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MESOZOIC-CENOZOIC SEDIMENTS OF THE EASTERN INDIAN OCEAN

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ABSTRACT

Nineteen sites have been drilled in the Eastern Indian Ocean. Sediments range in age from Oxfordian (155 m.y.) to Recent. They are divided acoustically into a lower transparent unit, a layered unit, and an upper transparent unit. These generally correspond to pelagic clay, calcareous ooze, and siliceous ooze respectively. The pelagic clays appear to have been deposited below the lysocline. Locally, these clays are rich in zeolites, and also in places in nannofossil remains. The clays are highly siliceous; the silica is mainly of terrigenous origin, some is of biogenic origin, and a small amount may be volcanic. The calcareous oozes are composed mainly of foraminiferal and nannoplankton remains. These oozes are particularly abundant on shallow ridge and plateau sites, above the lysocline, but in places turbidity currents have also deposited calcareous oozes well below the lysocline. The siliceous oozes appear to be associated with the equatorial zone of high productivity. Other sediment types include volcanogenic mud, sand, and gravel, and pyroclastics, all of which are mainly restricted to the ridge and plateau sites. Glauconitic calcareous sediments are also common at some of these shallow sites. Terrigenous silts and clays form a thick sequence in the northwest corner of the Eastern Indian Ocean, where they have been deposited by turbidity currents associated with the Late Cenozoic Bengal Fan.

Compositionally, the Eastern Indian Ocean sediments are similar to oceanic sediments from elsewhere, although less rich in some metals. Regional trends cannot be established here but several inter-element associations are evident. The $CaCO_3$ content of the sediments varies markedly, though the general trend is of poorly calcareous Mesozoic sediments (with a significant increase in the Albian) and richly calcareous Cenozoic sediments. The rate of sedimentation also varies widely but there appears

to be a correlation of calcareous periods with times of rapid sedimentation. The pattern of sedimentation for the Mesozoic suggests that most of the sediment was derived from Australia, with a minor source from the south (Antarctica) and possibly also a small contribution from the northwest. In the Cenozoic the dominant sediment source was still from the east but was mainly calcareous material derived from the shelf and slope. Bengal Fan sediments form a major contribution in the northwest.

Overall, sedimentation was discontinuous at most sites, with numerous unconformities within the sequence. These gaps in the records and also the rate and type of sedimentation is related to the pattern of continent dispersal in the Mesozoic-Cenozoic. The northward movement of India was important as it opened a seaway to the west of Australia and enabled cool erosive currents to enter the region, thus modifying the sediment pattern and producing major hiatuses. Subsequently, the influx of Antarctic Bottom Water, and later the development of the Circum-Antarctic Current have been important in influencing sedimentation in the Eastern Indian Ocean.

INTRODUCTION

The Eastern Indian Ocean is a geologically complex area of ridges, plateaux and basins. It has been investigated by Legs 22, 26 and 27 of the Deep Sea Drilling Project, and also to a limited extent by Leg 28. Nineteen sites were drilled within the study area (Figure 1) in a variety of physiographic-geologic locations ranging in water depth from 1253 m to 6243 m, including the Naturaliste Plateau (sites 258, 264); on ocean ridges such as Broken Ridge (site 255), and the Ninetyeast Ridge (sites 214, 217, 253, 254); and on the Bengal Fan (site 218). Nine sites (211, 212, 213, 256, 257, 259, 260, 261, 263) were drilled in ocean basin locations (the Wharton Basin and its subsidiary Cocos Basin). The Bengal Fan sediments (site 218) are dealt with elsewhere in this publication and consequently will not be considered in detail here. Site 262 in the Timor Trough is regarded as being geologically outside the Indian Ocean. One site (215) was drilled in the central Indian Basin.

The stratigraphic information obtained from the nineteen drill sites in the Eastern Indian Ocean is summarized in Figure 2. Up to 773 m of sediment was drilled in the Bengal Fan (site 218), 746 m in the Wharton Basin (site 263), and 664 m on the Ninetyeast Ridge (site 217). The oldest basement penetrated in the region was at site 261 (155 million years) in the northeast corner of the Wharton Basin. The youngest basaltic basement intersected was at site 254 on the Ninetyeast Ridge, with an age of about 40 million years.

The aims of the various DSDP legs in the region were to:

(i) obtain the oldest oceanic basement in the Eastern Indian Ocean and hence date the initial break up of Gondwanaland;

(ii) determine the stratigraphy and biostratigraphy of the various ocean basins, ridges and plateaux and so establish their age, nature, and history;

(iii) establish the paleoenvironment of the area and the effects of the initiation of the Circum-Polar Current;

(iv) relate ocean basin history to the continental geologic record;

(v) determine the history of the Bengal Fan and hence the course of Neogene denudation of the Himalayas.

The physical and chemical composition of the Mesozoic-Cenozoic sediments of the Eastern Indian Ocean is relevant to all of these questions. This paper will examine the regional stratigraphy, sedimentology and geochemistry, and will attempt to relate them to the history and paleoenvironments of the Mesozoic-Cenozoic Eastern Indian Ocean.

SEDIMENT THICKNESS AND DISTRIBUTION

The sediments of the Eastern Indian Ocean range in age from Oxfordian (155 my) to Recent. The thickness of sediments deposited since the initial rifting and establishment of open ocean conditions, range from 100 m or less in the western portion of the region to more than 1000 m adjacent to the Australian continental shelf and within the Bengal Fan (Fig. 3). The isopachous map obtained by incorporating the results of Ewing et al. (1969) and the DSDP seismic profiles (Fig. 3) serves to illustrate the dominant sediment sources in the region; the Australian continent to the east and the Ganges and Brahmaputra Rivers to the northwest. The thick sediments to the south of the Indonesian archipelago are thought to be more the result of increased sedimentation associated with the equatorial zone of high productivity than a consequence of proximity to the volcanic arc. Another general feature which is apparent from figure 3 is the relatively thick sedimentary sequence on ridges, plateaux and rises i.e. above the carbonate compensation depth, where thick carbonate sequences are able to accumulate. Conversely, in the ocean basins (below the carbonate compensation depth), the sedimentary sequence is comparatively thin, with local exceptions (e.g. near site 212) where sediments have been trapped in small basins.

Previous workers (Ewing et al., 1969; Veevers, 1974; Veevers and Heirtzler, 1974a) have shown that in many areas, particularly the abyssal zone, the sedimentary sequence consists of three acoustically distinct zones: a lower transparent unit, a middle layered unit, and an upper transparent unit (Fig. 4). Deep Sea Drilling has revealed that the three acoustic units may be correlated with particular lithologies, as shown in Figure 2. The nature of the various sedimentary units will be dealt with in detail later, but it is apparent from Figure 2 that the lower transparent unit is a brown, grey and green clay, and claystone with minor nannofossil ooze. The layered unit consists predominantly of light-coloured nannofossil or foraminiferal-nannofossil ooze with some graded beds. The upper transparent unit is a siliceous diatom-radiolarian ooze. The vertical and lateral extent of these three units within the Wharton Basin is shown schematically in Figure 4. On the shallower ridges and plateaux, the three-fold division is generally absent. In the ocean basins, the boundary between the lower transparent and the layered unit is very sharp, apparently corresponding to a well defined unconformity in many areas (Fig. 5). Comparison of the acoustic record with the drilling results (Fig. 2) indicates that in most areas this boundary may be correlated with a major Mesozoic-Tertiary break. The only instance where the boundary between these two acoustic units extends down into the Cretaceous is at site 212 (von der Borch et al., 1974). Conversely, to the south the lower transparent unit extends up into the Cenozoic (e.g. at site 257).

Looking briefly at the extent and thickness of the lower transparent unit (Fig. 6), the general picture is one of marked thinning to the west. It should be pointed out that the data from which this and the other isopachous maps in this paper are plotted are inadequate, and at best the maps represent no more than an approximation. In addition the present day oceanic configuration shown is obviously not valid for the Mesozoic and early Cenozoic. Nevertheless, these maps do indicate regional trends. The overall trend in Figure 6 is consistent with derivation of the sediment (predominantly clay) from the east, i.e. Australia. There is no indication from this figure of a westerly sediment source. There is a suggestion of a minor source area to the north or northwest the data here are insufficient to be certain of this, but information discussed later gives further support for this suggestion and also for some contribution from Antarctica in the Cretaceous.

The layered unit has a more complex distribution pattern (Fig. 7). Again the section is thickest to the east, particularly adjacent to the northwest Australian shelf where thick calcareous oozes are developed above the carbonate compensation depth. In addition, the layered unit is thick on the ridges and plateaux. In the abyssal zone it becomes much thinner and is absent in many places. Locally, the layered unit is ponded in basins (such as near site 212), well below the carbonate compensation depth. These sediments have probably been deposited by the mass movement of calcareous sediment from the slope to below the lysocline. A second type of acoustically layered sediment as exemplified by the seismic profile at site 218 (von der Borch et al., 1974, p.331) is present near the Bengal-Nicobar Fan. However, unlike the layered sediments elsewhere, these sediments are non-calcareous or poorly calcareous, and represent the distal portion of the Bengal Fan turbidites. The Bengal Fan deposits are not included in the isopachous map (Fig. 7).

The upper transparent unit is of very limited extent. It is present as an east-west band across the northern part of the Eastern Indian Ocean, thinning rapidly to the south. Acoustically transparent sediments occur only at sites 211, 213, 215, 260 and 261 (Fig. 8).

A minor amount of volcanic ash is present in the sequence, but there appears to have been little input of terrigenous sediment from the Indonesian archipelago, probably because of the trapping of sediment by the Java Trench. Most of the sediment is siliceous biogenic material associated with equatorial high productivity.

So far, discussion of sediment thickness has been concerned primarily with the abyssal zone. Data from the ridges and plateaux are less abundant, although as mentioned earlier the layered unit (calcareous oozes) is commonly thicker on the shallow features than in the abyssal zone. An additional trend which might be expected is that as the Ninetyeast Ridge becomes progressively older and deeper to the north, (Pimm, 1974a; Sclater and Fisher, 1974; Luyendyk and Davies, 1974), the sediments would also become thicker. This does not appear to be the case either from the isopachous map (Fig. 3) or from the information provided by drill sites on the Ridge (sites 217, 216, 214, 253 - Fig. 2). In fact, sediment thickness is highly variable along this ridge; a rugged topography has produced local basins in which there are thick sequences of ponded sediments, and topographic highs from which sediment has been eroded. In addition, input of volcanogenic material, such as at site 253 (Fig. 2) results in marked local increases in sediment thickness.

The sediment thickness across marginal plateaux is rather more uniform, although Petkovic (1975a, b) has shown that the sediment thickness on the Naturaliste Plateau ranges from 1 km or less on the western flank, to over 2 km on the eastern flank.

LITHOLOGY

The lithology of sediments at DSDP sites in the Eastern Indian Ocean has been previously discussed by Pimm (1974a), Luyendyk and Davies (1974), Robinson et al. (1974), and Bezrukov (1974), and this summary draws extensively upon their work. The general range of sediments on the present day sea floor is shown in Figure 10. It has been indicated earlier that a three-fold division of the sedimentary sequence is possible, based on acoustic characteristics which are in turn related to lithology. However, the detailed picture is much more complex with a wide range of lithologies present at both the deep-water and shallow-water drill sites. This range of lithologies, based mainly on shipboard examination of smear mounts, is indicated in Figure 2. They may be grouped into a smaller number of lithological units. The lateral and vertical disposition of the various sediment types in the abyssal zone and shallow-water sites is shown in Figure 10. Figure 10 is not meant to represent a cross-section across the Eastern Indian Ocean; it merely illustrates schematically the facies changes which occur between drill sites. Nevertheless, again in the abyssal zone the trend is of abundant siliceous oozes to the north and west, calcareous oozes in the center, and clays to the south. A feature not evident earlier is the characteristic occurrence of clays rich in nannofossils, at the base of the sequence. The lateral changes in the shallower drill sites are rather different. There is a general lack of clays on ridge and plateau sites, except at site 258 on the Naturaliste Plateau where clays are abundant at the base of the section. As is to be expected at these shallow sites above the carbonate compensation depth, calcareous oozes are the dominant sediment type; however, as a result of the volcanic origin of many of these features (e.g. the Ninetyeast Ridge), volcanogenic sediments are common in places. The cherty limestones are also unique to the ridges and plateaux. Thick silts and clays associated with the Bengal Fan are present in the northwest corner of the Eastern Indian Ocean. The various sediment types will now be discussed.

DETRITAL SEDIMENTS

Siliceous clays and claystones

Siliceous clays and claystones occur throughout the Mesozoic-Cenozoic of the abyssal zone drill sites but are particularly abundant in the Mesozoic where they comprise the majority of the lower acoustically transparent unit. They contain the highest percentage of clay-size material (82% clay, see Table 1) and are also the most siliceous of the sediments, with an average SiO_2 content of 59.3 percent (Table 2). Most of the silica is in the form of microcrystalline or cryptocrystalline quartz and crystobalite. The degree of induration of the clays appears to correlate directly with the abundance of silica in the sediment and possibly also with the depth below the sediment-water interface.

The clays range from pale brown, pale green and pale grey to olive grey and black. The classical brown or red-brown pelagic clays are comparatively rare. In many cases the darker the sediment the higher the percentage of organic carbon; the clays of site 263, contain up to ten percent organic carbon, compared with an average of about 0.5 percent organic carbon in most deepsea clays. Fossils are generally absent or rare, but bioturbation is common in places (Fig. 11). Luyendyk and Davies et al. (1974) report that at site 258, bioturbation in the form of horizontal or sub-horizontal burrowing is ubiquitous throughout more than 200 m of clays. In some cases, color mottling, probably of biogenic origin, is also comparatively common. Where there has been little or no biogenic activity the clays and claystones are finely laminate.

Mineralogically the siliceous clays and claystones are composed of approximately equal amounts of quartz/crystobalite and clay minerals, with minor to trace feldspar, iron oxides, zeolites, calcite (from nannofossils), detrital heavy minerals, and apatite (mainly from fish remains, though Cook (1974a) records a thin phosphorite at site 259). Some of the silica is probably of terrigenous origin, reaching the area by aeolian transport particularly from Australia. However, a significant proportion of the silica is probably of biogenic origin, the silica from the siliceous organisms having been dissolved and redistributed within the sediments. The clay minerals appear to be predominantly of detrital origin, with kaolinite most common and illite, chlorite, montmorillonite and palygorskite present in varying amounts. Venkatarathnam (1974), has shown that three provinces may be delineated in the Eastern Indian Ocean on the basis of sediment source - the Australian Province which extends as far north as 15°S and as far west as the Ninetyeast Ridge, the Indonesian province which extends south and west of the Indonesian archipelago, and the Ganges Province which comprises the region covered by the Bengal and Nicobar Fans. The abundance of kaolinite in most of the siliceous clays and claystones indicates their location was mainly within an ancestral Australian province. Kaolinite is particularly common at site 263 with the kaolinite occurring not only in the form of dispersed clay size material but also as pellets (Fig. 12), some of which may have formed in situ as kaolinite blebs or by the alteration of pre-existing pellets (Fig. 13). Others are probably of intraclastic origin. This abundance of kaolinite together with a high sedimentation rate is taken to indicate the proximity of site 263 to a fluviatile source and probably also comparatively shallow (?bathyal rather than abyssal) conditions. Elsewhere, siliceous clays were mainly deposited in deep water. The volcanic component in the clays throughout much of the Eastern Indian Ocean seems to be comparatively minor, although at site 211 montmorillonite is an abundant as kaolinite. Whether the montmorillonite has formed by in situ alteration of volcanic material or is derived from continental volcanic sources is not certain. In addition to modifying the mineral assemblage, diagenesis in the siliceous clays also results in nodules of dolomite (Fig. 14), barite, siderite and calcite, and some pyrite spheres. Manganese micro-nodules are present but comparatively rare.

Zeolitic clays

Zeolitic clays are similar in appearance and composition to siliceous clay and claystones, but are less abundant. They are generally brown to yellow brown; bedding ranges from poor to moderate and from lenticular to laminate. Bioturbation is seldom present. They are more silty than the siliceous clays (Table 1), probably owing to the presence of silt-size zeolite crystals. The presence of zeolites is similarly reflected in the higher percentage of Na_2O and CaO (Table 2). Mineralogically, the two types of clay are similar except for the abundance of zeolites (up to 10% of the total sediment), particularly clinoptilolite or phillipsite. Pimm (1974a) suggests on the basis of the Leg 22 data that clinoptilolite is the dominant zeolite in Eocene and older sediments whereas phillipsite is dominant in the younger sediments. Elsewhere, this trend is not evident. Zeolitic clays occur sporadically throughout the post-Aptian/pre-Pliocene section of the abyssal zone drill sites (Fig. 2). They are generally absent from the ridge and plateau sites although zeolites are common in many of the sediments of these shallower sites, particularly in the volcanogenic marine sediments. At site 214 zeolites are also present in coal-bearing non-marine sediments.

In general the zeolite crystals are euhedral (Fig. 15); in some instances they are scattered throughout the clay; commonly they are present as clusters, in some cases infilling radiolarian moulds (Robinson et al., 1974; Plate 1). This mode of occurrence suggests that the zeolite crystals have undergone little or no transport and that many could have formed diagenetically. Although there is a notable absence of volcanic glass, a volcanic association for the zeolites is supported by the abundance of palygorskite and montmorillonite in the zeolitic clays. Robinson et al. (1974) suggest that the silica in the zeolitic clays may also be a volcanic origin and this is supported by the presence of minor volcanic quartz (Fig. 16); however, the close similarity of the trace element content (particularly barium) in the zeolitic and siliceous clays (Table 4) may be taken as evidence that the silica of the zeolitic clays is also in part of biogenic origin despite the apparent lack of siliceous fossils in most of these sediments.

Nannofossil Clays

Nannofossil-rich clays represents an intermediate member in a continuous sediment sequence between the two end members, siliceous clay and nannofossil ooze. Consequently it is not a distinctive sediment as are most of the other sediment types discussed. As with siliceous and zeolitic clays, nannofossil clays are found mainly in the abyssal zone drill holes. The only exception to this is site 217, but there the nannofossil clays result from a mixing of nannofossil ooze with distal clays of the Bengal Fan rather than with pelagic clays. Nannofossil clays vary in composition from the siliceous clays primarily in their abundance of calcium carbonate, averaging 7.4 percent total CaO plus CO_2 (Table 2) owing to the incorporation of calcareous nannofossil tests into the clays.

The nannofossil clays range in age from Valanginian to Recent, but it is evident from Figure 10 that they are most abundant at the base of the sequence. This is particularly so at sites 213, 211, 261, 260, and 257. The implication of this preferred stratigraphic location is that this location corresponded with a time shortly after the formation of a mid-ocean ridge when the sea floor was elevated above the carbonate compensation depth. Consequently, the fragile nannofossil tests would have been incorporated into the sediments being deposited on the flanks of the rise rather than being dissolved out.

Sandy muds and muddy sands

Detrital sediment falling into the categories sandy clay, clayey sand, silty sand, sandy silt, and sand-silt-clay of Shepard (1954) is here referred to by the general term sandy mud/muddy sand. Such sediments are comparatively rare in the Eastern Indian Ocean drill holes. They appear to occupy two stratigraphic locations, at or near the base of the sequence (site 254), or within a turbidite sequence (sites 211, 215 (?), and 218).

The basal sandy muds/muddy sands of site 254 are typically poorly sorted and associated with conglomerates, including some containing volcanic pebbles. Bioturbation and macrofossil fragments are comparatively common, resulting in the destruction of most laminations. Some intraformational breccias are present. These basal sandy muds/muddy sands are poorly calcareous; they contain abundant glass shards and montmorillonite, with phillipsite commonly present. Pyrite is also relatively abundant. Glauconite, kaolinite, clinoptilolite, analsite, and a variety of heavy minerals are present in trace amounts. These sediments appear to have formed under very shallow water conditions, which were at times sufficiently vigorous to produce intraformational breccias. The basaltic source area was evidently in close proximity as indicated by the coarseness of the associated sediments.

The sandy muds/muddy sands of the turbidite sequence contain up to 15 percent calcite derived from included microfossils, in contrast to the poorly calcareous basal sandy muds/muddy sands. They are, in addition, finer-grained, with no associated conglomerates. Feldspar is abundant, comprising up to 85 percent of the total sediment in places; heavy minerals and opaques each comprise up to 5 percent of the total sediment. Thompson (1974) discusses the heavy mineral assemblages and concludes that the source area was dominated by metamorphic and acid igneous rocks. This is consistent with a Himalayan source area. Using mineralogical and textural data it is possible to show that at site 218, there have been four major pulses of relatively coarse terrigenous sedimentation. The second pulse was of sufficient magnitude to reach as far as site 211, a distance of almost 4000 km from the head of the Bay of Bengal. The turbidity flow which produced these sediments was evidently of considerable magnitude, though the distance was such that only the distal portion of the sediment load reached the vicinity of the drilling sites. Consequently these sediments are not associated with rudaceous sediments as is the case with basal sandy muds and muddy sands. Clearly then, there are two genetic types of sandy muds and muddy sands distinguishable by their stratigraphic location and the nature of the associated sediments: the sandy muds/muddy sands of the deep water turbidite deposit; and those of the basal unit which are commonly coarse because of their shallow-water depositional environment and frequently contain volcanogenic material because of their proximity to basalt.

Sand and gravels

Sands and gravels composed of detrital (non-calcareous) material are not found at any of the ocean basin sites with the possible exception of site 263 where a few thin laminae composed of sand-size quartz grains are present near the base of the thick clay sequence. However, most of the sand-size material at site 263 is composed of kaolinite (Figs 12, 13), which has undergone only very minor transportation, and which may have formed authigenically. Therefore the detrital nature of this kaolinite sand is rather uncertain.

Sands and gravels are more common on the ridge and plateau sites, particularly sites 254 and 255 where the sands and gravels are of Eocene-Oligocene age, and site 264 with Campanian or Santonian sands and gravels. At site 254 and 264 these coarse sediments are a relatively short distance above the sediment/basalt contact. The gravel at site 255 rests directly on the Santonian/Eocene unconformity (Fig. 2). Therefore in each of these cases the conglomeratic sand is a fairly typical basal conglomerate. The gravel at site 255 is mainly composed of fragments of the underlying Santonian limestone and chert, including abundant reworked fossil fragments. At sites 254 and 264 the clasts are up to 10 cm in diameter, and are typically basaltic. Such conglomerates could perhaps be regarded as volcanogenic rather than detrital (see later).

VOLCANOGENIC SEDIMENTS

It is apparent from the previous discussion that in the oceanic regime it is difficult at times to clearly identify a sediment as detrital or volcanogenic. Conglomerates commonly contain basalt clasts, and zeolitic clays are composed of abundant material of probable volcanic origin. In some cases, it is not clear whether many of the fragments are clasts within a volcanogenic sedimentary rock or lithic fragments in a pyroclastic rock. In this section, only those sediments of clear volcanic affinities are considered. Such sediments are found only on the ridges and plateaux.

Volcanogenic sands and gravels

Volcanogenic gravels (possibly with some detrital affinities) occur, as previously mentioned, at sites 254 and 264. Hayes et al. (1975) report that the conglomerate at site 264, which is about 38 m thick, is composed of subround pebbles up to 6 cm diameter of basalt and vitrophyre in a tuffaceous sandy matrix, cemented by sparry calcite. The gravelly unit at site 254 is 91.5 m thick although gravel forms a minor amount of the total thickness. The clasts are subround to angular pebbles, up to 10 m diameter, composed of glassy or fine-grained porphyritic basalt. Ferruginization and pyritization are common, probably as a result of hydrothermal alteration associated with the underlying basalt.

Volcanogenic sands and gravels within a predominantly volcanic ash sequence are present in the lower part of the Ninetyeast Ridge sequence at sites 214, 216 and 253. At site 253 the volcanogenic sequence is 388 m thick, and consists mainly of altered vitric ash and lapilli. Davies and Luyendyk et al. (1974) report that most of this tuffaceous material has undergone some aqueous modification such as the rounding of glass shards. Most of the clays present in this sequence are believed to be the result of situ alteration of fine-grained vitric tuffs. Montmorillonite and calcite are the dominant minerals, with minor plagioclase and zeolites (phillipsite, clinoptilolite, analcite) and traces of glauconite (probably an alteration product of volcanic glass), cristobalite, pyrite, and other accessory minerals. The site 253 pyroclastics were studied in some detail by McKelvey and Fleet (1974). They conclude that these pyroclastics were produced primarily by the fragmentation of basaltic lavas quenched by sea water. Extensive replacement of the tuffs by smectites and the presence of analcine and calcite cements as a result of diagenesis have markedly affected the geochemistry of these rocks. McKelvey and Fleet (1974) nevertheless consider that the bulk chemistry and particularly the rare earth geochemistry are consistent with a mantle plume origin for the Ninetyeast Ridge.

The volcanogenic sediments at sites 214 and 216 are rather less developed, but have many features in common with site 253. At sites 216 and 253, and the upper portion of the volcanogenic sequence at site 214, micarb fragments of microcrystalline calcite of uncertain origin is abundant. The micarb may be derived from nannoplankton, primary precipitation of calcium carbonate, or the in situ alterations of glass. A biogenic origin for at least some of the micarb is supported by the presence of thin laminae of nannofossil ooze or chalk in places, the occurrence of scattered macro-fossils within the sequence, and locally abundant bioturbation. These biogenic features also offer clear support for a submarine site of deposition for the volcanogenic deposits at sites 216 and 253. However the tuffs at site 214 (Unit 3 of von der Borch et al., 1974) appear to be almost totally pyroclastic and do not contain any marine fossils. The presence of interbeds of lignite up to 80 cm thick, which are believed by Cook (1974) to be autochthonous, offers clear evidence of a terrestrial (e.g. delta or swamp) environment. Pimm (1974a, Fig. 18) indicates that a few thin beds (up to 15 cm) of rhyolitic ash ranging in age from Pliocene to Recent are present in the northern part of the Eastern Indian Ocean. These deposits appear to be derived from the nearby volcanic province of the Indonesian archipelago, whereas the thicker, more ancient volcanogenic deposits are related to tectonism and volcanism within the Indian-Australian plate.

BIOGENIC SEDIMENTS

The biogenic sediment of the Eastern Indian Ocean are overwhelmingly calcareous ooze and chalk, with only minor siliceous ooze. In many places they are admixed with varying amounts of detrital sediments, particularly clays, or more rarely with volcanogenic sediments. There is consequently a continuous series from pure oozes to pure clays or volcanic ash. In many cases, it is the degree of admixing of the non-biogenic components which is responsible for the differences in color, texture, mineralogy, etc of the various oozes rather than changes in the biogenic material. In some instances, the original biogenic nature of the sediments may be masked by diagenesis. As indicated earlier, much of the siliceous clays and claystones may in fact be of biogenic origin though there is now only indirect evidence for this, such as the higher than normal concentration of some trace elements.

Foraminiferal-nannofossil and nannofossil ooze and chalk

Calcareous ooze is abundant at most drill sites in the Eastern Indian Ocean (Fig. 10), particularly the Cenozoic portion of the sequence. These calcareous sediments comprise the majority of the acoustically layered unit, which is thickest on the eastern side of the study area (Fig. 3). Most calcareous oozes are composed of mixtures of foraminiferal and nannofossil remains (Fig. 17); some are composed exclusively of nannofossils; few, if any, are entirely foraminiferal. It appears that nannofossil ooze is commoner at the base of the sedimentary sequence, particularly in the ocean basin sites, whereas foraminiferal-nannofossil ooze is more common in the upper part of the sequence. The lack of a calcareous ooze composed exclusively of foraminiferal remains is probably a reflection of the ubiquitous nature of nannoplankton. Conversely, the abundance of calcareous ooze composed exclusively of nannofossil remains is the result of these remains being more resistant to dissolution (resulting in a depressed carbonate compensation depth for nannoplankton) than the calcareous tests of pelagic foraminifera. Work by Pimm (1974a) and Berggren et al. (1974) on the species distribution of foraminifera in Leg 22 drill holes indicates that not only do foraminifera as a whole decrease in abundance down many of the drill holes, but in addition at sites 214, 216 and 217 they found that the foraminiferal species least resistant to dissolution are the first to disappear. This probably is the result of increasing dissolution in progressively deeper water, although the possibility of diaganetic dissolution within the sedimentary column cannot be completely discounted.

The calcareous oozes range from pink to greyish orange, light brown, and green depending on the abundance of clays. Bedding ranges from thin to laminate; graded beds are present in places. The foraminiferal-nannofossil ooze which contain 25.6 percent sand-size material is markedly coarser-grained than the nannofossil ooze (Table 1), which contains an average of only 5.9 percent sand. The calcareous oozes are composed predominantly of low-magnesian calcite, (though aragonite is also abundant at the top of site 263), with minor amounts of clay, detrital quartz, feldspar, zeolites, pyrite (commonly found in the tests of the foraminifera; Fig. 18), and accessory heavy minerals. The chemical composition of the calcareous oozes is somewhat variable, depending on the amount of detrital and volcanogenic material included in the ooze. Overall however, the foraminiferal and the nannofossil oozes are chemically very similar (Table 2).

Despite a large measure of uniformity within the various calcareous oozes, there are three distinct deposition locations (Fig. 10): (i) Near the base of the sedimentary sequence. This probably corresponds to the period shortly after the development of a spreading ridge when the sea floor in that area was above the carbonate compensation depth. In general, these calcareous oozes are nannofossil-rich and appear to be particularly well developed in the Mesozoic. (ii) Cenozoic calcareous oozes (ranging into the Recent) which are in ocean basin locations well below the carbonate compensation depth, and yet are highly calcareous. This location, together with the presence of some graded beds, and the laminated nature of the deposits indicate that they have probably been deposited below the carbonate compensation depth in response to mass movement (turbidity flows). This is also supported by the many comminuted foraminifera found in these sediments and also by the presence of reworked fossils from older units. (iii) Cenozoic calcareous oozes (ranging into the Recent) which are on ocean ridge or plateau locations above the carbonate compensation depth. These deposits have formed by the settling of calcareous remains through the water column, collecting on the sea bottom at locations above the carbonate compensation depth and therefore subject to little or no dissolution.

Micarb ooze and chalk

Ooze and chalk composed mainly of fragments of calcite (micarb) of uncertain origin are referred to in the DSDP scheme for sedimentary rocks as a micarb ooze, or if lithified as a micarb chalk. Micarb fragments are a common component of many of the foraminiferal or nannofossil oozes, but micarb chalk is present only in the northern part of the Eastern Indian Ocean (Fig. 10), particularly at sites 214, 216 and 217. The micarb chalk at sites 214 and 216 forms a distinctive unit approximately 60 m thick, whereas at site 217 it occurs mainly as interbeds within a volcanogenic sequence. It ranges from light grey to grey green and olive grey; some interbeds of mud are present but generally bedding is poorly developed. Silt-size calcite fragments form up to 80 percent of the total sediment, with a few recognizable foraminiferal, nannofossil or macrofossil (Inoceramus; oysters) fragments. Other components include clay (up to 20%) and glauconite (up to 5%) with minor silica (mainly of biogenic origin), quartz, feldspar, pyrite, dolomite, and apatite, and trace amounts of various heavy minerals. The micarb chalk is very fine-grained containing on average only 0.1 percent of sand-size material (Table 1). This fine fragmentary nature of the micarb chalk, together with the presence of glauconite and rare macrofossils indicate a very shallow-water environment of deposition. There is a physical problem in fragmenting particles as fine as micarb material (less than 0.5 mm) even in a vigorous environment and this could be taken as supporting a direct carbonate precipitate origin. However, the associated fossils and minerals do not seem to support a chemical origin, and a biogenic origin is considered most likely.

Cherty limestones and chalks

Cherty carbonates are of fairly limited distribution. They are found only in ridge or plateau locations, at sites 217, 255, 258 and 264 (Fig. 10). They are also restricted in time to the Eocene-Paleocene and the Santonian-Campanian (Fig. 2). The Tertiary cherty limestones are light grey to grey brown nannofossil chalks composed predominantly of nannofossils with some foraminiferal and siliceous remains, minor amounts of clay, and traces of volcanic quartz. Chert is present as scattered light grey nodules and irregular patches. Chalk showing various degrees of silicification, as well as siliceous infillings of foraminifera, occurs sporadically. These Tertiary siliceous carbonates are clearly biogenic calcareous deposits which have accumulated above the lysocline. Although some biogenic silica is present, most of the silica is secondary and of uncertain origin.

The underlying Late Cretaceous cherty carbonates are somewhat thicker and coarser-grained. They are composed of abundant nannofossils, but it addition also contain abundant foraminifera and fragments of Inoceramus. Micarb makes up 5-20 percent of the limestone; dolomite rhombs are present in places, particularly at site 217 where there is 60 m of dolarenite chert and claystone. Clay occurs in varying amounts. Glauconite, mica, collophane, and pyrite are all present in trace amounts. The silica occurs as black or grey chert nodules and veins, as patches of silicified or partly silicified limestone, and as a siliceous matrix. At site 217, von der Borch and Trueman (1974) found a positive correlation between the abundance of silica and the abundance of dolomite rhombs; they conclude that there must be a genetic association, both having formed diagenetically in response to prevailing conditions below the sediment-water interface. The origin of the silica is not clear though von der Borch, Sclater et al. (1974) make the observation that at site 217 siliceous remains decrease in abundance as chert becomes more common. The depositional environment for the cherty limestone appears to have been comparatively shallow. This is indicated by the fragmentary nature of the shells, the presence of abundant burrows, and the occurrence of cross-beds. It is suggested by von der Borch and Trueman (1974) that the cherty carbonates at the base of the section at site 217 represent a reef complex, and they consider that the seepage refluxion mechanism of Adams and Rhodes (1960) accounts for the dolomitization.

Siliceous ooze

Siliceous oozes are present only in the northern part of the Eastern Indian Ocean at sites 211, 213, 215, 260 and 261. As pointed out earlier, the distribution of the upper acoustically transparent unit (Figs 3, 8) indicates the extent of the siliceous ooze. With the exception of a thin bed of Albian age at site 260 (Fig. 2), siliceous ooze is restricted to Miocene and younger sediments. However, the silica in many of the siliceous clays and claystones could conceivably be of biogenic origin despite the lack of any recognizable siliceous fossil remains.

The siliceous oozes, which range from brown to green and grey, are composed of radiolarians and diatoms, with minor sponge spicules and silicoflagellates. A few nannofossil fragments are present in some beds; iron and manganese oxides are present sporadically as micro-nodules or as partings. Volcanic glass of rhyolitic composition, and probably derived from the nearby Indonesian volcanic arc, is commonly present in trace amounts, and locally comprises up to 25 percent. Terrigenous clay is invariably present, ranging from minor to abundant. Texturally the siliceous ooze corresponds to a silty clay (Table 1); the sand-size material is probably composed of larger siliceous organisms. Compositionally the radiolarian-diatom ooze is characterized by high SiO_2 and MnO, and low CaO + CO_2 (Table 2) contents. The high barium content (Table 4) is also a feature of the siliceous oozes.

The siliceous oozes are pelagic deposits which have accumulated below the lysocline. Their appearance in the Late Tertiary is probably the result of the northward movement of the region into the zone of high equatorial productivity.

CHEMICAL COMPOSITION

The chemical composition of sediments from the DSDP sites in the Eastern Indian Ocean is dealt with by Pimm (1974b), Fleet and Kempe (1974), Calder et al. (1974), and Cook (1974a, b). Average compositions (Tables 2 and 4) were derived from these publications. In general the data are insufficient to establish vertical or synchronous lateral trends and it is possible to do nothing more than point to the compositional variation of the various sediment types, and to indicate some probable inter-element associations.

Major and minor oxides

Most Mesozoic-Cenozoic sediments of the Eastern Indian Ocean are either calcareous oozes (predominantly calcium carbonate) or siliceous clays (silica and alumino-silicates), with a scatter of sediments between the two end-members. In general the major and minor oxide content of these sediments (Table 2) is similar to the "average" deep-sea sediment (Table 3).

SiO_2 occurs in the Eastern Indian Ocean sediments predominantly as quartz (including chalcedony-chert), tridymite and cristobalite (including opaline material), and alumino-silicates; minor amounts are present as feldspar, feldspathoid and zeolite, and traces occur as pyroxene and amphibole. These components are of terrigenous, volcanic, or biogenic origin. Terrigenous SiO_2 is dominant in most sedimentary units and in most parts of the Eastern Indian Ocean. Biogenic silica is an important component of the Cenozoic siliceous oozes; it may also be important in siliceous clays and claystones despite the lack of direct evidence of a biogenic origin for the silica, though it is implied by some of the trace element contents. Locally, particularly in ash and volcanoclastic sequences, the SiO_2 is obviously of direct volcanic origin; the siliceous volcanogenic input is rather less certain in the pelagic clays and zeolitic clays. Other terrigenous and/or volcanic oxides which show a positive correlation with SiO_2 include Al_2O_3, TiO_2, Fe_2O_3, Na_2O, K_2O and H_2O, predominantly the result of the quartz-clay mineral association. Concentrations of these elements are similar to those found in "average" pelagic sediments (Table 3), although the TiO_2 content of the glauconitic silty clay (1.28%) is particularly high, possibly an indication of a nearby source area. The nannofossil clays similarly have a high TiO_2 content (0.77%) when compared with calcareous ooze or clay (Table 2). As most nannofossil clays occur low in the sequence (Fig. 2), again it is possible that there was a nearby source area (mid-ocean ridge) providing a titaniferous input into these sediments.

The Fe_2O_3 content of the sediments results in part from iron oxide associated with clays or in some sediments as glauconite, as indicated by the high Fe_2O_3 content (12.3%; Table 2) of the glauconitic silty clay. However, abnormally high iron contents are also found in some thin basal iron oxide units overlying basalt. Pimm (1974b) studied the geochemistry of this facies at sites 211, 212 and 213 and found that the total iron content ranged up to 16 percent. This iron-rich facies is believed to formed by volcanic hydrothermal exhalations, and elsewhere contains relatively high metallic concentrations particularly of copper, though the Eastern Indian Ocean occurrences do not contain especially high concentrations of copper or even manganese. Relatively high concentrations of these elements has been noted in the Pacific (von der Borch & Rex, 1970; Cronan, 1973). Manganese appears to be most abundant in the siliceous oozes where it occurs as bands and patches of manganese oxides containing up to 8 percent MnO. Overall, the siliceous oozes are high in manganese (1.2% MnO; Table 2). It is uncertain whether this is the result of a slow rate of sedimentation, submarine fumaroles, biochemical concentration, or all three, though the author considers that the biogenic action of siliceous organism is of great importance to the concentration of manganese and other metals.

CaO is an abundant oxide in many pelagic sediments, and is particularly common in the calcareous oozes where CaO + CO_2, occurring mainly as calcite, averages more than 60 percent of the total sediment. Minor amounts of CaO are also present as feldspar and zeolite in some sediments. MgO is commonly associated with CaO in calcareous sediments, presumably as a result of the occurrence of dolomite rhombs in oozes, chalk and limestone.

The P_2O_5 content of the sediments varies (Table 2) though the range corresponds closely with average values from other areas (Table 3). There are few correlations of P_2O_5 with other oxides evident from factor analysis. Detrital apatite is seldom present in detectable amounts, but biogenic collophane or bone and teeth fragments are present in places. However, in most pelagic sediments the phosphate is probably adsorbed on clays; a possible P_2O_5 - Fe_2O_3 correlation reported by Cook (1974b) from Leg 27 results may indicate the presence of trace amounts of vivianite but is more likely the result of adsorption of phosphate by iron oxides.

Trace elements

In general, the trace element content of the Mesozoic-Cenozoic Eastern Indian Ocean sediments (Table 24) is similar to average values for deep-sea sediments (Table 5). However, the Eastern Indian Ocean clays have a lower metal content than the average pelagic clay. This may be ascribed to the incorporation of Pacific sediment with high metal contents in the average value of Turekian and Wedepohl (1961), the greater input of terrigenous material into the Eastern Indian Ocean, and possibly also the paucity of submarine fumarolic activity.

Strontium is associated with the biogenic carbonates, substituting for calcium in the calcite lattice. The highest strontium value (950 ppm) is found in foraminiferal-nannofossil ooze (Table 4); this is significantly below the value for average pelagic carbonates (2000 ppm).

Barium is highest in the siliceous oozes and lowest in the glauconitic clays. Some of the barium is present as barite nodules and veins, such as those found at site 263. Brongersma-Sanders (1966) has speculated that much of the barium in marine sediments is associated with siliceous organizm, and factor analysis on the Indian Ocean sediments (Cook, 1974b) would seem to support a biogenic silica-barium correlation. A minor amount of the barium is also associated with iron and manganese-rich sediments. Copper, zinc, cobalt and nickel also appear to be associated with ferromanganese oxides, probably in an adsorbed state. This does not, however, appear to be the case for lead, which from factor analysis seems to be associated more with the clay component. Some zinc is also associated with clay minerals.

In conclusion, the major minor and trace elements may be grouped into four groups: (i) the alumino silicate group which is derived from terrigenous and volcanic sources and includes SiO_2, Al_2O_3, TiO_2, Fe_2O_3, Na_2O, K_2O, H_2O, Zn and (?)Pb; (ii) the ferromanganese group, the product of syngenetic (or very early diagenetic) mineralization and including Fe_2O_3, MnO, Cu, Zn, Co, and Ni; (iii) the biogenic silica group derived mainly from diatoms and radiolaria and composed of SiO_2, BaO and possibly MnO; and (iv) the biogenic carbonate group, derived mainly from foraminifera and nannofossils and composed of CaO, CO_2, SrO and possibly MgO.

Calcium carbonate content

Geochemical data for the Eastern Indian Ocean are in general inadequate for determination of variations of the components with time, the only exception being $CaCO_3$ content which has been routinely analysed throughout the DSDP program. It has been evident from earlier discussions that the general picture which has emerged so far is of poorly calcareous Mesozoic sediments and highly calcareous Cenozoic sediments. In addition the distribution pattern (Fig. 9) indicates that in the Eastern Indian Ocean at the present day calcareous sediments are abundant on continental margins and ocean ridges above the carbonate compensation depth, or locally as ponded sediments below the carbonate compensation depth. Elsewhere in the abyssal zone the sediments are either siliceous oozes or clays.

The distribution of $CaCO_3$ in both the deep-water and shallow-water sites is shown in Figure 19. It is apparent from this that the $CaCO_3$ content is extremely variable both within the same section and between sites, although again the trend is generally one of a high $CaCO_3$ content in the Cenozoic and a low $CaCO_3$ content in the Mesozoic. Overall, as is to be expected, deep-water sites are less calcareous than shallow-water sites. In the abyssal zone where sediments range in age from Late Jurassic to Recent, the $CaCO_3$ content of sites 256, 257 and 263 is uniformly low throughout most of the section. Sites 256 and 257 appear to have always been below the carbonate compensation depth, and also outside of the range of calcareous turbidite flows. At site 263 the low $CaCO_3$ content is the result of a very high rate of terrigenous sedimentation, and the consequent swamping of the calcareous component. Similarly, low carbonate contents are found at site 218 because of the major input of fine terrigenous sediment from the Bengal Fan. At site 253 the low carbonate content of the lower two-thirds of the drill hole results from a major input of non-calcareous volcaniclastics. Those sites with a uniformly high carbonate content throughout are either the result of being above the lysocline for most of the time (sites 217, 216, 214), or they have been the site for ponding of calcareous turbidite deposits over long periods (site 212). Therefore the $CaCO_3$ content of the sediments is the result not only of the rate of calcareous biological activity but also of the rate of terrigenous or volcanic sedimentation (and to a minor extent the rate of siliceous biological activity), water depth, and water temperature.

Despite this complex interplay of variables it is possible to discern trends: The general calcimetric pattern at shallow sites on the Ninetyeast Ridge and the Naturaliste Plateau (the data are insufficient to establish any trend for Broken Ridge) is one of low $CaCO_3$ content at the base of the section followed by a rapid increase and then stabilization at a fairly uniformly high $CaCO_3$ content for the remainder of the Cenozoic. The low carbonate content at the base of the section may be the result of a high rate of volcanic input in the time shortly after the formation of the ridge (e.g. site 253). An alternative explanation that these sites were below the lysocline shortly after initiation of volcanism is untenable because of the abundant sedimentary evidence (discussed earlier) of shallow-water conditions in the oldest sediments of the Ninetyeast Ridge. This may not be the case for the Naturaliste Plateau, and it seems likely from both the sedimentology (Luyendyk and Davies, 1974) and calcimetry that in the Cretaceous the Naturaliste Plateau was below the lysocline but that it underwent rapid uplift during the late Cenomanian-early Turonian to a location above the lysocline. It then continued to occupy a shallow location for the remainder of the Cretaceous and the Tertiary.

The calcimetry of the deep-water sites is rather more complex. There is a general tendency for the $CaCO_3$ content to be moderately high at the base of the sequence but to decrease rapidly to nearly zero. There is commonly an increase in $CaCO_3$ in the Albian (sites 257, 259 and ?263), particularly at sites near the eastern margin of the study area, but by the late Albian the $CaCO_3$ content had again decreased almost to zero, and remained at this level throughout the rest of the Cretaceous, except for site 212. A marked increase in $CaCO_3$ content then took place at the Cretaceous-Tertiary boundary at most sites. Major fluctuations occur in the calcimetry of the Cenozoic sediments but the average carbonate content is much higher than that generally found in the Mesozoic, except sites 256 and 257 (the data are inadequate for sites 213 and 211 to be able to establish a trend).

The sequence of events most likely to produce this pattern of $CaCO_3$ distribution seems to be, first, the formation of a spreading center and the consequent elevation of the sea floor on the flanks of the mid-ocean ridge to a level above the nannofossil lysocline so producing slightly calcareous sediments at the base of the sequence. This was followed by the gradual depression of the site to below the carbonate compensation depth, resulting in the deposition of non-calcareous pelagic clays. During the Albian, the lysocline was depressed either in response to an increased rate of input of calcareous (nannofossil) sediments or, alternatively, a change in water temperature, resulting in the deposition of nannofossil-rich clays and nannofossil oozes. By the close of the Albian, conditions reverted back to normal and for the remainder of the Cretaceous (in places persisting into the Cenozoic) pelagic clays were deposited. In the Cenozoic (and at site 212 the Late Cretaceous) there was a new onset of calcareous sedimentation owing to the massive influx of allochthonous calcareous oozes from the continental slope into the abyssal zone.

SEDIMENTATION

Hiatuses and unconformities

Deep-sea drilling has shown large gaps in the sedimentary record of all of the oceans. In many areas, the deep-sea record is essentially one of gaps interspersed with an occasional atypical period of sedimentation. Hiatuses and unconformities within the Indian Ocean sequence have been considered in some detail by Pimm and Sclater (1974) and Davies et al. (1975).

They concluded that there are major breaks in the stratigraphic record in the Oligocene, Early Tertiary and Late Cretaceous, which are the consequence of climatic events in Antartica and subsequent variations in the circulation pattern of the Indian Ocean.

Only at site 255 (Fig. 2) is an angular unconformity (between Santonian limestone and chert and Eocene sands and gravels) recognizable in the cores. However, an angular discordance of regional magnitude between the lower acoustically transparent unit and the layered unit can be recognized from the seismic profiles (Fig. 5). Elsewhere in the sequence, unconformities are less obvious and there is no angular discordance. In some instances there are marked changes in lithology, but the main indication is from the chronostratigraphy and biostratigraphy. The stratigraphy of both deep-water and shallow-water sites is summarized schematically in Figures 20 and 21. At some drill sites there is obviously a major hiatus. At site 258 (Fig. 20) there is, for instance, a gap of about 65 m.y. during which no sediments were laid down or of which all trace has been removed. At other sites, however, the magnitude of the hiatus is less certain. At site 256 for example, there are no fossils representative of the entire interval from the Cenomanian to the Pliocene, an interval of about 100 m.y. However, 105 m of barren sediments was laid down at some time during this interval. These sediments may have been deposited at a rate of 1 m per million years and therefore the interval might represent a very slow rate of sedimentation and not a true hiatus. Alternatively the sediment was deposited at a more normal rate of say a minimum of 5 m per million years and that consequently the total 105 m of sediment would have been laid down in 20 m.y., leaving a hiatus of 80 m.y. If Figure 20 is compared with Figure 21 it is apparent that the deep-sea record is far more incomplete than the record from shallower areas. Considering the shallow water first (Fig. 20) there appear to be well defined hiatuses at all sites, except 214 and 264, in the early Eocene and at most sites (excluding 214, 253 and 254) in the early Oligocene. There are, however, marked differences between the sites on the Ninetyeast Ridges (214, 216, 217, 253, 254) where the sedimentary record is comparatively uninterrupted once sedimentation has been initiated, and the Broken Ridge-Naturaliste Plateau sites (255, 258, 264) where there is major break in the sequence extending from the base of the Campanian to the Paleocene (20 m.y.). This was followed by sporadic sedimentation in the Eocene and then a second break of 10-15 m.y. throughout the Oligocene and extending to the late Miocene on the Naturaliste Plateau. At site 255 there has obviously been a major phase of uplift and subsequent erosion in the Late Cretaceous-Early Tertiary. This same phase of tectonic uplift similarly may be responsible for loss of section at sites 258 and 264, although Davies et al. (1975) consider that the gaps on the Naturaliste Plateau are more the result of variation in oceanic circulation and sediment supply than tectonic events. Nevertheless as both features - sediment supply and oceanic circulation - are so commonly affected by tectonism it is difficult to completely dismiss tectonism as a related cause. Whatever the cause, it appears not to have affected the Ninetyeast Ridge at this time.

The Oligocene hiatus (extending into the early and middle Miocene in places) is also best developed on Broken Ridge-Naturaliste Plateau although an early Oligocene hiatus is also present at the northern end of the Ninetyeast Ridge (Fig. 20). There is no evidence of angular discordance associated with this gap in any of the sequences, nor is there any sedimentological or palentological evidence of a major change in water depth. Consequently the hiatus is most likely the result of the rate of sedimentation decreasing to zero, or the influx of erosive bottom current which prevented sedimentation or eroded the sedimentary sequence or both.

At the deep-sea sites the distribution of hiatuses is less clear, not because of their lack but because of their abundance. The almost total lack of datable Late Cretaceous and Tertiary sediments is a marked feature of Figure 21. The Late Cretaceous hiatus appears to be particularly marked in the southern and eastern portions of the Ocean, whereas the general Tertiary hiatus occurs throughout the region. The various gaps in the sequence appear to be:

(i) Barremian (5 m.y.)

(ii) Cenomanian-Paleocene (35-40 m.y.). This hiatus occurs only in the southern and eastern parts of the abyssal zone.

(iii) Middle Eocene-early Miocene (35 m.y.). This hiatus occurs throughout the abyssal zone.

(iv) Middle and upper Miocene (9 m.y.). This hiatus is present only in the southern and eastern parts of the abyssal zone.

The deep ocean hiatuses are synchronous with those of the shallower ridges and plateaux, but also extend beyond them. Some of these hiatuses are also recognizable on the continental shelf (Veevers & Johnstone, 1974) and as far afield as Papua (Veevers and Evans, 1973). There is no structural or sedimentary evidence that any of the abyssal zone sites have been at anything other than deep ocean basin locations since early in their history. Consequently, shallow-water erosion cannot be invoked to account for any loss of section. Equally well it is unlikely that a source of fine-grained terrigenous sediment would have been lacking for many millions of years. Deep contour currents may account for loss of section in the abyssal zone sites but cannot also be used to account for hiatuses on shallow ridge and plateau sites. The initial separation of Australia and Antarctica took place about 55 m.y. ago (Kennett et al., 1975), and the Circum-Antarctic Current developed about 30 m.y. ago (Kennett et al., 1974). Until that time the Circum-Antarctic Current was probably driven north through the Eastern Indian Ocean. The Late Cretaceous hiatus initially affected only the ocean basin (Cenomanian-Santonian) but later (Campanian-Paleocene), both ocean basin and some shallow sites (Broken Ridge and Naturaliste Plateau) were affected. However, the hiatus at both locations may not necessarily have resulted from the same immediate cause. There is ample evidence that the hiatus at site 255 on Broken Ridge is the consequence of uplift and subsequent erosion; such a mechanism might also be possible for the Naturaliste Plateau, but not for the abyssal sites. It is likely that the hiatus in the abyssal zone resulted from strong bottom currents which may have both prevented sedimentation and produced some erosion. These strong currents were probably the consequence of the ancestral Circum-Antarctic Current being driven north; in the Cretaceous the juvenile Indian Ocean was also relatively narrow, thus increasing the force of these currents. The Late Cretaceous-Early Tertiary uplift of Broken Ridge and perhaps also the Naturaliste Plateau may have restricted the path of such currents resulting in an intensification of the bottom currents in places, thus enhancing their erosive power in those areas.

Davies et al. (1975) propose that the Tertiary hiatuses in both the Indian and Pacific Oceans may be correlated with periods of climatic deterioration which produced glaciation in Antarctica and the formation of large amounts of cold, erosive Antarctic Bottom Water which moved north into the Wharton Basin. They consider that these periods would have been associated not only with periods of increased storminess, and hence a deeper wave base and wave erosion penetrating to greater depths, but also a shallowing of the carbonate compensation depth. This hypothesis would seem to provide a means for accounting for many of the Early Tertiary hiatuses. However, problems would seem to arise with the older and younger hiatuses of the Eastern Indian Ocean. Major breaks occur in the Cretaceous record, yet there is no evidence of climatic deterioration or of an Antarctic ice cap during this time. Quilty (1975) records uniformly warm to hot conditions throughout the Late Cretaceous of the Western Australian Region. However, if Antarctic Bottom Waters did not exist at this time there must nevertheless have been water movement associated with west wind drift after India started to drift north, leaving open ocean to the west of Australia. The northward deflection of this westerly current may be responsible for the Late Cretaceous sedimentary gaps at abyssal sites off the west coast of Australia.

Once separation of Australia and Antarctica was complete and the Circum-Antarctic Current established (estimated by Kennett et al. (1975) to have occurred at about 30 m.y.), there was probably little direct input of Antarctic Bottom Water because of the Circum-Antarctic Current. In addition, by this time Broken Ridge and the Naturaliste Plateau considerably restricted the entrance of deep water into the Wharton Basin from the south. Consequently, any post-Oligocene hiatus in the abyssal zone is unlikely to be due to such currents. Despite the gaps in the records in the deep ocean, on the adjacent West Australian shelf carbonate sedimentation was fairly continuous. This extensive phase of shallow Tertiary carbonates indicates that little terrigenous sediment was being received from the Australian continent at this time. On the shelf, the Oligocene to the middle Miocene was marked by a progradation of carbonates across the shelf. Once this sediment wedge reached the shelf edge there was likely to have been a massive build-up of carbonates on the upper slope which ultimately slumped down the slope creating turbidity currents which carried large volumes of calcareous sediment into the Wharton Basin.

Therefore it appears that no single mechanism can be used to account for all the Mesozoic-Cenozoic hiatuses which occur in the deep water of the Eastern Indian Ocean and also, in some instances, on the shallower flanking structures. The Late Cretaceous-Paleocene hiatus may be ascribed to extensive west wind drift, and an associated deep current sytem which was forced north along the eastern side of the Indian Ocean. The Eocene and Paleocene hiatuses may be, as suggested by Davies et al. (1975), the consequence of climatic deterioration, glaciation, and the development of large bodies of northward-moving Antarctic Bottom Water. However the northward movement of Australia and the attendant development of the Circum-Antarctic Current precluded the entry of this deep current system by the late Oligocene. The gaps in the late Oligocene-early Miocene may have resulted from the lack of input of terrigenous material from the Australia continent. This phase was brought to a close by the massive influx of allochthonous carbonates in the middle Miocene and later.

Rates of Sedimentation

Determination of the rate of sedimentation from the Eastern Indian Ocean drill sites is made difficult by the many gaps and the thick sequences of barren sediments in the stratigraphic record. Average rates of sedimentation were determined using only those parts of the sequence which could be confidently dated from their fossil assemblages. These average values show that there were quite marked fluctuations in the rate of sedimentation throughout the Mesozoic-Cenozoic, ranging from 0.8 to 20.3 m per million years (Table 6). There were also some well defined peaks of sedimentation rates in the Aptian-Albian, Coniacian, Maestrictian, and Pliocene-Quaternary. These maxima do not appear to coincide with those proposed by Veevers et al. (1974) from seismic information, but as their time intervals are greater, no direct comparison of their results and those given here can be made. Minima in the rate of sedimentation are commonly, though not exclusively, found within periods which contain hiatuses. There is also a tendency for sedimentation maxima to be common at times when highly calcareous sediments were deposited in the abyssal zone. A third feature evident from Table 6 is that the sedimentation rate was far more variable in the Mesozoic than the Cenozoic, perhaps indicating the more unstable Mesozoic conditions (climatic, oceanographic and/or tectonic) in the Eastern Indian Ocean region. It should perhaps be noted that the high rate of sedimentation in the Aptian-Albian coincides with a magmatic-tectonic maximum in Australia (Veevers and Evans, 1973). Some inflation of the rate of sedimentation in the Plio-Pleistoncene might be attributable to the increase in volcanism which is thought to have taken place in the past two million years (Kennett and Thunell, 1975), although most of the increase is probably the result of an increase in the rate of calcareous sedimentation at that time.

It is not possible to determine the regional variation in the sedimentation rate for each epoch because there are unsufficient data, consequently the regional change can only be determined for the Cretaceous and the Cenozoic (Table 7). These data are useful for indicating likely source areas in a somewhat more definitive way than by total sediment thickness. For the Cretaceous (Fig. 22) there is a clear increase in the rate of sedimentation as the Australian continent is approached, which is consistent with it being a major source of sediment at that time. There is the suggestion of a source area to the south (?Antarctica) which would be feasible, as Australia and Antarctic did not separate until the Paleocene. There may also have been a source for Cretaceous sediments to the northwest as indicated by the increase in the rate of sedimentation in that direction. This would seem to add support to the proposal of Crawford (1974), Larson (1975) and others that a continental landmass (such as Tarim) lay to the northwest of Western Australia during the Jurassic-Cretaceous. The central portion of the Eastern Indian Ocean was evidently a considerable distance from land throughout the Cretaceous.

The pattern of variation in the rate of sedimentation is rather different in the Cenozoic (Fig. 23). The rate still increases markedly towards Australia, a feature also noted by Veevers et al. (1974), but now the sediment is primarily calcareous and it is perhaps more the Australian shelf and upper slope which is contributing the bulk of the sediment rather than the continent itself. There is no evidence of a source area to the south, but a marked increase in sedimentation rate occurs in the center of the basin and also to the northwest. The north-westerly trend is attributable to the Bengal Fan which consituted a major source of sediment supply to this area by the Late Cenozoic (Curray and Moore; 1971). The maximum in the center of the ocean basin is probably the consequence of this area being a low point into which turbidity currents descended, and where they were able to deposit their suspended load.

Therefore, although the data are sparce, it is possible to recognize by means of variations in the rates of sedimentation the changes in the source areas and in the type of sedimentation in the Cretaceous and the Cenozoic of the Eastern Indian Ocean.

SEDIMENTARY HISTORY

There is abundant evidence from the onshore and shelf sedimentary sequence that marine conditions persisted throughout much of the Phanerozoic on the northwest margin of Australia, with a northern connection open to the Tethys (Veevers et al., 1971). A new phase of sea-floor spreading may have taken place as early as the Callovian (Veevers and Heitzler, 1974b) although the oldest oceanic basement sampled by deep sea drilling was at site 261, with an Oxfordian age (155 m.y.). At about this time a spreading ridge was initiated, running approximately east northeast. At first the sea floor was raised just above the nannoplankton lysocline on the ridge and consequently in places a nannofossil-bearing or nannofossil-rich clay was deposited. As spreading proceeded, the sea floor previously on the ridge flanks descended below the lysocline, resulting in the deposition of brown pelagic clays. From then until the early Aptian, our knowledge of the area is based on the onshore or nearshore sequence and on information from site 261. During this time, the rate of sedimentation appears to have been rather slow (1-2 m per million years). There were probably several hiatuses, although the only one recognized to date (from site 261) is the gap in the Barremian. This slow rate of sedimentation may also indicate a low hinterland from which there was little input of terrigenous sediment. It may also be taken as evidence in favor of a relatively arid hinterland. Locally, there was rupturing during the period 155-113 m.y. which may have produced horsts and grabens and some semi-enclosed small ocean basins (Veevers and Heitzler, 1974b). However, in general the period 155-113 m.y. was probably relatively quiet tectonically.

During the Aptian-Albian, conditions became more tectonically active; an accelerated phase of ocean-floor generation took place as indicated by the widespread occurrence of oceanic basalt of Aptian-Albian age. Volcanism is reflocted in the occurrence of zeolitic clays at site 259. There was widespread continental tectonism at this time coupled with the development of extensive epicontinental seas. This tectonism resulted in a marked increase in the rate of sedimentation, particularly in the vicinity of site 263 where a thick sequence of organic-rich clays was deposited. A secondary trend in the Albian was the increase in the carbonate content of the sediments. It is conceivable that there was some uplift of the sea floor associated with this period of tectonism. However, it is more probable that there was a warming phase at this time leading to a lowering of the lysocline and increased carbonate production. Therefore by the close of the Albian (100 m.y.) a broad seaway, opening to the north, existed off Western Australia. Sediment supply (mainly clay) was predominantly from the east with some input from the south (Antarctica) and possibly a minor amount from the northwest. The continental configuration at this time is shown schematically in figure 25B. It is based essentially on the Smith and Hallam (1970) fit for the southern continents and used subsequently by Luyendyk (1974) and others, as this has been shown by Embleton and McElhinny (1975) to provide the best Indian Ocean fit.

Sedimentary conditions changed markedly in the Cenomanian. The sediments became less calcareous, there was a major decrease in the rate of sedimentation, and in many areas sedimentation either ceased completely or there was extensive erosion of the existing sediments. These conditions appear to have prevailed throughout most of the Late Cretaceous and extending into the Early Tertiary in places. The most likely cause of this change was the northward movement of India commencing in the Cenomanian (95-100 m.y.), providing a seaway to the west of Australia so allowing the influx of cooler westerly currents which swept west, then north along the eastern margin of the ancestral Eastern Indian Ocean by the latter part of the Cretaceous. This is shown schematically in Figure 25C. During this same period the Naturaliste Plateau and Broken Ridge formed, though they were probably not as extensive as at the present day as they do not appear to have inhibited the influx of cooler water from the west and southwest.

By the Santonian or earlier, the uplift and volcanism associated with the early development of the Ninetyeast Ridge had commenced in the vicinity of site 217. The sediments of the Ninetyeast Ridge give no real indication of the origin of the Ridge, and whether it was the result of a transform fault (Sclater & Fisher, 1974), a fixed mantle plume (Morgan, 1972), or both, coupled with a relative motion of the plates (Luyendyk and Davies, 1974) is immaterial to this discussion. What is apparent is that it was a very shallow feature early in its history - sufficiently shallow for coral reefs and in places coal to form on its crest. It is also a strongly diachronous structural unit, as is evident from Figure 21, with an age of formation of 80 m.y. or older at the northern end, and about 40 m.y. at the southern end. This chronology would seem to fit with the known northward movement of the Indian plate (McIlhinny, 1970).

Therefore by the Paleocene (about 60 m.y.) the Ninetyeast Ridge existed as an elongate feature, shallowest at its southern (young) end (Fig. 25D). Volcanogenic and calcareous sedimentation continued along its crest and flanks, but on Broken Ridge and the Naturaliste Plateau and in the abyssal zone there was little or no sedimentation. The Eastern Indian Ocean was broader by this stage but deep currents from the west, deflected north, continued to sweep across the shallow features in the south and over the abyssal plain.

At about 50-55 m.y. the final separation of Australia and Antarctica commenced. At first there was little impact on the sedimentary pattern in the Eastern Indian Ocean, with calcareous sedimentation continuing in shallower waters and little or no sedimentation in deeper waters. However in the early Eocene (about 50 m.y.) and early Oligocene (35-40 m.y.) the hiatuses extended onto the shallower feature. It may be that these hiatuses, as suggested by Davies et al. (1975), correspond with cooling and climatic deterioration and the development of erosive northward-moving Antarctic bottom waters (Fig. 25E). By 30-35 m.y. the separation of Australia and Antarctica was complete and a strong Circum-Antarctic Current established. This, together with the development of the Ninetyeast Ridge (the Australian and Indian plates were by this stage welded together) on the western margin of the Wharton Basin and the Naturaliste Plateau and Broken Ridge on the southern margin, resulted in a marked decrease in the influx of Antarctic Bottom Water. Conditions became warmer as the plate drifted north and there was a massive development of carbonates on the continental shelf and slope, and on other shallow structures. However, there was little terrigenous sediment entering the Eastern Indian Ocean and consequently little or no sedimentation at abyssal depths. By the Miocene (10-20 m.y.), these carbonates had prograded across the shelf and now periodically slumped down the slope and into the abyssal plain to provide bedded units (the acoustically layered unit) of allochthonous carbonates (foraminiferal-nannofossil oozes) transported across the abyssal plain by massive turbidite flows. At about this same time the Bengal Fan began adding large volumes of clayey and silty sediment to the northwest portion of the Eastern Indian Ocean (Fig. 25F). A third feature, the movement of the northern margin of the plate into the equatorial zone of high productivity also produced the upper acoustically opaque unit and an increase in the abundance of siliceous sediment (radiolarian-diatom ooze). All of these processes resulted in a marked increase in the rate of sedimentation throughout much of the Eastern Indian Ocean in the Late Tertiary and Quaternary. They also produced the pattern of sedimentation that we now see at the present day.

REFERENCES

ADAMS, J.E., & RHODES, M.L., 1960 - Dolomitization by seepage refluxion. Amer.Assoc.Petroleum Geol.Bull. 44, 1912-1920.

BERGGREN, W.A., LOHMANN, G.P., & POORE, R.Z., 1974 - Shore laboratory report on Cenozoic planktonic foraminifera: Leg 22. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 635-655.

BEZRUKOV, P.L., 1974 - Sedimentary formation of the Indian Ocean and their relationship with tectonics. Geotectonics, 1, 1-7.

BRONGERSMA SANDERS, M., 1966 - Barium in pelagic sediments and diatoms. Konikl Ned.Akad.Wetensch Proc., 70, 93-99.

CALDER, J.A., HORVATH, G.J., SHULTZ, D.J., & NEWMAN, J.W., 1974 - Geochemistry of the stable carbon isotopes in some Indian Ocean sediments. In Davies, T.A., Lyendyke, B.P., et al., Initial reports of the Deep Sea Drilling Project Volume 26, Washington (U.S. Government Printing Office), 613-618.

COOK, A.C., 1974 - Report on the petrography of a Paleocene brown coal sample from the Ninetyeast Ridge, Indian Ocean. In von der Borch, Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 485-488.

COOK, P.J., 1974a - Phosphate content of sediments from Deep Sea Sites 259 to 263, Eastern Indian Ocean. In Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 27, Washington (U.S. Government Printing Office), 455-462.

COOK, P.J., 1974b - Major and trace element geochemistry of sediments from Deep Sea Drilling Project, Leg 27, Sites 259-263, Eastern Indian Ocean. In Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 27, Washington (U.S. Government Printing Office), 481-498.

CRAWFORD, A.R., 1974 - A greater Gondwanaland. Science, 184, 1179-1181.

CRONAN, D.S., 1973 - Basal ferruginous sediments cored during Leg 16, Deep Sea Drilling Project. In van Andel, T.H., Heath, G.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 16, Washington (U.S. Government Printing Office), 601-604.

CURRAY, J.R., & MOORE, D.G., 1971 - Growth of the Bengal deep-sea fan and denudation of the Himalayas. Geol.Soc.Amer.Bull. 82, 565-572.

DAVIES, T.A., LUYENDYK, B.P., et al., 1974 - Initial Reports of the Deep Sea Drilling Project Volume 26, Washington (U.S. Government Printing Office), 1129 p.

DAVIES, T.A., WESER, O.E., LUYENDYK, B.P. & KIDD, R.B., 1975 - Unconformities in the sediments of the Indian Ocean. Nature, 253, 15-19.

EL WAKEEL, S.K., & RILEY, J.P., 1961 - Chemical and mineralogioal studies of deep sea sediments. Geochim.Cosmochim.Acta., 25, 110-146.

EMBLETON, B.J.J., & McELHINNY, M.W., 1975 - The paleoposition of Madagascar: paleomagnetic evidence from the Isalo Group. Earth Plan.Sci.Letters(in press).

EWING, M., EITTREIM, S., TRUCHAN, M., & EWINGS, J.I., 1969 - Sediment distribution in the Indian Ocean. Deep Sea Res., 16, 231-248.

FLEET, A.J., & KEMPE, D.R.C., 1974 - Preliminary geochemical studies of the sediments from D.S.D.P. Leg 26, Southern Indian Ocean. In Davies, T.A., Luyendyk, B.P., et al., Initial reports of the Deep Sea Drilling Project Volume 26, Washington (U.S. Government Printing Office), 541-552.

GOLDBERG, E.D., & ARRHENIUS, G., 1958 - Chemistry of Pacific pelagic sediments. Geochim.Cosmochim.Acta., 13, 153-212.

HAYES, D.E., FRAKES, L.A., et al., 1975 - Initial reports of the Deep Sea Drilling Project Volume 28, Washington (U.S. Government Printing Office).

KENNETT, J.P., et al., 1974 - Development of the circum-Antarctic current. Science, 186, 144-147.

KENNETT, J.P., HOUTZ, R.E., et al., 1975 - Initial Reports of the Deep Sea Drilling Project Volume 29, Washington (U.S. Government Printing Office).

KENNETT, J.P., & THUNELL, R.C., 1975 - Global increase in Quaternary explosive volcanism. Science, 187 (4176), 497-503.

LARSON, R.L., 1975 - Late Jurassic sea-floor spreading in the Eastern Indian Ocean. Geology, 3(2), 69-71.

LUYENDYK, B.P., 1974 - Gondwanaland dispersal and the early formation of the Indian Ocean. In Davies, T.A., Luyendyk, B.P., et al., Initial Reports of Deep Sea Drilling Project Volume 26, Washington (U.S. Government Printing Office), 945-952.

LUYENDYK, B.P., & DAVIES, T.A., 1974 - 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 Volume 26, Washington (U.S. Government Printing Office), 909-943.

McILHINNY, M.W., 1970 - Formation of the Indian Ocean. Nature,228, 977-979.

McKELVEY, B.C., & FLEET, A.J., 1974 - Eocene basaltic pyroclastics at Site 253, Ninetyeast Ridge. In Dvaies, T.A., Luyendyk, B.P., et al., Initial Reports of the Deep Sea Drilling Project Volume 26, Washington (U.S. Government Printing Office), 553-565.

MORGAN, W.J., 1972 - Deep mantle convection plumes and plate motions. Amer.Assoc.Petroleum Geol.Bull., 56, 203-213.

PETKOVIC, P., 1975a - Origin of the Naturaliste Plateau. Nature, 253, 30-33.

PETKOVIC, P., 1975b - Naturaliste Plateau. In Veevers, J.J. (Ed.), Deep Sea Drilling in Australasian waters, Challenger Symposium Sydney, 24-25.

PIMM, A.C., 1974a - Sedimentology and history of the northeast Indian Ocean from the Late Cretaceous to Recent. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 717-804.

PIMM, A.C., 1974b - Mineralization and trace element variations in deep-sea pelagic sediments of the Wharton Basin, Indian Ocean. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 469-476.

PIMM, A.C., & SCLATER, J.G., 1975 - Early Tertiary hiatuses in the north-eastern Indian Ocean. Nature, 252, 362-265.

QUILTY, P.G., 1975 - Late Jurassic to Recent geology of the western margin of Australia. In Veevers, J.J., (Ed.), Deep Sea Drilling in Australasian waters, Challenger Symposium Sydney, 15-23.

ROBINSON, P.T., THAYER, P.A. COOK,P.J., & McKNIGHT, B.K., 1974 - Lithology of Mesozoic and Cenozoic sediments of the Eastern Indian Ocean, Leg 27, Deep Sea Drilling Project. In Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 27, Washington (U.S. Government Printing Office), 1001-1047.

SCLATER, J.G., & FISHER, R.L., 1974 - Evolution of the East Central Indian Ocean, with emphasis on the tectonic setting of the Ninetyeast Ridge. Geol.Soc.Amer.Bull., 85, 683-702.

SHEPARD, F.P., 1954 - Nomenclature based on sand-silt-clay ratios. Sediment. Petrol., 24, 151-158.

SMITH, A.G., & HALLAM, A., 1970 - The fit of the southern continents. Nature, 225, 139-144.

THOMPSON, R.W., 1974 - Mineralogy of sands from the Bengal and Nicobar Fans, Sites 218 and 211, Eastern Indian Ocean. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 711-714.

TUREKIAN, K.K., & WEDEPOHL, K.H., 1961 - Distribution of the elements in some major rock units in the earth's crust. Geol.Soc.Amer.Bull.,172, 175-192.

VEEVERS, J.J., 1974 - Seismic profiles made underway on Leg 22. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports on the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 351-367.

VEEVERS, J.J., & EVANS, P.R., 1973 - Sedimentary and magnetic events in Australia and the machanism of world-wide Cretaceous transgressions. Nature (Phys.Sci.), 245, 33-36.

VEEVERS, J.J., FALVEY, D.A., HAWKINS, L.V., & LUDWIG, W.J., 1974 - Seismic reflection measurements of northwest Australian margin and adjacent deeps. Amer.Assoc.Petroleum Geol., 58(9), 1731-1750.

VEEVERS, J.J., & HEIRTZLER, J.R., 1974a - Bathymetry, seismic profiles, and magnetic anomaly profiles. In Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 27, Washington (U.S. Government Printing Office), 339-381.

VEEVERS, J.J., & HEIRTZLER, J.R., 1974b - Tectonic and paleogeographic synthesis of Leg 27. In Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 27, Washington (U.S. Government Printing Office), 1049-1054.

VEEVERS, J.J., & JOHNSTONE, M.H., 1974 - Comparative stratigraphy and structure of the Western Australian margin and the adjacent deep ocean floor. In Veevers, J.J., Heirtzler, J.R., et al., Initial Reports of the Deep Sea Drilling Project. Volume 27, Washington (U.S. Government Printing Office), 571-585.

VEEVERS, J.J., JONES, J.G., & TALENT, J.A., 1971 - Indo-Australian stratigraphy and the configuration and dispersal of Gondwanaland. Nature, 229, 383-388.

VENKATARATHNAM, K., 1974 - Mineralogical data from Sites 211, 212, 213, 214 and 215 of the Deep Sea Drilling Project, Leg 22 and origin of noncarbonate sediments in the equatorial Indian Ocean. In von der Borch, C.C., Sclater, J.R., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 489-502.

von der BORCH, C.C., & REX, R.W., 1970 - Amorphous iron oxide precipitates in sediments cored during Leg 5, Deep Sea Drilling Project. In McManus, D.A., et al., Initial Reports of the Deep Sea Drilling Project Volume 5, Washington (U.S. Government Printing Office), 541-544.

von der BORCH, C.C., SCLATER, J.G., et al., 1974 - Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 890 pp.

von der BORCH, C.C., & TRUEMAN, N.A., 1974 - Dolomitic basal sediments from the northern end of Ninetyeast Ridge. In von der Borch, C.C., Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project Volume 22, Washington (U.S. Government Printing Office), 477-483.

CAPTIONS FOR FIGURES

Figure 1. Location of drill sites, cruise tracks and major physiographic features in the Eastern Indian Ocean.

Figure 2. Stratigraphic sequence of DSDP sites in the Eastern Indian Ocean.

Figure 3. Isopachous map of total sediment thickness in the Eastern Indian Ocean as determined from Ewing et al. (1969) and DSDP seismic profiles.

Figure 4. Schematic representation of stratigraphic columns in the Wharton Basin, illustrating the three-fold lithologic and acoustic division of the abyssal sediments.

Figure 5. Seismic profile in the vicinity of Site 261, showing the lower acoustically opaque, the layered, and the upper acoustically opaque units.

Figure 6. Isopachous map for the lower acoustically opaque unit in the Eastern Indian Ocean as determined from DSDP seismic profiles.

Figure 7. Isopachous map for the layered unit in the Eastern Indian Ocean as determined from DSDP seismic profiles.

Figure 8. Isopachous map for the upper acoustically opaque unit in the Eastern Indian Ocean as determined from DSDP seismic profiles.

Figure 9. Distribution pattern of modern sediments in the Eastern Indian Ocean.

Figure 10. Vertical and lateral changes in sedimentary facies as determined from deep water (A) and shallow water (B) drill sites in the Eastern Indian Ocean.

Figure 11. Siliceous claystone showing extensive burrowing. Sample from Core 21, Site 263, depth of 527 m.

Figure 12. White kaolinite pellets in silty claystone. Sample from Core 24, Site 263, depth of 638 m.

Figure 13. Calcite-cemented kaolinitic sandstone. The pellets, which are pale green in colour, are composed almost entirely of kaolinite; the cement is of sparry calcite. Sample from Core 28, Site 263, depth of 737 m.

Figure 14. Dolomite rhombs from a dolomite nodule within a siliceous clay. Sample from Core 22, Site 259, depth of 207 m.

Figure 15. Cluster of euhedral clinoptilolite crystals in a zeolitic clay. Sample from Core 17, Site 259, depth of 159 m.

Figure 16. Sand-size quartz grain with prominent marginal embayments, in a zeolitic silty clay. The embayments may be the result of diagenetic marginal replacement, or alternatively, the quartz grain is of volcanic origin.

Figure 17. Foraminifera-nannofossil ooze. Sample from Core 1, Site 263, depth of .2 m.

Figure 18. Foraminiferal test partly infilled with pyrite. Sample from Site 263.

Figure 19. Variation of $CaCO_3$ content at deep (A) and shallow (B) drill sites in the Eastern Indian Ocean.

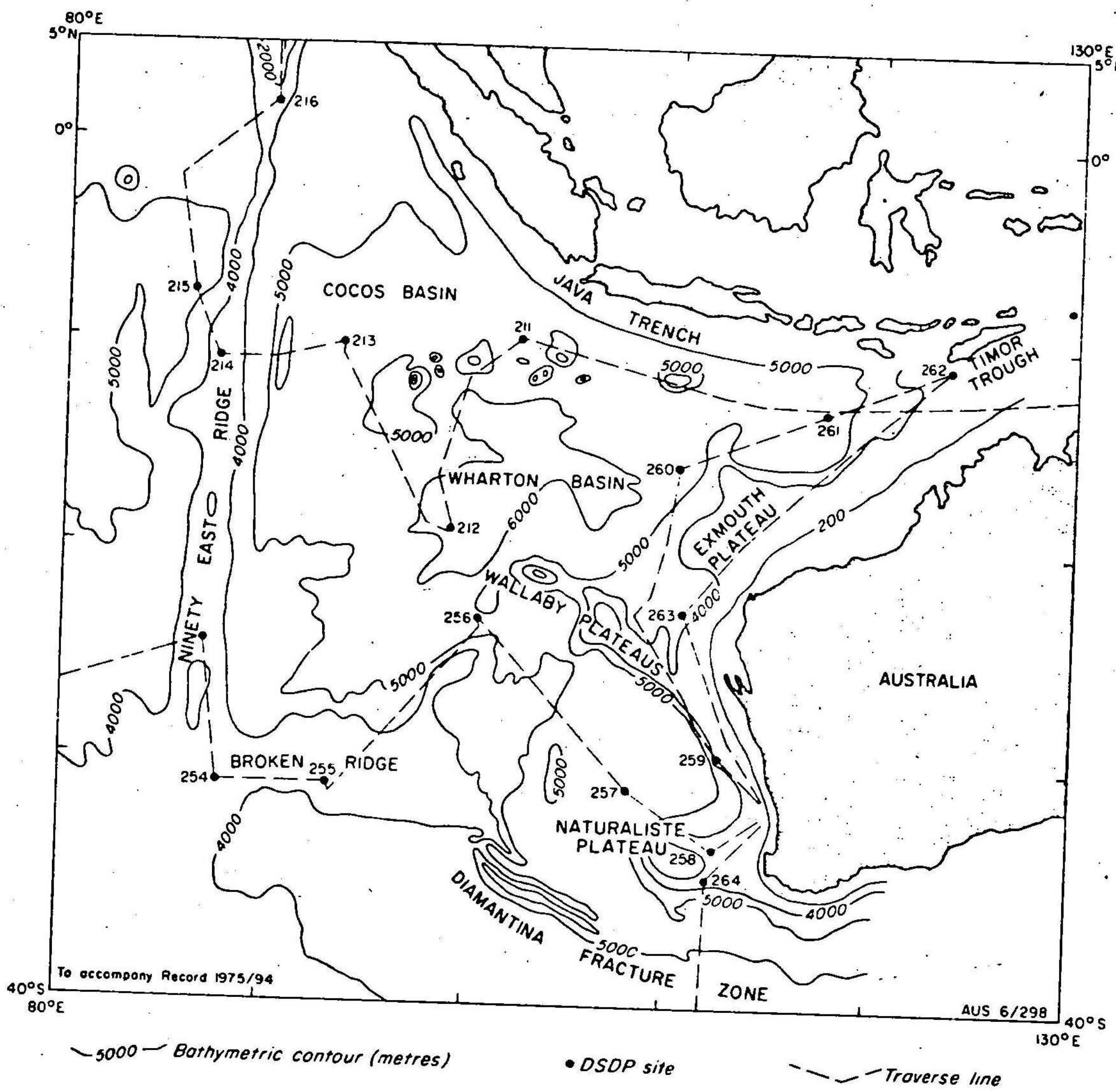
Figure 20. Schematic representation of the distributions of hiatuses at shallow drill sites in the Eastern Indian Ocean.

Figure 21. Schematic representation of the distribution of hiatuses at the deepwater drill sites in the Eastern Indian Ocean.

Figure 22. Variation in the rate of sedimentation during the Cretaceous in the Eastern Indian Ocean.

Figure 23. Variation in the rate of sedimentation during the Cenozoic in the Eastern Indian Ocean.

Figure 24. The pattern of continental dispersal during the Late Mesozoic-Cenozoic and the influence of this movement on ocean currents and sedimentation. Position of continents and the time intervals are only approximate.



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WHARTON BASIN
EXMOUTH PLATEAU
WALLABY PLATEAUS
NINETY EAST RIDGE
BROKEN RIDGE
NATURALISTE PLATEAU
DIAMANTINA FRACTURE ZONE
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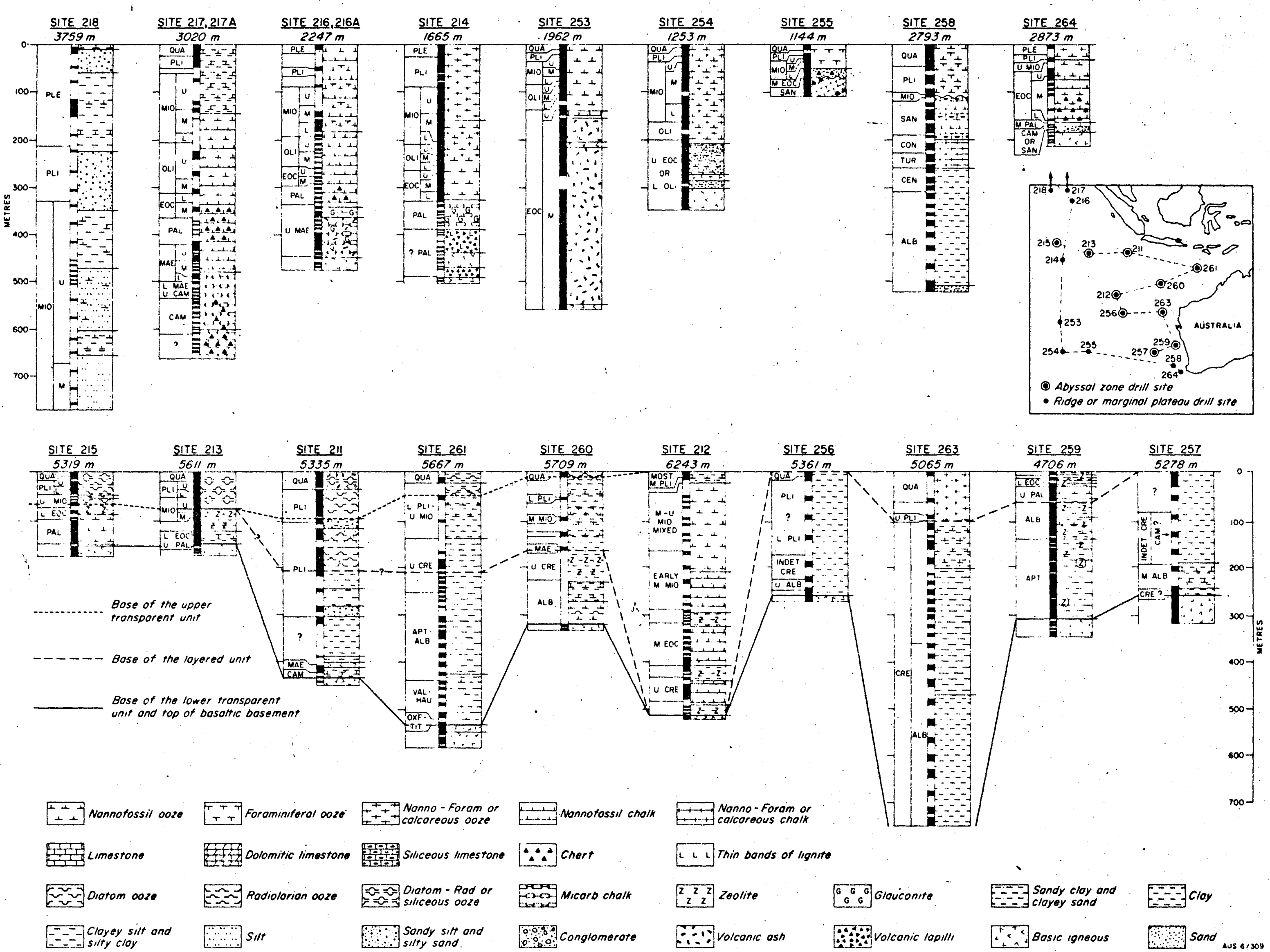
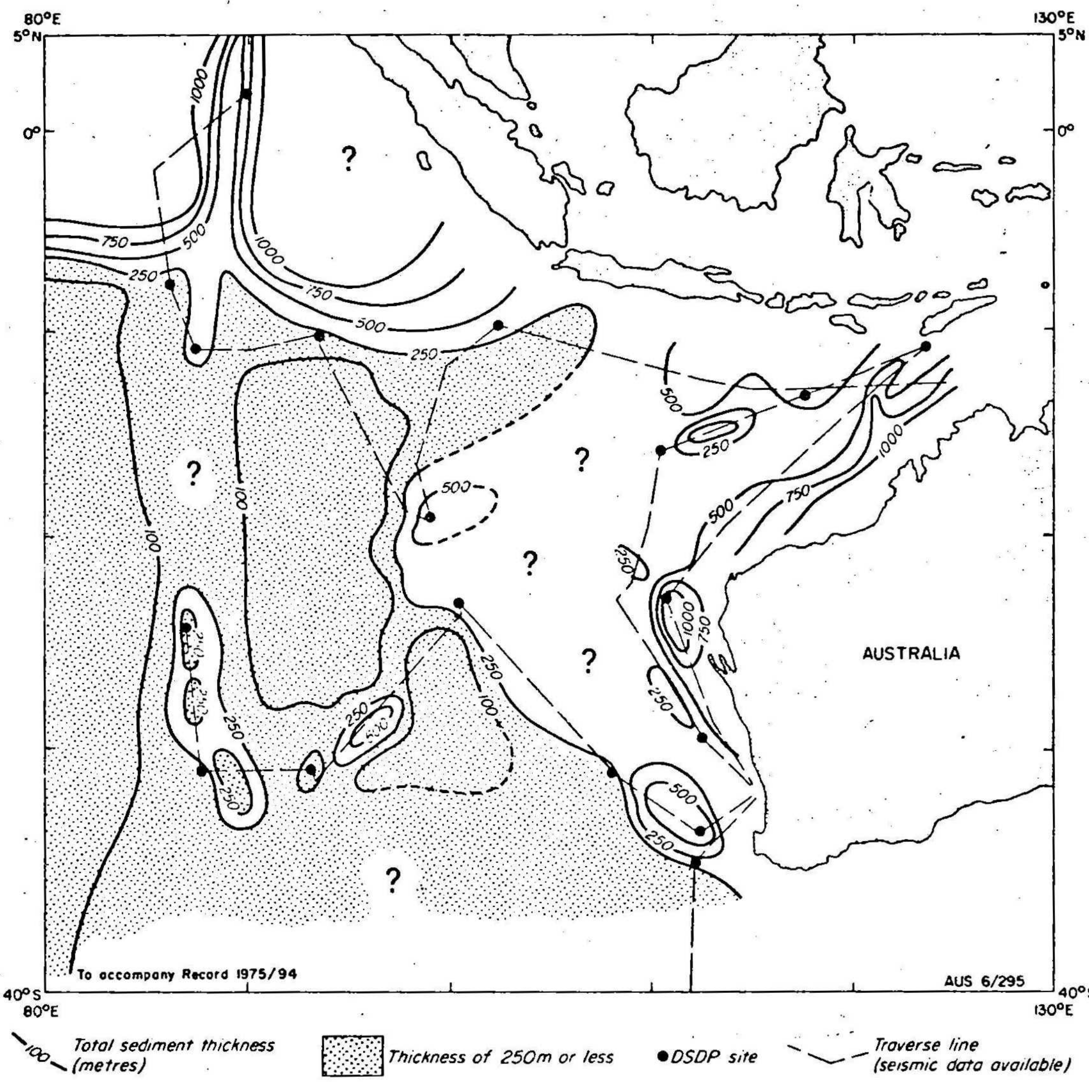
To accompany Record 1975/94
AUS 6/298
5000 Bathymetric contour (metres)
• DSDP site
Traverse line

Figure 1



To accompany Record 1975/94

Figure 2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AUSTRALIA
To accompany Record 1975/94
AUS 6/295
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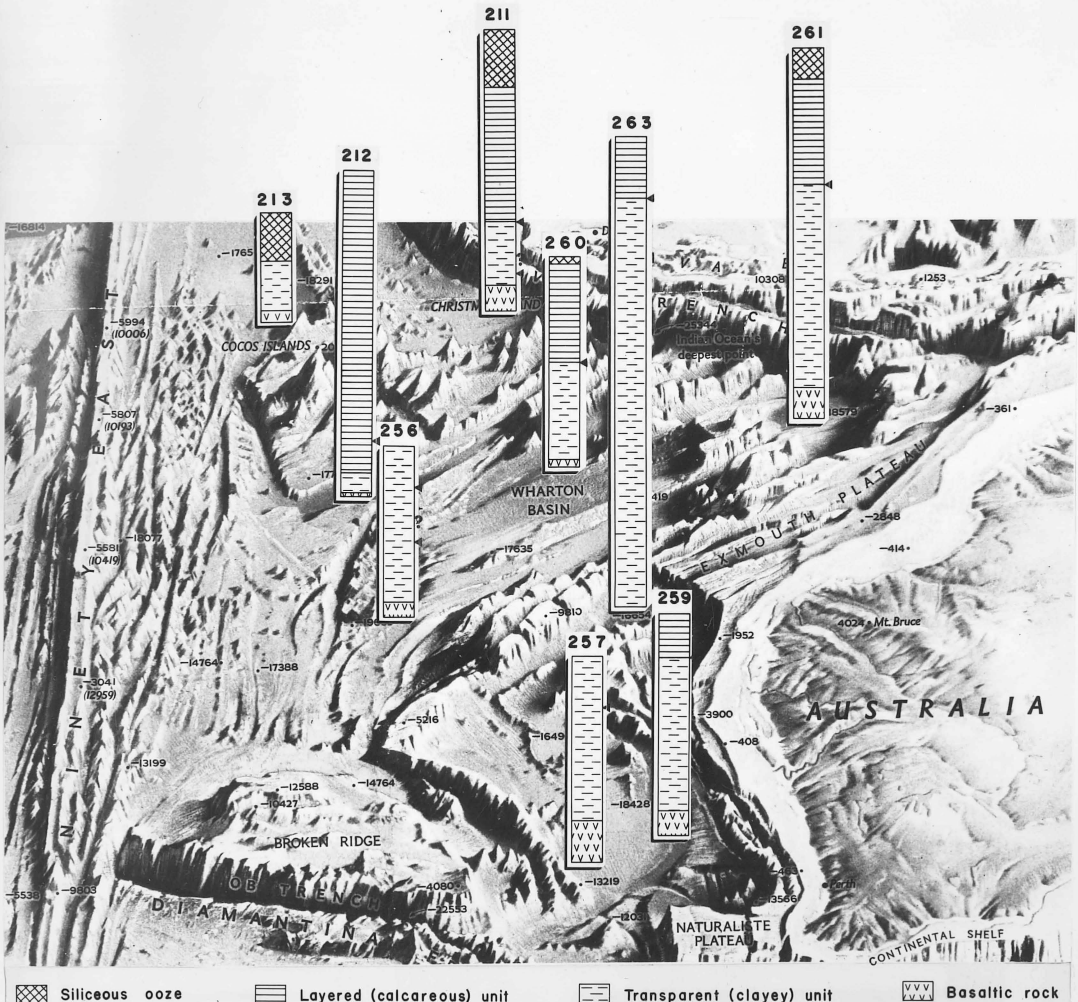
Total sediment thickness (metres)
Thickness of 250m or less
DSDP site
Traverse line (seismic data available)

Figure 3



SCHEMATIC REPRESENTATION OF STRATIGRAPHIC COLUMNS AT DSDP SITES IN THE WHARTON BASIN

Figure 4

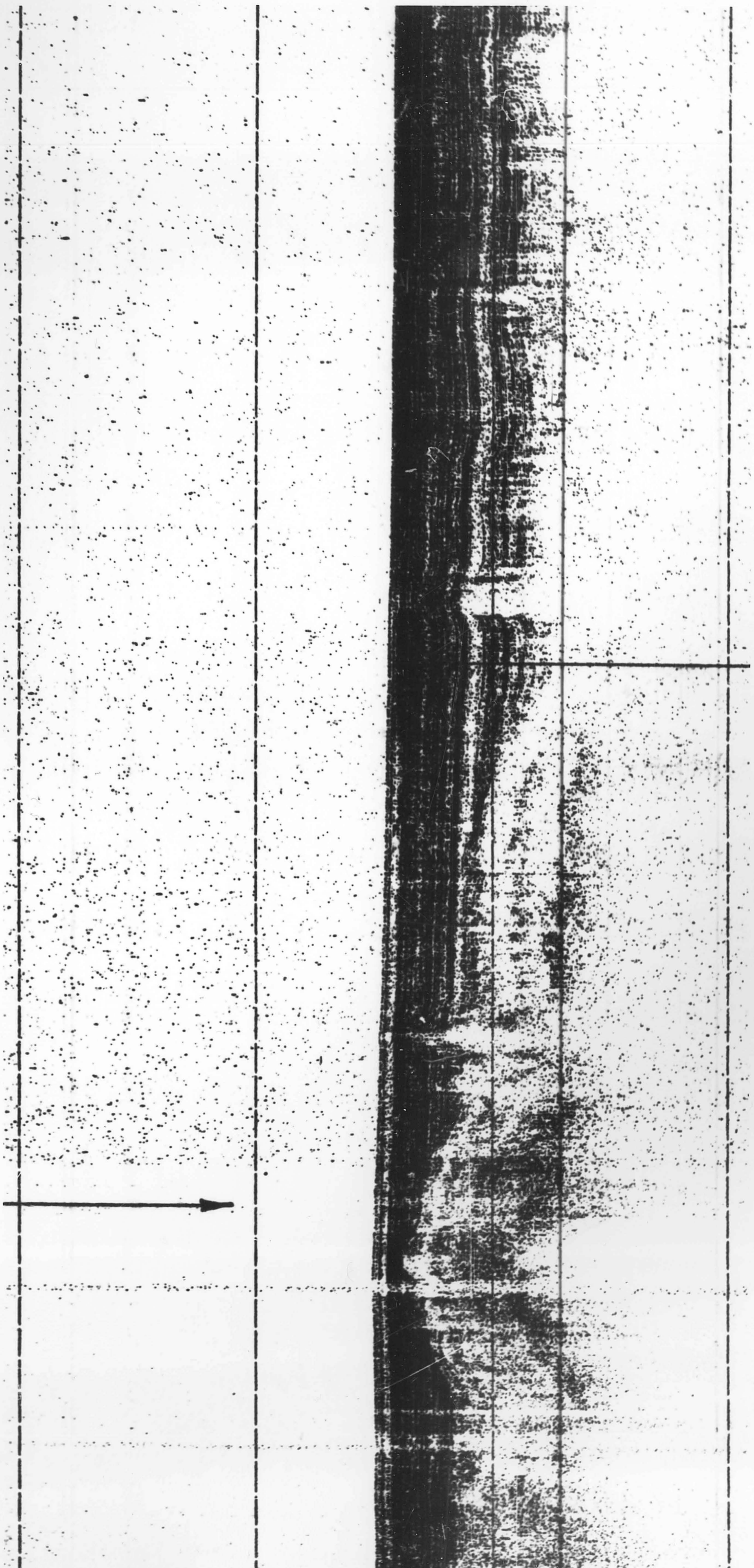
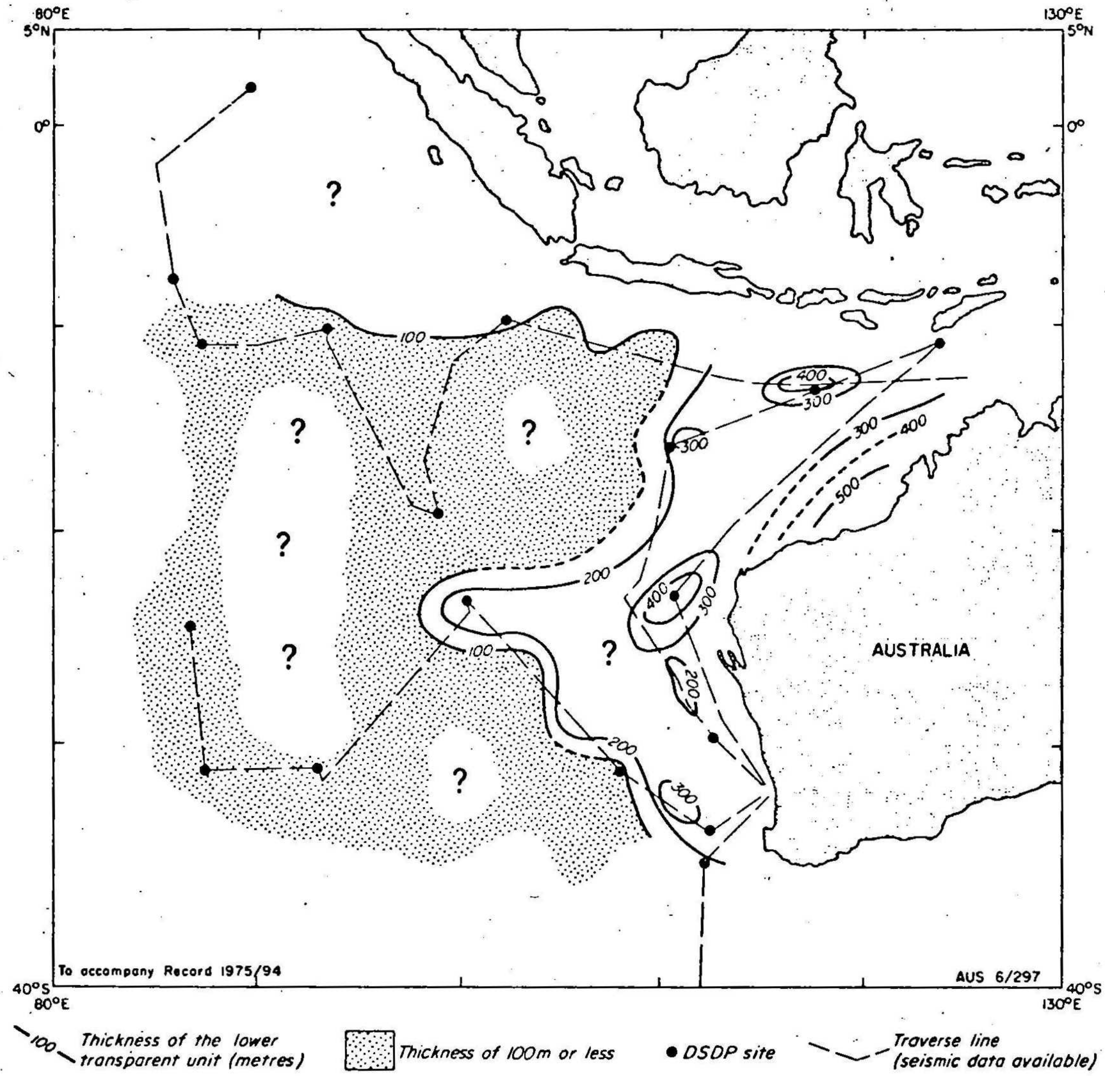


Figure 5



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AUSTRALIA
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40°S
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100 Thickness of the lower transparent unit (metres)
Thickness of 100m or less
DSDP site
Traverse line (seismic data available)

Figure 6

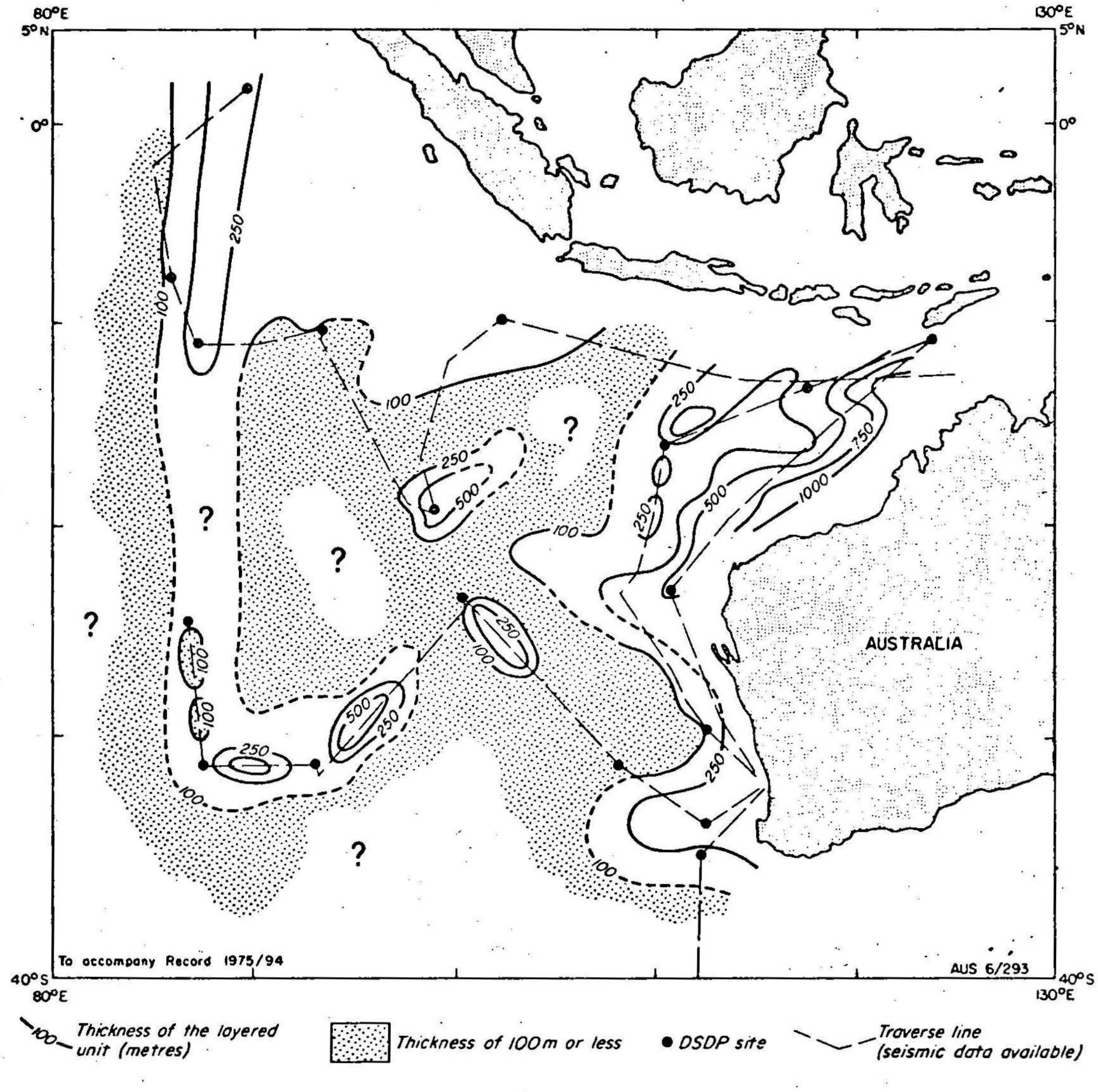

80°E
130°E
5°N
0°
40°S
AUSTRALIA
100
250
500
750
1000
?
To accompany Record 1975/94
AUS 6/293
Thickness of the layered unit (metres)
Thickness of 100m or less
DSDP site
Traverse line (seismic data available)

Figure 7

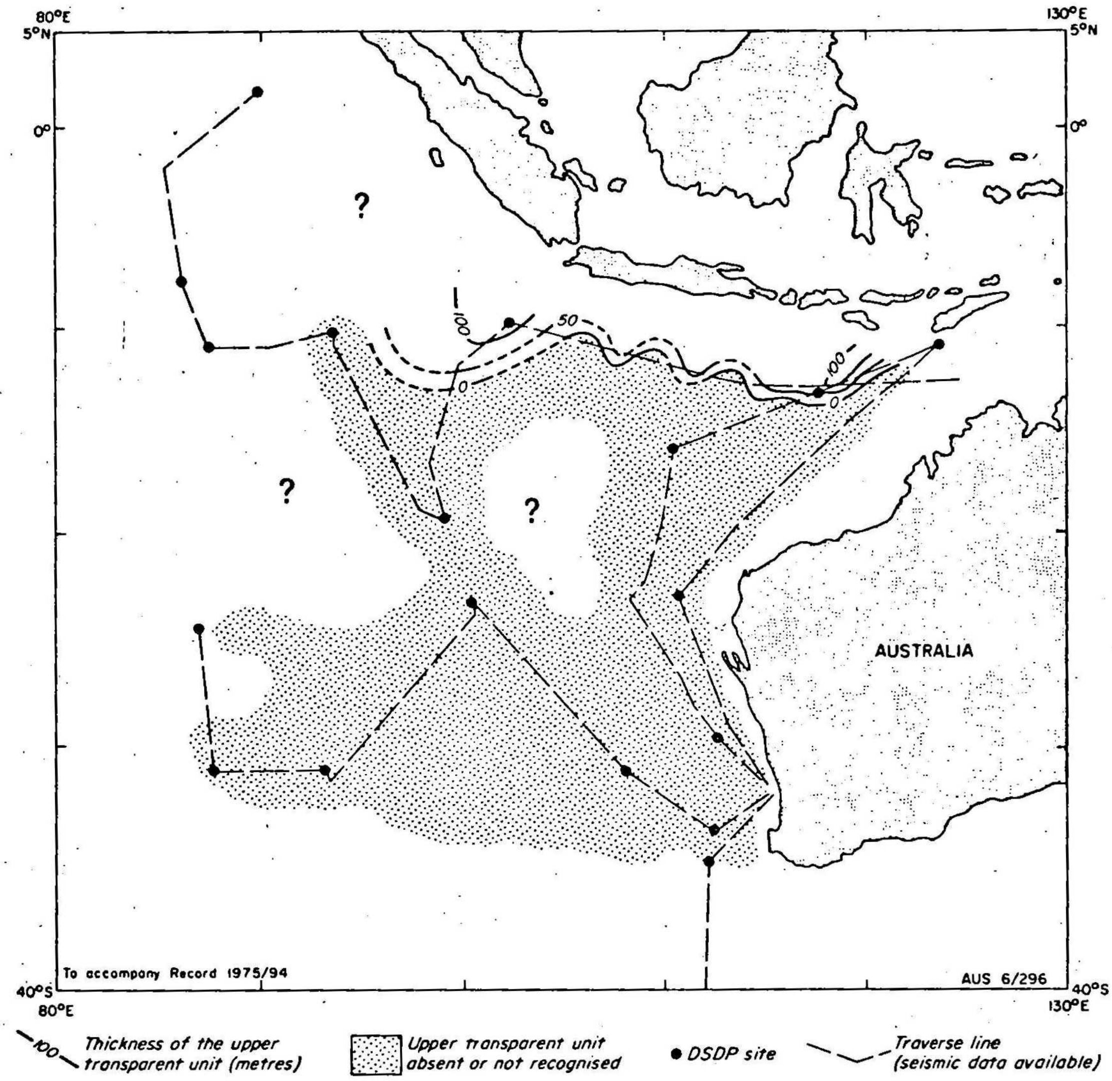
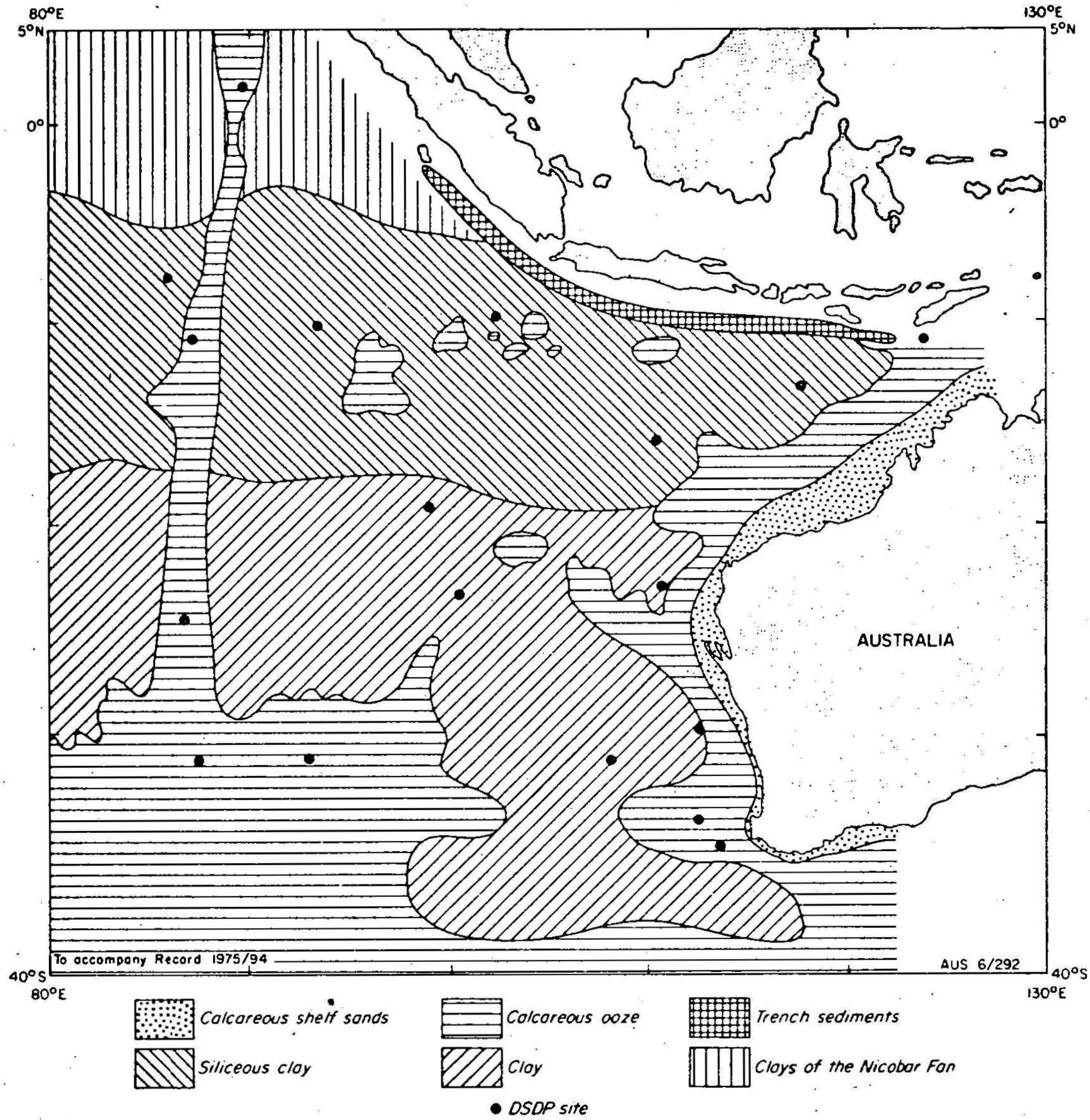

80°E
5°N
0°
130°E
5°N
0°
?
?
?
100
50
0
100
0
AUSTRALIA
To accompany Record 1975/94
AUS 6/296
40°S
80°E
40°S
130°E
100
Thickness of the upper transparent unit (metres)
Upper transparent unit absent or not recognised
DSDP site
Traverse line (seismic data available)

Figure 8



80°E
130°E
5°N
5°N
0°
0°
AUSTRALIA
To accompany Record 1975/94
AUS 6/292
40°S
40°S
80°E
130°E
Calcareous shelf sands
Calcareous ooze
Trench sediments
Siliceous clay
Clay
Clays of the Nicobar Fan
DSDP site

Figure 9

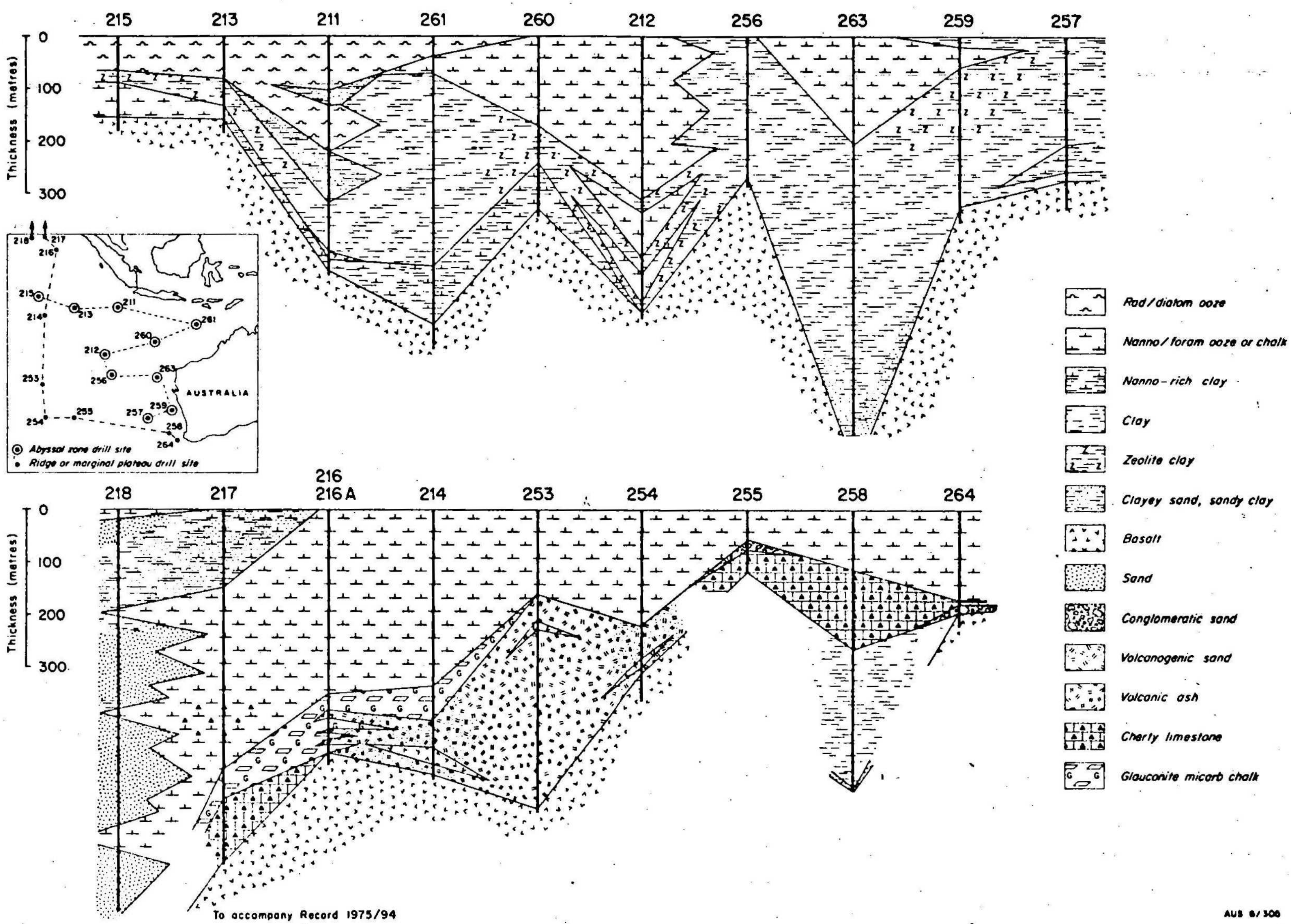

215 213 211 261 260 212 256 263 259 257
Thickness (metres)
0
100
200
300
218 217 216 216A 214 253 254 255 258 264
AUSTRALIA
Abyssal zone drill site
Ridge or marginal plateau drill site
Rad/diatom ooze
Nanno/foram ooze or chalk
Nanno-rich clay
Clay
Zeolite clay
Clayey sand, sandy clay
Basalt
Sand
Conglomeratic sand
Volcanogenic sand
Volcanic ash
Cherty limestone
Glauconite micarb chalk
To accompany Record 1975/94
AUS 6/306

Figure 10

Figure 11

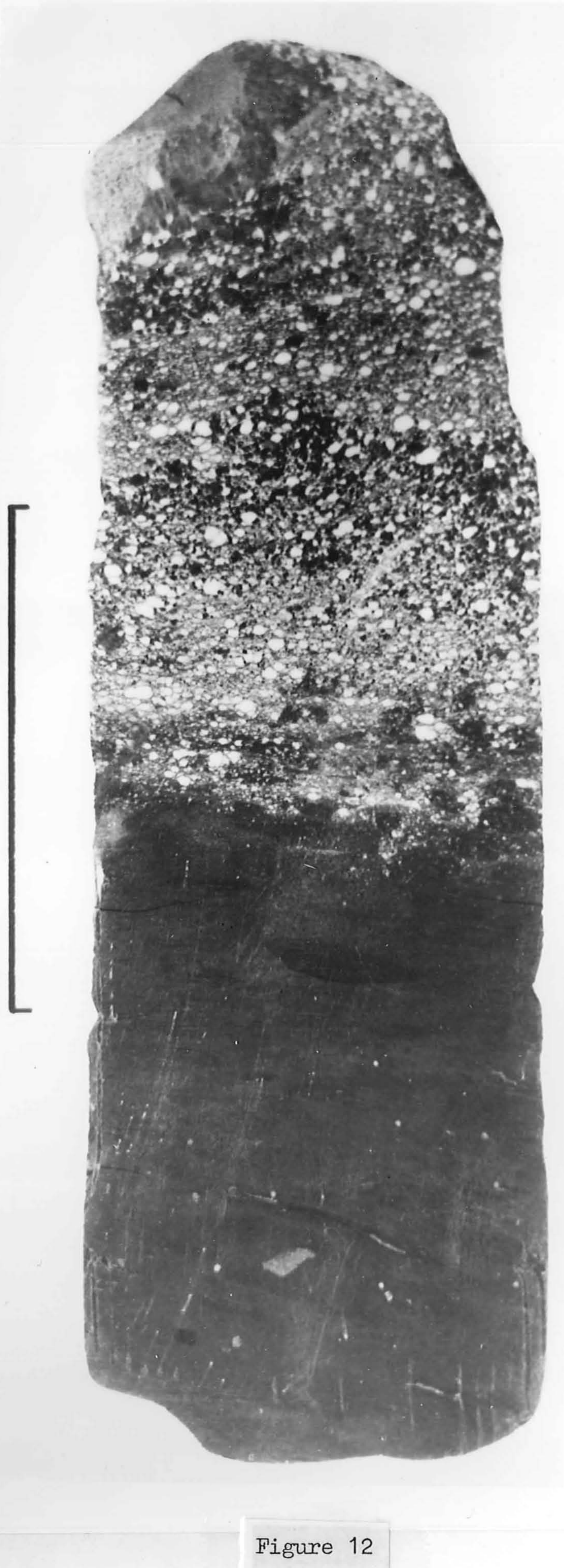


Figure 12

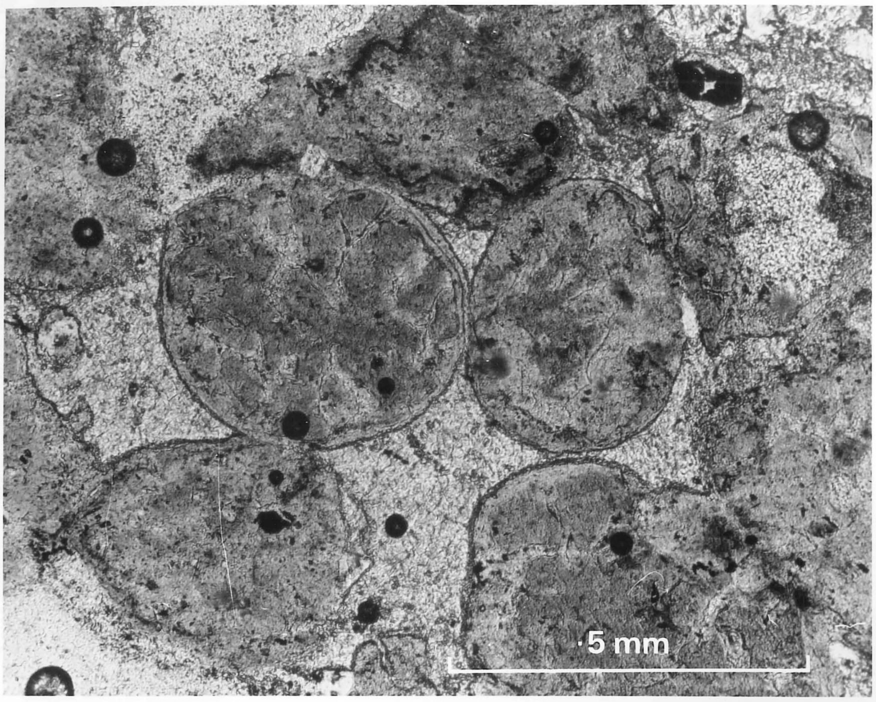


Figure 13

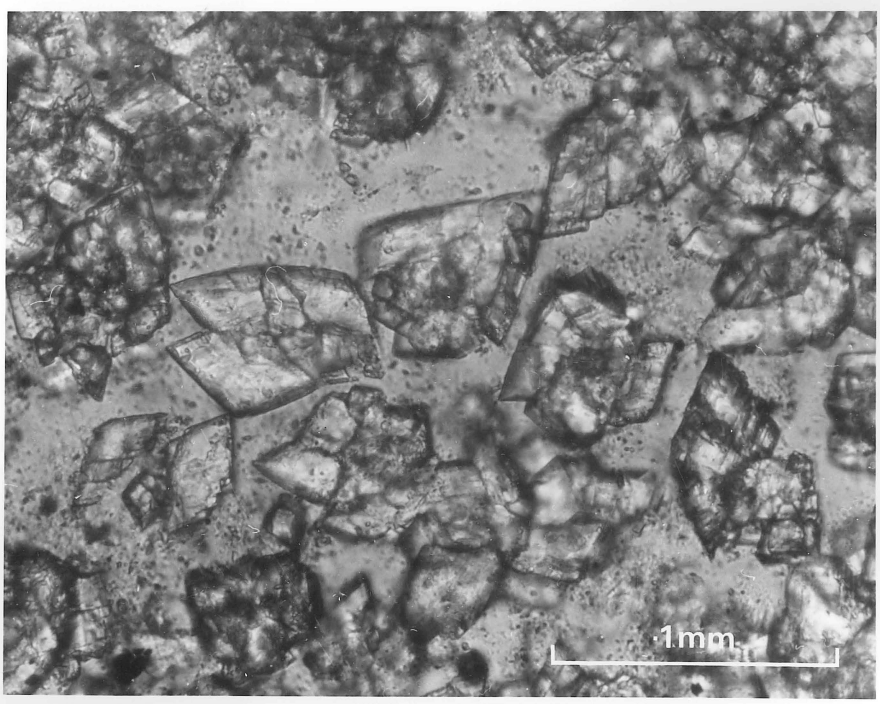


Figure 14

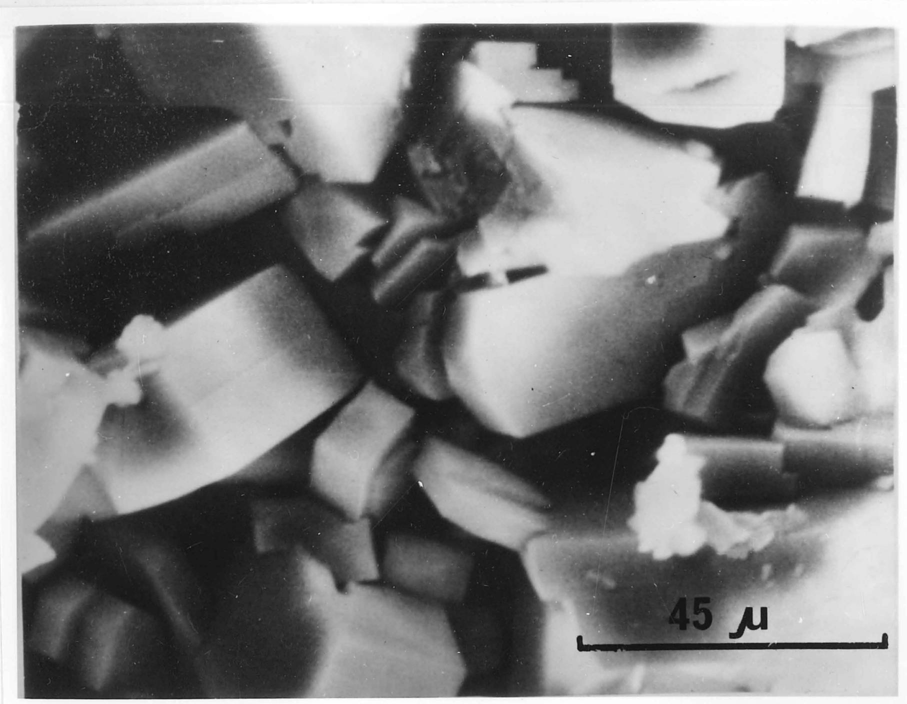


Figure 15

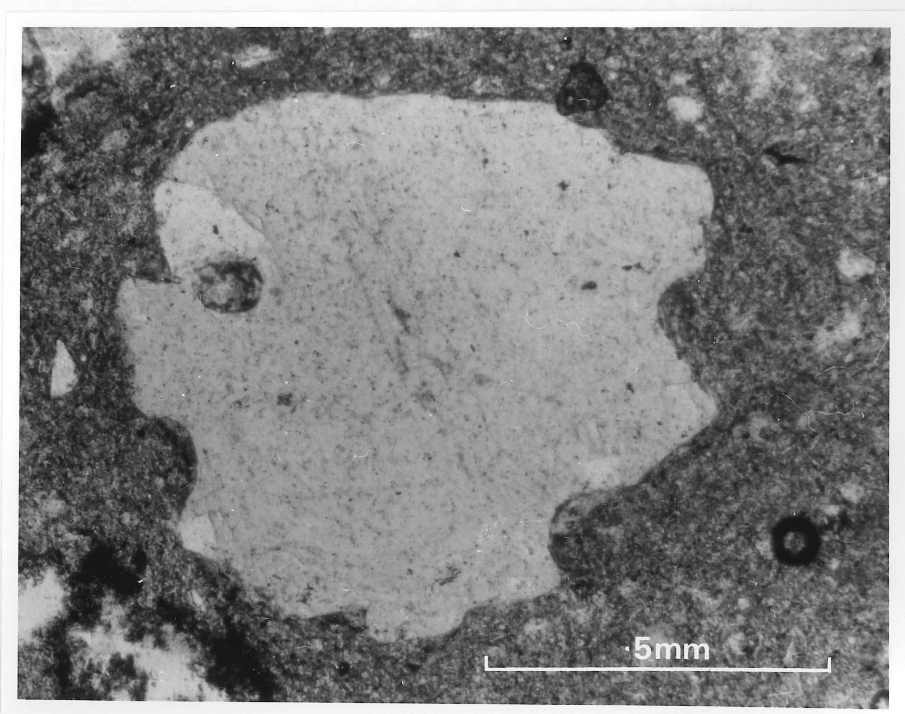


Figure 16

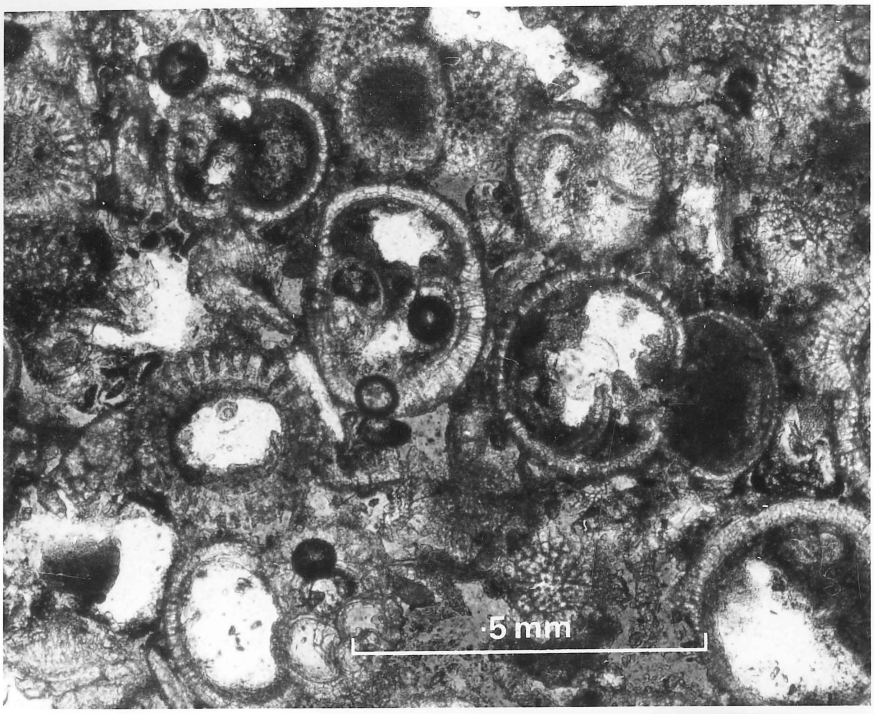


Figure 17

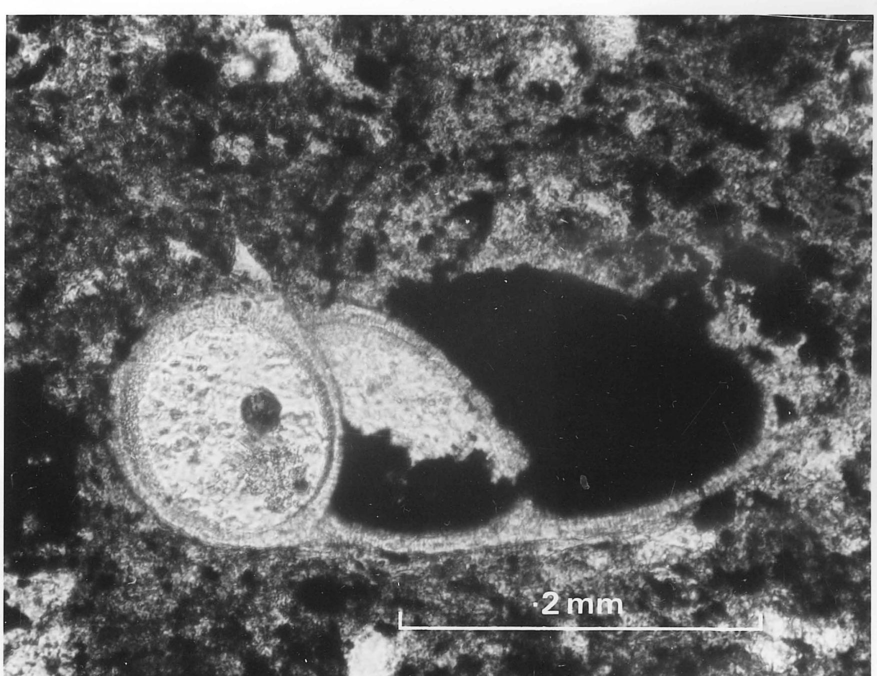
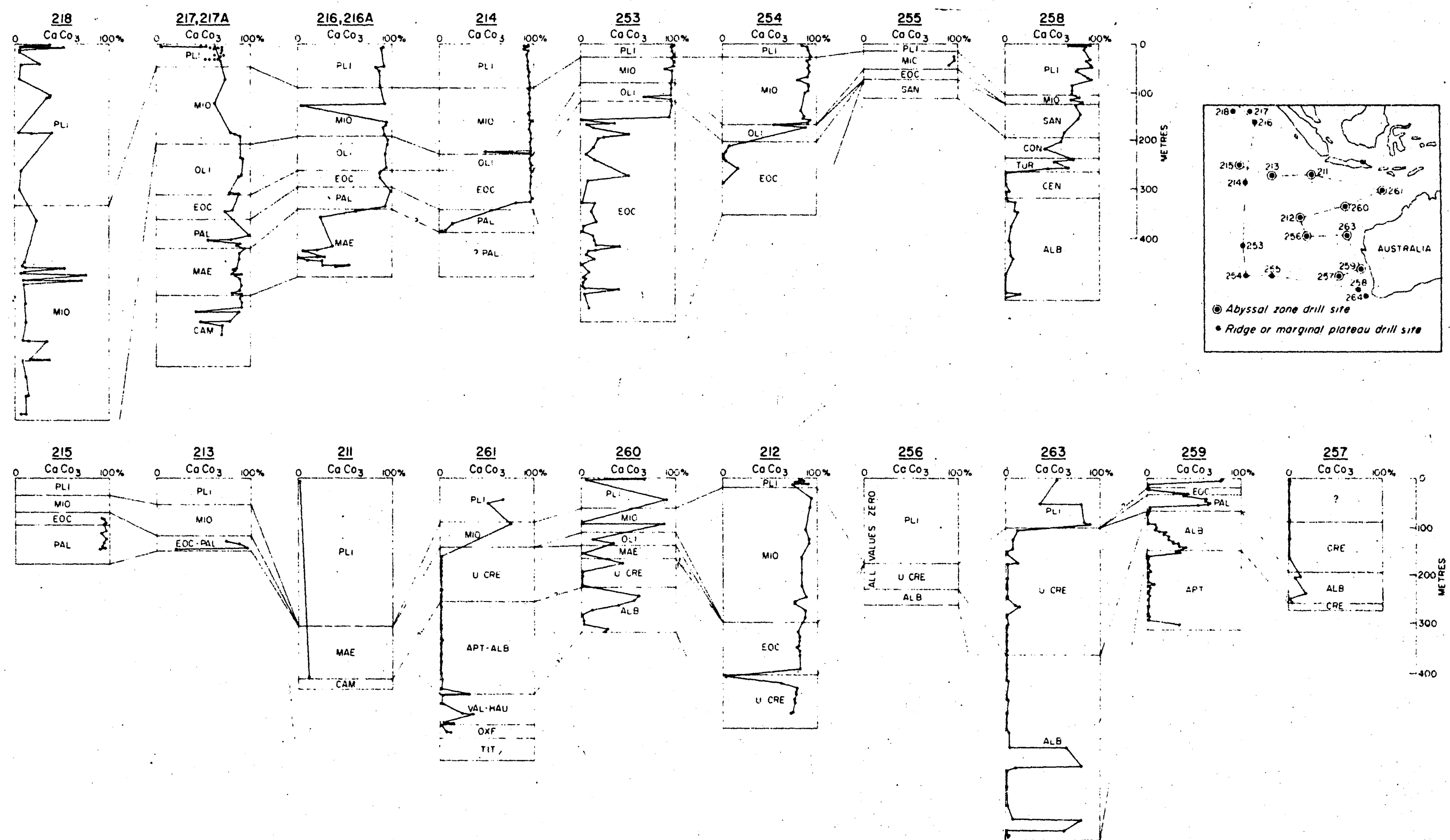


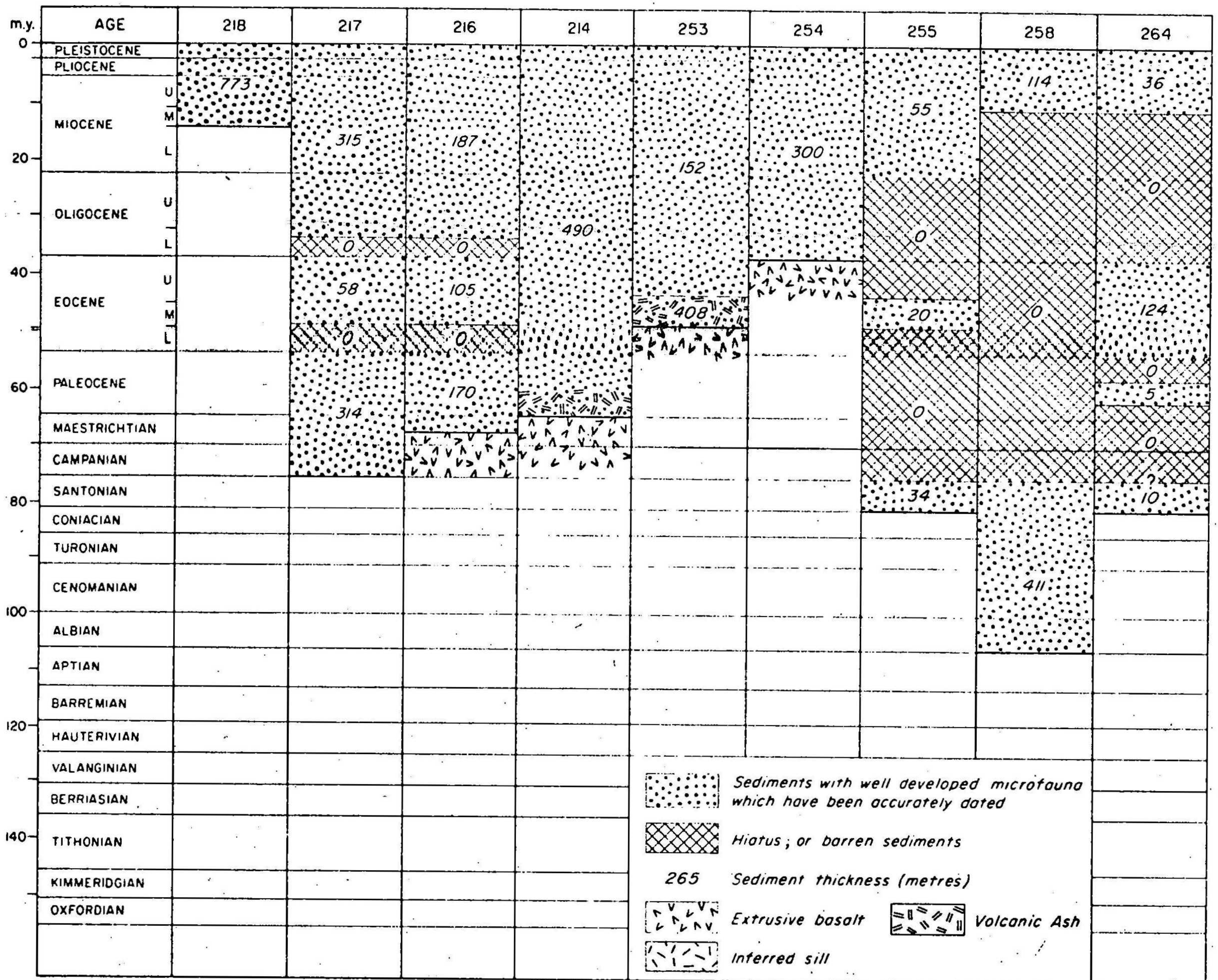
Figure 18



To accompany Record 1975/94

AUS 6/311

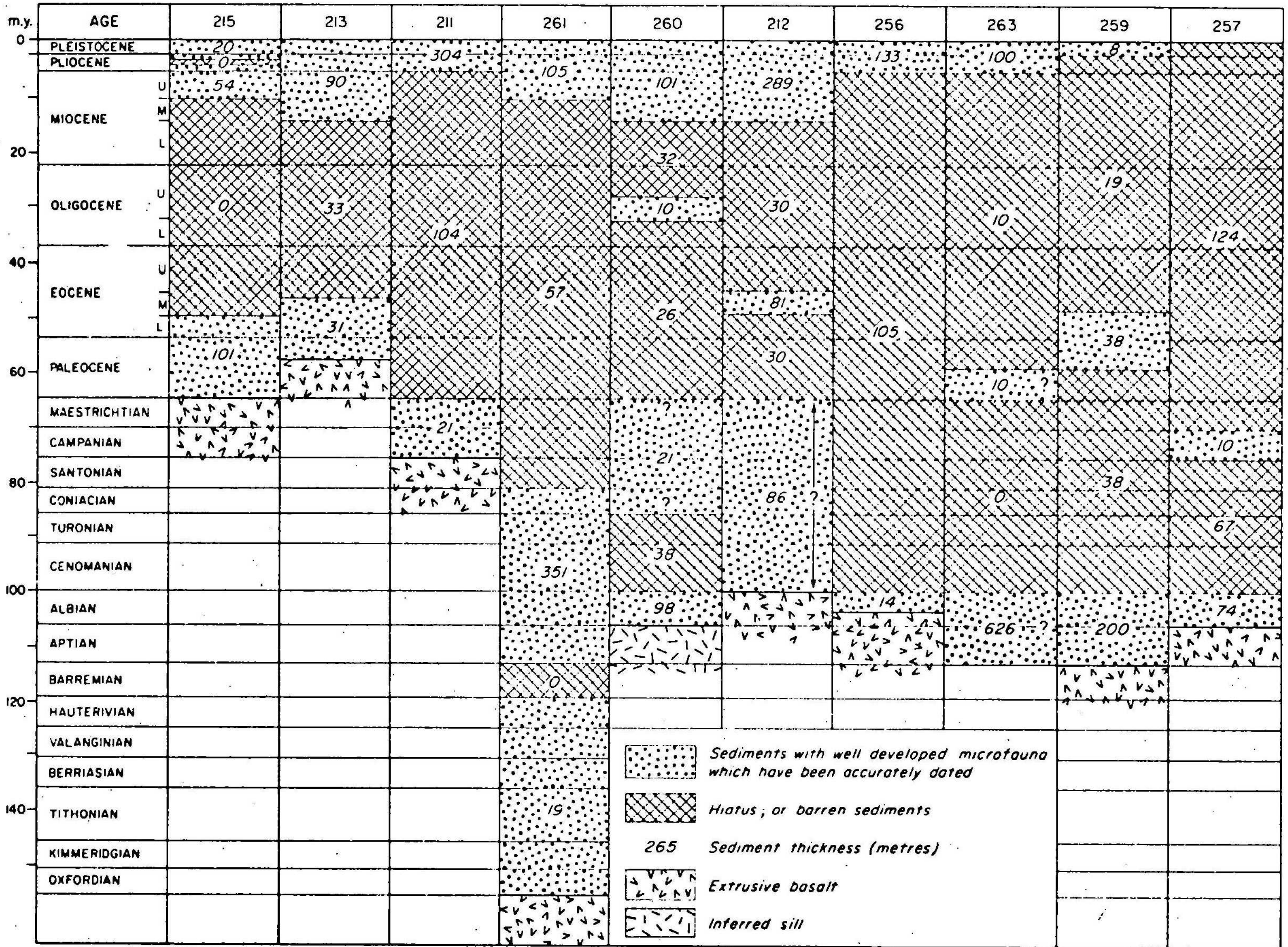
Figure 19



To accompany Record 1975/94

AUS 6/291A

Figure 20



To accompany Record 1975/94

AUS 6/291

Figure 21

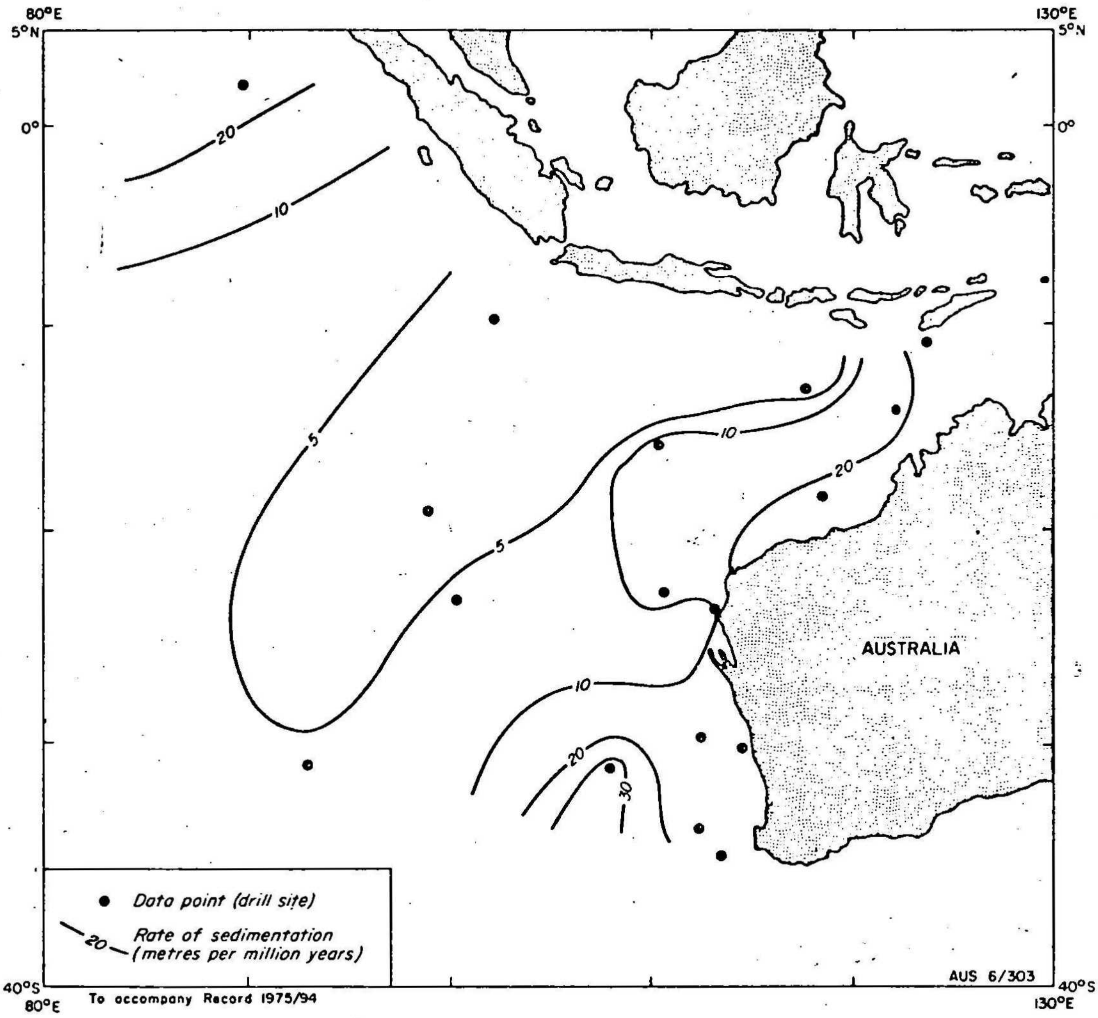

80°E
5°N
130°E
5°N
0°
0°
20
10
5
5
10
20
10
20
30
AUSTRALIA
Data point (drill site)
20
Rate of sedimentation
(metres per million years)
40°S
80°E
To accompany Record 1975/94
AUS 6/303
40°S
130°E

Figure 22

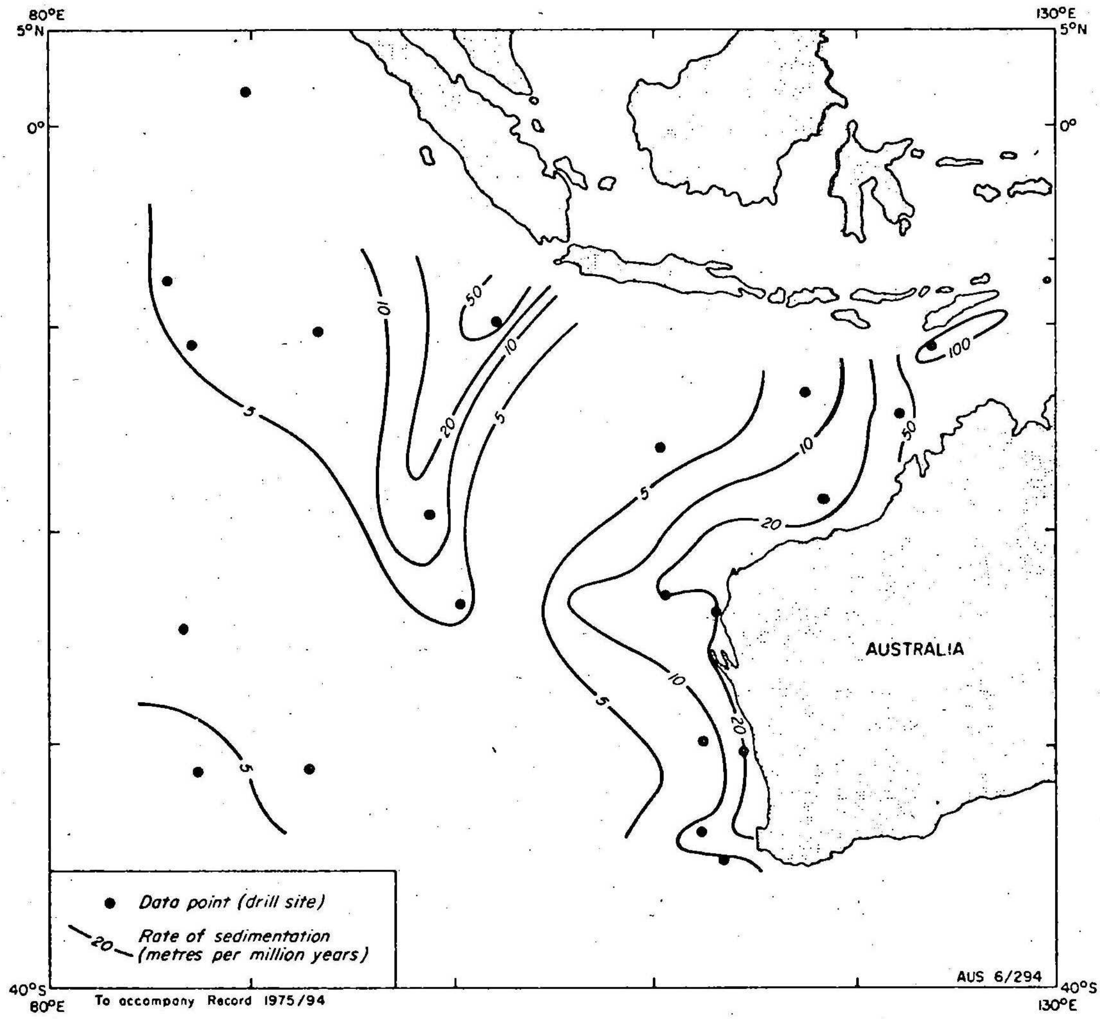
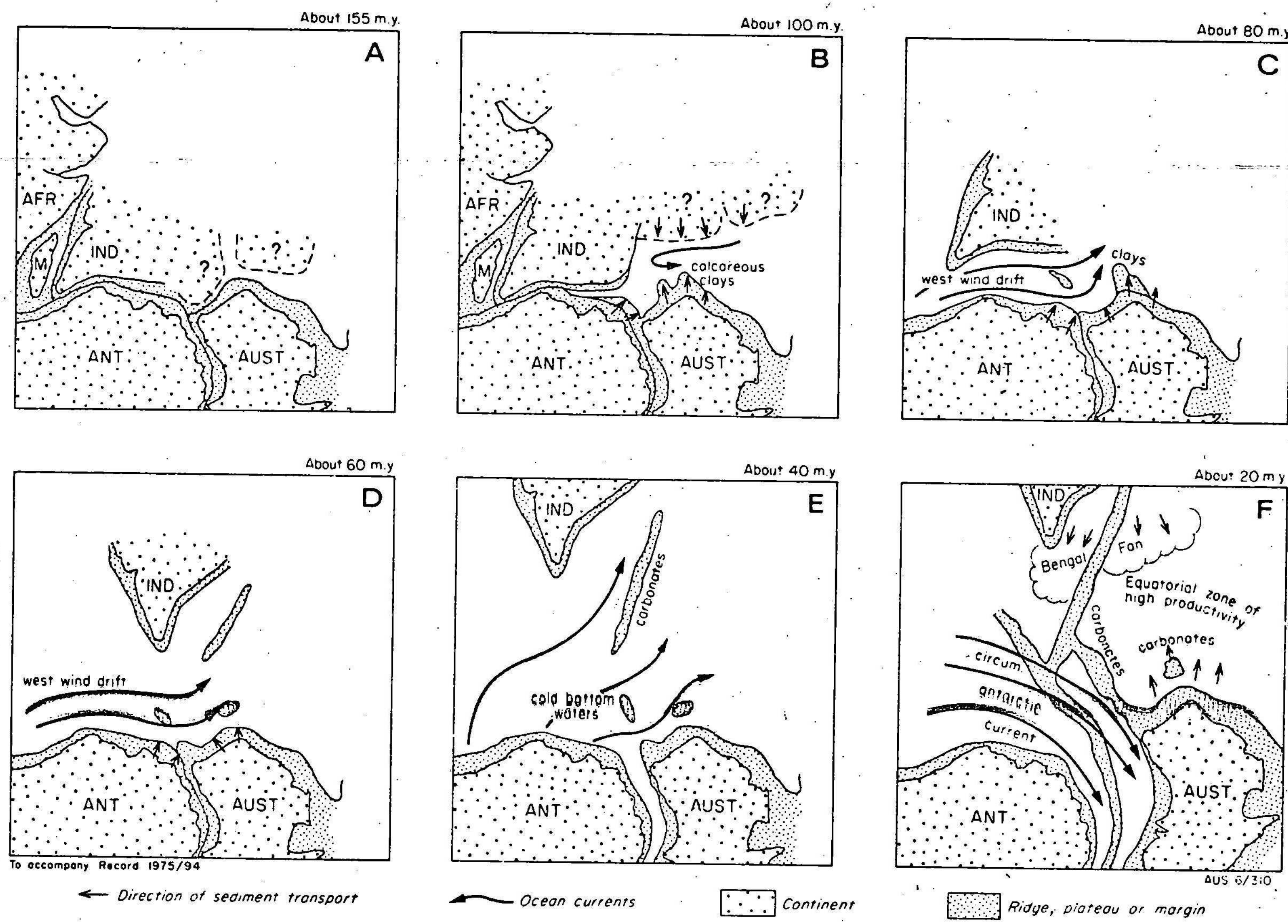

80°E
5°N
0°
130°E
5°N
0°
50
10
20
10
5
5
5
100
50
10
20
5
10
20
AUSTRALIA
Data point (drill site)
20
Rate of sedimentation
(metres per million years)
AUS 6/294
40°S
80°E
To accompany Record 1975/94
40°S
130°E

Figure 23



About 155 m.y.
A
AFR
M
IND
?
?
ANT
AUST
About 100 m.y.
B
AFR
M
IND
?
?
calcareous
clays
ANT
AUST
About 80 m.y
C
IND
clays
west wind drift
ANT
AUST
About 60 m.y
D
IND
west wind drift
ANT
AUST
About 40 m.y
E
IND
carbonates
cold bottom
waters
ANT
AUST
About 20 m.y
F
IND
Bengal
Fan
Equatorial zone of
high productivity
carbonates
carbonates
circum
antarctic
current
ANT
AUST
To accompany Record 1975/94
AUS 6/310
Direction of sediment transport
Ocean currents
Continent
Ridge, plateau or margin

Figure 24