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THE NORTHEAST AUSTRALIAN MARGIN AND ADJACENT AREAS -

A BIOSTRATIGRAPHIC REVIEW AND GEOHISTORY ANALYSIS

by

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SUMMARY

A review of the Tertiary biostratigraphy of the northeast Australian offshore region is presented in this report, based on seven wells in the Papuan and Capricorn Basins, six DSDP Sites in the Coral Sea Basin and Lord Howe Rise, and a number of dredges and cores taken on various research cruises in the region.

Three Tertiary sedimentary packages, each separated by unconformities are present in the basin margins of the region, but only two are present in the basins.

The first package ranges in age from middle to late Eocene (Zones P.11 to P.17 - Ta_3), and overlies older rocks, both sedimentary and igneous, ranging in age from Palaeozoic to early Eocene. At basin margin locations this package was deposited in non-marine environments at the southern end of the Marion Plateau, and shallow marine situations north of the Plateau.

Deposition of the second sedimentary package was initiated during the late Oligocene, within Zone N.19/20 in the Coral Sea Basin, in Zone P.21 in Anchor Cay-1, and within Zones N.3 or N.4A elsewhere, and then continuing into the middle Miocene, Zone N.9. Water depths on the basin margins were shallow, with larger foraminiferal-red algal carbonates dominating the late Oligocene and early Miocene. Within the late early and early middle Miocene (Zones N.6 to N.9; lower T*f*), growth of coral and *Halimeda* commenced in the Papuan Basin, but elsewhere to the south there is no evidence of coral growth, although corals probably were able to survive on the northern parts of the Queensland Plateau. Along the basin margins, sedimentation ceased in the middle Miocene, until the late Miocene, but within the deeper water areas sedimentation appears continuous to the Holocene, except for some localised, short-lived breaks.

Deposition of the third package was initiated during either the latest Miocene (Zone N.17B) or earliest Pliocene (N.18) on the basin margins and plateaux, continuing to the Holocene. Coral and *Halimeda* are present in basal limestones of this package at least in the Papuan Basin, where this initial carbonate phase is overlain by terrigenous and shallow marine siliciclastic sediments. To the south, carbonate sediments were deposited at depths similar to those in the areas at the present time. There is evidence for a widespread hiatus separating the latest Pliocene (Zone N.21) from the middle Pleistocene.

Using the data from the various drill holes and dredge samples taken in the region, it is possible to predict the probable biostratigraphic succession likely to be encountered in any drilling both within the Great Barrier Reef and any sites either in troughs or on plateaux of the southern margins of the Coral Sea Basin.

Geohistory analyses have been made for all wells and DSDP Sites. These results suggest that heatflow regimes throughout the Tertiary cooled from those prevailing during the formation of the basins. Subsidence rates appear to have been gradual through Eocene to Miocene time, rapidly increasing during the Pliocene and Pleistocene for all basins. Sediments in the Papuan Basin became marginally mature by the end of the Mesozoic, but there is strong evidence that maturity levels increased during the Pliocene and Pleistocene. Within the Capricorn Basin, geohistory modeling indicates that levels in the lower part of Aquarius-1 approached marginal maturity only during the Pliocene or Pleistocene.

INTRODUCTION

Eight wells from the southeastern part of the Papuan Basin (Anchor Cay-1, Borabi-1, Kusa-1, Pasca-A1, Pasca-A2, Pasca-C1, Pasca-C2 and Uramu-1A) and four wells from the southern end of the Great Barrier Reef (GBR) and Capricorn Basin (Aquarius-1, Capricorn-1A, GSQ Sandy Cape-1-3R and Wreck Island-1) provide the data base for this study (Figure 1). In addition Deep Sea Drilling Project (DSDP) Sites in the region (208, 209, 210, 287, 587 and 588) have also been used. All but the DSDP sites were drilled on potential reefal structures established either on basement highs or shelf edges, in relatively shallow water. Of the DSDP sites only 588 penetrated to the Mesozoic; 209 and 210 penetrated the Eocene; 587 the latest Miocene, and 208 and 587 were barren over much of the interval drilled. Sites 588 and 287 are very close to 208 and 210 respectively and so should contain a similar section. Thus the sections available for study provide information for the biostratigraphic sequence likely to be encountered in the sites to be drilled during Ocean Drilling Program (ODP) Leg 133. Also a number of dredges and gravity or piston cores were taken during several cruises in the north-east Australian region have also provided data for this study. Well analysis diagrams (Plates 1 to 15) have been prepared for all wells and DSDP sites. The data for these has been obtained from well completion reports, from compilations by Robertson et al., (1984) Research Australia Ltd., and Flower Doery Buchan Ltd., (1984) and from the DSDP Initial Reports. In addition geohistory analysis has been carried out on all drill sites using input data from the same sources as the well analysis diagrams. As with the biostratigraphy, emphasis has been placed on the Tertiary section; the Mesozoic sections are only from the wells of the Papuan and Capricorn Basins.

The biostratigraphic part of this review is based almost entirely on the Tertiary. In those few sections which penetrated the Mesozoic this part of the column marine faunas are solely represented by a few dinoflagellate species and biostratigraphic studies have been based entirely on studies of palynomorph assemblages. In addition, there is also uncertainty as to the stratigraphic units intercepted. Because the Mesozoic part of the section is of importance for petroleum exploration and must be taken into account in any geohistory analysis, summaries for this part of the section are to be found in the well analysis diagrams (Plates 1 to 15); these summaries are based on the unpublished work of H. Struckmeyer (pers. com., 1990). Detailed biostratigraphic reviews have been left to others (e.g. Davey, 1987, and Morgan, 1989).

As would be expected, the wells penetrated sequences which have been deposited in shallow water marine sites during the Tertiary. Deposition for some of the DSDP sites was initiated in shallow water, but show gradual deepening with time (particularly those on the Lord Howe Rise, which subsided to its present depths in the Palaeogene). Other sites have remained at similar depths throughout their history. The majority of dredges taken in the region have sampled shallow water sequences. Of the cores, most sampled only the Pleistocene, but at three sites the late Pliocene was encountered.

To date foraminiferal faunas only from Borabi-1 have been examined; additional faunal and floral data has been obtained from various reports and publications (e.g. Robertson Research Australia Ltd., and Flower Doery Buchan Ltd., 1984; Lloyd, 1978, 1988; Palmieri, 1971, 1974, 1975 and 1984; Chaproniere, 1983; Kennett and von der Borch, 1985). In addition the Pleistocene planktic foraminiferal biostratigraphy for the area around the Queensland and Marion Plateaux is summarised here and detailed results will be published elsewhere.

The time scales used in this work are based on the following sources: Tertiary (Berggren et al., 1985a, b), Cretaceous (Burger, in prep a), Jurassic (Burger, in prep b) and Triassic (Haq et al., 1989).

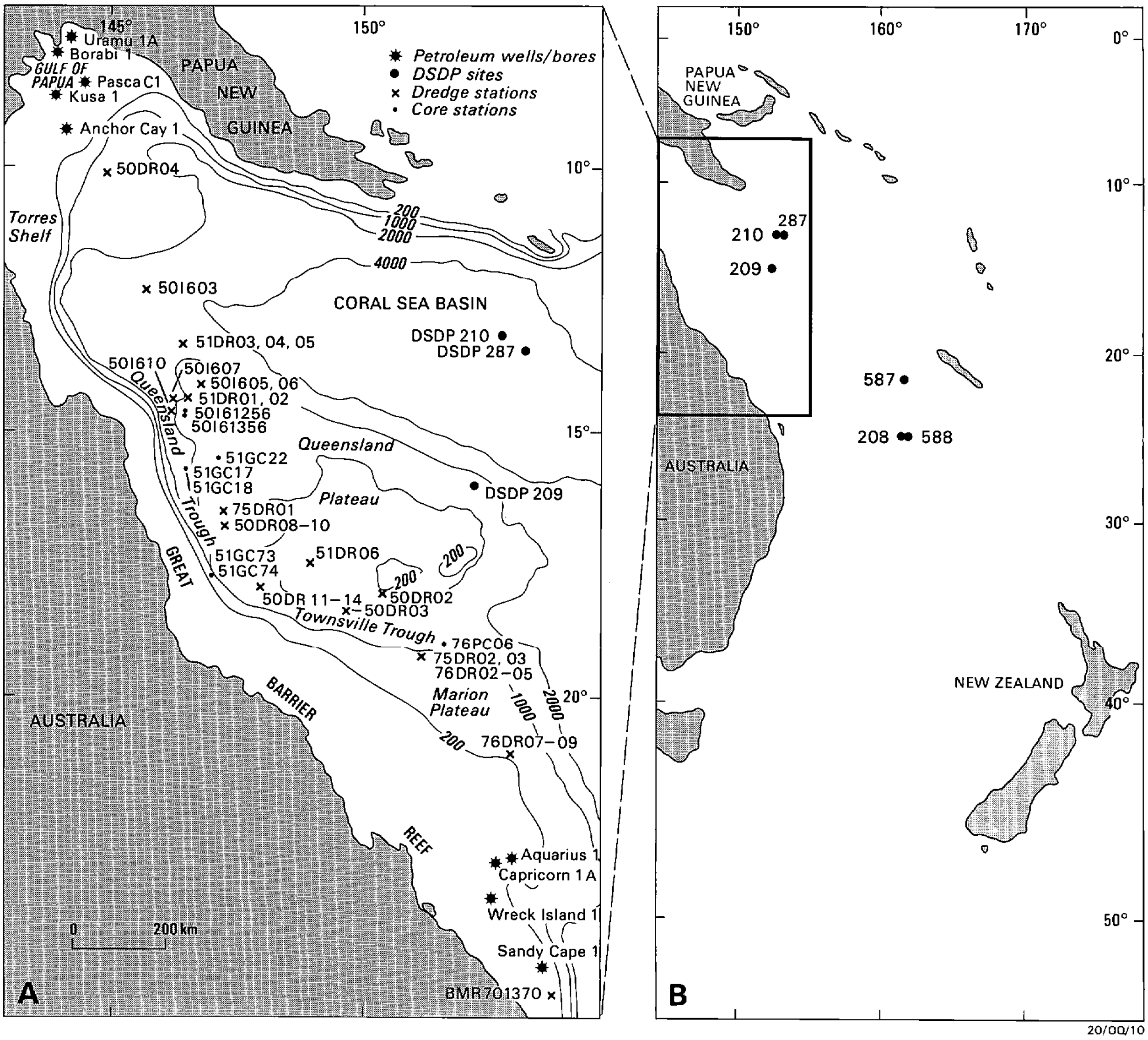


Figure 1. Locality map showing data points used in this study. A: Exploration wells, dredge and core sites; B: DSDP drill sites.

BIOSTRATIGRAPHIC SUMMARY

A number of bore holes have been drilled into sites at both deep and shallow water localities. In addition a number of sites have been dredged, mainly in the shallow water parts of some of the marginal shelfal areas and plateaux bounding the western part of the Coral Sea Basin. The various sections are discussed below and an attempt is made to relate the dredge material to these sequences. The planktic zonal scheme of Blow (1969) as modified by Kennett and Srinivasan (1983) together with the East Indies Stage Classification (Adams, 1970, 1984; Jenkins et al., 1985) provide the basis for the Tertiary biostratigraphy used in this report (Figure 2); for the Quaternary, the zonation of Bolli & Premoli Silva (1973) as modified by Chaproniere (1985a), is utilised. Figure 2 summarises the stratigraphy for all the sections and dredges used in this study. Figure 3 is an idealised sequence for both the basin margins (A) and the deep basin (B) locations.

Basin Margin Sections

In the sequences studied from the southeastern Papuan Basin, Eocene sediments are found to unconformably overlie Mesozoic or older rocks. The Eocene is overlain disconformably by a late Oligocene or early Miocene to early middle Miocene sequence, which in turn is overlain by Pliocene and younger sediments. In the southern sequences, Eocene marine sediments are lacking. Instead late Oligocene unconformably overlies a non-marine sequence of unknown age, but possibly Eocene, the remaining section is similar to that from the Papuan Basin.

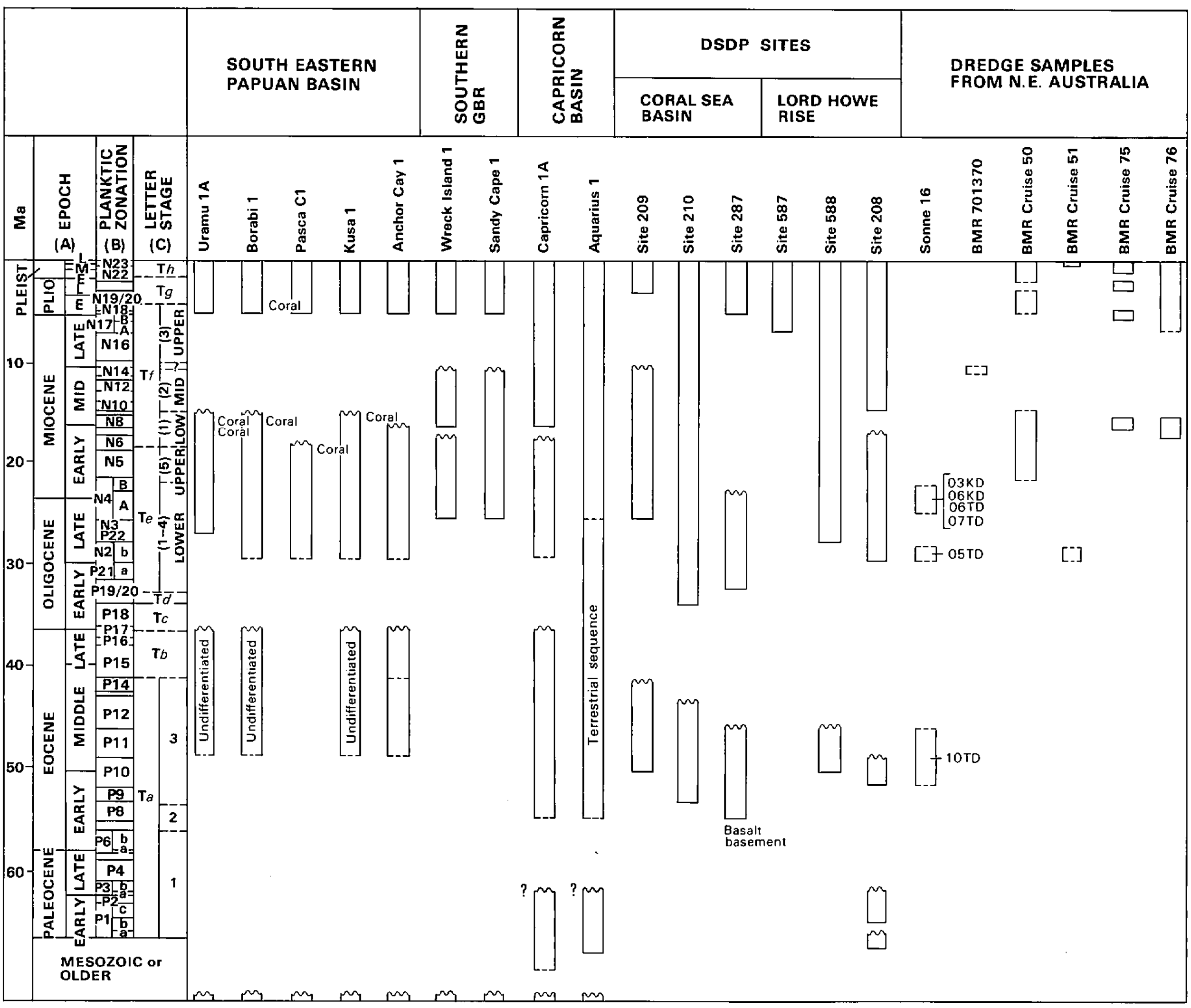


Figure 2. Biostratigraphic summary for all localities used in this study. (A) after Berggren et al., (1985a, b); (B) after Blow (1969), Berggren (1969), Kennett and Srinivasan (1983; (C) after Adams (1984), Adams et al., (1986), Chaproniere (1981, 1983) and Jenkins et al., (1985).

Eocene: The identification of levels within the Eocene is dependent on the quality of fauna present. Thus, in some sections (Anchor Cay-1) both middle (Ta_3) and late (T*b*) Eocene can be identified, but in others (Kusa-1, Borabi-1) only undifferentiated middle to late Eocene (Ta_3 to T*b*). In those sections with a diverse fauna (such as Anchor Cay-1), planktic foraminiferids *Acarinina* and *Morozovella* indicate middle Eocene, and higher up, *Subbotina linaperta* indicates late Eocene. In other sections (e.g. Borabi-1) planktics are absent and the presence of larger foraminiferids *Asterocyclina* and *Discocyclina* indicate a general middle to late Eocene age (Ta_3 to T*b*), but the presence of *Pellatispira* (in Anchor Cay-1) indicates late Eocene (T*b*). A number of other species (such as *Heterostegina saipanensis*, *Spiroclypeus vermicularis* and *Nummulites pengaronensis*) typical of the middle to late Eocene shallow water carbonate sequences in the adjacent Indo-Pacific area (such as Fiji, Tonga, Saipan and Enewetak Islands) are absent from the sections studied here. These species appear to be tropical forms and their absence may have resulted from cooler water temperatures in the study area at that time.

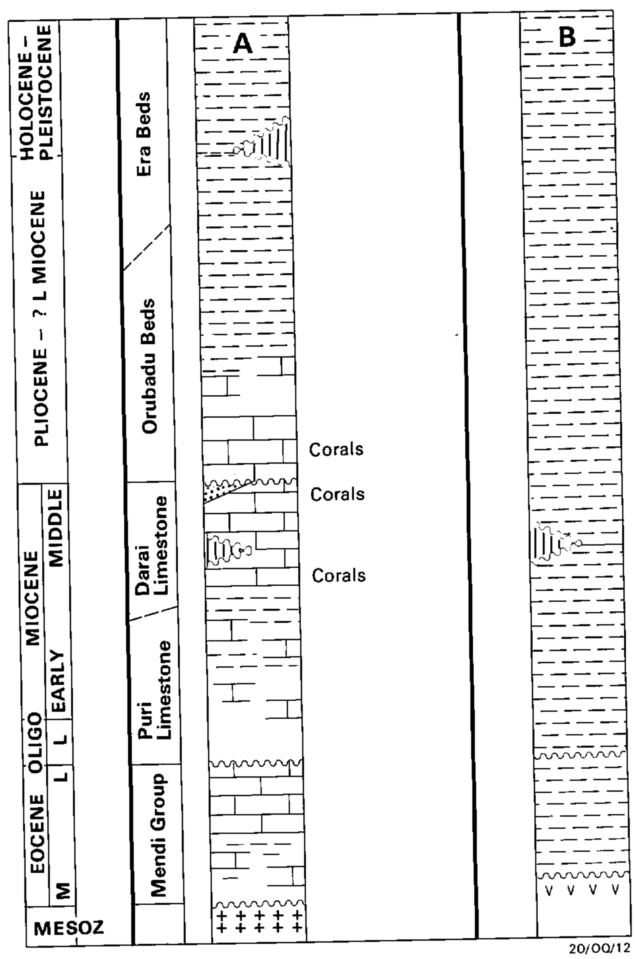


Figure 3. Composite biostratigraphic sequences for (A) basin margin locations, and (B) for basinal locations for the Coral Sea area of northeastern Australia.

With the exception of the Pasca wells, all wells studied from the Papuan Basin contain an Eocene section which has been referred to the Mendi Group (by Lloyd, 1978), a unit made up of bioclastic calcarenites or limestones. The absence of typical T*b* sediments (that is those with *Pellatispira*) in most of the wells (except for Anchor Cay-1) may be the result of either their removal by the erosion episode marked by the unconformity separating these sediments from the late Oligocene or Miocene sequence, due to the intense recrystallisation zone which sometimes appears to cover this interval, or to the absence of *Pellatispira* due to environmental reasons.

To conclude, all shallow water sections show an earlier deeper water, planktic-rich phase, initiated within the middle Eocene, Ta_3 letter stage, which grades upwards into a shallowing sequence, in which larger benthics may become dominant, by the late Eocene, T*b* stage. The degree of completeness of the section is probably controlled by the amount eroded off during the interval represented by the unconformity prior to the deposition of the Darai Limestone, or by the amount of recrystallisation which has destroyed the original fabric of the sediments.

Late Oligocene to Early Middle Miocene: Definite late Oligocene planktic assemblages are present in only one well, Anchor Cay-1, where Zone P.21 planktic faunas from the Puri Limestone overlie the Eocene Mendi Group. Larger foraminiferids appear with the gradual lithologic change marking the transition from Puri Limestone to Darai Limestone. The appearance of both *Heterostegina borneensis* and *Lepidocyclina (Eulepidina) ephippioides*, without *Miogypsina* indicates the presence of lower T*e*. Adams (1984) correlates lower T*e* with Zones P.19/20 to N.4A (see Figure 2) and at least one locality containing a Zone P.19/20 planktic fauna is present in the region, but in a deep basinal setting (Site 210), which contrasts with the shallow water sequences in which the larger foraminiferids occur. However, larger foraminiferids typical of lower T*e* are first recorded from levels within Zones N.3 to N.4A elsewhere (Chaproniere, 1976), and it seems probable that the appearance of larger foraminiferal faunas in the shallow water parts of the region took place within the zonal interval N.3 to N4A; for this reason I have correlated the levels with lower T*e* larger foraminiferids to Zones N.3 and N.4A in Figure 2. The FAD (first appearance datum) of *Miogypsina* within the range of *L. (Eulepidina) ephippioides* marks the base of upper T*e* (Jenkins et al., 1985), and the LAD (last appearance datum) of *L. (Eulepidina)* defines the base of lower T*f*, an event which takes place within Zone N.6 (Chaproniere, 1981; Belford, 1984). This sequence of events is found in all the wells studied. In Anchor Cay-1, the presence of *Globigerinoides sicanus* and *Praeorbulina glomerosa curva* above the FAD of *Miogypsina* indicates a level within Zone N.8 (late early Miocene). The stage of evolutionary development of both *L. (Nephrolepidina)* (parameter F of Chaproniere, 1980) and *Miogypsina* (parameter V of Drooger, 1952) is typical of that for lower T*f*. The highest *Miogypsina* within the upper part of the Darai Limestone is *M. (Lepidosemicyclina) thecideaeformis*, and as this disappears at a level below the LAD of *M. (Miogypsina) antillea* (Adams, 1984), its extinction level cannot be used as evidence for correlation with a level high in lower T*f*, which would be equivalent to a correlation with planktic Zone N.10 or higher (Adams, 1984). Thus the youngest larger foraminiferal assemblages within the top of the Darai Limestone in Anchor Cay-1 are no younger than early middle Miocene, Zone N.9. A similar sequence for the Darai Limestone is present in the other wells studied, but the Puri Limestone is absent. However, Lloyd (1978) has identified a Zone N.12 to N.14 planktic fauna above the highest larger foraminiferids in Uramu-1A, and Palmieri (1971, 1984) records a similar occurrence in Wreck Island-1 and GSQ Sandy Cape-1-3R. Lloyd (1978) bases his conclusions for a Zone N.12 to N.14 determination on the overlap of *Gr. (Gr.) cultrata* and *Gr. (Turborotalia) siakensis*; the remainder of the fauna ranges from Zones N.12 to N.18. Though the only other record of Zone N.12 to N.14 from shallow water sections is that from Wreck Island-1 to the south, Zone N.18 to N.22 assemblages are found in all the shallow water sections. The species *siakensis* is a homomorph of *N. humerosa*, a form which ranges from Zone N.18 to N.22 (Kennett and Srinivasan, 1983); the two forms are thus very difficult to differentiate. In addition the geophysical logs indicate a major unconformity marking the top of the early to early middle Miocene limestones, with no evidence for a marl phase overlying these limestones. Thus, on balance of probabilities, a better interpretation is that specimens of *humerosa* and not *siakensis* are present, indicating that earliest Pliocene (Zone N.18) directly overlies the early middle Miocene (Zone N.9) in Uramu-1A. Further south, however, (in Wreck Island-1, and sample BMR701370 from the shelf east of Sandy Cape-1-3R) good faunal evidence indicates that a middle Miocene (Zone N.10 to N.14) planktic phase overlies the early middle Miocene larger foraminiferal limestones, as it does in the basinal sections.

In Anchor Cay-1 the Oligocene-Miocene cycle of sedimentation commenced during the Late Oligocene (Zone P.21B) with a deeper water planktic limestone (Puri Limestone), containing a subtropical/tropical planktic foraminiferal assemblage. This grades upwards into a shallow water sequence of larger foraminiferal-algal limestones (Darai Limestone), later in the Late Oligocene (Zones N.3 to N.4A). In the other wells from the Papuan Basin incorporated in this study, this planktic phase is absent, and sedimentation commenced with the larger foraminiferal-bearing limestone, probably at the same time that this facies developed in Anchor Cay-1, within lower T*e*. This larger foraminiferal assemblage is widespread and is present in all the wells (including Wreck Island-1). Study of faunas from cores in Borabi-1 (Table 1) suggest that the Darai Limestone was deposited in gradually shallowing conditions. The larger foraminiferal sequence is similar to that recorded from northwestern Australia, exhibiting changes believed to have been in response to a gradually shallowing environment (Chaproniere, 1975). In support of this conclusion is the gradual increase in proportion of miliolids in the Borabi section from the top of upper T*e*, until they are the predominant faunal element prior to the appearance of corals within lower T*f*; coralline algae are ubiquitous throughout the section, but appear to become more numerous at the top of the lower T*f* part of the well. Similar faunas are found in other wells. Corals are recorded from both the upper T*e* (Pasca-C1) and lower T*f* (Borabi-1, Kusa-1, Uramu-1A) indicating that conditions favourable to the development of corals appear to have occurred at different times in the southeastern Papuan Basin. It is possible that at other locations more than one phase of coral development occurred. Conditions conducive to coral growth did not seem to have developed further south in Wreck Island-1 where the larger foraminiferal faunas seem to be constant throughout the section. In some wells (Sandy Cape-1-3R and Wreck Island-1) the planktic foraminiferal faunal component seems to increase with a corresponding reduction in the larger foraminiferids during the early middle Miocene (Zones N.10-N.12).

Post-Middle Miocene: In the Papuan Basin the Darai Limestone is disconformably overlain by either the Era beds or the Orubadi beds (Stewart and Durkee, 1985, fig. 5). This sequence commences with shallow water carbonates, containing shallow water benthic foraminiferids, rare planktics and corals, which grade into more carbonaceous sandstones and mudstones. Lloyd (1978) and Stewart and Durkee (1985) consider that the Era beds are Pliocene to Pleistocene in age; the rare presence of *Globorotalia tosaensis* (in Anchor Cay-1) and *Calcarina spengleri* (in Pasca-C1) supports this assessment. The same authors consider the Orubadi beds, which underlie the Era beds in the Pasca wells and Urami-1A, to be latest Miocene and Pliocene lateral equivalents of the Era beds; the presence of *Pulleniatina primalis*, *Globigerinoides obliquus extremus* and *Sphaeroidinellopsis paenedehiscens* with *Sphaeroidinella dehiscens* (in the Pasca wells) and the overlap of *Dentoglobigerina altispira altispira*, *Globigerinoides obliquus extremus* and *Globoquadrina* *dehiscens* (in Uramu-1A) supports this contention. *Alveolinella quoyi*, which ranges from the late Miocene to Recent (Adams, 1984) is present in some wells. However, in Anchor Cay-1 this species occurs above the marker for Zone N.21 (late Pliocene), *Globorotalia tosaensis*; in another section *Calcarina spengleri* (Pliocene to Recent - Adams, 1984) is present. This evidence suggests that presence of *A. quoyi* in the beds overlying the Darai Limestone in the Papuan Basin is indicative of ages of no older than latest Miocene. Lloyd (1978, fig.2) considers that the oldest beds in the wells studied from the Papuan Basin in this report are early Pliocene.

		Acervulina inhaerens	Alveolinella quoyi	Amphistegina bikiniensis	Amphistegina radiata	Austrotrillina howchini	Biarritzina proteiformis	Borelis pygmaeus	Borodinia septentrionalis	Cycloclypeus (Cycloclypeus) carpenteri	Gypsina plana	Heterostegina borneensis	Lepidocyclina (Eulepidina) ephippioides	Lepidocyclina (Nephrolepidina) howchini praehowchini	Lepidocyclina (Nephrolepidina) sumatrensis	Marginopora vertebralis	Miogypsina (Lepidosemicyclina) thecideaeformis	Miogypsina (Miogypsina) sp.	Operculina complanata	Operculinella venosa	Planorbulinella larvata	Pseudorotalia schroeteriana	Sorites marginalis	Spiroclypeus margaritatus	indeterminable miliolines	indeterminable rotalines	indeterminable textularines	No foraminiferids	Bryozoa	Coralline algae	Corals	Echinoids	Gasteropods	Halimeda	Molluscs	Pelecypods		
4304.5ft	26	?	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	X	X	.	.	X	.	X	.	.	X	.	4304.5ft	26
4624.5ft	27	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	?	.	.	.	.	.	X	.	.	.	X	?	.	.	.	.	.	4624.5ft	27
4628.5ft	28	X	X	.	.	.	.	.	.	?	X	.	.	.	.	X	.	.	X	.	.	.	X	.	.	X	.	.	X	X	.	.	.	X	.	.	4628.5ft	28
4951.5ft	31	?	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	?	.	.	.	.	.	.	X	.	.	.	X	X	X	.	.	.	.	4951.5ft	31
4956.5ft	32	.	.	.	.	.	.	.	.	.	?	.	.	.	.	.	.	.	?	.	.	.	.	.	.	X	.	.	.	X	X	X	.	X	.	.	4956.5ft	32
5294.5ft	35	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	X	X	.	X	.	.	.	.	5294.5ft	35
5945.0ft	38	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	.	.	5945.0ft	38
6283.0ft	39	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	.	.	.	.	6283.0ft	39
6291.0ft	41	.	.	.	?	X	.	.	X	.	.	.	.	.	.	X	?	.	.	.	.	.	.	.	X	X	.	.	.	X	X	.	X	.	.	.	6291.0ft	41
6526.0ft	42	.	.	.	.	.	.	X	X	.	.	.	.	X	.	.	.	?	X	.	.	.	X	.	X	X	X	.	X	X	.	.	.	.	.	.	6526.0ft	42
6532.0ft	43	.	.	.	.	X	X	.	.	.	.	.	.	X	.	?	.	X	.	.	X	.	X	.	X	X	X	.	.	X	.	.	.	.	.	.	6532.0ft	43
7005.5ft	44	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	.	.	X	.	.	X	.	X	X	.	.	.	.	7005.5ft	44
7323.0ft	45	.	.	.	X	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	.	.	.	X	X	X	.	.	.	X	?	X	.	.	.	.	7323.0ft	45
7633.3ft	46	.	.	.	X	.	.	.	X	.	.	.	X	.	X	.	.	.	.	.	.	.	.	X	.	X	.	.	X	.	.	X	.	.	.	.	7633.3ft	46
7638.3ft	47	.	.	.	.	.	.	.	.	.	.	.	X	.	X	.	.	.	.	.	.	.	.	X	.	X	.	.	.	X	.	.	.	.	.	.	7638.3ft	47
7943.3ft	48	.	.	.	.	.	.	.	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	X	.	X	.	.	.	X	.	X	.	.	.	X	7943.3ft	48
7944.8ft	49	.	.	X	.	.	.	.	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	X	.	X	.	.	X	X	.	X	.	.	.	.	7944.8ft	49
7948.5ft	50	.	.	.	.	.	.	.	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	7948.5ft	50
8286.0ft	51	.	.	.	.	.	.	.	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	.	.	X	.	.	X	X	.	.	.	.	.	.	8286.0ft	51
8288.0ft	52	.	.	X	.	.	.	.	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	.	.	X	X	.	X	X	.	.	.	.	.	.	8288.0ft	52
8294.0ft	53	.	.	X	.	.	.	.	.	.	.	X	X	.	X	.	.	.	.	.	.	.	.	.	.	.	.	.	.	X	.	.	.	.	.	.	8294.0ft	53

Table 1. Biostratigraphic range chart for samples studied from Borabi-1 well.

Basinal Sections

Capricorn Basin area: Two wells (Aquarius-1 and Capricorn-1A) were drilled in the Capricorn Basin (in the southern part of the GBR region), in water depths intermediate between the shallow water sequences and those drilled by the DSDP, effectively linking events between the two depth zones. Palmieri (1971, 1974, 1975) made detailed faunal and biostratigraphic studies of these wells. In both wells the lowest marine beds overlie a non-marine pre-late Oligocene sequence believed to be Eocene in age (Hekel, 1972; Foster, 1982). These marine beds are late Oligocene (Zones N.3 to N.4A) in age, and initially contain glauconite and larger foraminiferids (*Lepidocyclina, Miogysinoides* and *Operculina*), which give way to sediments with a foraminiferal fauna very similar to that from the Puri Limestone to the north. This planktic sequence appears to be fairly complete through to the Pliocene at least, on the evidence given by Palmieri (1971), although a hiatus is placed around Zone N.7/N.8 boundary in Capricorn-1A. Within the early to early middle Miocene section in both wells calcarenites containing larger foraminiferids (*Cycloclypeus, Lepidocyclina* and *Operculina*) occur interbedded with the planktic foraminiferal chalks, calcisiltites and marls. Palmieri (1974) believed that larger foraminiferids and iron oxides contained in calcisiltites from the lower part of the section in Aquarius-1 were derived from shelfal depths by slumping, and that calcarenites with a similar fauna were the result of localised shallowing. However, it is possible that all larger foraminiferids in both wells at levels other than at the base of the marine sequence were deposited by slumping from shallow water. Planktic faunas seem to be diverse at all levels above the basal beds within these two wells, and thus the larger foraminiferids seem to be out of place. Fourcade and Butterlin (1988) have linked the occurrence of larger foraminiferids in sediments containing good planktic faunas with slumping and redeposition due to changes in sea level in the Bahamas and a similar explanation may be valid for these occurrences. Palmieri (1974, fig. 2) shows that the highest larger foraminiferids occur within the early middle Miocene in both Aquarius-1 and Capricorn-1A, at the same level as in Wreck Island-1.

Coral Sea Basin: Three sites (Sites 209, 210, 287) from two legs (Legs 21 and 30, respectively) have been drilled in the Coral Sea Basin. Site 209 was drilled on the boundary between the northeastern margin of the Queensland Plateau and the southwestern side of the Coral Sea Basin. Sites 210 and 287 were drilled in close proximity in the central part of the basin.

Burns et al., (1973a) have described the sequence encountered at Site 209. The hole bottomed in a middle Eocene sequence of glauconitic sandy mudstones and silty sandstones, which were probably deposited at fairly shallow depths adjacent to a continental margin. Water depths gradually increased in the late Eocene accompanied by a reduction in terrigenous material, although some sediments contain fossil fragments derived from shallow water. The Eocene section is discomformably overlain by a late Oligocene to middle Miocene sequence, which, in common with the Eocene, was deposited in gradually increasing water depths, but poor core recovery prevented detailed biostratigraphic studies being made (Kennett, 1973). The middle Miocene is disconformably overlain by a probable continuous middle Pliocene to Holocene sequence containing a well preserved, exclusively tropical planktic foraminiferal fauna (Kennett, 1973).

Site 210 (described by Burns et al., 1973b), bottomed in an early Eocene sequence, which was deposited at greater depths than those of Site 209, but above the calcium carbonate compensation depth (CCD). The Eocene is disconformably overlain by an apparently complete late Oligocene to Holocene section. However, most of this part was deposited at depths hovering around the CCD producing parts either barren of planktic foraminiferids, or with dissolution effected faunas. From the late Miocene the sequence is made up of turbidites, sometimes containing reworked shallow water assemblages (Burns et al., 1973b). As noted above Fourcade and Butterlin (1988) have linked similar occurrences with slumping associated with lowering of sea level.

Site 287, which was a repeated attempt to intersect oceanic basement adjacent to Site 210, has been described by Andrews et al., (1975). The hole bottomed in basalt which is overlain by an early to middle Eocene nannofossil chalk with interbedded cherts. The Eocene is disconformably overlain by a late Oligocene nannofossil ooze, which in turn is disconformably overlain by a nonfossiliferous interval believed to be Miocene. A seemingly continuous Pliocene to Holocene sequence which disconformably overlies the ?Miocene sediments, completes the section. As for Site 210, detailed microfossil studies were not made due to the poor preservation and low diversity of the faunas, believed to be the result of deposition near the CCD.

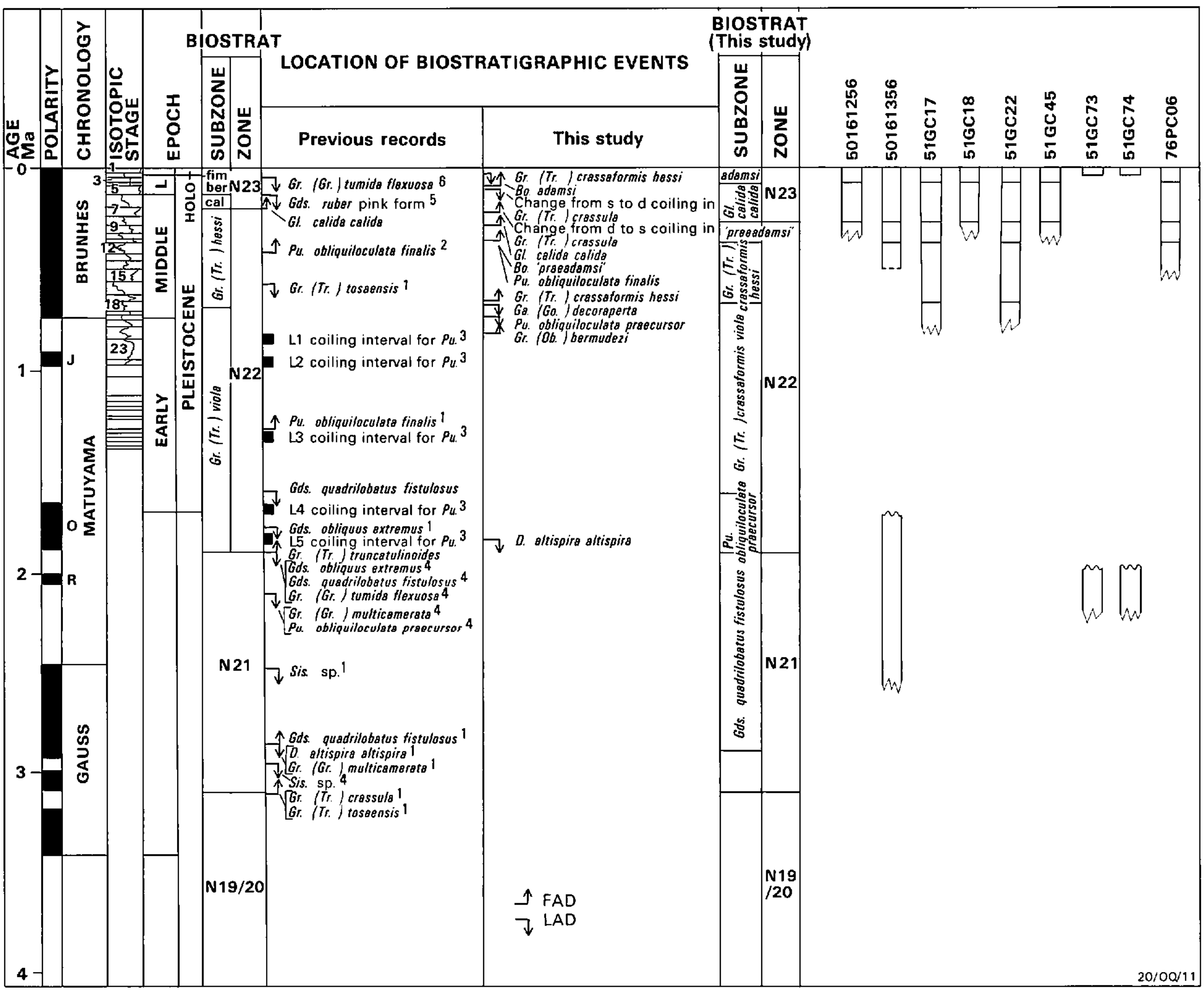
Lord Howe Rise: Only the three most northerly sites drilled on the Lord Howe Rise are discussed here: Sites 208 (Leg 21), 587 and 588 (Leg 90). Site 587 was drilled south of Lansdowne Bank, which forms the southern margin of the Coral Sea Basin. Sites 208 and 588 were drilled in close proximity on the western side of the Lord Howe Rise, south of Site 587.

Sites 208 and 588 penetrated virtually an identical section. Both intersected a siliceous-calcareous middle Eocene unit, but at Site 208 this unit was drilled through and the hole bottomed in a middle Paleocene to Cretaceous sequence. Thus the middle Eocene disconformably overlies the middle Paleocene, and is disconformably overlain by a late Oligocene to Holocene calcareous sequence. Kennett and von der Borch (1985) stated that the late Oligocene to Holocene section at Site 588 is complete, but at Site 208 a minor disconformity separates the early and middle Miocene (Kennett, 1973). The three sites have apparently remained at bathyal depths since at least the Eocene, although Boersma (1985) noted that at Site 587 shallow water benthic foraminiferids were reworked into deeper water deposits during the late Miocene (Zone N.17A).

Dredge Material

Palmieri (1974, 1984) described a fauna dredged from the Australian continental shelf near Fraser Island (BMR 701370 - Marshall, 1971, 1972) which contained a larger foraminiferal fauna including *Lepidocyclina (Nephrolepidina)* sp. with a Zone N.14 planktic fauna (*Globigerina nepenthes* and *Paragloborotalia mayeri*); similar faunas to this occur in nearby GSQ Sandy Cape-1-3R as well as in the deeper water sections such as Capricorn-1A and Aquarius-1. This may be evidence for an increase in water depths during the early middle Miocene (within the Zone N.8 to N.9 interval), with the larger foraminiferal faunas being replaced by planktic assemblages, but slumping of shallow water species into deeper water cannot be dismissed.

Chaproniere (1983) described faunas from four dredge hauls at the northern end of the Queensland Trough in the vicinity of Osprey Reef, at the northwestern corner of the Queensland Plateau, collected during R/V "Sonne" Cruise 16. The oldest sample contained a middle Eocene fauna made up of planktics *Acarinina bullbrooki* and *Globigerapsis ?subconglobata* and larger foraminiferids *Asterocyclina incisuricamerata* and *Operculina pacifica*. In addition samples of late Oligocene (lower T*e*) and early Miocene (upper T*e*) were collected. A sample of chalk (So16-03KD-D) collected during the same cruise, in the vicinity of the Osprey Embayment, NW of Osprey Reef, contained a well preserved, high diversity planktic fauna, including *Globorotalia (Fohsella) kugleri kugleri*, *Globoquadrina* *dehiscens*, *Globigerinoides quadrilobatus altiapertunus*, *Gds. q. subquadratus* and *Globigerina woodi woodi*, indicating Zone N.4B, basal Miocene.



1 Berggren et al 1985 2 Lamb & Beard 1975 3 Saito 1976 4 Kennett & Srinivasan, 1983 5 Thompson et al 1979 6 Bolli & Premoli Silva, 1973

Figure 4. Biostratigraphic summary for six gravity and piston cores taken in the Queensland and Townsville Troughs. Time scale after Bolli and Premoli Silva (1973) and Chaproniere (1985a); Oxygen isotope scale after Shackleton and Opdyke (1976).

More recently, a number of dredge samples were collected during four cruises (50, 51, 75, 76) of the R/V "Rig Seismic" over the Queensland and Marion Plateaux (Figure 1). Some of these (75DR03, 76DR04 to 76DR09) contained larger foraminiferal faunas (*Lepidocyclina (Nephrolepidina) howchini*) with values for Parameter F (Chaproniere, 1980, 1983, 1984) typical of Zones N.7 and N.8 (late early Miocene). A number of the late early Miocene samples from the Marion Plateau (e.g. 75DR03-III, 76DR02-15) had borings infilled with late Miocene to early Pliocene and Pleistocene planktic foraminiferal ooze, suggesting that they were collected from immediately below the regional late Miocene or early Pliocene unconformity. Also, some (e.g. 75DR02-III) contained lower T*f* larger foraminiferids reworked into a Pliocene (Zones N.18 to 19/20) planktic assemblage. These samples were probably collected above the regional unconformity and indicate that the late early Miocene carbonates were being eroded at that time.

Gravity and Piston Cores

A large number of gravity and piston cores have been collected during four cruises of the "Rig Seismic" and one of the "Sonne" off the northeast Australia region. All but two of these penetrated Holocene or Pleistocene (Zones N.22 to N.23) sediments; two (51GC73 and 51GC74) recovered only the latest Pliocene (Zone N.21) and one (So16-13SL) passed through the Pleistocene into the latest Pliocene. Detailed studies of the planktic foraminiferids have been made for six of these cores (see Figure 4) and 12 biostratigraphic events have been recognised for the middle and late Pleistocene (from within the top of the Matuyama Chron) (Chaproniere, in prep.). All six cores penetrated into the middle Pleistocene *Globorotalia crassaformis viola* Subzone of Zone N.22 (*sensu* Chaproniere, 1985a), but in one core (So16-13SL) this subzone directly overlies the late Pliocene Zone N.21. In addition the two cores which sampled only the latest Pliocene were sited in the floor of a canyon. The top of this Pliocene unit forms a reflector which can be traced on seismic data into the walls of the canyon. The evidence from the three cores suggests that there is a regional break, between the latest Pliocene and the middle Pleistocene, at least within the areas adjacent to the northeast Australian margin. Until detailed studies are made elsewhere, such as in the DSDP Leg 90 sites, the full extent of this break will not be known.

Regional Summary

Three main sedimentary packages can be recognised throughout the region, with one being confined to the shallow water areas. Each being bracketed by unconformities.

Eocene: An early or middle to late Eocene package overlies basaltic basement in the Coral Sea Basin, but in the Papuan Basin it overlies Jurassic or Cretaceous sediments, and on the Lord Howe Rise, Paleocene siliceous chalks. The topmost beds vary in age from middle to late Eocene, due almost certainly to erosion prior to the deposition of the overlying package in the late Oligocene. The Eocene sequence in all areas except the Capricorn Basin, is fully marine, with the basal sediments containing mainly planktic faunas. Gradually a shallow water component (including larger foraminiferids) displaces the planktic assemblage, indicating shallowing. In the deeper parts there is evidence for an increase in water depths (at Site 209), from the middle to late Eocene. In the Capricorn Basin the non-marine section underlying the marine late Oligocene is believed to be of Eocene age, being a possible correlative of the Eocene oil shales on shore.

Oligocene to Middle Miocene: A late Oligocene to late early or early middle Miocene package directly overlies the Eocene surface. The basal beds of this package vary in age from late Oligocene in the deep sea areas to basal Miocene in some of the shallow water sections. Sedimentation of this package ceased, probably within the basal middle Miocene in the shallow water sections, but in the deep sea continued without break to the present day.

Latest Miocene to Holocene: In shallow water areas the deposition of a third package was initiated either in the latest Miocene or the early Pliocene, and continues to the present day. The basal phase of this package is a carbonate platform sequence passing up into terrigenous muds and sands.

UNCONFORMITIES

There are three major unconformities recognised throughout the region, and at least one minor one of limited extent. The three major ones are: the base of the middle to late Eocene sediment package (middle Eocene); the base of the late Oligocene to early middle Miocene package (early Oligocene); and the base of the Pliocene to Holocene package (late Miocene).

Middle Eocene

This unconformity is found in all locations used in this study with the exception of Aquarius-1 where that part of the section below the late Oligocene marine phase is terrigenous (Figure 2). In the Coral Sea Basin, the sediments overlying this unconformity range from fairly shallow water deposits (at Site 209) to probably bathyal at Sites 210 and 287. At these locations the sediments overlie volcanic basement and so are associated with the formation of the Coral Sea Basin crust. The sediments overlying the unconformity at the Lord Howe Rise sites also are of fairly deep water origin and overlie Paleocene and Cretaceous sediments. This unconformity almost certainly is present in the Capricorn Basin, where it probably separates a terrestrial sequence from Palaeozoic rocks. In the Papuan Basin the unconformity universally separates shallow water sediments from Mesozoic or older rocks. Thus in the southeastern Papuan and Capricorn Basins the unconformity separates sedimentary units from rocks of considerably older ages, and is almost certainly related to the formation of the Coral Sea Basin. The formation of this basin permitted shallow marine or non-marine sedimentation to resume over an old topographic surface in the areas now marginal to the basin; within the basin moderate water depths existed as the basin developed. The youngest sediments underlying the unconformity are middle Paleocene, with late Paleocene and part of the early Eocene sediments absent from the region.

Early Oligocene

The oldest sediments overlying the Eocene sediments are of middle Oligocene age (Zone P.19/20), but these have limited distribution being restricted to Site 210 in the Coral Sea Basin only. The Puri Limestone in Anchor Cay-1 contains a Zone P.21B fauna, but it was in the later Oligocene (Zones N.3 to N.4A) that sedimentation became widespread throughout the region. To the east, at the edge of the Australian Plate in the vicinity of Tonga, basal Oligocene (within Zone P.18) sediments are found underlying late Oligocene (Zone P.21B) (Chaproniere, in press). Thus the smallest time gap represented by the unconformity ranges from earliest Oligocene to early middle Oligocene (approximately 3 ma), although in most places the length of the hiatus was longer, from the within Zone P.18 to within Zone P.21 (earliest Oligocene to late Oligocene) representing an interval of approximately 5 ma. This suggests that in some of the shallow water sections in the eastern Papuan Basin erosion may have removed much or all of the late Eocene.

This unconformity is widespread throughout the region ranging from northwestern Australia (Chaproniere, 1984) east to the Tonga Ridge at the edge of the Australian Plate (Chaproniere, in press); it is also present in deep sea sections in the Tasman Basin and Lord Howe Rise (Kennett and von der Borch, 1985), but appears to be absent in the southern parts of the Australian Plate, where sedimentation appears to have been continuous. Kennett et al., (1972) linked the unconformity to the opening of the seaway between Australia and Antarctica and the resulting circum-Antarctic current eroding any sediments. However, the apparent limitation of the unconformity to the northern part of the Australian Plate where it is universally present, from west to east, implies a vast current if the hypothesis of Kennett et al., (1972) is accepted. Furthermore, currents not only remove sediment they also deposit it, but early Oligocene sediments are not known in the region, with the exception of some isolated occurrences of *Tc* shallow-water carbonates in Papua New Guinea (Belford, 1984). There seems little doubt that the mechanism causing the removal of sediments over such a vast area is linked to the northern drift of Australia, but other scenarios must also have been involved. The northward drift of Australia must have had considerable effect on equatorial currents by forcing flows southward along barriers such as the Tonga Ridge, Lord Howe Rise and the eastern edge of the Australia-New Guinea landmass. Such currents may well have been able to erode sediment from shelves, but as noted above, sediment removed from one area should be deposited elsewhere. But where is this sediment? Corrosive bottom waters due to the initiation of Antarctic bottom water, related to the formation of the circum-Antarctic circulation and to the onset of major Antarctic glaciation (Keller et al., 1987) may have removed any sediments eroded from the shelves into deeper waters, but it seems unlikely that all shelfal sediments would have been removed. It is improbable that there was a large fall in sea level, as near continuous sedimentation occurred in shallow water areas both in southeastern Australia and New Zealand over the early Oligocene interval. The elevation of the CCD linked to onset of Antarctic glaciation could also explain removal of calcareous sediments, but those sediments of southeastern Australia and New Zealand referred to above, indicate that it did not rise to shelfal depths. It seems that a combination of events must have interacted during the early Oligocene to cause this major and regional unconformity, but the presence of some early Oligocene within the northern part of the Australian plate is expected, but other than some small isolated occurrences of *Tc* limestone in Papua New Guinea, it seems totally absent.

Late Miocene

This unconformity is present in the wells from the southeastern Papuan Basin and two bores (Wreck Island-1 and Sandy Cape-1-3R) at the southern end of the GBR (Palmieri, 1971, 1984) as well as being evident on the Marion Plateau (Pigram et al., in prep) and at Sites 209 and 287. Though sedimentation was continuous in most other basinal locations, the presence of reworked shallow water foraminiferids in two of the deeper water Sites 210 and 587 may be evidence for shallowing during the late Miocene.

The oldest sediments overlying the early middle Miocene carbonates are almost certainly Pliocene. It is possible that some of these may be latest Miocene as such sediments have been recorded from the Ok Tedi-Wabag area to the north (Belford, 1984), but this seems unlikely as no late Miocene has been reported from DSDP Sites 209 or 287. To the east, late Miocene (Zone N.17A) sediments have been recorded from the Tongan region (Chaproniere, 1985b; in press). Thus the hiatus spans the interval of Zones N.15 to N.16 representing approximately 3 to 4 ma., but as sediments between Zones N.10 and N.17 appear to be absent from the southeast Papuan Basin, the time interval may have been around 15 ma. For the shelfal areas of northeastern Australia, the time interval may have been around 5 ma for this area, based on the section in Sandy Cape-1-3R bore.

In the Papuan Basin wells the unconformity is overlain by carbonates which may contain corals, *Halimeda*, coralline algae and larger foraminiferids (e.g. in Borabi-1) which may represent short-lived reefal conditions. In some of the wells (e.g. Borabi-1, Kusa-1, Pasca-A2, Uramu-1A) loss of circulation coincides with the unconformity; this may indicate dissolution channels, possibly the result of development of karst topography on the older Miocene carbonates. There is variation in the age of the carbonates underlying the unconformity ranging from early to early middle Miocene. This variation is almost certainly due to the effects of subaerial erosion, a concept supported by the possible evidence for karst in Borabi-1 and other wells.

Because the unconformity is developed in all shallow water sections studied, it is almost certainly the result of sea level fall, the extent of the fall being considerable (Pigram et al., in prep.).

Early Pleistocene

As noted above much of the early Pleistocene is missing in the only core (So16-13SL) to have penetrated the Pleistocene into the late Pliocene. In this core the FAD of *Pulleniatina obliquiloculata finalis* (dated as 1.3 ma., by Berggren et al., 1985b) directly overlies the LAD of *Globigerinoides quadrilobatus fistulosus* (dated at 1.6 ma., by Berggren et al., 1985b), giving a maximum length of 0.3 ma. for the hiatus. The geographic extent of this hiatus is not known, but its presence in the floor of a canyon adjacent to Geranium Passage, some 500 km south of So16-13SL implies that it may be regional.

Minor Unconformities

Palmieri (1971) records an unconformity separating Zones N.7 and N.8 in Wreck Island-1 and Capricorn-1A, which may be equivalent to a minor hiatus separating the early and middle Miocene in Site 208 (Kennett, 1973). However Condon et al., (1953) and Chaproniere (1984) have recognised an unconformity at a slightly higher level, within Zone N.8, in the Northwest Cape area and elsewhere in the Carnarvon Basin, but it seems absent from sections further north, such as Ashmore Reef-1 (Chaproniere, 1981, 1984). It is possible that these records are of the same unconformity, which though regional, is discontinuous in geographic extent. Also it is very short-lived in time, probably being confined to within Zone N.8. It occurs in both the northwestern and northeastern parts of Australia, in areas of differing tectonic settings. This evidence implies a possible relationship to sea-level fall.

At Site 209 there is a marked hiatus from the top of the middle Miocene to the middle Pliocene (Kennett and von der Borch, 1985), and is followed by a continuous sequence to the Holocene. At Site 287 there is an unconformity between the late Oligocene and the barren ?Miocene, and between the ?Miocene and Pliocene to Holocene sequences. In the absence of faunas this unconformity cannot be accurately dated.

PALAEOENVIRONMENTS

Eocene

The Eocene sediments from wells drilled in the Papuan Basin may have a lower part which contain some planktic foraminiferids the presence of which indicates a connection with an open oceanic environment, together with a low diversity larger foraminiferal assemblage indicative of shallow water. Higher in the Eocene planktic forms disappear, and a more diverse larger foraminiferal assemblage is present. Coralline algae have been recorded only from the late Eocene (Lloyd, 1978); corals have not been recorded. Anchor Cay-1 differs from the other wells by the more diverse planktic faunas that occur throughout the Eocene section which are indicative of water depths greater than those for the other wells studied, although the presence of larger foraminiferids at the top suggest shallowing. Thus all sections studied indicate a marked shallowing in the Late Eocene, but the absence of corals and the low diversity of larger foraminiferids suggests that temperatures were not tropical.

DSDP sites in the region generally indicate bathyal water depths throughout the Eocene, but at Site 209 there is evidence for deposition on a continental margin during the late middle Eocene, followed by gradual deepening during the late Eocene. The faunas have a close affinity with temperate regions (Burns and Andrews, 1973).

Late Oligocene to Middle Miocene

As noted above the only faunas examined for this report are from Borabi-1, where the larger foraminiferid assemblages are associated with coralline algae, generally nodular forms, suggesting shallow depths, high in the euphotic zone. That depths continued to change throughout the deposition of the Oligocene-Miocene carbonates is shown by the gradual change in faunal composition, from one dominated by rotalines to one dominated by miliolines; in most of the wells from the Papuan Basin, the top of the sequence is marked by the presence of corals, indicating minimum depths of 25m or less. Thus water depths gradually shallowed with time. It is possible that increasing water temperature may have influenced the time of coral development, but as coral development occurred earlier in some wells (Pasca - where corals are present within upper T*e*) than that found in Borabi-1 (lower T*f*), temperature control seems unlikely; instead factors such as water depth and substrate may have controlled coral distribution. Anchor Cay-1 differs from the other wells in that planktic foraminiferids occur throughout the sequence, with larger foraminiferids appearing at the top of the section; these assemblages indicate greater water depths then those seen elsewhere, probably below the euphotic zone at the base of the sequence. Planktics gradually give way to larger foraminiferids and coralline algae, indicating gradual shallowing to depths within the euphotic zone, but not shallow enough to permit development of corals. Thus in the southeastern Papuan Basin, water depths appear to have gradually shallowed throughout the Oligocene-Miocene period, finally reaching depths at which coral development could take place at some locations.

Similar faunal assemblages to those found in the Papuan Basin wells are found in Wreck Island-1 and Sandy Cape-1-3R. The larger foraminiferal associations in the lower part of the sequence contain *Lepidocyclina (Eulepidina) ephippioides*, *L. (Nephrolepidina) sumatrensis/howchini* and *Miogypsina*; even though *Cycloclypeus* occurs in both sequences, other nummulitids *Heterostegina borneensis* and *Spiroclypeus margaritatus* have not been recorded. Higher in the section in Sandy Cape-1-3R, miliolids *Austrotrillina howchini*, *Flosculinella bontangensis* and *Marginopora vertebralis* appear (Palmieri, 1984). Planktic foraminiferids are present throughout the Wreck Island-1 section, but are present only in the upper parts in Sandy Cape-1-3R; coralline algae and corals have not been recorded from either bore, but almost certainly, coralline algae would be present. Thus, depths seem to have been within the euphotic zone throughout the late Oligocene to early middle Miocene, within an oceanic setting most of the time, but the presence of miliolids in Sandy Cape-1-3R suggests the development of localised areas of increased salinity. The presence of glauconite in the bottom parts of the sections implies warm temperate to subtropical temperatures, but the presence of larger foraminiferids suggests at least subtropical conditions.

The basal marine beds in both Capricorn-1A and Aquarius-1 are glauconitic muds containing planktic foraminiferids as well as a *Lepidocyclina (Nephrolepidina) - Miogypsina (Miogypsinoides)* assemblage (Palmieri, 1974), similar to that found at the base of the Wreck Island-1 sequence. This fauna indicates subtropical, shallow water, oceanic conditions. The presence of diverse planktic faunas without larger foraminiferids in the overlying section indicates greater water depths, probably below the euphotic zone. A more accurate palaeodepth estimation will have to await the description of the smaller benthic foraminiferids. Within the early and early middle Miocene, Palmieri (1974) reports levels containing larger foraminiferids interspersed with planktic intervals; he explains some of these occurrences of larger foraminiferids as resulting from slumping from adjacent shelfal areas, but others he explains by localised shallowing events. Without examination of the smaller benthic foraminiferids it is difficult arrive at any firm conclusions, but it seems that slumping from shallow waters, could explain all occurrences without recourse to proposing local shallowing events.

Within the Coral Sea Basin water depths throughout the Oligocene and Miocene remained close to the CCD (Kennett and von der Borch, 1985).

Post-Middle Miocene

In the southeastern part of the Papuan Basin the early or middle Miocene carbonates are locally overlain by a thin limestone which in Borabi-1 contains corals, coralline algae, *Halimeda* and a typically Pliocene or younger larger foraminiferal assemblage *Alveolinella quoyi*, *Marginopora vertebralis*, *Acervulina inhaerens* and *Gypsina plana*. This limestone is succeeded by a sequence of carbonaceous sands and marls containing shallow water benthic foraminiferids and some planktic forms. Elsewhere, the Miocene carbonates are succeeded by carbonaceous sands and marls containing diverse planktic faunas. Thus the beds overlying the early to middle Miocene carbonates show evidence of an initial reefal development within the Pliocene, which were soon swamped by a terrigenous-derived sequence in which depths varied; generally there was a connection to open oceanic conditions.

In the southern GBR area shallow water Pliocene calcarenites were succeeded by Pleistocene reefal sediments in Wreck Island-1 (Palmieri, 1974). In Sandy Cape-1-3R the middle Miocene is overlain by mixed carbonate and terrigenous sediments often containing coralline algae, corals, planktic and larger benthic foraminiferids. Within the Capricorn Basin planktic foraminiferids are very common in the Pliocene sediments, but lack of samples prevented study of the higher levels in Aquarius-1 and Capricorn-1A wells (Palmieri, 1974). However, it is likely that sedimentation continued through the Pleistocene at depths similar to those existing at these sites at the present day.

Within the Coral Sea Basin sedimentation continued throughout the Pliocene to the Holocene under similar conditions to the present day.

PREDICTED BIOSTRATIGRAPHIC SEQUENCE FOR THE NORTHEAST AUSTRALIAN REGION

From the above discussion and using the hypothesis for the control of reef development by the northward drift of Australia proposed by Davies et al. (1987), it is possible to predict the biostratigraphic sequence expected for the marginal platforms and troughs in the offshore area of northeastern Australia.

Platforms

Although DSDP Site 209 was drilled on the northeastern margin of the Queensland Plateau, no other drilling has taken place on either the Queensland or Marion Plateaux. Evidence for the predicted stratigraphic section comprising both plateaux comes from dredges and cores, which were taken mainly at the margins, as well as correlations with the few data points in the area, such as Aquarius-1, Capricorn-1A, Sandy Cape-1-3R and Wreck Island-1 wells for the southern end, and Anchor Cay-1 for the northern parts. The basement for the Queensland Plateau is believed to be a subsided extension of the Tasman Fold Belt (Ewing et al., 1970). Nothing is known for the Marion Plateau, but evidence from wells at the southern end of the plateau suggest that Mesozoic igneous or volcanic rocks and slightly metamorphosed sandstones and shale (Carlsen and Wilson, 1968a, b) may form the upper part of the basement sequence.

Southern Part: The biostratigraphic section on highs built-up on Mesozoic sandstones and shales or igneous rocks forming the basement of the Marion Plateau would be expected to be similar to that encountered in Wreck Island-1; that is the basal marine section would be a late Oligocene section directly overlying non-marine sediments of possible Eocene age. These older marine sediments would be glauconitic and contain larger benthic as well as planktic forms. Sedimentation probably continued into the early middle Miocene, with sediments composed mainly of larger foraminiferal limestones. Given the probable latitudinal position of this part (Marion Plateau) at this time (Davies et al., 1987; Feary et al., in prep.), it is unlikely that water temperatures would have been sufficiently warm to permit coral growth. A marked unconformity spanning the late Miocene is expected, with sedimentation recommencing in the early Pliocene with shallow water bioclastic deposits. At this time warmer temperatures, due to Australia's more northern position than during the earlier Miocene, may have permitted the initiation of reef growth, which has continued to the present day. Areas adjacent to the plateau may have been deeper throughout much of the Tertiary resulting in a sequence similar to that of the Capricorn Basin, that is with continuous planktic faunas with shallow water debris derived from adjacent shallow water areas.

Northern Part: The Queensland Plateau would be expected to exhibit an identical biostratigraphy to the Marion Plateau, but may differ in one respect. Shallow water Eocene marine sediments have been recorded in the vicinity of Osprey Reef (Chaproniere, 1983), indicating the possibility of such an occurrence elsewhere on the plateau, instead of the non-marine sequence found further south. Following the hypothesis advanced by Davies et al., (1987) it is possible that the slightly warmer water temperatures prevailing in this part of the area during the late Oligocene and early Miocene may be reflected in a more diverse larger foraminiferal assemblage, especially higher in the early Miocene, than that recorded in Wreck Island-1.

Troughs

As noted above the oldest marine sediments recorded from the Coral Sea Basin (at Site 287) are early or middle Eocene, directly overlying oceanic crust. In areas of continental crust (such as the Queensland and Townsville Troughs - Symonds and Davies, 1988), however, Mesozoic (possibly Cretaceous) sandstones and shales have been recorded from the wells in the Capricorn Basin (Carlsen and Wilson, 1968a, b), where they are overlain by a possible Paleocene to Eocene non-marine sequence (Hekel, 1972; Foster, 1982). The Eocene is disconformably overlain by a sequence of late Oligocene to Holocene pelagic sediments, deposited close to the CCD. The water depths in the Queensland and Townsville Troughs are much shallower than those of the Coral Sea Basin, and dissolution effects, if encountered, should be minimal. Thus the oldest marine sediments within the troughs could be expected to be early or middle Eocene carbonates of possible shallow water origin. The late Eocene should be disconformably overlain by late Oligocene sediments made up of pelagic sediments mixed with shallow water debris derived from adjacent shallow water areas. It is difficult to assess whether a continuous sequence from late Oligocene to Holocene is present, or whether disconformities in the late Miocene should be present. Evidence from the Capricorn Basin wells, drilled in shallower water depths than those within the troughs, suggests that a continuous section could be expected. Levels of concentration of shallow water derived fossils may be evidence for sea level fluctuations.

GEOHISTORY ANALYSIS

Introduction

Geohistory analyses for all wells and DSDP sites used in this study (Plates 16-30) were undertaken using the method described by Falvey and Deighton (1982) and Williamson and Pigram (1986). This method models subsidence and thermal maturation from data extracted from these well sections. Input data has largely been obtained from well completion reports, although, for the Papuan Basin wells, data has also been extracted from other sources, such as Burns and Bein (1980) and Stewart and Durkee (1985), and for the Capricorn Basin from Ericson (1976); reliability of the analysis is dependent upon the quality of this data. With the exception of Kusa-1 (drilled in 1977) and Sandy Cape-1-3R (drilled in 1980) all wells are old being drilled prior to 1970. Because of the age of these wells, temperature data is lacking for almost all locations except for some from the Papuan Basin, and even here temperature logs are limited to the upper part of the well. Also, of these locations the temperature logs appear to have been run to locate the position of cement during casing operations and appear to be distorted due to the exothermic reaction of setting cement and thus have no value for heatflow estimations. Vitrinite reflectance data is available for only two sections (Anchor Cay-1 and Kusa-1), and porosity data is lacking for all sections. For this discussion, vitrinite reflectance values in the range 0.6-0.8 are considered marginally mature, 0.8-1.3 represents the peak generation window, and values greater than 1.3 correspond to the dry gas-condensate window. As thermal conductivity is a major parameter, the lack of these data has required that the analyses depend on modelling to obtain these parameters. However, the results do have some implications for the oil prospectivity of the region, in particular the southern Papuan Basin, and provide a good basis for an analysis of the relative prospectivity of basins within the region.

At unconformities it is necessary to attempt to evaluate the amount of sedimentary section removed by erosion and the time interval involved, and based on these figures, to make an estimate of the amount of sediment removed. For the first of these figures it is appropriate to estimate the time at which sedimentation ended and erosion commenced; the second of these is constrained by the quality of the faunal or floral evidence. The ages used have been taken from Figure 2.

Heatflow modelling for the well locations in proximity to the rifted margins was undertaken using the method of Sleep (1971). This modelling shows that the heatflow rose to the time of breakup and then slowly decayed to the present day. For well and DSDP sites that are axial to seafloor spreading ridges (that is basins within transform margins such as the Capricorn Basin) numerical modelling was undertaken to ascertain the heatflow history at these locations. Present day heatflow values for the region are based on Cull and Conley (1983, fig. 4).

Heatflow within the region has been controlled by two rifting episodes: the first in the early Mesozoic, which defined the east-west trend of the northern margin of Australia (Pigram and Panggabean, 1984); the second in the Middle or Late Cretaceous, which preceded to the opening of the Coral Sea Basin; peak palaeoheatflow related to the latter regime occurred at the time of Coral Sea Basin breakup about 63Ma (magnetic anomaly 27) (Symonds et al., 1984; Weissel and Watts, 1979). Subsequently the general heatflow within the region has declined. The Cretaceous/Paleocene heatflow peak occurred during a period of time represented by a major unconformity, and so would not be shown on the palaeoheatflow plots; for this reason an artificial point has been inserted at 63Ma so that this heatflow event is incorporated into the analysis. Present day heatflow in the region is about $60mW/m^2$ (Cull and Conley, 1983), and this figure (as 1.43 h.f.u.) has been used in the geohistory analyses for all the sites in the Capricorn and Papuan Basins.

Results

Papuan Basin: Three major unconformities are present in the sections studied from the Papuan Basin and each has been modelled with different parameters. The age for the top of the Mesozoic section is poorly constrained because of poor fossil control or uncertainty as to the stratigraphic units represented, which is in contrast to the more closely dated start of Eocene sedimentation. Because of these age constraints this unconformity separating the Cainozoic from the Mesozoic has been modelled using an arbitrary figure of 1000m for the amount of section removed by erosion during the interval prior to the resumption of Tertiary sedimentation. This figure is supported by the findings of Hill and Gleadow (1989) who estimated that ≈800 m of Mesozoic section was removed during the Paleocene erosion event in the Iehi-1 well in the Papuan Fold Belt to the north of the wells studied here. For the break between the Eocene and late Oligocene it has been assumed that sedimentation ceased at the end of T*c* letter stage, coinciding with a major fall in sea-level at around 34Ma; shallow water sediments of T*d* age are virtually absent from the region suggesting that the T*d* stage coincides with this period of lowered sea-level. Because shallow water carbonates tend to become cemented shortly after deposition, the compaction of the Eocene limestones due to the overlying sediment load is assumed to be zero. Also, because erosion on limestones takes place by solution, it is expected that only a small amount of section has been removed and a figure of 50m is considered a reasonable estimate. The cessation of early middle Miocene sedimentation is estimated to have occurred at 13Ma, coinciding with a sea-level fall at the top of Zone N.11, with sedimentation being resumed at 5Ma. These Miocene sediments are limestones, so similar arguments for assessing the compaction effects and the amount removed for the Eocene carbonates are used here; because the time interval ranges from 12 to 15Ma (compared with approximately 6Ma between the Eocene and late Oligocene) a figure of 100m has been used for the amount removed by erosion.

Three wells, Anchor Cay-1, Kusa-1 and Borabi-1 form a north-south transect across the Papuan Basin. These geohistory plots show a marked similarity, with rapid subsidence through the early and middle Jurassic leveling out for the remainder of the Mesozoic. As noted above, much of the Cretaceous section is missing, presumably lost by erosion. The Tertiary again was a period of increased subsidence, particularly during the deposition of the post-Miocene section, which is time transgressive to the south. This subsidence phase is related to flexuring of the margin associated with foreland basin development caused by the collision to the north, which formed the New Guinea orogen, and to the subsequent loading by sediments derived from the rapidly uplifted rocks forming the orogen (Pigram et al., 1990).

The vitrinite data for the two wells (Anchor Cay-1 and Kusa-1), which penetrated a significant part of the pre-Tertiary section, show that the Mesozoic and older rocks within this part of the Papuan Basin became marginally mature by the late Jurassic, associated with the early Jurassic rift-related heatflow peak. The dead oil staining observed within the Jurassic section of Anchor Cay-1 is probably related to this period of maturation. These Mesozoic rocks were effectively frozen at this maturation level until the Late Miocene, when rapid subsidence associated with large volumes of clastic sediment entering the Papuan Basin from the New Guinea orogen, causing rapid burial. In all other wells, the computed vitrinite reflectance plots indicate values of less than 0.5.

All five Papuan Basin wells show similar geohistory plots, especially for the Tertiary, with gradual subsidence through the Eocene to Miocene, with the rate of subsidence increasing rapidly during the Late Miocene or Pliocene. Anchor Cay-1 and Kusa-1 are the only wells with a good Mesozoic section, with the former having the best section which may go to the base of the Triassic. Three wells show modelled vitrinite values of 0.5 or greater; in Anchor Cay-1 the 0.5 level was reached within the Late Jurassic (at approximately 2700m), the 0.6 level within the Middle Cretaceous (at approximately 3000m) and the 0.7 level within the Tertiary (at approximately 3300m); in Kusa-1 the 0.5 level was reached by the Middle Cretaceous (at approximately 2800m) and the 0.6 level by the Paleocene (at approximately 3200m); in Pasca-C1, for which there is no vitrinite reflectance data, the 0.5 to 0.7 levels were reached in the Pliocene (below 3100m).

The basement subsidence curves for all wells show a gradually subsiding basement throughout the Mesozoic, with uplift occurring by the Eocene, preceding the opening of the Coral Sea Basin. The rate of basement subsidence was again gradual during the Eocene to Miocene, increasing rapidly in the Late Miocene and Pliocene. The increase in rate of subsidence occurs slightly earlier in Uramu-1A than in the other wells indicating that the event was time transgressive, being later to the south. The basement subsidence curve for Anchor Cay shows some minor uplift during the Late Jurassic, which is probably related to water depth changes induced by possible sea-level fluctuations.

Though the computed iso-vitrinite reflectance plot appears to match the observed data plot for Kusa-1 (Plate 20), this is not the case for Anchor Cay-1, where there is a marked disparity between the two plots (Plate 16). In an attempt to reconcile these differences a number of models were produced. Firstly the palaeoheatflow curve was modified to reflect an increased heatflow peaking at magnetic anomaly 27 (63 Ma), plateauing until anomaly 22 (51 Ma) during the development of a possible transform plate boundary through the Pandora Trough area, and then declining through the rest of the Cainozoic. This change altered the original model moving the hypothetical curve closer to the vitrinite reflectance values (Plate 17). This model was further refined by doubling the amount of sediment removed by erosion during the Paleocene, and this resulted in both the computed and observed iso-vitrinite plots coinciding in part (Plate 18); increasing the erosion figure by a further 500m resulted in an even greater coincidence of the two plots, but the removal of 2500m of Cretaceous sediments during the Paleocene is considered to be highly improbable. An additional plot was made, where the unconformity between the ?Toro Sandstone and the Koi-Iange Formation was removed, and the sandstone was considered to be part of the Koi-Iange Formation; the figure of 1000m of eroded Cretaceous section was used as for the initial plot. The resulting model was little different to those noted above. To this model an additional heatflow event was placed in the Jurassic, but this too made little difference to the result. Thus the only way the two iso-vitrinite plots could be made to coincide was to add a thickness of sediment and to increase the heatflow regime at this site. However, it is difficult to envisage in excess of 2000m of erosion within the time constraints (Paleocene) within the region and a greater heatflow than used in these models. Even though the two iso-vitrinite plots coincide for Kusa-1, the heatflow was similarly modified to simulate the heatflow pulse due to the opening of the Coral Sea Basin, but because this well was sited further away from the heat source, the maximum heatflow levels were lower than those used for the Anchor Cay-1 model. This resulted in the two iso-vitrinite plots becoming separated (Plate 21), and it was only by using a lower modern day heatflow value of 1.2 h.f.u. that the two plots could be reconciled.

Capricorn Basin area: All locations have been modelled using a constant heatflow throughout time because of their distance from the heat source and is confirmed by modelling. Both Sandy Cape-1-3R and Wreck Island-1 show almost identical plots, but both differ from those for Aquarius-1 and Capricorn-1A, both of which are very similar. All sections show a gradual subsidence through the Eocene to Miocene, with the rate increasing rapidly in the Pliocene. The plots for Aquarius-1 and Capricorn-1A differ mainly in the thickness of sediment, which was sufficient to produce hypothetical (modelled) vitrinite reflectance values in excess of 0.5 in the Pliocene in Aquarius-1. The similarities between the two pairs of wells is to be expected since they penetrated similar stratigraphic sections. Both Aquarius-1 and Capricorn-1A penetrated a similar, poorly dated terrestrial section, which is absent in both Sandy Cape-1-3R and Wreck Island-1.

Coral Sea Basin: All sites were modelled using the same heatflow values as for the Papuan Basin, and with the heatflow being modelled as peaking between magnetic anomalies 27 and 22, gradually cooling until the present day. The plots show that water depths reached close to their present day depths soon after the end of this heatflow event. The sudden drop shown in the plots for the subsidence and decompacted burial curves for DSDP Site 287 is more artificial than real, due to the wide error bars for palaeodepth estimates based on the foraminiferids. All plots show a slow gradual subsidence through the Tertiary, rapidly increasing during the Pliocene.

Lord Howe Rise: The heatflow for these three DSDP Sites was modelled using slightly lower present day values (1.40 h.f.u.) than for the other sites. Also, the heatflow models were based on a heatflow peak at 76Ma (magnetic anomaly 33) because of the earlier opening of the adjacent Tasman Basin, gradually declining to the present day. The heatflow event is based on the rifting and breakup events which separated the Lord Howe Rise from the

Australian continent. The three sites show close similarities for all plots reflecting their similar geological histories.

Discussion

Though the four areas have different geological histories, one marked similarity for them all is the increase in the rate of subsidence in the Late Cainozoic which in the Papuan and Coral Sea Basins reflects flexuring of the margin due to collision and the development of a foreland basin. That a parallel increase in the rate of subsidence occurs in the Capricorn Basin and the southern end of the GBR is more difficult to explain but the timing of the event suggests that it is produced by intraplate stress effects related to tectonic events along the northern margin of Australia. Models of basin subsidence related to intraplate stress (Lambeck, 1983a, b) probably offer the most plausible explanation for associating distant collisional events to enhanced basin subsidence.

CONCLUSIONS

Though no one sequence used in this review provides a complete section, it is possible to construct such a section (Figure 3A, B). The study area spreads over in excess of 10° of latitude resulting in a significant temperature differential north to south which has effected faunal distribution since at least the late Oligocene when the region was well south of its present position. In addition the various sections on which this review is based are from a broad range of water depths, from abyssal depths below the CCD to near present day sea level. For these reasons it has been convenient to discuss the biostratigraphy in sections related by depth.

Marine sedimentation in the Papuan and Coral Sea Basins commenced in the middle Eocene, being linked to the formation of the Coral Sea Basin. In the northeastern Australian area, marine Eocene has been sampled only in the northern part of the Queensland Plateau (Chaproniere, 1983), but on seismic evidence such sediments may form a thin veneer over parts of both the Queensland and Marion Plateaux (Symonds and Davies, 1988). However, on the evidence from the wells drilled in the Capricorn Basin it is possible that non-marine Eocene sediments may be present on the southern parts of the Marion Plateau. To the north sedimentation continued into the late Eocene, and possibly into the basal Oligocene (as it did locally elsewhere in Papua New Guinea). There is evidence that water depths in the basin gradually increased with time, but in the shallow water sequences, depths decreased. Much of the Eocene sequence may have been removed during the early Oligocene erosion event which effected both shallow and deep water sequences. The rocks underlying the northerly sections range in age from Palaeozoic to Cretaceous, whereas in the south, they are probably Palaeozoic.

Sedimentation resumed again in the Late Oligocene, at first localised (during Zone P.21), but later (during Zones N.3 to N.4A) over the entire region. In the shallow water areas, larger foraminiferal-coralline algal limestones were deposited over the Eocene sediments. This shallow water sedimentation continued into the early and early middle Miocene; to the north water temperatures were sufficiently warm to permit coral development, but to the south, temperatures remained subtropical. In the north at least two phases of coral development took place, the first (in Pasca-C1) during upper T*e* (early Miocene) and the other (in Uramu-1A, Borabi-1 and Kusa-1) during lower T*f* (late early or early middle Miocene). In some sections (Anchor Cay-1) the late Oligocene sediments are dominated by planktic forms, grading upwards into larger foraminiferal carbonates. Thus all shallow water sections show evidence of shallowing. In the deeper water sequences depths remained stable. In the shallow sections, the early or early middle Miocene is truncated by a disconformity not present in the deeper water areas. The Miocene carbonates appear to have been exposed to subaerial weathering in most of the shelfal areas as seen in the wells of the southeastern Papuan Basin and in samples from the edge of the Marion Plateau. In some areas, particularly in the north, this erosional episode possibly resulted in the formation of solution channels (resulting in loss of drilling fluids). This hiatus appears to span an interval of approximately 15 ma., from at least within the early middle and including most of the late Miocene.

During the latest Miocene or early Pliocene sedimentation commenced in the shallow water areas over the eroded middle Miocene surface. However, in deeper water regions, sedimentation was continuous at most sites from the late Oligocene to the Holocene. In the Papuan Basin the initial sediments were dominated by carbonates, possibly reefal locally, but were soon overwhelmed by clastics. To the south carbonate sedimentation continued throughout the Pliocene to Holocene with only minor amounts of clastic material.

Three major and at least two minor unconformities are present in the sequence. The oldest is pre-middle Eocene and is present throughout the region, being probably related to the formation of the Coral Sea Basin. An early Oligocene unconformity is also universally present and in basinal areas is probably related to the initiation of corrosive Antarctic bottom waters linked with major glaciation in Antarctica (Keller et al., 1987), whilst in shallow areas it is due to erosion by currents resulting from major changes in oceanic circulation patterns due to the northward movement of Australia (Kennett et al., 1972). The third major unconformity represents most of middle and late Miocene time and effected only the shallow water areas, resulting in probable subaerial erosion and karst topography; this was almost certainly related to sea level fall. A short-lived, discontinuous, but nevertheless widespread unconformity is present within the Zone N.7 or N.8 (late early Miocene) interval, and again probably related to sea level fluctuation.

In the northern part of the area at least two periods of coral development occurred during the Miocene, and one in the Pliocene; to the south corals are definitely present only in the Pliocene to Holocene section. Thus in the northern area water temperatures during the early and early middle Miocene were warm enough to sustain coral growth with water depth and the presence of suitable substrate being the sole controls on reefal development. Because the latest early and earliest middle Miocene was a time when temperatures peaked in the region, it is possible that some reefal growth may have occurred at some locations in the southern part of the area reviewed.

Geohistory analyses have been made for all wells and DSDP Sites. These results suggest that heatflow regimes throughout the Tertiary cooled from those prevailing during the formation of the basins. Subsidence rates appear to have been gradual through Eocene to Miocene time, rapidly increasing during the Pliocene and Pleistocene for all basins. Sediments in the Papuan Basin became marginally mature by the end of the Mesozoic, but there is strong evidence that maturity levels increased during the Pliocene and Pleistocene. Within the Capricorn Basin, geohistory modeling indicates that levels in the lower part of Aquarius-1 approached marginal maturity only during the Pliocene or Pleistocene. Though the four areas have different geological histories, one marked similarity for them all is the increase in the rate of subsidence in the Late Cainozoic which in the Papuan and Coral Sea Basins reflects flexuring of the margin due to collision and the development of a foreland basin. That a parallel increase in the rate of subsidence occurs in the Capricorn Basin and the southern end of the GBR is more difficult to explain but the timing of the event suggests that it is produced by intraplate stress effects related to tectonic events along the northern margin of Australia. Models of basin subsidence related to intraplate stress (Lambeck, 1983a, b) probably offer the most plausible explanation for associating distant collisional events to enhanced basin subsidence.

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