28. REGIONAL ASPECTS OF DEEP SEA DRILLING IN THE SOUTHWEST PACIFIC

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INTRODUCTION

The region covered by the Tasman Sea is clearly an anomalous feature in any simple hypothesis of the evolution of the Pacific and the Pacific marginal basin structures. It is an area of great structural complexity which does not conform readily to any of the more general reconstructions by global scale plate tectonics. Distinctly separate from the Pacific basin on both the north and the east, this region (Figure 1) encompasses a series of marginal basins (Lau-Havre, South Fiji, Norfolk, New Caledonia, Tasman Sea, and Coral Sea), trenches (Tonga-Kermadec, North and South New Hebrides, South Solomon, and New Britain), ridges (Tonga-Kermadec, Lau-Colville, Three Kings, Norfolk and West Norfolk, and Lord Howe Rise), and a major continental marginal plateau (Queensland Plateau). Leg 21 was conducted as an initial attempt to answer a limited number of basic questions, as well as to provide a rationale for on-going investigations.

SEISMIC REFLECTION PROFILES

Considering the general track of the *Challenger* (Figure 2), it is clear that no specific additional insight could be anticipated in regard to the structural nightmare which comprises the northern boundary of the region. On the other hand, a long traverse (A-B, C-D; Figure 2) has provided new data which lend themselves to synthesis appropos the evolution of the more prominent features encompassing the marginal basins and the Lord Howe Rise.

The long seismic reflection profile (Figure 3), which transects the area along the track between Sites 204, 205, 206, 208, 209, and 210, may be used to show several general classes of structures in the area. There appear to be five contrasting types of topography structure, as follows:

1) Smooth with step faults: Pacific Plate near the Tonga Trench.

2) Rough–jagged, with little or no sediment cover: Lau Basin and Ridge; and margin between Three Kings Rise and the South Fiji Basin.

3) Smooth-flat, with rough, relatively shallow acoustic basement: South Fiji Basin (except western margin); and some sediment ponds within the Lau Basin.

4) Smooth, rolling topography and structure with relatively deep basement: Norfolk Ridge and West Norfolk Ridge; New Caledonia Basin; Lord Howe Rise; eastern side of Dampier Ridge; and Queensland Plateau.

5) Blocky structure–normal faults, horst and graben: Three Kings Rise to the Norfolk Ridge; and west side of the Dampier Ridge to the Queensland Plateau.

In a general sense, based on Figures 1 and 3 (both in pocket at back of volume), the area appears to be transected by two major boundaries which separate regions of contrasting topography-structure. The Tonga-Kermadec Trench separates the Western Pacific Plate Province from the Eastern Marginal Basin Province (Tonga-Kermadec Ridge, Lau-Havre Basin, Lau-Colville Ridge, and South Fiji Basin). In turn, the eastern is separated from the Western Marginal Basin Province at the western edge of the South Fiji Basin along a line running from the Loyalty Island Group, east of New Caledonia, to the region of the Bay of Plenty, North Island, New Zealand. These boundaries appear to separate provinces of different ages.

Western Pacific Plate Province

Although the sea floor east of the Tonga-Kermadec Trench is generally smooth, it is broken into blocks by step faults on the eastern slope of the trench. The age of the sea floor on the eastern slope has been determined (Figure 4) to be at least Late Cretaceous and, as suggested by plate tectonic hypotheses, it appears that it is being deformed as a result of extension during subduction. This relatively recent tectonism is the only recognizable development following massive volcanism which occurred apparently during the Cretaceous.

Eastern Marginal Basin Province

Lau Basin

From both the drilling results at Site 203 and an extrapolation based on the seismic profiles, a Late Miocene age is suggested for the opening of the Lau Basin. In addition, the seismic profiles suggest that the basin could have formed by the splitting of a single arc as postulated by Karig (1970). The discontinuous and irregular distribution of rough topography and small sediment pockets, which had been reported earlier (Karig, 1970 and 1971), was observed during Leg 21 operations. This has been interpreted as resulting from an irregular development of the basin floor. Normal faulting in some of the basins appears to have continued into very recent times, and is interpreted as indicating continuing extension.

South Fiji Basin

An extrusive flow of basaltic pillow lava was found underlying Late Oligocene sediments at Site 205. Considering the depth at which this flow was encountered, an interpretation of the seismic profiles suggests that this Late Oligocene age is close to the age of the formation of

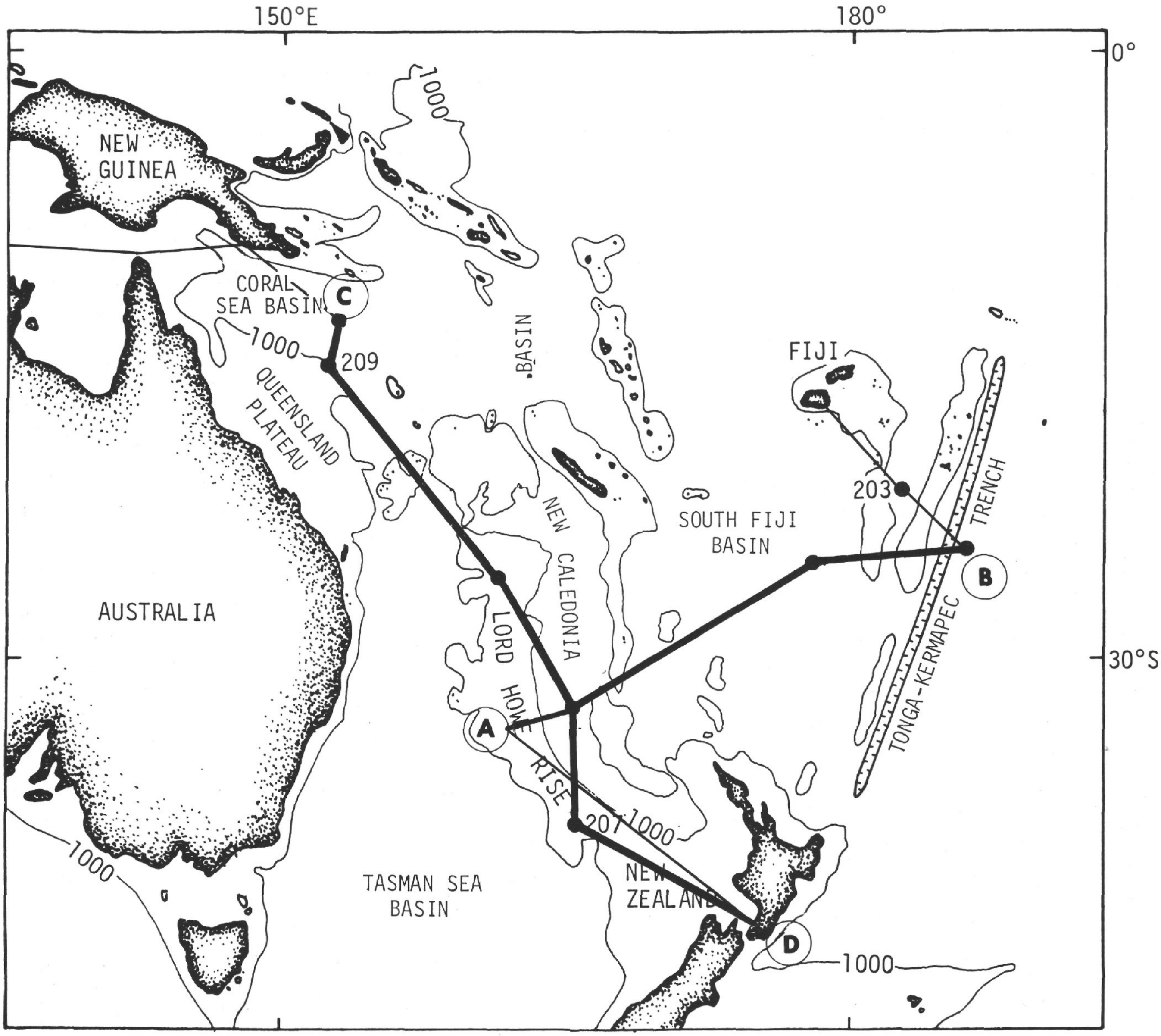


Figure 2. *Summary of track of* Glomar Challenger *on Leg 21. Heavy lines refer to seismic profiles shown in Figure 3 (in pocket at back of book).*

the basin. With this premise, the basin is considered to represent crust which was accreted to the southern part of the preexisting Western Marginal Basin Province during the Oligocene, possibly behind an eastward migrating Tonga-Kermadec arc in the manner suggested by Karig (1971) and Packham and Falvey (1971).

Western Marginal Basin Province

The drilling results confirm that all of the major morphologic features of this province were in existence by Middle Eocene time. However, displaced Paleocene and Cretaceous material found during the drilling program, together with the thicknesses indicated on the seismic profiles, suggest that most of the prominent features of this western province (e.g., Lord Howe Rise, New Caledonia Basin, and Tasman Basin) were in existence by the Late Cretaceous.

Within the western province, the type 4 (smooth, rolling topography and structure, with relatively deep basement) and type 5 (blocky structure; normal faults, horst and graben) topography-structures give evidence of three possible phases of tectonic activity with distinctly different natures. The smooth rolling type 4 structure appears to be the earliest and is associated with initial formation of the basic features in the western province.

One of the prominent characteristics of the western province found during the drilling program, and not readily predicted form the seismic records, is a major regional

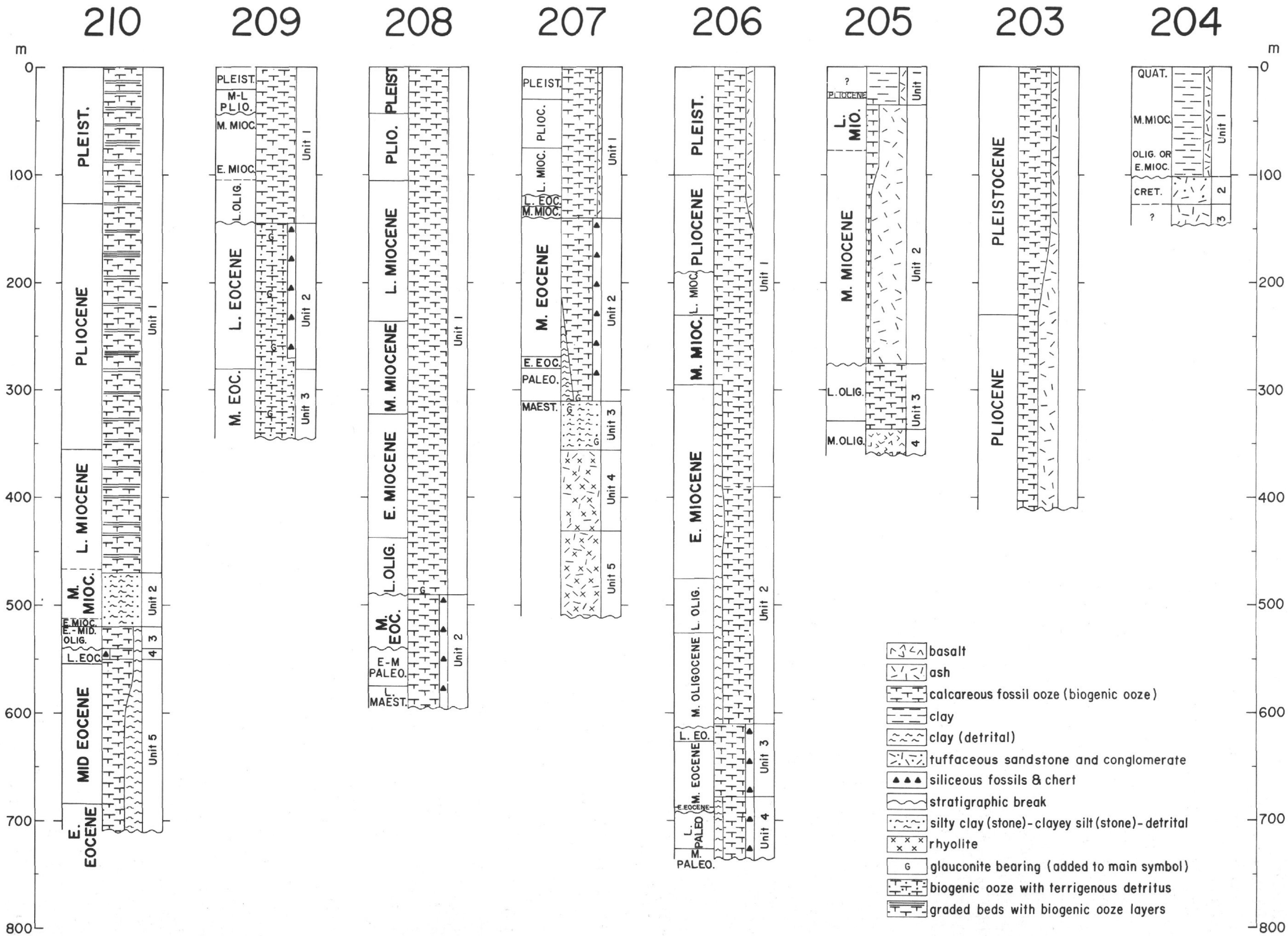


Figure 4. *Summary of the results of drilling at Sites 203 through 210.*

unconformity (Figure 5) centered in the Early Oligocene. This was found at all of the sites in the western province and is present both on ridges and in basins which have present day water depths of 1400 to 4600 meters. It generally appears as a sharp contact with little evidence of winnowing and no prominent lithological changes at the contact. In view of this, and considering the lack of evidence of paleodepth changes across the unconformity, there appears to be little reason to propose that the unconformity was the result of any prominent local tectonic activity. On the other hand, the age suggests that it could be related to major changes in current patterns and intensities (Kennett et al., 1972) associated with diversion of the circum-Antarctic current during the separation and migration of Australia away from Antarctica.

Tectonism of comparable age does appear to be important along the eastern margin of the western province. These events include the overthrusting of oceanic crust and mantle in eastern Papua (Thompson, 1969; Davies, 1971) and the emplacement of the New Caledonia ultramafics, probably again by overthrusting (Avias, 1967). Some folding in the type 4 (smooth) structure of the western province may also be of this age, resulting in the broad structures of the topographic highs and the shorter wavelengths of the basins. In addition, the type 5 (blocky) structure appears to be associated with this tectonic episode.

The seismic profiles also suggest that minor additional disturbance has taken place rather recently (Late Pliocene-Pleistocene) resulting in small-scale faulting of the sedimentary section on much of the type 4 structure. Disturbances of similar age are well established in New Zealand (Kaikouran Orogeny) and less well dated in Australia (Kosciusko Uplift).

REGIONAL EVOLUTION

Background

Any comprehensive discussion of the structures and history of the marginal basins of the southwest Pacific must be derived from both land based geological studies and marine geophysical investigations. Several studies available in the literature (see for example Cullen, 1967 and 1970; Shor et al., 1971; van der Linden, 1967; Woodward and Hunt, 1971), provided a basis for the drilling program undertaken during Leg 21. Karig (1970, 1971) has presented the major marine synthesis based on results of the 1967 *Nova* expedition. On the basis of these data, he interprets morphologic patterns and relationships among the frontal arcs, third arcs, fossil ridges, and interarc basins. These descriptions are applicable to the Eastern Marginal Basin Province of this work. The asymmetric, facing aspect of the frontal and third arcs led Karig to propose their development as a result of the splitting of an original frontal arc to produce the present-day arc/basin/arc sequence. This would suggest a common parent structure for the Tonga-Kermadec Ridge, the Lau-Coleville Ridge (and possibly the Three Kings Rise) with the South Fiji and Lau-Havre basins developing behind the eastward migrating frontal arc. New crustal material behind the migrating arc is formed as a result of thermal diapirism of material from the upper surface of the subducting Pacific lithospheric plate. Barazangi and Isacks (1971) have demonstrated the presence of low Q- (high attenuation) and P-wave velocities underlying the Lau Basin. This zone is reasonably well defined by the morphologic limits of the basin, which also defines a region of high heat flow (Sclater, et al., 1972) that decreases west of the Lau Ridge in the South Fiji Basin. These data suggest partial melting in the upper mantle beneath the basin, and Hussong (1972) has described a crustal structure of extreme irregularity which would be consistent with massive uneven implacement of the crust rather than a uniform sea-floor-spreading mode of origin. Sediment distribution and basin structure in the Lau Basin also suggest irregular and episodic development of the basin (see Site 203 summary).

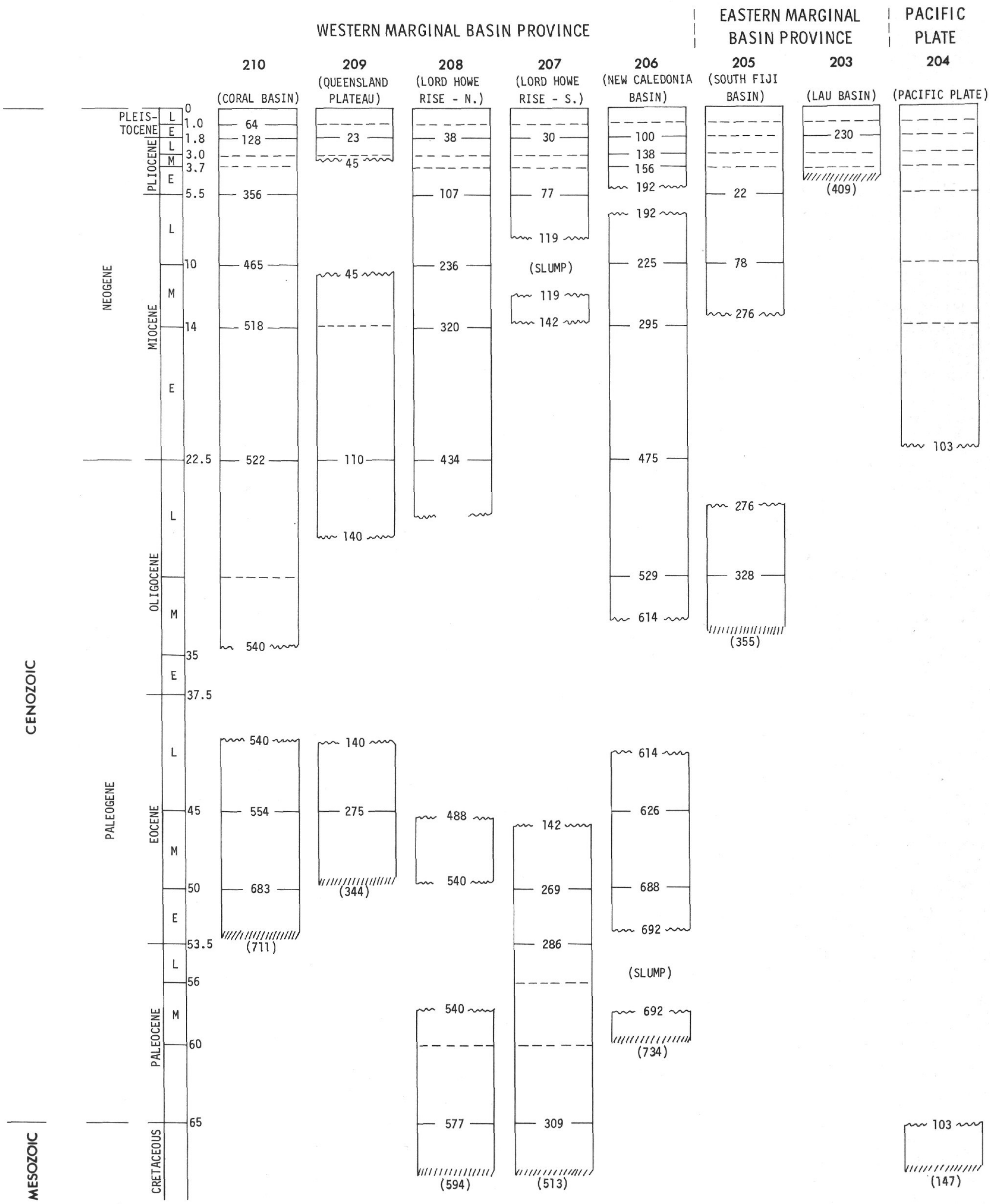
One major problem in the Eastern Marginal Basin Province is the age pattern of the ridges. Hoffmeister (1932), Sterns (1971), and Ewart & Bryan (1972) discuss the Eocene to Recent history for Eua in the Tonga gorup. Eocene appears to be the maximum age for the present frontal arc. By contrast, Ladd and Hoffmeister (1945) show an oldest age of Miocene for Lau Island on the Lau Ridge; presumably a fragment of the original (?) Eocene frontal arc. In addition, the morphology and structure of the Three Kings Rise is very unlike that of the Tonga and Lau ridges, and it appears more reasonable to suggest that this was a preexisting feature of the Western Marginal Basin Province. Arc migration and basin formation was perhaps strongly influenced by the Paleogene structures of this province.

In contrast to the Eastern Marginal Basin Province, the ridges and basins of the Western Marginal Basin Province are older and did not develop in any sense by arc migration. The western province displays a mixture of continental, quasi-continental, and oceanic crustal sections. Shor et al. (1971) have presented the crustal structure for the region and show quasi-continental characteristics for the Lord Howe and the Norfolk Rises. Conversely, the Tasman and the New Caledonia basins have oceanic characteristics, and Hayes and Ringis (1972) propose that the Tasman Sea has developed by opening from a spreading center which was active between 85 and 60 m.y. B.P. (anomalies 32-24). The structure of the rises is generally symmetrical and does not present any case for common parent structure in the manner of the Lau/Tonga situation. Lord Howe and Norfolk islands, the highest points on the western province ridges, are basalt of Miocene and post mid Miocene age, but older silicic rocks have been recovered (see for example, Site 207 report, this volume). Miocene age volcanism on the Lord Howe Rise is also evident in the form of structures intruding and deforming pre-Miocene sediments.

Mesozoic

Although direct evidence for conditions at the close of the Mesozoic is lacking (Mesozoic material was sampled only at Sites 204, 207, and 208), a general impression of the situation is possible.

On the Pacific plate, vitric tuff overlain by tuffaceous sandstone and conglomerate was accumulating by the Late Cretaceous. These sediments appear to have originated relatively close to an andesitic-to-basaltic source. As such,



Numbers along left hand column are million years before present (mybp).

Numbers in the site columns are meters depth below sea floor where an identifiable time boundary was encountered.

Numbers in parentheses at bottom of site columns indicate meters depth below sea floor of deepest sample obtained.

Figure 5. *Stratigraphic intervals sampled at Sites 203 through 210.*

they do not appear to be related directly to formation of new Pacific crust at a spreading center, but extensive volcanism is implied. The Louisville Ridge (Hayes and Ewing, 1971), now located several hundred miles south of the location of the samples, is suggested as a possible source. Initially, during the growth of the ridge, the underlying vitric tuff was accumulated and later, as volcanism subsided and the ridge was somewhere close to sea level, the tuffaceous sandstone and conglomerate was deposited. Subsequent subsidence of the ridge is inferred from the Mesozoic to Late Oligocene-Early Miocene unconformity observed at Site 204. This unconformity implies subsidence but with intense enough bottom currents to prevent deposition of normal oceanic pelagic sediment until the Late Oligocene-Early Miocene.

There is no evidence, either directly from the drilling program or indirectly from the seismic records, to indicate that any of the features of the Eastern Marginal Basin Province were in existence at the close of the Mesozoic. On the other hand, there is continuity of the type 4 (smooth rolling structure with deep basement) features of the Norfolk Ridge to the west and north. An extrapolation of basement age in the New Caledonia Basin (based on thickness of sediment remaining above acoustic basement when coring was terminated at Site 206) and the structural continuity with the Norfolk and Three Kings Rise implies the existence of these features of the Western Marginal Basin Province by the close of the Mesozoic.

On the Lord Howe Rise, Mesozoic materials were sampled at both sites (207 and 208). Rhyolitic flows had been emplaced as early as 92 m.y. B.P. and sedimentation had been begun well before the end of the Cretaceous. At the southern site (207), an alternation of rhyolitic (pumiceous) lapilli tuffs, and vitrophyric rhyolitic flows underlie basal sandstone which, in turn, underlies glauconitic claystone. To the north (Site 208) a siliceous fossil-bearing nannofossil chalk to nannofossil-bearing radiolarite or diatomite had been deposited. Based on the rarity of planktonic fossils and the generally fine-grained texture of the sediment, water depths over the Lord Howe Rise during the late Cretaceous may have been relatively shallow, particularly at the south. On the other hand, there is evidence at both sites that a subsidence had begun by the close of the Mesozoic that continued until present day depths were reached in the Early Eocene.

At the western boundary of the Western Marginal Basin Province, the opening of the Tasman Sea (Hayes & Ringis, 1972) began at about 85 m.y. B.P. and continued into the Cenozoic.

No direct evidence as to the conditions in the area of the Queensland Plateau and the Coral Sea has been added by this drilling program. Although the oldest material recovered (Sites 209 and 210) was of Eocene age, both the continuity of structure observed on the seismic profiles and an extrapolation of the age of the basement indicate that these features were probably part of the general framework of the Western Marginal Basin Province by the close of the Mesozoic.

Early Cenozoic (Paleogene)

Western Pacific Plate Province

The record of early Cenozoic events on the Pacific plate at Site 204 is lost in the Mesozoic to Late Oligocene-Early Miocene unconformity. Accumulation of abyssal clay and ash in deep water below the carbonate compensation depth probably began at the very end of the Paleogene. This deposition was on the unconformity, and sediment contains many reworked assemblages which may represent the effect of decreasing current velocities resulting from a change in the general circulation. A comparable unconformity in the Samoa Passage has been described by Johnson (1972) who believes that situation to be related to bottom erosion and non-deposition associated with the movement of the Antarctic Bottom Water. The abundance of volcanic detritus in the sediment from Site 204 implies that the site was in or near an area of active volcanism during the Paleogene.

Eastern Marginal Basin Province

There is no indication that features of the Eastern Marginal Basin Province were in existence during the early Paleogene. A Late Oligocene age is suggested for the formation of the South Fiji Basin, which appears to be related to later stages of the tectonism that resulted in the emplacement of the New Caledonia ultramafics, basic volcanism on New Caledonia and Fiji, and the Late Oligocene unconformity in the New Hebrides. The Late Oligocene sediment recovered appears to be very close to the basement of the South Fiji Basin, and it overlies an extrusive basaltic pillow lava. Deep-water accumulation of temperate fauna and flora in a glass shard bearing nannofossil-ooze took place at or just above the carbonate compensation depth.

The Late Eocene-Early Oligocene regional unconformity which is a prominent feature in the western province is not recorded in the sedimentary column recovered at Site 205, and it is considered improbable that it exists in the eastern province because of the suggested age of formation of the South Fiji Basin.

Western Marginal Basin Province

In general, the events of the Early Cenozoic that can best be defined from the results of the drilling program are those in the western province, the principal features of which were in existence at the close of the Mesozoic. Most of the tectonism described or implied for the province took place during the Early Cenozoic in contrast with the relatively quiet Neogene. Paleodepth indications provided by the benthonic foraminifera suggest there was a general deepening of the province. This deepening, however, did not occur at a uniform rate over the entire province, and there is evidence for considering the major features to be essentially independent entities throughout the period. The evidence for deepening of the area is such that, with the exception of the outer margin of the Queensland Plateau, present depths were reached in the western province by the end of the Eocene and there has been essentially no change since.

Data for estimating sediment accumulation rates are uneven for the Paleogene. Characteristically, the highest rates appear to be in the mid Eocene, particularly over the Lord Howe Rise and in the Coral Sea. Here, high biogenic sediment accumulation rates and the only significant deposition of siliceous forms could reflect relatively unique conditions of high productivity. In addition to a generally poorer core recovery than from the Neogene, the Paleogene microfossil sequence in the western province is interrupted by several depositional breaks, the most universal (Figure 5) being the regional Eocene-Oligocene unconformity. Calcareous nannofossils are generally abundant but frequently are only moderately-to-poorly preserved. Planktonic foraminifera are less well represented than in the Neogene and these frequently are poorly preserved. In spite of these deficiencies, the Paleogene succession of planktonic foraminifera and calcareaous nannofossils indicates a rather strong affinity for the temperate areas (e.g., New Zealand).

Although direct evidence was not collected during Leg 21, the Early Cenozoic was also the time when the opening of the Tasman Basin was completed (about 60 m.y.B.P.), the separation of Australia and Antarctica (Weissel & Hayes, 1971) began (about 55 m.y.B.P.), and the northern and northeastern parts of the region were involved in the intense tectonism which is reflected by metamorphism in the New Hebrides and the emplacement of the ultramafics in New Caledonia. The New Caledonia Basin was relatively deep at the beginning of the Paleogene but somewhat above carbonate compensation depth. Deposition of nannofossil-calcic ooze and clay with minor cherts continued into the mid Eocene, interrupted by a minor unconformity in the Late Paleocene-Early Eocene. By the middle mid Eocene there was an increase in siliceous content, and a radiolarian-rich nannofossil-calcic ooze was deposited until the earliest Late Eocene when the record is interrupted by the regional unconformity of the western province. A general slow increase in the clay content beginning before, and continuing above, the regional unconformity could reflect tectonic events in the Norfolk Ridge or in New Zealand or New Caledonia. Some relief in the local area is implied from the presence of slump structures in the Late Oligocene in which the sediment could have slumped from either Norfolk Ridge or Lord Howe Rise.

Although at the north there is some indication that Maastrichtian sediments were elevated prior to Paleocene, the general subsidence of the Lord Howe Rise began in the Early Paleogene and continued until Middle Eocene, from which time the area has been relatively stable at depths comparable to those found today. The predominant sediment which was accumulated over the rise during the early Paleogene was nannofossil ooze with many foraminifera. A terrigenous clay component was characteristically present in the south, but absent in the north. Sedimentation was interrupted by a minor disconformity in the Early to Middle Eocene in the north but was continuous in the south, and continued to be predominantly nannofossil ooze and planktonic foraminifera but with a marked increase in siliceous microfossils. This siliceous component is prominent enough to characterize the Middle-Late Eocene as a period of siliceous microfossil accumulation in the Western Marginal Basin Province. The regional unconformity of the western province is very pronounced on the Lord Howe Rise, and its longest time span (into the Middle Miocene) is over the southern portion of the rise. At the northern site, deposition of well preserved nannofossil ooze and foraminifera-rich nanno ooze was reestablished in the Late Oligocene.

On the Queensland Plateau, the oldest material recovered in the cores is late Middle Eocene in age and consists of shallow-water deposits. These are probably associated with the Australian continental margin, are bioclastic sediment rich in foraminifera, and contain prominent amounts of terrigenous silt and clay. During this period of deposition, fresh glass fragments were being accumulated from ash showers of intermediate composition. As sedimentation continued through the Eocene, a detrital-rich foraminifera ooze was accumulated. A gradual deepening at the site is reflected in an increase in the sand sized planktonic forms and in the reduced frequency of terrigenous materials. Some secondary silicification and replacement of the radiolarian components of the sediment reflect the general increase in silica content of the sediment which is characteristic of the Middle-Late Eocene in the western province. A pronounced reduction in the terrigenous components in mid Eocene appears to be associated with an increased rate of subsidence of the region. The terrigenous components appear to be cut off by blocking their transport to the outer margin of the Plateau, either due to the development of Middle Eocene reefs and cays on the central plateau to the west, or to the development of the Queensland and Townsville troughs. The regional unconformity of the western province (Late Eocene to Late Oligocene) at the site contrasts with other occurrences in that there is evidence of a continued deepening during the period of unconformity. When accumulation resumed in the Late Oligocene, the site was deeper than before the unconformity and the sediment was an almost purely planktonic foraminifera ooze.

By the late Early Eocene, the Coral Basin was accumulating clay, foraminifera, and nannofossils by pelagic deposition at depths generally above the carbonate compensation depth. The detrital clays apparently had their source in the Queensland region since they contain detritals of metamorphic origin and, although metamorphism was taking place in the southern Papua-Louisiade Archipelago region at this time, the Queensland area is the one which had metamorphic rocks available for erosion and transport. By the Late Eocene there was an increase in the proportion of the biogenic component of the sediment and also an increase in the siliceous component, principally in cherts recrystallized from the siliceous microfossils. The regional unconformity begins in the Late Eocene and when sediment accumulation resumed in Middle Oligocene the deposition was principally nannofossil ooze at oceanic depths near the carbonate compensation depth.

Later Cenozoic (Neogene)

Western Pacific Plate Province

The Neogene at Site 204 is best characterized as a period of slow accumulation of a predominantly dark brown clay at abyssal depths. Aperiodic high influx of fresh glass shards and volcanic debris imply that a volcanic source was relatively nearby and most of the volcanic components were carried to the site by airborne transport. In contrast with the Paleogene, coarser volcanic debris is absent, implying a change in source (e.g., cessation of volcanism and subsidence of a source at the Louisville Ridge) and/or the establishment of the Tonga Trench, which prevented coarser volcanic debris of Tonga source from reaching the sites. On the basis of their composition and the indication of freshness, the volcanic glass shards which accumulated during the Neogene are assumed to be of Tonga source. The fossil record at this site is relatively poor and age determination is imprecise, but the estimated accumulation rate for the whole of the Neogene is 4 to 5 m/m.y., a rate not excessive for the accumulation of the predominantly abyssal clay.

Eastern Marginal Basin Province

Although the South Fiji Basin was established at the beginning of the Neogene, conditions to the east are not clearly defined. It is probable that the Tonga Trench and an associated ridge were in existence but that the Lau Basin was not. The oldest sediment collected at the Lau Basin site is of Pliocene age, but extrapolation (based on estimated accumulation rate and thickness of sediment shown on the seismic reflection profiles) indicates the basin was probably opened by the splitting of a parent ridge sometime in the Late Miocene. Once the basin was opened, accumulation of a brown nannofossil ooze with admixture of volcanic glass began. Based on their acidic character and an affinity with the Tonga volcanics, the latter are considered to be of Tonga origin. Lower bathyl depths persisted through the Neogene and the estimated accumulation rates are very high (e.g., about 50/m.y. in the Pliocene and greater than 120 m/m.y. in the Pleistocene). Although a moderate to high rate of pelagic sedimentation is probable, these very high accumulation rates are principally an indication of the high frequency of volcanic components at the Lau Basin.

The Neogene at the eastern South Fiji Basin began as a period of nonaccumulation which is reflected in the Middle Miocene with quiet-water deposition of nannofossil ooze at depths slightly above the carbonate compensation level. Accumulation of volcanic debris was accomplished both in the form of fresh glass shards, which were probably the result of ash showers from a relatively nearby source of intermediate composition, and as pumice fragments and other volcanic debris, which show evidence of having been transported some distance by ocean currents. The estimated accumulation rate is very high for the Middle Miocene (approximately 55 m/m.y.) reflecting accumulation of both calcareous nannofossils and volcanic debris. In contrast, the accumulation rate for the Late Miocene is considerably less (approximately 10 m.y.) reflecting a slight subsidence of the floor of the basic to below the carbonate compensation depth as well as a decrease in volcanic debris. The decrease in volcanic debris appears to be related to a decrease in water borne fragmental volcanic products which were prominent in the Middle Miocene but are essentially absent in the later period. Volcanic ash showers continued into the Late Miocene but cease to be an important component of the sediment by the end of the Miocene. The sediment from the Pliocene-Pleistocene is predominantly an abyssal brown clay with minor amounts of nannofossil ooze accumulated at levels very close to carbonate compensation depth. The estimated accumulation rate for the Pliocene-Pleistocene is very low (less than 5 m/m.y.) and is a reflection of today's conditions—accumulation of abyssal clays with little biogeneous or volcanic contribution. Based on a relatively poor fossil record, the faunal affinity at the eastern part of the South Fiji Basin is with the temperate forms of the New Zealand section.

Western Marginal Basin Province

Having reached abyssal depths during the Paleocene, the New Caledonia Basin continued to receive a generally uniform oceanic pelagic sediment. This consisted of foraminifera-rich to foraminifera-bearing nannofossil ooze which was accumulated in abyssal depths but above the carbonate compensation depth. At the beginning of the Neogene, detrital clays made up from 5 to 10 percent of the deposits, but the clay content decreased by Middle Miocene. These clays may reflect some tectonism in the Norfolk-New Zealand trend and, together with slumping in the early Neogene, also imply the possibility of some local submarine relief. Other than for a minor disconformity in the Late Miocene, the Neogene section reflects continuous sedimentation in the basin and by the Pliocene, the clay content had decreased so that it forms a negligible component of the sediment. Accumulation rates appear to increase through the Neogene, and are estimated at 20 to 30 m/m.y. for the Pliocene, increasing to more than 50 m/m.y. in the Pleistocene. Although a portion of the Pleistocene increase may be attributed to volcanic ash (possibly associated with intermediate composition volcanism in the New Hebrides and on North Island, New Zealand), the general increase appears to be a reflection of increased productivity during the later portion of the Neogene. The microfossil assemblages of the Miocene are predominantly of temperate- or mid-latitude affinities, whereas, the Plio-Pleistocene assemblages have strong tropical affinity. In addition, the Plio-Pleistocene sequence shows alterations of warm and cool periods, indicating that the region was being subjected to changing environment. These changes are probably related to changes in the oceanic circulation patterns as well as to the general change from mid- to low-latitudes associated with the separation of Australia and Antarctica, which began in the Paleogene and continued through the Neogene.

With the exception of indications from the microfossils of slight shoaling during the late Middle Miocene, the Lord Howe Rise continued to receive sedimentation at the mid-bathyl depths which had been reached during the

Paleogene. The regional unconformity of the western province had its greatest temporal extent over the Lord Howe Rise. It appears to have extended much longer on the southern portion of the rise where (at Site 207) sediment accumulation did not resume until the Late Miocene. Characteristically, the Neogene sediment accumulating over the rise was a foraminifera-nannofossil ooze. To the south, there is intercalation of Eocene and Miocene sediment with some clay and siliceous microfossils. Although this is clearly an oceanic accumulation, some implications may be drawn concerning slumping from nearby submarine relief features, and a source of terrigenous clays, probably to the south, may be inferred. Microfossil assemblages indicate alternations of subtropical and sub-Antarctic water masses over the southern site, and the latest Miocene is marked by a prominent cool incursion which correlates with similar events in the New Zealand section and to the south of Australia. However, in spite of these alternations, the southern site is best characterized as a temperate section. To the north, the drilled site is intermediate between tropic and temperate conditions and there are many well-preserved warm-water assemblages. These abundant, well-preserved, warm-water forms indicate a persistence of relatively shallow-water accumulation at relatively low latitudes during the whole of the Neogene. The northern section was also subject to alternation of warm and cool cycles beginning in the early Neogene and becoming quite pronounced by the Pleistocene. There are some traces of eolian quartz in the Pilo-Pleistocene at the northern site which can be related to a period of aridity in Australia. In general, the sediment accumulation rates appear relatively constant over the Lord Howe Rise, with a general trend toward an increase during the Neogene and a possible trend toward a slight decrease in the later Pleistocene. Rates in general run between 10 and 20 m/m.y., increasing upwards, with higher rates over the northern portion of the Rise.

On the outer margin of the Queensland Plateau, the Neogene began with the deposition of an almost pure foraminiferal ooze. The presence of some apparently reworked shallow benthonic forms may reflect transport of these forms to the site, and the relatively low frequency of calcareous nannofossils implies possible winnowing by bottom currents. Abundant well-preserved planktonic foraminifera and a high degree of preservation of the more delicate forms, indicate that, although winnowing may have taken place, bottom currents were not strong at the site. As contrasted with other parts of the Western Marginal Basin Province, there is distinct evidence for continuing deepening of the margin of the Queensland Plateau reaching upper bathyl depths in the Middle Miocene and present depths (about 1400 m) during the Pleistocene. As deepening progressed through the Neogene, deposition of the biogenic ooze was interrupted by a minor disconformity which extends from Middle Miocene to Middle Pliocene. This disconformity may simply represent local loss of record due to slumping but may be related to a lack of deposition due to localized increase in bottom current speeds. In either case, the deposition from Middle Pliocene reflects a decrease in the winnowing activity of submarine currents in that the nannofossil planktonic-foraminifera ratio is considerably higher than earlier. Accumulation rates are difficult to estimate for the Neogene, but they are probably not more than 10 to 15 m/m.y.

Neogene deposition in the Coral Basin began with the accumulation of noncalcareous clay and silty clay in what can be interpreted as a severely compressed sequence or a minor disconformity which extended from the Middle Oligocene to Early Miocene. These sediments accumulated at a rate of about 4 m/m.y. and are interpreted as abyssal clays deposited below the carbonate compensation depth. By the latest Middle Miocene, the accumulation of a thick series of graded cycles began. These graded cycles contain reworked neritic and upper bathyl forms and are interbedded with nannofossil oozes which contain common -to-abundant well-to-moderately preserved foraminifera and calcareous nannofossils. The degree of dissolution of the calcareous forms indicates that deposition was probably slightly below carbonate compensation depth, with calcareous forms preserved because of quick burial by the graded cycles. Mineralogical evidence indicates an apparent shift in source of the graded cycles from the Queensland area in the Miocene to the New Guinea area by the Plio-Pleistocene. Although some degree of dissolution exists, autocthanous microfossil assemblages from the interbeds are predominantly of tropical affinity throughout the Neogene. In addition, although strongly influenced by the deposition of the graded cycles, estimated accumulation rates increase through the Neogene and range from approximately 24 m/m.y. in the Late Miocene to 60 m/m.y. in the Pliocene and to slightly over 70 m/m.y. in the Pleistocene.

SUMMARY AND CONCLUSIONS

Although only limited additional insight into pre-Cenozoic conditions was gained during the drilling program, the major features of the Western Marginal Basin Province appear to have been formed by the end of the Mesozoic, and there is evidence that volcanic debris was accumulating on the Pacific plate during the Cretaceous. Further, there is good evidence that the Eastern Marginal Basin Province, as such, did not exist until the late Paleogene.

In the western province, the early Cenozoic was the period of greater tectonism. Paleodepth indicators show a general deepening of the province which, with the exception of the margin of the Queensland Plateau, was essentially completed during the Eocene when present-day depths were reached. Depths have remained relatively stable in the western province since then, and there is little evidence of tectonism during the later Cenozoic.

Neogene floral and faunal assemblages collected at the five sites in the western province have a generally stronger affinity with tropical regions, while Paleogene assemblages show a closer relationship to temperate zones. Even after consideration of the possibility of broader temperate and transitional latitudinal faunal belts during the Paleogene, and the probability of distinctly different current patterns, this contrast of Paleogene/Neogene affinities provides additional support for the concept of equatorward drift of the western province since the Paleogene. As such, it supports the hypothesis that the western province has been part of the Australian plate during the period of northward separation of Australia from Antarctica since the Middle Eocene.

An unconformity of regional extent is present in the sections at all five of the sites from the western province. Extending from Late Eocene to Late Oligocene in the basins (Coral and New Caledonia) it has its greatest time extent on the Lord Howe Rise where, at the southern site, it extends from Middle Eocene to Early-Middle Miocene. Although the sedimentary record indicates an anomalously high frequency of siliceous microfossils in the Eocene, the lithologies are generally uniform across the unconformity and there are no indications of local tectonism or depth changes. Although tectonism of this age was associated with the eastern and northern margin of the western province, the unconformity appears to be non-tectonic in origin and to represent a period of nonaccumulation and/or submarine erosion. Consequently, it is suggested that the unconformity was caused by changing bottom current patterns and intensities which can be related to the onset and continuation of separation of the Australian plate from Antarctica.

Although not fully conclusive in themselves, the results of the drilling program lend strong support to the suggestion of general age progression eastward from the western province through the South Fiji Basin to the Lau Basin. This is based on the age determination of the vitrophyric rhyolitic flows on the southern Lord Howe Rise (92 m.y.B.P.), the Oligocene age for formation of the South Fiji Basin, and the Late Miocene age for opening of the Lau Basin. Also, indications of higher frequency of volcanism are generally younger moving eastward, and only the eastern sites show evidence of basic volcanism.

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