean is similar to that observed in the Pacific and Atlantic. Thus we have confidence from this data that we can construct paleobathymetric charts with the depth versus age relation of the Pacific and Atlantic.

DSDP Holes on Aseismic Ridges

One of the dominant features of the Indian Ocean which contrasts it with the central and southern Atlantic and the central and eastern Pacific is the large number of aseismic ridges. Their past tectonic history is critically important to determining the paleobathymetry of this ocean. The major aseismic features are Broken Ridge, the Ninetyeast and Chagos-Laccadive Ridges, the Mascarene Plateau, the Madagascar Ridge and Crozet and Kerguelen Plateaus (Figure 1). Five sites (214, 216, 217, 253, and 254) were drilled on the Ninetyeast Ridge and one each on the Chagos-Laccadive Ridge (219), Mascarene Plateau (237), Madagascar Ridge (246), Mozambique Ridge (249), and Broken Ridge (255). Two sites were drilled on the Naturaliste Plateau (258, 264) and although neither of them reached basement they gave important information concerning the past history of this feature.

From paleontological information it is possible to determine whether the environment of deposition was shallow water marine, shelf or deep ocean facies. This information was used with considerable success by Pimm et al. (1974), Luyendyk and Davies (1974) and Luyendyk (this volume) to analyze the past history of the Ninetyeast Ridge. This is the best known aseismic ridge in the Indian Ocean and forms the type example to which the limited information gathered on the other aseismic ridges is compared. Sclater and Fisher (1974) have argued that the Ninetyeast Ridge is the same age as the oceanic crust to the west and is attached to the Indian plate. Further there is evidence (Table 3) that the depth of the Ninetyeast Ridge increases with age. In fact, this depth increase is close to that predicted by assuming that the ridge was created at sea level and that since the onset of shallow water marine facies it has subsided at the same rate as the oceanic crust to which it is attached (Table 3; Figure 3). With this assumption, it is possible from the DSDP holes, to predict the subsidence history at every point along the ridge.

All other sites on aseismic ridges in the Indian Ocean have evidence from the sediments for subsidence from a depth close to sea level to their present depth (Table 3). The most striking is Site 219 on the

TABLE 3. Depth and Age from Sites on Aseismic Ridges

Site	Latitude	Longitude	Description of Subsidence History	Age: Basal Sediment m.y.b.p.	Age: Non-Shelf* Facies m.y.b.p.	Depth m	Sediment Thickness	Corrected+ Depth	Expected Depth from North Pacific subsidence curve.**
A) NINETYEAST RIDGE									
214	11°20.21'S	88°43.08E	Shallow water Paleocene basalt sediments with the onset of oceanic facies starting in early Eocene	57-59	49-54	1671	490	1980	2300
216	01°27.73'N	90°12.48'E	Shallow water late Maastrichtian basal sediments with onset of oceanic facies in the earliest Paleocene	69-65	65-60	2262	457	2530	2600
217	98°55.57'N	90°32.33'E	Shallow water early Campanian basal sediments with the onset of oceanic facies in the early Maastrichtian	76-82	68-72	3030	∿663	3442	2800
253	24°52.65'S	87.21.97'E	Shallow water mid-Eocene basal sediments with the onset of oceanic facies in the uppermost mid-Eocene	43-49	43-45	1962	558	2294	2200
254	30°58.15'S	87.53.72'E	Shallow water Oligocene/Eocene boundary basal sediments with the onset of oceanic facies in the early Miocene/late Oligocene	36.39	20-26	1253	∿301	1435	1400
B) OTHER									
219	09°01.75N	72°52.67'E	Shallow water late Paleocene basal sediments with the onset of oceanic facies in early Eocene	54-60	49-54	1764	∿600	2137	2300
237	07°04.99'S	58°07.48'E	Shallow water early Paleocene basal sediments with the possible onset of oceanic facies in the early Eocene/late Paleocene	60-65	49-60	1623	∿694	2054	2250-2500
246	33°37.21'S	45°09.60'E	Shallow water early Eocene basal sediment with the onset of oceanic facies in the early Miocene	49-54	20-23	1030	∿194	1151	1400
249	29°56.99'S	36°04.62'E	Shallow water early Cretaceous basal sediments - subsidence history unknown?	121-134		2088	408	2352	
255	31°07.87'S	93°43.72'E	Cretaceous limestone at bottom possibly uplifed in the Paleocene with onset of oceanic facies in the early Miocene		20-23	1144	∿109	1211	1400
258	33°47.69'S	112°28.42'E	Shallow water mid-Albian to Cenomanian basal sediments with the onset of oceanic facies in the mid-Albion with rapid shoaling through the Cretaceous	93-102	93-102	2793	∿525	3119	3000
264	34°58.13'S	112°02.68'E	Volcanoclastic conglomerate as basal sediments subsidence to moderately great depths by Santonian	70-100		2873	171	3003	2800

* By non-shelf we mean the onset of clearly shallow water marine facies (see text).
\+ Depth adjusted for isostatic loading of the sediments (see Sclater et al., 1971, Appendix 3), $\rho s = 1.8$ g/cm^3.
** From Sclater et al. (1971).

Chagos-Laccadive Ridge, where the onset of oceanic facies occurs in the early Eocene (Whitmarsh, 1974b). Assuming that the ridge was formed at sea level close to a spreading center and since then has sunk at the same rate as the adjacent crust gives an expected depth very close to that observed. This and the general morphological similarities to the Ninetyeast Ridge argue strongly that the Chagos-Laccadive Ridge can be treated in the same fashion as this ridge. Site 237 lies on the Mascarene Plateau. There is no direct evidence from the sediments for subsidence from shallow to abyssal depths. However, the Mascarene Plateau and the Chagos-Laccadive Ridge have a similar subsidence history as is clear from the benthonic foraminifera and sedimentation rates at both Sites 237 and 219 (Vincent et al., 1974). For the purposes of constructing the paleobathymetric charts we have assumed that the plateau and the ridge have had the same history of subsidence.

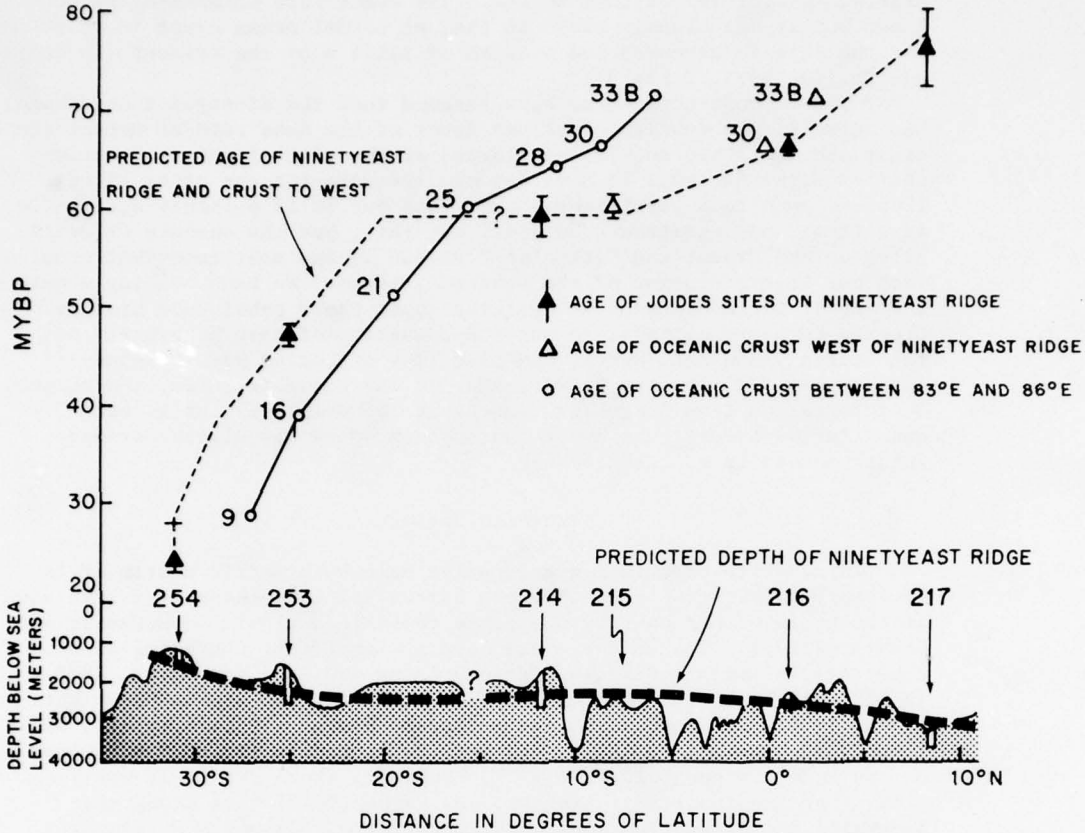

Fig. 3. Plot of the ages of the sediment 'basement' contacts on the Ninetyeast Ridge, the oceanic crust between 83°E and 86°E, and between 86°E and the Ninetyeast Ridge, all against latitude. Also shown is the actual depth of the crest of the Ninetyeast Ridge and the predicted depth (dashed line) assuming that it was formed at sea level and has the same age as the oceanic crust immediately to the west (after Sclater and Fisher, 1974).

Drilling at Site 246 on the Madagascar Ridge was terminated prematurely owing to technical problems. There is evidence from the basal sediments of a shallow water environment in the early Eocene. However, by the early Miocene the onset of deep water facies is observed. This history of subsidence from a shallow to deep water environment suggests that the ridge behaves like oceanic basement, and that prior to the Oligocene it was close to or above sea level. Unfortunately, we know nothing about its history prior to the Eocene. Site 249 is on the Mozambique Ridge. Though the oldest sediments were clearly formed near sea level the subsidence history is unknown. The same is true for Site 258 on the Naturaliste Plateau. However, this plateau subsided quite fast after formation (Table 3). Site 255 on Broken Ridge has the most complex history of the sites on the aseismic ridges. Luyendyk and Davies (1974) believe that the basal Cretaceous limestone was formed at depths less than 600 m but that the Ridge was uplifted in the Paleocene and then

started to sink in the late Eocene. The exact rate of sinking is not known but it was clearly close to that of normal ocean crust in order for the site to have reached a depth of 1,144 m by the present (Luyendyk and Davies, 1974, Table 3).

For our reconstructions we have assumed that the Ninetyeast and Chagos-Laccadive Ridges subsided from sea level at the same rate as normal ocean crust and that this subsidence started at the time of onset of marine shallow water facies. We have assumed the same for the other ridges. There is much less justification for this but it is probably acceptable as a first approximation. However, not this, but the absence of drill sites on the Crozet and Kerguelen Plateaus is the most important problem with our interpretation of the aseismic ridges. We know nothing about the age of these Plateaus and nothing about their subsidence history. Clearly both are critical to our understanding of past bathymetry of the Indian Ocean and, hence, the past flow of bottom water around Antarctica. In fact, as we will show in our reconstruction, the absence of information from Kerguelen renders it impossible for us to make quantitative predictions about past bottom water circulation around Antarctica prior to the Miocene.

Tectonic History

In order to construct quantitative paleobathymetric charts it is necessary to know the past tectonic history of the oceans. We have used as the basis of our history the plate tectonic analysis of McKenzie and Sclater (1971). Though there has been a significant upgrading of data especially between Australia and Antarctica (Weissel and Hayes, 1972), in the Wharton Basin (Sclater and Fisher, 1974), the Arabian Sea (Whitmarsh, 1974a) and the Crozet and Mascarene Basins (Schlich et al., 1974b) these data have not radically changed the reconstruction history worked out by McKenzie and Sclater (1971). However, there are three modifications that are important. Weissel and Hayes (1972) have shown that Australia and Antarctica separated approximately 53 m.y.b.p. (anomaly 22). Also Sclater and Fisher (1974) have argued that India started to move with respect to Australia roughly 33 m.y.b.p. (anomaly 11). These same authors have shown that the Ninetyeast Ridge was initiated at this time and has remained fixed to the Indian plate. As a consequence of these changes, we have chosen to reconstruct the paleobathymetry at 36, 53 and 70 m.y.b.p. We present a 36 m.y.b.p. reconstruction because this is close to the time of the major change in direction of all the spreading centers in the central and western Indian Ocean. It is also close to the time at which the Chagos Fracture Zone separated into the Mascarene Plateau and the Chagos-Laccadive Ridge. The 53 m.y.b.p. reconstruction is the time we believe Australia started to separate from Antarctica. The last reconstruction at 70 m.y.b.p. is the time of anomaly 32 and is the furthest we can go back in time using magnetic anomalies. We have considerable confidence in the 36 m.y.b.p. reconstruction and some confidence in the position of the continents for 70 m.y.b.p. but not in the exact position of the ridge axes. However, the 53 m.y.b.p. reconstruction is speculative because there are serious problems with aligning fracture zones and lineation trends.

The basic magnetic lineations superimposed upon a contour chart of the Indian Ocean are presented in Figure 1. The present positions of all the JOIDES deep sea drilling sites are also shown on this chart. Throughout the reconstructions that follow we shall assume only four major plates for this ocean (Figure 4a). These are (1) the African plate bounded by the Carlsberg, Central Indian and Southwest Indian Ridges, (2) the Indian plate bounded by the Carlsberg, Central Indian, Southeast Indian

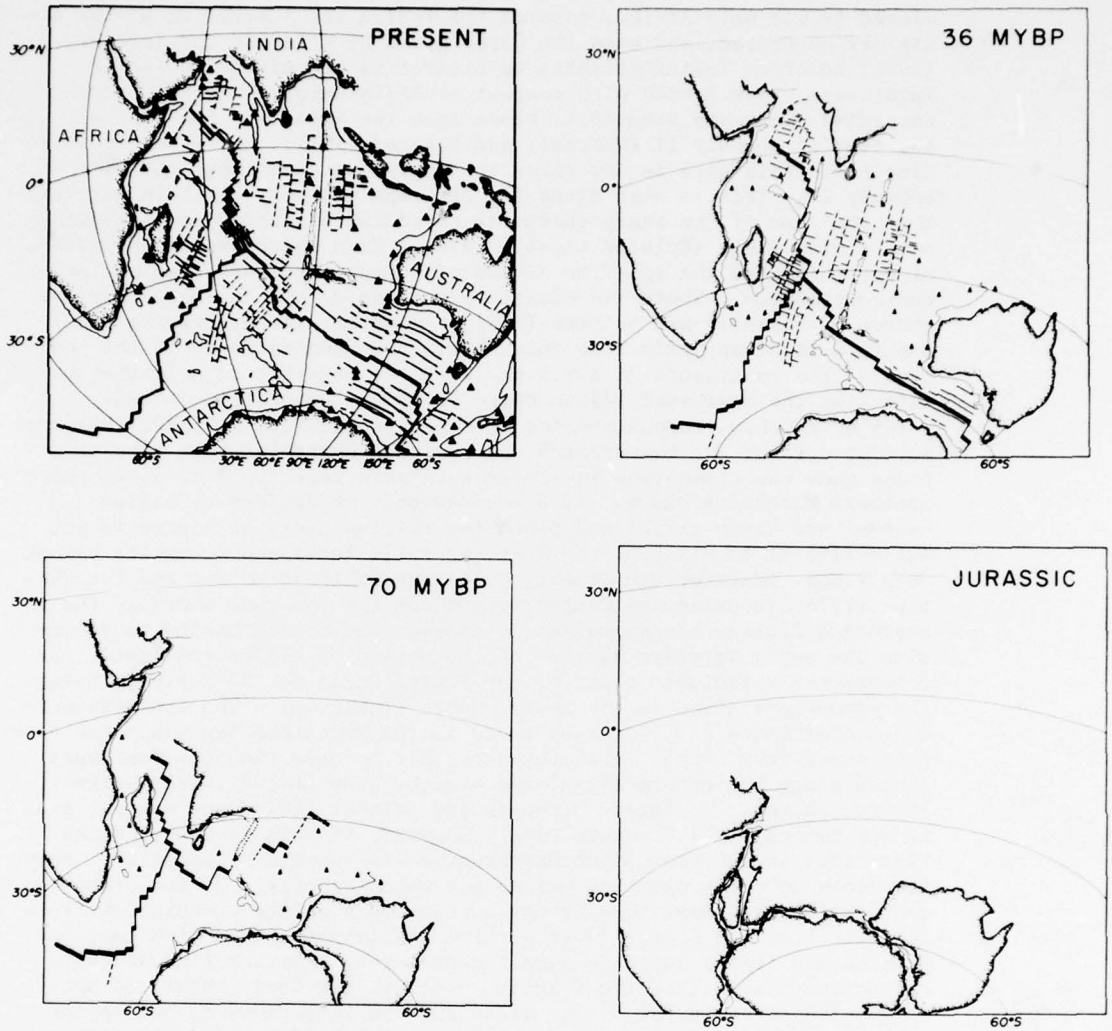

Fig. 4a. Tectonic chart of the Indian Ocean at present.

Fig. 4b. Tectonic chart of the Indian Ocean 36 m.y.b.p. (after McKenzie and Sclater, 1971).

Fig. 4c. Tectonic chart of the Indian Ocean 70 m.y.b.p. (after McKenzie and Sclater, 1971).

Fig. 4d. Reconstructed position of the Indian Ocean (after Smith and Hallam, 1970). The paleolatitude was determined using the paleomagnetic data for Australia.

and Ninetyeast Ridges, (3) the Australian plate bounded by the Ninetyeast and Australia/Antarctic Ridges and (4) the Antarctic plate bounded by the Southwest and Southeast Indian Ridges and the Australia/Antarctica Ridge. For the 36 m.y.b.p. reconstruction (Figure 4b) we have

closed Arabia onto Africa, assumed the Indian and Australian plates are rigidly connected, and used the poles given by McKenzie and Sclater (1971) to close India/Australia to Antarctica and Africa to India/Antarctica. For Africa with respect to India/Antarctica the Chagos-Laccadive Ridge was assumed to close onto the Saya de Malha bank at the time of anomaly 11 (McKenzie and Sclater, 1971). With our modified time scale this date is now close to 36 m.y.b.p. and marks the time of anomaly 13. This is also close to, although probably a little earlier than, the time of the sharp change in spreading direction on the Southeast Indian Ridge (Sclater et al., 1976). Thus the change in direction of spreading and the split up of the old Chagos Fracture Zone may be contemporaneous. There are clearly errors in detail in the parameters chosen by McKenzie and Sclater (1971). However, the errors are small and to a first approximation this chart is a good estimate of the position of the continents 36 m.y.b.p. It is of interest to note that by this time the Southwest Indian Ridge is almost completely closed.

The 45 m.y.b.p. reconstruction of McKenzie and Sclater (1971) has more serious errors. We constructed the tectonic chart for this time and found that the lineations in the Crozet Basin overlapped those in the Southern Mascarene Basin. As a consequence, we decided to follow Weissel and Hayes (1972) and place the rifting apart of Australia and Antarctica at 53 m.y.b.p. Further, we split India and Australia before 36 m.y.b.p. (Sclater and Fisher, 1974) and followed Molnar and Francheteau (1975) in using the Chagos trench and the fracture zones in the Mascarene Plateau and anomalies in Arabian and Somali Basins to determine the early Tertiary history of the motion of Africa and India. We constructed a tectonic chart of the Indian Ocean for 53 m.y.b.p. using the parameters given in the above papers (Table 4a). The lineations in the Crozet Basin still overlap those in the Mascarene Basin but the overlap is not very large. This suggests that by this time the Southwest Indian Ridge had completely disappeared as a spreading center between the two basins. We follow McKenzie and Sclater (1971) and suggest that it was dominantly a fracture zone. However, if this is the case the lineations in the Crozet and Mascarene Basins should be parallel. They are close to being parallel but do not match exactly. In the present qualitative treatment this is not considered a severe restriction since the data from the Crozet Basin and the preliminary poles of Molnar and Francheteau (1975) may have significant error. Another flaw of this reconstruction is that the fracture zones in the Ceylon Basin do not align with those in the Crozet Basin and the lineations do not appear to coalesce on the same pole as the Ninetyeast Ridge. Clearly more detailed work with all the available magnetic data is needed to resolve these problems. However, even given all these objections, we feel that it is unlikely that the positions of the continents and the magnetic lineations have been significantly misplaced in our proposed reconstruction and we used it to construct a preliminary bathymetric chart of the Indian Ocean 53 m.y.b.p. However, we do not show the tectonic reconstruction for fear that it might be believed quantitatively reliable.

For the 70 m.y.b.p. reconstruction we have used the anomaly 32 poles of McKenzie and Sclater (1971) but corrected the misprint in their pole for the earthquakes between Africa and Antarctica (Table 4b). As there is little information on the floor of the Indian Ocean older than anomaly 32 it is difficult to check this reconstruction in as much detail as that for 53 m.y.b.p. On the other hand, the positions of the continents and of the Ninetyeast Ridge are compatible with the sites on this Ridge and Site 250 between Africa and Antarctica. Also the overlap of anomaly 32 on the Indian and Antarctic plates severely con-

TABLE 4a. Rotation Poles and Angles for the 53 m.y.b.p. Reconstruction

	Latitude	Longitude	Angle	Reference
South America to Africa →	58.0	-37.0	26.14	Le Pichon and Hayes (1971)
Atlantic Ridge to Africa →	58.0	-37.0	13.07	Le Pichon and Hayes (1971)
Arabia to Africa →	36.5	18.0	- 6.14	McKenzie and Sclater (1971)
Africa and above to India →	13.63	40.91	29.91	Molnar and Francheteau (1975)
Carlsberg Ridge to India →	14.35	40.75	14.96	
Southwest Indian Ridge to India →	14.35	40.75	14.96	
India and above to Antarctica →	- 5.3	49.4	27.6	Sclater and Fisher (1974)
Southeast Indian Ridge to Antarctica →	- 5.3	49.4	13.8	
Southwest Indian Ridge to Antarctica →	- 5.3	49.4	13.8	
Antarctica and above to Australia →	- 6.0	40.5	31.6	McKenzie and Sclater (1971)
Southeast Indian Ridge to Australia →	- 6.5	37.8	15.8	
Australia and above to South Pole →	0.0	216.0	19.0	Sclater and Fisher (1974)

TABLE 4b. Rotation Pole for the Indian Ridge to the South Pole for 70 m.y.b.p.

	Latitude	Longitude	Angle
Southwest Indian Ridge	7.18.	87.97	-10.91

All the rest of the rotations are the same as those given in Table 10 of McKenzie and Sclater (1971).

strains the possible geometry of the plates. However, neither the position of the ridge axis between India and Africa nor that between Africa and Antarctica is well known. We have assumed that the spreading center between India and Africa jumped south sometime prior to anomaly 32 to account for the extra crust in the northern Mascarene Basin. For the ridge between Africa and Antarctica we have assumed that it consisted of two very long fracture zones, the westerly being the Prince Edward and the easterly separating the Crozet and Mascarene Basins and offset by three short ridge sections south of the Madagascar Basin. The position of the spreading center in the Wharton and Central Indian Basins and the history of the Ninetyeast Ridge and Broken Ridge are reasonably well known. However, the spreading centers in the western portion of the basin and the exact position of Africa with respect to Antarctica is still uncertain. It is likely a better understanding of these two continents will have to wait until the lineations observed in the Madagascar Basin (Bergh and Norton, 1976) have also been recognized and identified in the Crozet Basin south of the southwest Indian Ridge. However, for a preliminary paleobathymetric chart it is unlikely that the reconstructed positions of the continents and ocean floor are in serious error and since we have considerable confidence in the position of the continents we present this tectonic reconstruction as Figure 4c.

In order to produce a paleobathymetric chart for 70 m.y.b.p. it is necessary to know the positions of 4,000 m and 5,000 m isobaths. This in turn requires the determination of the position of the 90 m.y.b.p. and 120 m.y.b.p. isochrons on the 70 m.y.b.p. tectonic reconstruction (Appendix I). By 120 m.y.b.p. all the continents except Africa and Antarctica were probably closed onto each other and even in the case of Africa and Antarctica there was little sea floor between them. To determine the position of the 90 m.y.b.p. and 120 m.y.b.p. isochrons we have chosen to start with a tentative position for the continents all closed into one continent called Gondwana. From this position of the continents we work forward in time. For our speculative 70 m.y.b.p. paleobathymetry we have assumed that the Gondwana continents started in positions close to those given by Smith and Hallam (1970) (Figure 4d). In the early Cretaceous, Africa and South America split away from Madagascar, India, Australia, and Antarctica. Sometime in the mid-Cretaceous Africa picks up Madagascar which then becomes attached to Africa about the same time India separates from Antarctica and by the early Cretaceous we have the configuration shown in Figure 4c. In this reconstruction the dominant features are spreading centers completely surrounding the south tip of India with large fracture zones connecting them to the Tethys, a spreading center in the Wharton Basin and the mid-Atlantic Ridge. This configuration continues until 53 m.y.b.p. when Australia separates from Antarctica and the ridge axis west of the Ninetyeast Ridge jumps south. The next major change occurs in the late Eocene-early Oligocene when there is a reorientation in spreading direction in the central Indian Ocean, the Chagos Fracture Zone opens, the Ninetyeast Ridge moves away from the Southeast Indian Ridge and Southwest Indian Ridge is created. It has been noticed by many that this major change in morphology occurs at the onset of rapid uplift in the Himalayas. It is probable that these two features are causally related. After this major change, the development of the ocean essentially continues in the same fashion until the present.

The Paleobathymetric Charts

Once the relation between depth and age has been determined, the paleobathymetric charts follow directly from the tectonic history.

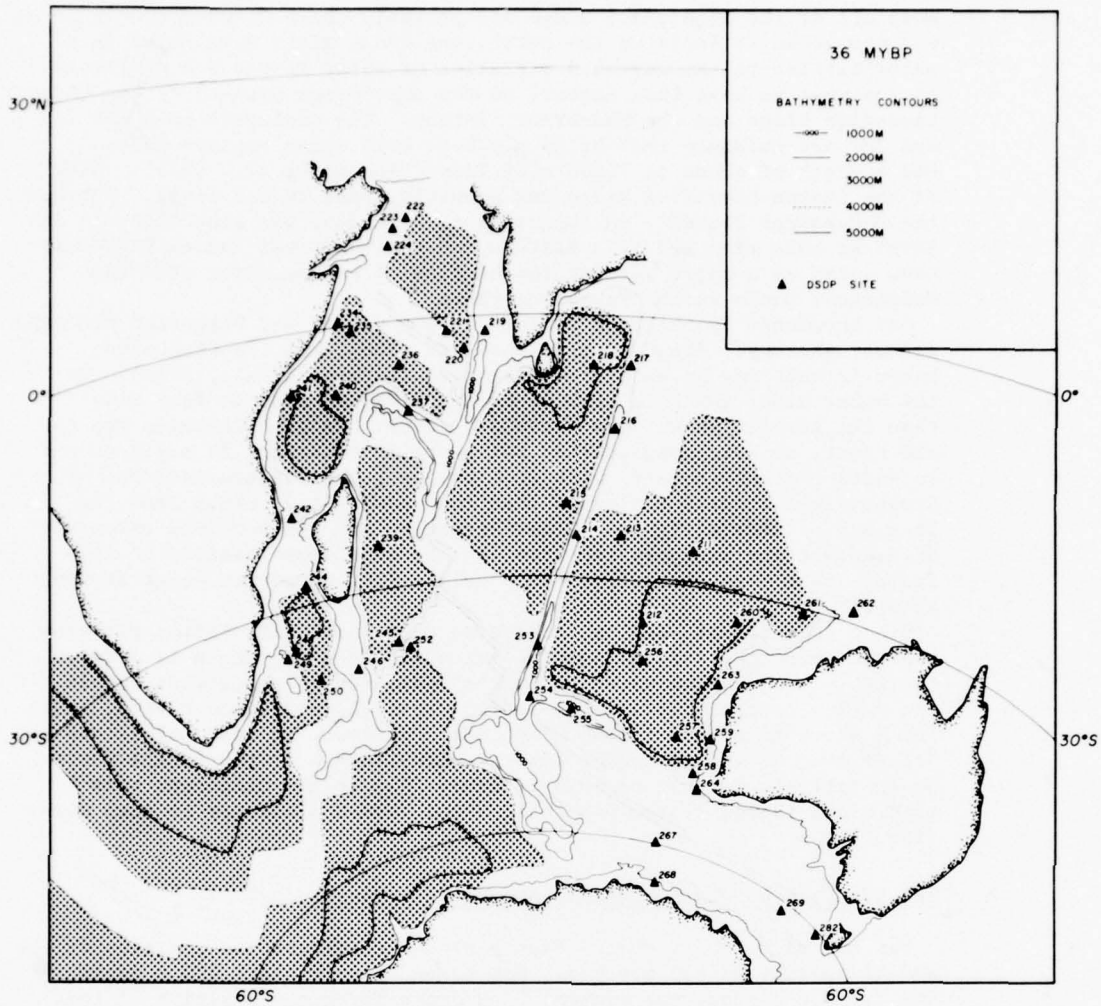

Fig. 5. The predicted bathymetry of the Indian Ocean for the early Oligocene (36 m.y.b.p; anomaly 13). The shaded area represents depths greater than 4000 m.

The method we used to construct these charts is discussed in detail in Appendix I. In this section we discuss the problems found in constructing each chart and the implications the contours might have upon the flow of deep and bottom water in the ocean.

The 36 m.y.b.p. (Early Oligocene, Anomaly 13) Chart

For the 36 m.y.b.p. reconstruction (Figure 5) we determined the relative depth of the Ninetyeast Ridge by assuming it was created at or above sea level and has sunk at the same rate as the crust to which it is attached. At this time much of the Ninetyeast Ridge was shallower than 2,000 m and the southern portion and the section near Broken Ridge were clearly close to or above sea level (Luyendyk et al., 1974). Al-

most all of the Ninetyeast Ridge was probably above 3,000 m and if it was connected to India to the north, the Ridge might have acted as a major barrier to the eastward migration of water masses and sediments. To the west we have less control on the subsidence history of the Chagos-Laccadive Ridge and the Mascarene Plateau. The sediments in holes 219 and 237 are evidence that by 36 m.y.b.p. both these regions probably had a depth of close to 1,000 m or less (Vincent et al., 1974). Some of the Chagos-Laccadive Ridge was probably close to sea level. Further, the Madagascar Plateau, on the basis of Site 246, was also close to sea level at this time and this plateau and the southwest Indian Ridge may have acted as a major barrier to the flow of bottom water from the Madagascar Basin to the Mascarene Basin.

Our knowledge of the past history of the Crozet and Kerguelen Plateaus is very sketchy. The Crozet Islands are young, but the Kerguelen-Heard Islands may be as old as Oligocene (Watkins et al., 1974). On the other hand, the bulk of both plateaus may be considerably older than the islands which show above sea level. As both features lie on old crust, we have assumed that both were in existence 36 m.y.b.p. and in their present geometry with probably only the southeastern end of Crozet significantly shallower then than now. It is clear from the 36 m.y.b.p. chart (Figure 5) that Kerguelen and its possible extension into Antarctica are very important as the subsidence history of this feature must have controlled the possible flow of bottom water around Antarctica.

Other features of some importance to deep water circulation patterns are the Amirantes Islands and the Amirantes Trench. There is a major hiatus in the shallow water carbonate sediments which extends across the entire central and eastern Indian Ocean (Luyendyk and Davies, 1974) for a short time span in the Oligocene. However, it does not extend in either deep or shallow water into the Arabian Sea or the Somali Basin. We tentatively suggest on this evidence that in the Oligocene this trench and island system was shallow and formed a barrier to deep water flow.

The 53 m.y.b.p. (Early Eocene, Anomaly 22) Chart

For the 53 m.y.b.p. chart (Figure 6) the reconstructed position of the end of anomaly 32 (70 m.y.b.p.) was taken to mark the 4,000 m contour. The 5,000 m contour was estimated by determining the position of the 100 m.y.b.p. isochron on this reconstruction. The depths for the Ninetyeast Ridge, the Chagos-Laccadive Ridge, the Mascarene Plateau and Broken Ridge were determined from the DSDP sites on these features. Long portions of all of these Ridges were probably close to sea level at this time. Unfortunately we know very little about the Madagascar Ridge and the Crozet and Kerguelen Plateaus. We have assumed for our 53 m.y.b.p. reconstruction that the Madagascar Ridge was close to sea level and that the Kerguelen Plateau was already in existence. We have omitted the Crozet Plateau.

The dominant features of this reconstruction are the closure of Australia and Antarctica and the segmentation at the 4,000 m level of the ocean into a series of small isolated basins; the Madagascar, Somali, Mascarene, Ceylon and Wharton Basins, all lying to the north of the Southwest and Southeast Indian Ridges. Another important feature is the possible existence of major land bridges along the Ninetyeast and Broken Ridges between Australia and India and along the Chagos Fracture Zone between Madagascar and India.

Between 53 m.y.b.p. and 36 m.y.b.p. Broken Ridge is above sea level and we have postulated that the Kerguelen Plateau was very shallow.

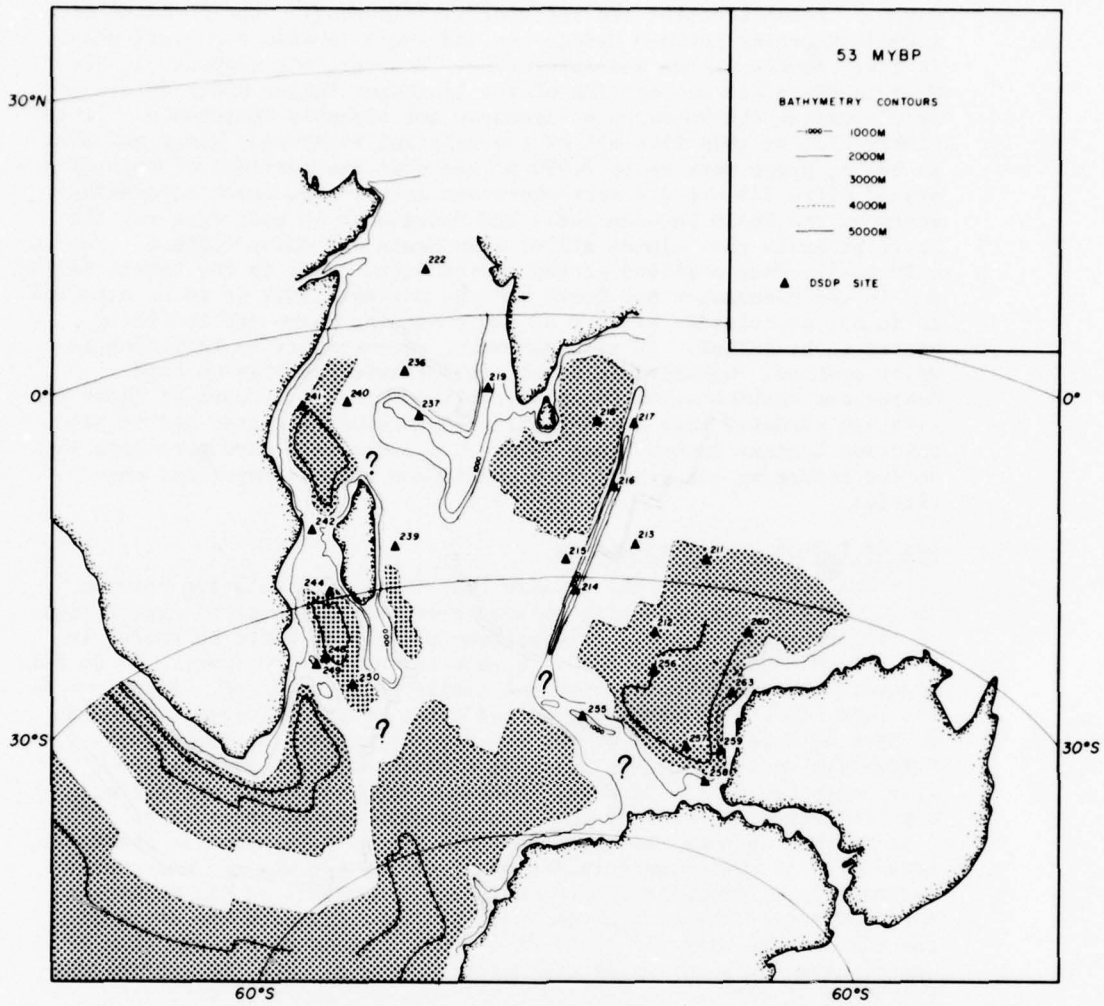

Fig. 6. The estimated bathymetry of the Indian Ocean for the Early Eocene (53 m.y.b.p.; anomaly 22). The shaded area represents depths greater than 4000 m.

During this time span Tasmania and its extension to the south was always close to Antarctica. Thus, except for the small region between Broken Ridge and Naturaliste Plateau, the basins between Antarctica and Australia were totally closed to deep water either from the east or west. It is possible that this geometry could have led to major changes in the deep sea sedimentary record. The absence of an Oligocene hiatus at Site 267 may be evidence of such a change.

The 70 m.y.b.p. (Late Cretaceous, Anomaly 32) Chart

Apart from the position of the ridge axis between India and Australia-Antarctica, the 4,000 m contour in the Wharton Basin, and the contours off the coast of Africa, all other contours and ridge axes on the 70

m.y.b.p. reconstruction are speculative (Figure 7). The position of spreading center between Madagascar and India is also speculative as is that between Africa and Antarctica. However, the contours in the Wharton Basin and either side of the Southeast Indian Ridge determined by estimating the 90 m.y.b.p. isochron are probably reasonable. It is likely that at this time all of the existing Ninetyeast Ridge and most of Broken Ridge were above 2,000 m and that the portions of both ridges around Sites 255 and 217 were above sea level. The exact paleobathymetry of the basin between India and Madagascar is much less certain. It is probable that almost all of this basin was above 4,000 m. The only really deep portions of the Indian Ocean occur in the Somali Basin and in the Madagascar and South Enderby Basins. This is to be expected as in our speculative history of early opening these are the first basins to be formed. As with our other reconstructions Kerguelen is a major problem. Kaharoeddin et al. (1973) have reported on some Cretaceous shallow water fossils from this ridge. If correct these fossils are evidence that the Kerguelen Plateau was elevated and in its position against Broken Ridge 70 m.y.b.p. However, much more data is needed before we can accept with confidence such an important conclusion.

Use of Paleobathymetric Charts

It has been shown in the Pacific that there is a relation between the circulation of Antarctic bottom water and the level of dissolution of calcarecus sediments. Paleobathymetric charts would be useful in the determination of the paths of such currents in the past. To do this, however, other information not now available is required. First, we do not know how bottom water was formed prior to the Oligocene. Second, we have no understanding of the exact structure of the Kerguelen/Antarctica contact and the relative closure of South America and Antarctica beyond the Miocene. Consequently, we cannot predict with any confidence the flow of such a water mass around Antarctica.

It is thus obvious that we cannot use the paleobathymetric charts at present to obtain a quantitative model of how and why the deep water sediments are formed in the Indian Ocean. However, we can backtrack the DSDP sites (Berger and von Rad, 1972) and estimate the depth of the CCD through time for the Indian Ocean. These depths can then be superimposed upon the paleobathymetric charts to map the surface distribution of calcareous and non-calcareous sediments at different geologic times. In the next section we compute the CCD as a function of time and use this and the paleobathymetric charts to investigate the surface distribution of calcareous sediments in the Indian Ocean.

Distribution of Sedimentary Facies in the Indian Ocean

The Calcite Compensation Depth

The most readily observable boundary between distinct sedimentary facies in the oceans is the Calcite Compensation Depth (CCD), the level where the dissolution rate of calcite equals the supply rate in the deep ocean (Peterson, 1966). The CCD is found today at approximately 3.5 to 4.5 km water depth (Berger and Winterer, 1974) sloping upwards close to continental margins and in the polar to subpolar regions of the world oceans. The depth variation of the CCD with time is still under considerable discussion (van Andel, 1975). First, the coverage of the world ocean with DSDP sites is geographically uneven and second, only a certain portion of the drill sites are suitable for determining the age/depth position of the CCD. This unevenness and scarcity of

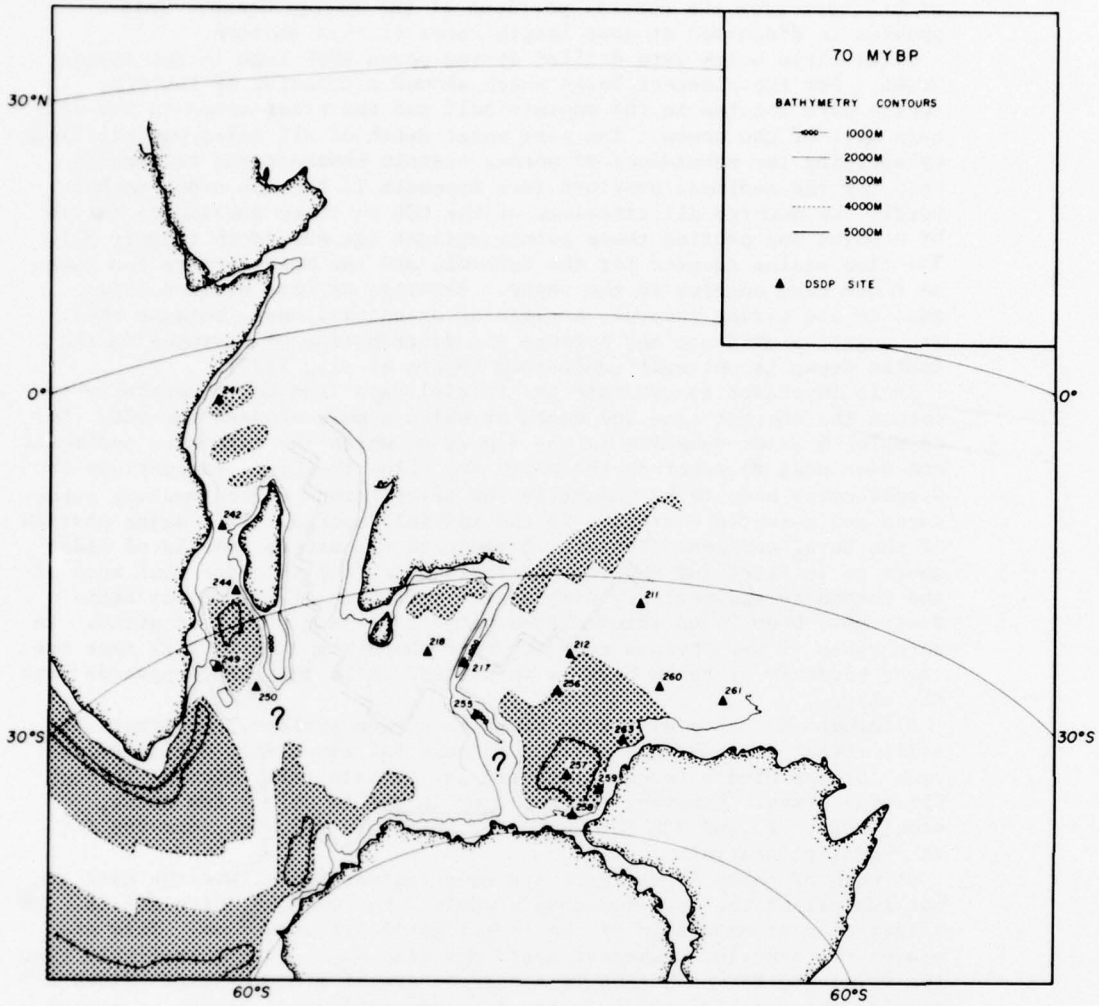

Fig. 7. A possible bathymetry of the Indian Ocean for the Late Cretaceous (70 m.y.b.p.; anomaly 32). The shaded area represents depths greater than 4000 m.

data have resulted in a considerable delay in compiling the geological history of this boundary between major pelagic sediment facies. The first attempt to describe the history of the CCD on a world wide scale has been completed only recently by van Andel (1975).

The Indian Ocean poses a special problem for reconstructing the CCD as a function of time. There are no deep sites in the central Indian Basin and none south of the Southeast or Southwest Indian Ridges. Of the sites that are available many did not reach basement and of the few that did only nineteen have an adequate sediment record. Certain sites, especially those of DSDP legs 23, 27 and 28, were drilled close to the Arabian and Australian continental margins or in the polar regions south of Australia where the CCD is known to be situated much shallower than in the open ocean. Thus these sites cannot easily be compared

with others from the central portions of the Indian Ocean. This problem is discussed at some length later in this section.

Fifty-three holes were drilled during seven DSDP legs in the Indian Ocean. For the nineteen holes which showed a crossing of the CCD, twelve were located in the eastern half and the other seven in the western half of the ocean. The past water depth of all sites was calculated by applying the subsidence of normal oceanic basement and correcting only for the sediment overload (see Appendix II for the exact method used). We denoted all crossings of the CCD on these subsidence curves by a point and plotted these points against age and depth (Figure 8a). The time scales adopted for the Cenozoic and the Mesozoic are the same as those used earlier in the paper. Finally, we have avoided using gaps in the coring records, artificial or natural ones, because they are negative evidence and because the distribution of hiatuses in the Indian Ocean is not well understood (Moore et al., 1977).

It is important to evaluate the initial data from holes carefully to obtain the correct time and depth at which a hole crosses the CCD. For example, a major question is the degree to which the carbonate sediments are displaced to water depths which are below the CCD. Indications for displacement have to be sought in the descriptions of sedimentary structures and textures contained in the initial reports. If a major portion of the total sediment consists of reworked calcareous fossils of older zones as in Sites 260 and 261, there is excellent evidence that much of the carbonate sediments is displaced. Thin beds of calcareous sediments have been found intercalated with clays at a number of sites. In some cases it was obvious from the core photographs (Site 212) that the lower boundary of these beds is very sharp while they grade upwards into the clays.

Although the cases discussed above have been avoided, the crossings still reveal considerable scatter (Figure 8a) especially during Paleocene through Middle Eocene times and during late early Miocene through Pliocene times. However, this scatter is due to only a few sites, namely 212, 223 and 239 for the older interval, 222, 261, and 265 for the younger interval.

At each of these sites there are good reasons to believe the data are not typical of the deep ocean as a whole. For example, Site 212 is situated on an extension of the Investigator Fracture Zone. This explains the anomalous basement depth and also makes it highly likely that the Paleocene-Eocene carbonate sequences are of slump origin. Sites 222 and 223 are situated close to the Arabian continental margin, a region which is today and was throughout the Neocene highly fertile (Thiede, 1974). The age of the oceanic basement at Site 239 in the southern Mascarene Basin is only known to be pre-Campanian (Simpson et al., 1974) the oldest sediments consisting of brown clay interbedded with nanno ooze and thus suggesting a hiatus between the basement and the oldest sediment (van Andel and Bukry, 1973). The Neogene cores of Site 261 contain partly calcareous sediments interbedded with clays (Veevers and Heirtzler, 1974); the nanno oozes were probably displaced to water depths below the CCD. Site 265 lies north of Antarctica, and has a much shallower CCD in the Miocene than the other sites. The reason for this is unknown but it could possibly be related to the proximity of the site to the deep circumpolar current. We return to a discussion of this site and Sites 222, 223 and 239 in the next section.

If the above six sites are ignored then this considerably simplifies the history of the CCD. During the Tithonian the CCD was close to 3.5 km. It shallowed during the Albian and Aptian to 2.5 to 3.0 km and then dropped to 4.0 km for the Maastrichtian. From then until the Oligocene it remained fairly flat before another drop to approximately

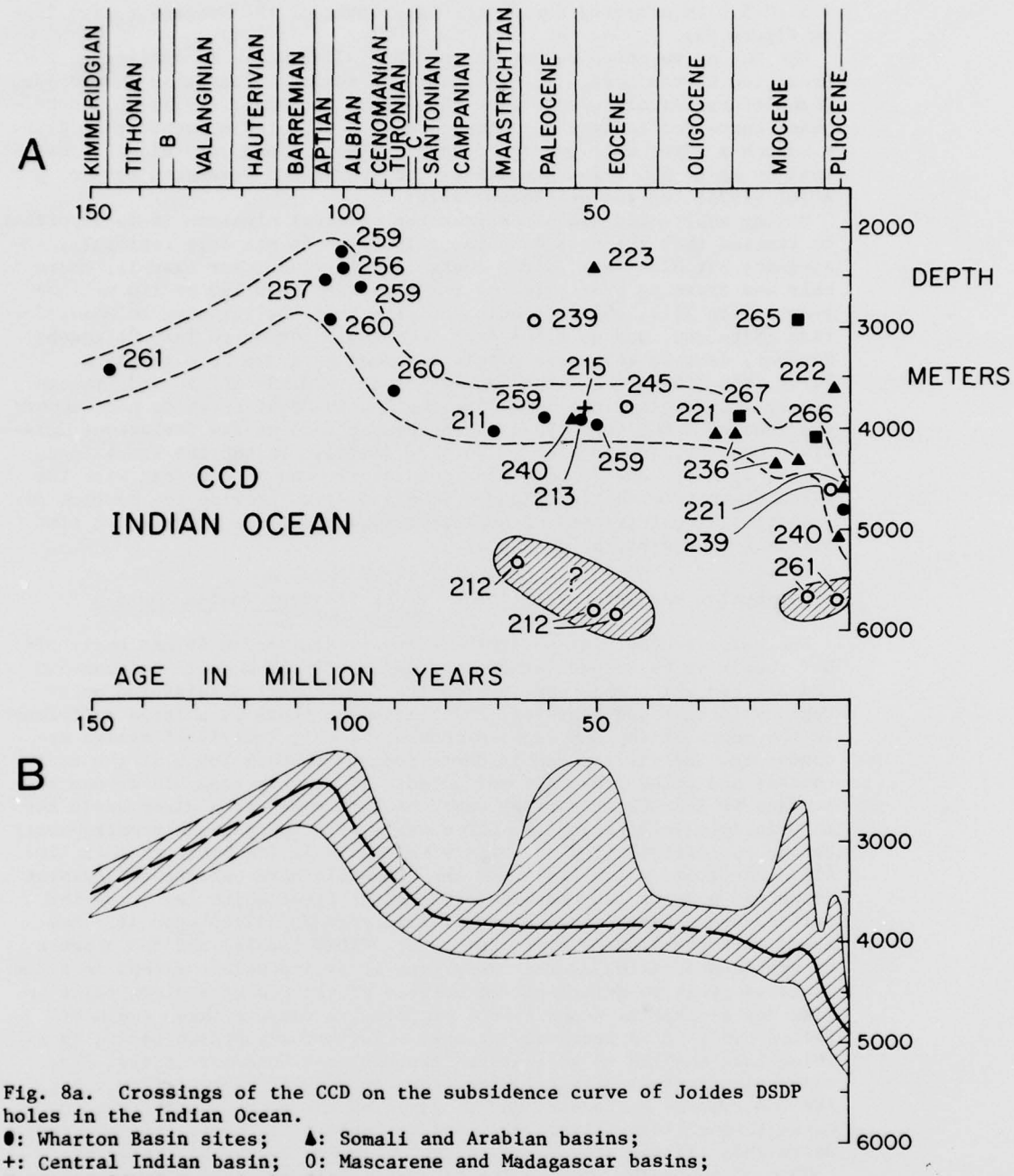

Fig. 8a. Crossings of the CCD on the subsidence curve of Joides DSDP holes in the Indian Ocean.
●: Wharton Basin sites; ▲: Somali and Arabian basins;
+: Central Indian basin; O: Mascarene and Madagascar basins;
■: Australia-Antarctic basin.

Fig. 8b. The range of distribution of the Indian Ocean Calcium Carbonate Compensation Depth (CCD) since Jurassic times. The solid line has been fitted by hand through the majority of the crossings on figure 8a, the stippled lines and the hatched area circumscribe the scatter of all variable points except sites 212 and 261.

4.5 to 5.0 km occurred during the later part of the Neogene (heavy line on Figure 8b).

The CCD curve which we obtain for the Indian Ocean is similar to that presented by van Andel (1975) except for regions older than the Eocene. The differences all result from the use by van Andel (1975) of a subsidence curve for younger crust which starts at 3,100 m rather than 2,700 m. Such a curve will tend to deepen sediment found very close to basement by up to 400 m and results in the deeper CCD presented by van Andel (1975) for the pre-Eocene sites.

Having subtracted six sites from the original nineteen it is important to realize that the data base for this curve is not only regionally inadequate but also very poorly controlled in time. For example, there is only one crossing available for the time span from 150 to 110 million years (Site 261), there is only one site from the Turonian to Maastrichtian (Site 260) and no sites from the middle Eocene to late Oligocene. However, certain tentative conclusions can be drawn from the data. First, the CCD in the Tithonian was close to 3,500 m. Second, though poorly distributed, the data from the Indian Ocean sites do not support the idea of a CCD very close to the sea surface at the Cretaceous/Tertiary boundary as proposed by Worsley (1974). Third, the simplified curve, with all the caveats mentioned above, can be combined with the paleobathymetric charts (Figures 5, 6 and 7) to provide the surface distribution of calcareous and non-calcareous sediments at selected time slices (Figures 9a, b, c, and d).

Distribution and Interpretation of Major Sediment Facies Changes

The calcite compensation depth in any present ocean is not horizontal but rather it is an undulating surface usually at a depth between 5.0 and 3.5 kms which shallows towards the continental margins and polar regions (Berger and Winterer, 1974). Though there is a large difference in the depth of the CCD between oceans, if only individual basins are concerned, the differences in depth reduce to about 500 m if the near coastal and polar areas are neglected. If it were possible to map the surface of the CCD at a given epoch back in time for a given basin then in principle interfacing the CCD surface with the paleobathymetry would define the distribution of surface sediments in the basin at that time. All ocean floor which lay above the CCD would have calcareous sediment deposited upon it and conversely all ocean floor which lay below the surface would have clay and radiolarian ooze deposited upon it. However, with the present distribution of JOIDES samples and the absence of continuous coring on the early legs it is impossible except in a few isolated areas to determine the surface of the CCD at a given point in time for any basin. As a result of this, to compute these sediment facies maps, it is necessary to make a further assumption beyond those which have enabled us to compute the CCD as a function of age. The assumption is that within ±300 m from the present back to 70 m.y.b.p. the CCD remains horizontal and is given by the mean point of the CCD curve through time (Figure 8a). If we neglect the Australia/Antarctic Basin then all the sites back to the Paleocene appear to lie within ±300 m of the mean. Before the Paleocene this assumption appears less valid. We applied this assumption of a horizontal CCD to the paleobathymetry to produce the sediment facies maps. We believe only the 35 m.y.b.p. chart to be quantitative. The other two charts for 53 and 70 m.y.b.p. have merely been included for the sake of completeness and to speculate as to how far our assumptions would lead us.

The errors in the charts are difficult to evaluate. We believe that apart from the Australian-Antarctic Ridge and between South Africa and

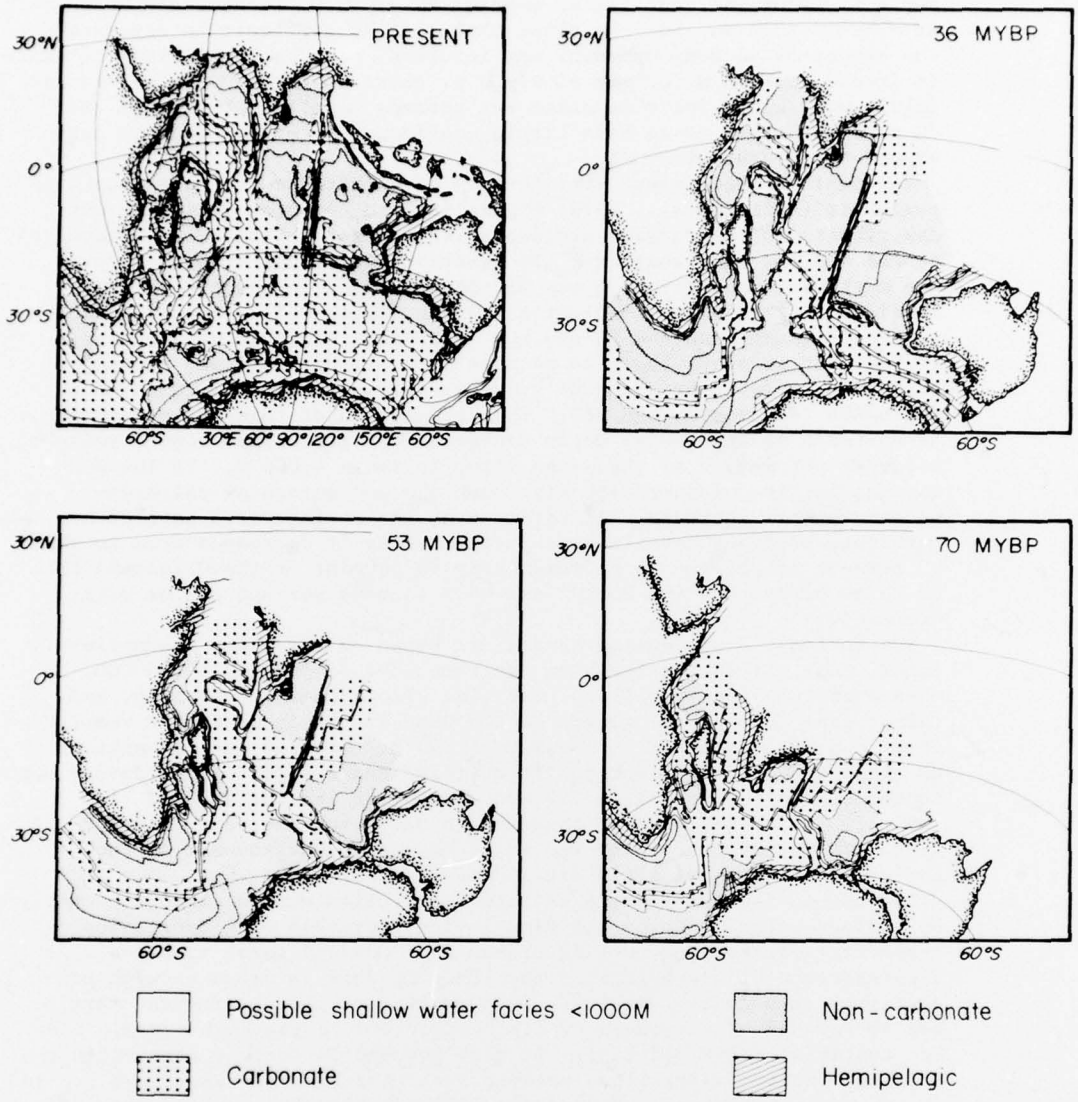

Fig. 9a. Present distribution of carbonate, clay, hemipelagic and shallow water marine sediments (Kolla et al., 1976).

Fig. 9b. Probable distribution of surface sediments in the early Oligocene, (36 m.y.b.p.).

Fig. 9c. Speculative distribution of the surface sediments in the early Eocene, (53 m.y.b.p.).

Fig. 9d. Highly speculative distribution of the surface sediments in the Late Cretaceous, (70 m.y.b.p.).

Antarctica our sediment facies map for 36 m.y.b.p. is accurate on the average to ±300 m. For the older charts it is difficult to estimate the errors as so many unknowns are involved. A probable maximum estimate is around 400-500 m for the 53 m.y.b.p. chart as the 4,000 m contour is fairly well known for this chart but perhaps more than 500 m for the 70 m.y.b.p. chart as we have little confidence in either the CCD curve or the paleobathymetry.

We compiled the present distribution of calcareous and non-calcareous sediments (Kolla et al., 1976; Figure 9a) and compared this with our distribution of calcareous sediments for the early Oligocene (Figure 9b). As the CCD was much shallower the distribution of calcareous sediment was much more restricted in the Oligocene than at present. We are confident of the above conclusions as the CCD is well controlled back to the Oligocene and the 36 m.y.b.p. paleobathymetry is believed reliable. It is clear that, as we move back further in time, the major basins are covered by a steadily increasing proportion of calcareous sediments (Figures 9c and 9d). The explanation of this is very simple. As the size of the Indian Ocean decreases and the basins become younger, a larger percentage of the ocean floor is above 4,000 m. If the CCD remains fairly constant with time then the percentage of calcareous sediments will increase. An estimate of the surface area covered by carbonate sediment reveals that in this ocean it decreases from roughly 60 percent at present to approximately 40 percent in the Oligocene back up to 50 percent by the Eocene and more than 60 percent in the early Cretaceous.

The sediment distribution charts are based on three key assumptions. First, that all the basins have the same CCD; second, that the CCD, when averaged over 10 million year time slices, changes smoothly; and third, that from the Oligocene to the Campanian this depth has remained at a constant depth fairly close to 4,000 m. Clearly our assumptions do not hold for the Oligocene hiatus (Pimm and Sclater, 1974; Davies and Luyendyk,1974)and for Sites 222 and 223, Sites 265 and 266 and Site 239. It is our belief that these sites and Sites 256, 257, 259 and 260 give information concerning the past changes of environment of the basins in which these sites are located.

The CCD is the level where calcite dissolution equals carbonate supply by surface waters. Carbonate dissolution increases with decreasing temperature, increasing partial pressure of CO_2 and total pressure. As a consequence of these factors the CCD goes down in areas of high productivity such as the equator. It goes up near the continental margin due to removal of carbonate by dislocation due to the high organic carbon controls of the sediment. It also goes up in regions over which the Antarctic bottom water flows because such water is undersaturated due to decreasing temperature and increased CO_2 and also because the rate of supply of this water is increased (Berger and Winterer, 1974). We now examine the anomalous sites within the framework of this model.

Sites 222 and 223 are close to the coast of Arabia and thus it is not surprising that they show a shallow CCD. Sites 265 and 266 in the Miocene lie under the path of the deep Antarctic Circumpolar Current. This may be the explanation of why these sites should show an anomalously shallow CCD. Site 239 is an anomaly. However, it is possible that bottom water passed from the Enderby basin off Antarctica to the Tethys. If such a current was undersaturated in carbonate it could explain the shallow CCD at Site 239. The explanation of the shallow Sites 256, 257, 259 and 260 in the Wharton Basin is much simpler. Sclater and Fisher (1974) and Markl (1974) predict that India and its Tibetan extension closed against western Australia between 100 and 120 m.y.b.p. Thus from initial opening at 120 m.y.b.p. until at least 100 m.y.b.p., the Tibetan

extension of India, the Exmouth Plateau and the Kerguelen Ridge would have made the Wharton a totally enclosed basin with nearby continental shelves and consequent removal of carbonate.

In this study we have concentrated upon questions to which we think we have plausible answers. However, there are problems which have arisen which we cannot answer. For example, in the previous section we have attributed the shallowness of the CCD in the Miocene at Sites 265 and 266 to circumpolar currents. Further Kennett et al., (1975) have attributed the Oligocene hiatus in Sites 280, 281 and 282 which range in depth from 4200 m to 1600 m to the opening of the gap between the Tasman Rise and Antarctica and the onset of a vigorous shallow and deep circumpolar current. We feel both our own interpretation of Sites 265 and 266 and that of Kennett et al. (1975) of Sites 280, 281 and 282 very plausible. The problem with both interpretations lies in the fact that the late Oligocene is complete in both holes 267 and 269. However, at this time, both sites were close to the ridge axis (Figure 5) and directly under the proposed axis of the supposedly very vigorous Antarctic Circumpolar Current. At present we do not have a convincing answer to this problem which yet again illustrated the difficulties of trying to speculate about global circulation with an inadequate data base.

A second problem occurs with the Oligocene hiatus in the Indian Ocean sediments. If it is defined solely as an absence of calcareous sediments where they would otherwise be expected then the evidence for its occurrence is limited only to shallow water sites. Also these sites (249, 246, 214, 216, 217, 264, 258, and 261) all lie east of a line joining the east coast of Madagascar, the Seychelles, the Chagos-Laccadive Ridge and India. Thus the hiatus is evidence only for (1) a possible shallow and deep water barrier between the Amirantes and the Seychelles and (2) some shallow water relation between the sediments in the sites east of our proposed shallow water line joining Africa to India. At present there is no data supporting a deep water hiatus in the eastern Indian Ocean.

Conclusions on Sediment Distributions

The major conclusions from our study of the variation of CCD with time and the examination of the influence of this on the distribution of surface sediments with time are (a) that the mean CCD shallows from around 5,000 m at present to close to 4,000 m for the Oligocene through the Campanian; (b) that the variations of the CCD away from this mean can be attributed to deep water currents and proximity to continental margins; (c) that the surface distribution of calcareous sediments in the Oligocene is considerably less than what is observed at present; and (d) that the presence of calcareous sediments throughout the history of almost all the aseismic ridges can be explained by the fact that except during the Albian and Aptian the CCD was never shallower than 2,500 m.

There are some outstanding problems which our study has not resolved. These include the exact vertical distribution of the Oligocene hiatus in the Indian Ocean, the past sedimentary history of the Kerguelen and Crozet Basins and the general history of bottom water circulation south of the southwest and southeast Indian Ridges. We feel strongly that these and many other paleooceanographic problems of major order might well be rendered soluble by a carefully designed program of deep sea drilling in the southern Indian Ocean.

Acknowledgements. Much of the speculation discussed in this paper arose out of spirited discussions with R. Schlich, H. Bergh, I. Norton and P. Molnar. We are grateful for their interest and, at first, often unheeded advice. The paper was reviewed by J. van Andel, E. L. Winterer and E. Vincent and we have benefited significantly from their comments. The work of Sclater and Abbott was supported by contract number N00014-75-C-0291 from the Office of Naval Research. The assistance of N. A. Brewster in compiling the sediment data is gratefully acknowledged.

References

Anonymous, Russian Chart of the Indian Ocean, 1:15,000,000, Committee of Management for Geodesy and Cartography of the Soviet Ministry of the U.S.S.R., Moscow, 1964.

Anderson, R. N., D. McKenzie, and J. G. Sclater, Gravity, bathymetry and convection in the earth: Earth Planet. Sci. Lett., 18, 391-407, 1973.

Berger, W. H., and U. von Rad, Cretaceous and Cenozoic sediments from the Atlantic Ocean, in Haues, D. E., Pimm, A. C. et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 14, 787-954, 1972.

Berger, W. H., and E. L. Winterer, Plate stratigraphy and the fluctuating carbonate line, International Assoc. of Sed., Spec. Publ. 1, 11-48, 1974.

Berggren, W. A., and J. A. van Couvering, The late Neogene-biostratigraphy, geochronology and paleoclimatology of the last 15 million years in marine and continental sequences, Palaeogeogr. Palaeoclimatol., Palaeoecol., 16, 1-216, 1974.

Bergh, H. W., and I. O. Norton, Prince Edward Fracture Zone and the evolution of the Mozambique Ridge, J. Geophys. Res., 81, no. 29, 5221-5239, 1976.

Bunce, E. T., Djibouti to Seychelles Islands, in Fisher, R. L., Bunce, E. T. et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 24, 591-605,1974.

Carpenter, G., and M. Ewing, Crustal deformation in the Wharton Basin, J. Geophys. Res., 78, no. 5, 846-850, 1974.

Davies, T. A., and R. B. Kidd, Sedimentation in the Indian Ocean through time in Indian Ocean Geology and Biostratigraphy, AGU, Washington, this volume, 1977.

Davies, T. A., and B. P. Luyendyk, in Davies, T. A., Luyendyk, B. P., et al., Initial Reports of the Deep Sea Drilling Project, Washington (U. S. Government Printing Office) 26, 1192, 1974.

Davis, E. E., and C.R.B. Lister, Fundamentals of ridge crest topography, Earth and Planet. Sci. Letts., 21, 405-413, 1974.

Detrick, R., J. G. Sclater, and J. Thiede, Subsidence of aseismic ridges, Earth Planet. Sci. Letts., 34, 185-196, 1977.

Eittreim, S. L., and J. Ewing, Mid-plate tectonics in the Indian Ocean, J. Geophys. Res., 77, no. 32, 5413-6421, 1972.

Ewing, M., S. Eittreim, M. Trauchan, and J. I. Ewing, Sediment distribution in the Indian Ocean, Deep-Sea Res., 16, 231-248, 1969.

Falvey, D. A., Sea floor spreading in the Wharton Basin (Northeast Indian Ocean) and the breakup of eastern Gondwanaland, Australian Petroleum Exploration Association, 12, no. 2, 1972.

Frey, F. A., J. S. Dickey, G. Thompson, and W. B. Bryan, Eastern Indian Ocean DSDP sites: correlations between petrography, geochemistry and tectonic setting, in Indian Ocean Geology and Biostratigraphy, AGU Washington, this volume, 1977.

Hayes, D. E., A. C. Pimm, J. P. Beckmann, W. E. Benson, W. H. Berger, P. H. Roth, P. R. Supko and U. von Rad, Initial Reports of the

Deep Sea Drilling Project, 14, Washington (U. S. Government Printing Office) 975, 1972.

Heirtzler, J. R., G. O. Dickson, E. M. Herron, W. C. Pitman and X. Le Pichon, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents, J. Geophys. Res., 73, 2119-2136, 1968.

Houtz, R. E., and R. G. Markl, Seismic profiler data between Antarctica and Australia, in Antarctic Oceanology II, The Australian-New Zealand Sector, edited by D. E. Hayes, Amer. Geophys. Un., Washington, 147-164, 1972.

Johnson, B. D., C. McA., Powell, and J. J. Veevers, Spreading history of the eastern Indian Ocean and greater India's northward flight from Antarctica and Australia, Bull. Geol. Soc. Amer., 87, 1560-1566, 1976.

Kaharoeddin, A., F. M. Weaver, and S. W. Wise, Cretaceous and Paleogene cores from the Kerguelen Plateau, Antarct. J. U. S., 8, 297-298, 1973.

Kahle, H. G., and M. Talwani, Gravimetric Indian Ocean Geoid, Zeitschrift für Geophysik, 39, 491-499, 1973.

Kennett, J. P., R. E. Houtz, P. B. Andrews, A. R. Edwards, V. A. Gostin, M. Hajos, M. A. Hampton, D. Graham Jenkins, S. V. Margolis, A. T. Overshine, and K. Perch-Nielsen, Cenozoic paleooceanography in the southwest Pacific Ocean, Antarctic glaciation and the development of the circum-antarctic current, in Kennett, J. P., Houtz, R. E., et al., Initial Reports of the Deep Sea Drilling Project, 29, Washington, (U. S. Government Printing Office) 1155-1170, 1975.

Kolla, V., A.W.H. Be, and P. E. Biscaye, Calcium carbonate distribution in the surface sediments of the Indian Ocean, J. Geophys. Res., 81, no. 15, 2605-2616, 1976.

Larson, R. L., Late Jurassic sea floor spreading in the Eastern Indian Ocean, Geology, 3, 69-71, 1975.

Larson, R. L., and W. C. Pitman, World wide correlation of Mesozoic magnetic anomalies and its implications, Bull. Geol. Soc. Amer., 83, 3645-3662, 1972.

Larson, R. L., and W. C. Pitman, World wide correlation of Mesozoic magnetic anomalies and its implications: discussion and reply, Geol. Soc. Annual Bull., 86, 267-272, 1975.

Le Pichon, X., and D. E. Hayes, Marginal offsets, fracture zones and the early opening of the South Atlantic, J. Geophys. Res., 76, no. 26, 6283-62-93, 1971.

Luyendyk, B. P., and T. A. Davies, Results of DSDP Leg 26 and the geologic history of the southern Indian Ocean, in Davies, T. A., Luyendyk, B. P., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office) 26, 909-943, 1974.

Luyendyk, B., T. A. Davies, et al., Report on Site 253, in Davies, T. A., Luyendyk, B. P., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office) 26, 153-232, 1974.

Luyendyk, B. P., Deep sea drilling on the Ninetyeast Ridge: synthesis and tectonic model, in Indian Ocean Geology and Biostratigraphy, AGU, Washington, this volume, 1977.

Markl, R. G., Evidence for the breakup of eastern Gondwanaland by the early Cretaceous, Nature, 251, no. 5471, 196-200, 1974.

McKenzie, D., and C. Bowin, The relationship between bathymetry and gravity in the Atlantic Ocean, J. Geophys. Res., 81, no. 11, 1903-1915, 1976.

McKenzie, D. P., and J. G. Sclater, The evolution of the Indian Ocean since the Late Cretaceous, Geophys. J. Roy. astr. Soc., 25, 437-528, 1971.

Menard, H. W., Gravity anomalies and vertical tectonics as indicators of

plate motions, Amer. Geophys. Un. Trans., 54, 4, 239, 1973.
Molnar, P., and J. Francheteau, The relative motion of "hot-spots" in the Atlantic and Indian Oceans during the Cenozoic, Geophys. J. Roy. astr. Soc., 43, no. 3, 763-774, 1975.
Moore, T. C., T. H. van Andel, C. Sancetta, and N. Pisias, Cenozoic hiatuses in pelagic sediments, Proc. 3rd Internat. Plankt. Conf. (Kiel, 1974), 1977, in press.
Parsons, B., and J. G. Sclater, An analysis of the variation of ocean floor heat flow and depth with age, J. Geophys. Res., 1977, in press.
Peterson, M.N.A., Calcite: rates of dissolution in a vertical profile in the central Pacific, Science, 154, 1542-1544, 1966.
Pimm, A. C., B. McGowran, and S. Gartner, Early sinking history of Ninetyeast Ridge, Northeastern Indian Ocean, Bull. Geol. Soc. Amer., 85, no. 8, 1219-1224, 1974.
Pimm, A. C., and J. G. Sclater, Early Tertiary hiatuses in the sediment record of Deep Sea Drilling Sites in the northeastern Indian Ocean, Nature, 252, 362-365, 1974.
Schlich, R., Structure et age de l'ocean Indien Occidental, Memoire Hors-Serie 6, Paris, France, 103, 1975.
Schlich, R., E.S.W. Simpson, and T. L. Vallier, Introduction, in Simpson, E.S.W., Schlich, R. et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 25, 5-24, 1974a.
Schlich, R., E.S.W. Simpson, and T. L. Vallier, Regional aspects of deep sea drilling in the western Indian Ocean, Leg 25, DSDP, in Simpson, E.S.S., Schlich, R., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C., (U. S. Government Printing Office), 25, 743-760, 1974b.
Sclater, J. G., R. N. Anderson, and M. L. Bell, Elevation of ridges and evolution of the central eastern Pacific, J. Geophys. Res., 76, 7888-7915, 1971.
Sclater, J. G., C. Bowin, R. Hey, H. Hoskins, J. Peirce, J. Phillips, and C. Tapscott, The Bouvet Triple Junction, J. Geophys. Res., 81, no. 11, 1857-1869, 1976.
Sclater, J. G., and R. L. Fisher, The evolution of the east central Indian Ocean, Bull. Geol. Soc. Amer., 85, 683-702, 1974.
Sclater, J. G., R. Jarrard, B. McGowran, and S. Gartner, Comparison of the magnetic and biostratigraphic time scales since the late Cretaceous, in von der Borch, C., Sclater, J. G., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 22, 381-386, 1974.
Sclater, J. G., S. Hellinger, and C. Tapscott, The paleobathymetry of the Atlantic Ocean (in press), 1977.
Sclater, J. G., L. A. Lawver, and B. Parsons, Comparison of long wavelength residual elevation and free air gravity anomalies in the North Atlantic and possible implications for the thickness of the lithospheric plate, J. Geophys. Res., 80, 1031-1052, 1975.
Sclater, J. G., and D. P. McKenzie, The paleobathymetry of the south Atlantic, Bull. Geol. Soc. Amer., 84, 3203-3216, 1973.
Simpson, E.S.W., and R. Schlich et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 25, p. 884, 1974.
Smith, A. G., and A. Hallam, The fit of the southern continents, Nature, 225, 139-144, 1970.
Thiede, J., Sediment coarse fractions from the western Indian Ocean and the Gulf of Aden (Deep Sea Drilling Project Leg 24), in Fisher, R. L., Bunce, E. T., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 24, 651-765, 1974.

Thiede, J., Evidence from sediments on the Rio Grande Rise (SW Atlantic Ocean): Subsidence of an aseismic ridge, Amer. Assoc. Petro. Geol. Bull., (in press), 1977.

Thierstein, H. R., Mesozoic biostratigraphy of marine sediments by calcareous nannoplankton, Proc. 3rd Internat. Plankt. Conf. (Kiel, 1975), (in press), 1977.

van Andel, T. H., Mesozoic-Cenozoic calcite compensation depth and the global distribution of calcareous sediments, Earth Planet. Sci. Lett., 26, 187-194, 1975.

van Andel, T. H., and D. Bukry, Basement ages and basement depths in the Eastern Equatorial Pacific from Deep Sea Drilling Project Legs 5, 8, 9 and 16, Bull. Geol. Soc. Amer., 84, 2361-2370, 1973.

Veevers, J. J., Seismic profiles made underway on Leg 22, in von der Borch, C., Sclater, J. G., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C., (U. S. Government Printing Office), 22, 351-368, 1974.

Veevers, J. J., and J. R. Heirtzler, Bathymetric, seismic profiles, and magnetic anomaly profiles, in Veevers, J. J., Heirtzler, J. R., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 27, 339-382, 1974.

Vincent, E., Cenozoic planktonic biostratigraphy and paleooceanography of the tropical western Indian Ocean, Deep Sea Drilling Project, Leg 24, in Fisher, R. A., and Bunce, E. T., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C., (U. S. Government Printing Office) 24, 1111-1150, 1974.

Vincent, E., J. M. Gibson, and L. Brun, Paleocene and early Eocene microfacies, benthonic foraminifera, and paleobathymetry of deep sea drilling project sites 236 and 237, Western Indian Ocean, Deep Sea Drilling Project, Leg 24, in Fisher, R. L., and Bunce, E. T., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C., (U. S. Government Printing Office), 24, 859-886, 1974.

Vogt, P. R., and O. E. Avery, Detailed magnetic surveys in the northeast Atlantic and Labrador Sea, J. Geophys. Res., 79, no. 2, 363-389, 1974.

Watkins, N. D., B. M. Gunn, J. Nougier, and A. K. Baksi, Kerguelen: continental fragment or oceanic island?, Bull. Geol. Soc. Amer., 85, 201-212, 1974.

Weissel, J. K., and D. E. Hayes, Magnetic anomalies in the southeast Indian Ocean, in Antarctic Oceanology II, the Australian-New Zealand sector, edited by D. E. Hayes, A.G.U., Washington, D. C., 1972.

Weissel, J. K., and D. E. Hayes, The Australian-Antarctic discordance: new results and implications, J. Geophys. Res., 79, no. 17, 2579-2587, 1974.

Whitmarsh, R. B., Some aspects of plate tectonics in the Arabian Sea, in Whitmarsh, R. B., Weser, O. E., Ross, D. A., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C., (U. S. Government Printing Office), 23, 527-536, 1974a.

Whitmarsh, R. B., Summary of general features of Arabian Sea and Red Sea Cenozoic history based on Leg 23 cores, in Whitmarsh, R. B., Weser, O. E., Ross, D. A., et al., Initial Reports of the Deep Sea Drilling Project, Washington, D. C. (U. S. Government Printing Office), 23, 527-536, 1974b.

Worsley, T., The Cretaceous-Tertiary boundary crust in the ocean, Soc. Econ. Paleont. Mineral.. Spec. Publ., 20, 94-125, 1974.

Appendix I

The Construction of the Paleobathymetric Charts

In this section we outline in detail the basis and process by which we computed the paleobathymetric charts.

Sclater et al. (1971) have shown that for much of the ocean floor younger than 80 m.y.b.p. there is a simple relation between depth and age. Many authors have shown that this relation is compatible with a simple cooling model where new crust is intruded at the ridge axis which cools and contracts as the crust increases in age. Parsons and Sclater (1977) have demonstrated that for crust younger than 60 - 80 m.y.b.p. and older than 1 m.y.b.p. to the relative subsidence of the ocean crust, ΔH, follows within ±300 m the following simple empirical relation

$$\Delta H = 350 \sqrt{t} - 200$$

where t is in millions of years. For older ocean floor the depth follows a relation predicted by the plate model (Parsons and Sclater, et al., 1977). The closeness of the fit to this simple relation is a very strong agreement that the ridge crest topography at least in the range 0-70 m.y.b.p. or 2700 to 5500 m is dominated by simple conductive cooling of the originally hot crust.

The simple depth versus age relation has been obtained by averaging many closely spaced topographic profiles and with some modification probably holds for between 70 and 80 percent of the ocean floor. However, the absolute depth of the relation does not hold for four specific types of ocean crust (1) local topographic relief, (2) aseismic ridges, (3) localized regions of young crust that are anomalously shallow (for example, the Azores High or the Reykjanes Ridge) and (4) areas of crust which appear to have long wavelength topographic anomalies which may correlate with the long wavelength gravity field.

Fortunately, the first two and possibly the third region of anomalous crust may have simple explanations which make them readily adaptable to the normal subsidence relation. McKenzie and Bowin (1976) have demonstrated that most local topographic relief originates at the ridge axis by the construction of excess crust. This relief is fixed into the crust at the spreading center and remains with the crust throughout its history. Thus localized offsets from the subsidence curve for calculating CCD's with time can simply be accounted for by assuming the observed offset has occurred throughout the entire history of the crust. For the aseismic ridges, Detrick et al. (1977) and ourselves in an earlier section have shown that a similar model accounts for the subsidence of these features. However, in this case subsidence normally starts with the aseismic close to or above sea level. The third and fourth type of anomalous regions are much more difficult to model. Vogt and Avery (1974) and Sclater et al. (1977) have argued that the Azores high and the Reykjanes Ridges are localized topographic anomalies with their origin totally within the oceanic plate. If this is the case then these local regions will probably show the same subsidence curve as normal ocean floor except offset by a certain amount. The residual depth anomalies that correlate with the gravity field are much more difficult to model as they are thought to result from sub-lithospheric processes (Anderson et al., 1973; Menard, 1973 and Sclater et al., 1975) and it is not clear how the process responsible for the anomalies will vary with time. Fortunately apart from an area near Crozet Island another between Australia and Antarctica (Weissel and

Hayes, 1974) and the Bengal fan gravity low (Kahle and Talwani, 1973), these features are not widespread in the Indian Ocean and no allowance has been made for them in constructing the paleobathymetric charts.

For the paleobathymetric charts we have assumed that the floor of the Indian Ocean consists of only typical ocean floor and aseismic ridges. From the relation given by Parsons and Sclater (1977) it can be seen that the 3,000 m isobath corresponds to 2 m.y. old ocean crust and the 4,000 m and 5,000 m isobaths to approximately 20 m.y. and 50 m.y. old crust respectively. For the aseismic ridges we have assumed they were created close to sea level at a spreading center and have sunk with the crust to which they are attached.

Having determined the relation between depth and age we assume that this relation has been the same for the past 100 m.y. and use the histories of the relevant plate motions to determine the age of the ocean floor. First the number of plates to be considered in the history are determined and their relative histories designated by a series of rotation parameters which describe their history through time. In the Indian Ocean we assume four plates, Africa, India, Australia and Antarctica. From the rotation parameters there are two simple ways to construct charts of the age of the ocean floor. The first is to digitize the position of the ridge crest or the earthquakes which define the ridge axis and then to rotate these coordinates through the parameters given for the relation rotation of the plates. In this method it is necessary to rotate one plate with respect to another by the rotation prescribed for the given age. The ridge axis, between the two plates, is then rotated by half the angle of rotation and then by the rotations necessary to define the 2, 20, and 50 m.y. isochrons either side of the ridge axis. These rotations give the positions of the ridge crest and the 3,000, 4,000 and 5,000 m isobaths on the given reconstruction (Sclater and McKenzie, 1973; Sclater et al., 1977).

Unfortunately this simple method cannot be applied to the Indian Ocean because of the dramatic change in spreading direction around 36 m.y.b.p. For this paper, we digitized the magnetic lineations in the Indian Ocean and for each reconstruction we attached them to their relevant plate and rotated the plates by the necessary amount to overlap anomalies 13, 22 and 32 (36, 53 and 70 m.y.b.p.). The parameters for the 36 and 70 m.y.b.p. reconstructions are given in McKenzie and Sclater (1971) and for the 53 m.y.b.p. reconstruction they are presented in Table 4a. To determine the paleolatitude we rotated the plates with respect to a fixed Australia and then rotated Australia the distance necesssary to superimpose the paleomagnetic poles for Australia on the North Pole.

We then determined by eye, using the rotated lineations as a guide, the positions of 2, 20 and 50 m.y.b.p. isochrons on the given tectonic chart. For example, on the 36 m.y.b.p. chart the position of the 3,000 m contour was drawn on crust 38 m.y. old (anomaly 15). Anomaly 24 which has an age of 56 m.y.b.p. is 20 m.y. older than the crust at the ridge axis. Thus, the position of anomaly 24 on the 36 m.y.b.p. chart marks the 20 million year old isochron and hence the 4,000 m isobath. Similarly, the 5,000 m isobath on the 36 m.y.b.p. reconstruction is marked by the position of the 85 m.y.b.p. isochron. Anomaly 34 is approximately 80 m.y. old. Thus by extrapolating the age of the ocean floor a little beyond this anomaly it is possible to estimate the position of this isochron.

On the 53 m.y.b.p. reconstruction a position just beyond anomaly 32 (70 m.y.b.p.) was used to obtain the 4,000 m contour. The 5,000 m contour is given by the position of the 103 m.y.b.p. isochron. This was extrapolated from the tectonic history. For the 70 m.y.b.p. recon-

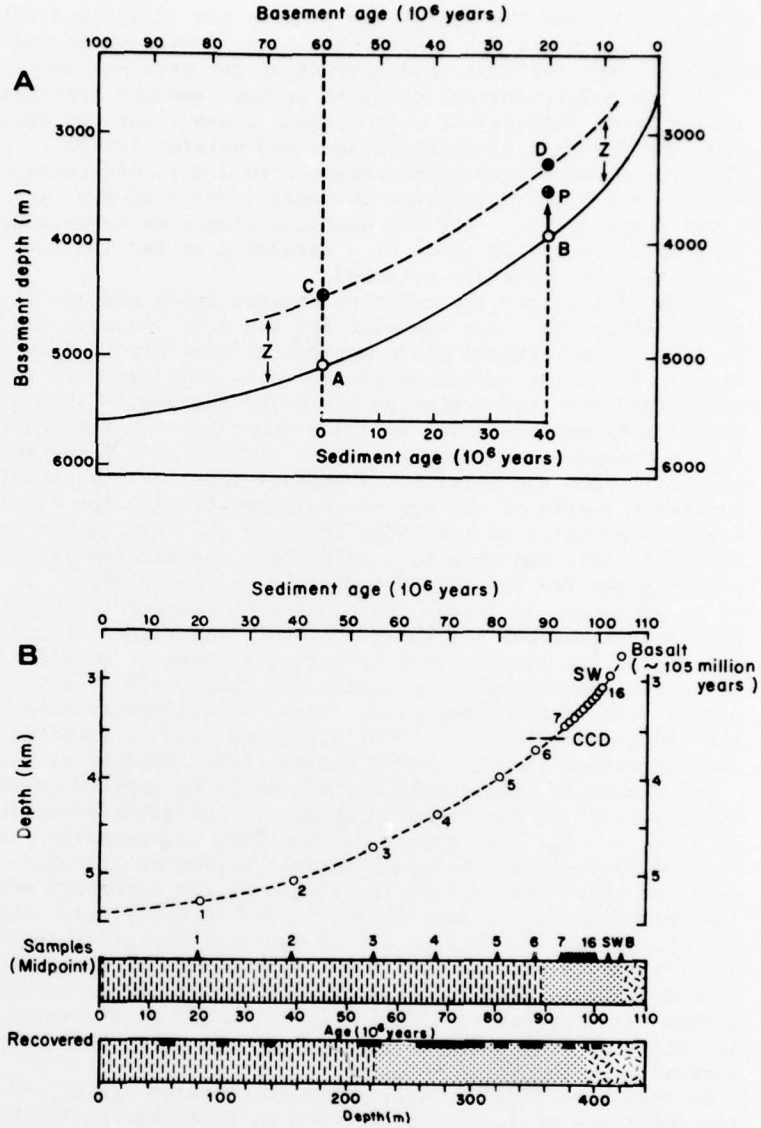

Fig. 10a. Paleodepth determination by vertical backtracking parallel to idealized subsidence track.
A and B: present depth and paleodepth (40 m.y.b.p.) on idealized curve;
C: actual size;
D: analogue to B on parallel curve;
Z: distance between A and C;
P: final paleodepth after correction for isostatic loading (see text) (after Berger and Winterer, 1974).

Fig. 10b. Backtracking of site 137, leg 14 (Hayes et al., 1972). Symbols from left to right: clay, calcareous ooze, basalt. The sample numbers represent core numbers from site 137 (after Berger and Winterer, 1974).

struction the 90 and 120 m.y.b.p. isochrons extrapolated from the tectonic histories were used to determine the 4,000 m and 5,000 m contours.

It is clear from the above analysis that only the 3,000, 4,000 and 5,000 m depths on the 36 m.y.b.p. reconstruction, the 3,000 and 4,000 m depth on the 70 m.y.b.p. reconstruction are known with any certainty.

Appendix II

Backtracking

In order to explain precisely what we did to compute the past depths of the calcium carbonate line we present here a precis of our method. A more complete description can be found in the excellent paper by Berger and Winterer (1974).

To determine the past depth of the carbonate line from Deep Sea Drilling data, we need to know its depth at the time the sediment column passes through the carbonate clay boundary. In order to determine this depth we make two basic assumptions, first, that sea level has not changed by more than 100 to 200 m since the Jurassic and second, that there is a simple relation between depth and age for oceanic crust that also has not changed since the Jurassic. Having made these assumptions we can immediately obtain an estimate of the depth of deposition from the standard subsidence curve if we know the age of basement and the age of the sediment in question.

We assumed the subsidence curve of Sclater et al. (1971) and Parsons and Sclater (1977) starting with 2,700 m as the depth for newly formed sea floor. The age of the basement defines the starting point (A) on the idealized subsidence curve, whereas the age of the sediment determines the distance we have to back track on this curve to find the depth (B) at which the sediment was being deposited (Figure 10a; basement age = 60 m.y.b.p.; sediment age = 40 m.y.b.p.; A = 5,200 m; B = 4,000 m. These depths are slightly shallower than those used by Berger and Winterer (1974). This results from the fact that we have used a slightly shallower subsidence curve). However, for two reasons this method is too simple. First, a particular piece of the sea floor does not follow the absolute paleodepth curve rather it subsides parallel to the curve. Second, we have neglected to correct for the isostatic adjustment of the sediment. To correct for these features we use actual site depth and depth from the bottom of the hole. We relocate the curve parallel to itself by the vertical distance between the actual site depth (C) and the expected depth (A). The subsidence curve now goes through the actual depth (C) and we find a preliminary paleo-depth (D) as before. To compensate for isostatic loading we go downward from point (D) by the total depth of sediment in the hole and then up again by two-thirds of the depth from the bottom of the hole of the sediment in question to obtain point (P). The correction for sediment loading was calculated from the relation given by Sclater, et al. (1971, Appendix III) assuming a mean density of 1.8 g/cm^3 for the sediments. For example for Z = 700 m, a total sediment thickness of 600 m and a depth from the bottom of the hole for 40 m.y.b.p. sediment of 500 m the final paleodepth is 3,550 m (Figure 10a).