XTENDED ABSTRACTS

Palaeogeography, Sea Level, & Climate

Implications for Resource Exploration

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Extended Abstracts - Palaeogeography, Sea Level & Climate

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Tracking global sea level change

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The usefulness of chronostratigraphic-eustatic framework in exploration geology lies in the fact that it provides predrill estimates of geological parameters from seismic data. This enhances inter-regional correlations, particularly in frontier areas, leading to better stratigraphic, structural and facies interpretations. First such eustatic-stratigraphic framework (Vail, et al., 1977) was an outcome of developments in seismic stratigraphy that were based on the realisation that primary seismic reflectors had chronostratigraphic significance. The cycles of sea-level change were derived from seismic data, aided by palæontologic age control from selected wells. Now a new generation of Mesozoic and Cenozoic sea-level curves has been constructed (Haq, et al., 1987), representing considerable improvement on the earlier onlap curves constructed from seismic data alone. This has been made possible by developments in sequence stratigraphy that envisions depositional sequences as genetically related sediment packages formed during different phases of the sea-level cycle.

Sequence-stratigraphic concepts can be used to identify genetically related strata and their bounding regional unconformities, or their correlative conformities, in seismic, well-log and outcrop data. Documentation and age dating of these features in marine outcrops around the world have led to the creation of the new cycle charts which will be the subject of discussion of this talk.

Examples of marine sections from North America, Europe and Asia will be used to illustrate sequence analysis of outcrop data and the integration of chronostratigraphy with sea-level history. The key to accurate chronostratigraphic correlations of sea-level cycles lies in documentation of sequences in stage stratotypes of the Mesozoic and Cenozoic, all of which are located in Western Europe. In these outcrops and other reference sections, depositional systems tracts (genetically related facies of various phases of the sea-level cycle, i.e., lowstand, transgressive and highstand systems tracts) can be identified between three prominent depositional surfaces. The first is the "transgressive surface", which occurs at the top of lowstand systems tract and marks the inundation of the shelf. This surface is usually marked by the most prominent lithologic changes, e.g., from marginal marine or non-marine below to marine above, or from more terrigenous to less terrigenous.

The lowstand deposits below the transgressive surface are characterised by sediments of the most regressive phase of the sequence.

The second readily recognisable surface in outcrops of the shelf strata is the "surface of maximum flooding". This surface manifests itself as a downlap surface on seismic profiles and is associated with the period of depositional starvation on the outer shelf and slope, which produces a physically "condensed section". The condensed section forms partly within the transgressive and partly within the highstand systems tracts of the sequence.

The third surface is the "sequence boundary", expressed as the downward (basinward) shift of the coastal onlap pattern, or by truncation on seismic profiles. In outcrops the sequence boundary may be an obvious conformity or its correlative conformity, depending on the position of the section along the shelf-to-slope profile and the rate of sea-level fall. Shoreward the sequence boundary may coincide with the transgressive surface, whereas basinward it becomes conformable.

The cycles of sea-level change, interpreted from the rock record, are tied to an integrated chronostratigraphy, that combines state-of-the-art geochronologic and magneto- and biostratigraphic data.

Mechanisms of sea-level change throughout the Phanerozoic

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There are a number of ways to change sea-level eustatically. They may be classified into two types.

1. Those that change the volume of water in the ocean basins: i) the waxing and waning of continental glaciers, ii) the release or entrapment of water as a chemical constituent of the earth's crust and mantle, iii) the release or absorption of water in the atmosphere and in lakes and rivers.

2. Those that change the volumetric capacity of the ocean basins: i) changing the volume of the mid-ocean ridge system, ii) expansion or contraction of the continents, iii) sediment deposition or removal in the oceans, iv) expansion or contraction of the earth.

The table below gives estimates of the maximum magnitude and rates of these various mechanisms.

TOTAL	MAGNITUDE (metres)		RATE (cm/1000yrs)		DURATION (MY)
	Max.	Absurd Max.	Max.	Absurd Max.	
Glaciation	150	250	1500	2500	0.1
Lakes/rivers atmosphere	10	20	?	?	?
Mantle water	?	?	?	?	?
Ridge volume	300	500	0.45	0.75	70
Orogeny	80	100	0.16	0.2	50
Hot spots	25	100	0.125	0.5	20
Sediments	40	80	0.1	0.2	?
Extension of margins	40	60	0.04	0.06	100

The mechanisms that have probably been most dominant during the Phanerozoic are changes in the volume of the mid-ocean ridge system, changes in area of the continents, variations in the flux of sediments in the oceans, plus episodic continental glaciation. We will deal mostly with the Mesozoic. Pangea began to break up at the end of the Triassic - continent collision was at a minimum - new ocean basis were being created. Break up continued episodically until the end of the Cretaceous. As the Pangea continent separated and the new oceans were created, sea-level rose. The rate of plate separation appears to have increased through the mid Cretaceous. The net effect of the rifting and the increased rate of plate separation caused a sea-level rise estimated to have culminated at an elevation of 300-350 m above present level.

As separation of the continental fragments continued through the Cretaceous and into the Tertiary, continental collision became increasingly frequent - oceanic ridge systems were subducted and there was a noticeable decrease in the rate of plate separation. These factors, plus the upper Tertiary construction of permanent ice sheets in Greenland and Antarctica, contributed to the drop in sea-level of 300-350 m since the upper Cretaceous.

Geohistorical resolution and correlation: biostratigraphy and event stratigraphy

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Biostratigraphy as a coherent geohistorical discipline arose during the shift from neptunist stratigraphy, based on lithology and mineralogy, to a stratigraphy based on palaeontology. Fossils were used to trace strata (Smith), to identify strata (Cuvier and Brongniart) and to clarify facies (Brongniart). By the 1820s (Brongniart, Phillips) chronological biostratigraphic correlation (in subsequent jargon) was well established on the basis (i) the recognition of successional assemblages of fossils, (ii) the confirmation of that succession in other sections, and (iii) the perception that similarity among assemblages indicates similarity in geological age. The development of classical biostratigraphy has included the following themes:

(i) Long after the establishment of biological taxonomy and classification and of biostratigraphy, organic evolution explained why those disciplines worked so successfully. Every speciation event was a cosmic singularity, even if an imperfect fossil record obscures the event. Thus biochronology is based on irreversible phylogeny. In practice, not much changed.

(ii) In the biostratigraphy of Oppel and Quenstedt in the 1850s the zones were based opportunistically and broadly on assemblage criteria - i.e. the fossiliferous contents of a packet of strata which distinguished it from contiguous packets - and on boundary criteria - i.e. identifying horizons or narrow intervals with some concentration of first and last appearances.

(iii) "Correlation" means two things in stratigraphy and basin studies. Where stratigraphic sections are matched by logged physical and sometimes biological criteria, correlation means homotaxial identification - we merely interpolate between the section actually available. Otherwise, and more appropriately, correlation means coeval, and it is opposite to homotaxy in so far as chronological correlation has had to cope with the facies concept. Thus, there has developed the notion of the "facies fossil" as a corollary of the theory that boundaries between different lithologies could not be taken as "time-parallel". Diachronism has been a ruling paradigm.

(iv) Along with correlation there has to be calibration - by radiochronology and, most recently, by geomagnetochronology. However, no physical method of age determination has come even close to challenging biochronology as the most pervasively valuable framework for Phanerozoic geohistory.

(v) Some of the more entertaining polemics in the literature have pertained to the split between European and American views on stratigraphy: the former have maintained a generally holistic view of the record which the latter have anatomized into lithostratigraphy, biostratigraphy and chronostratigraphy.

(vi) The clutter of various kinds of zone in terms of rock, fossil, evolution and time were reduced by Glaessner (1) to "Rapid changes of environmental conditions create faunal zones characterised by distinctive assemblages of fossils. Evolutionary changes create primarily biozones". I suggest (Fig. 1) that we can identify an ascending series of biostratigraphic units as follows:

(a) Zones based on fossil ranges in strata, yielding assemblage and boundary criteria: Oppel zones.

(b) Zones based, implicitly or explicitly, on phylogenetic models of ancestry and descent: culminating in phylozones (based on single or multiple phylogenetic lineages within the same group of organisms). Developments in the micropalaeontology of planktonic organisms have included the sidestepping of demands for stratotype or reference sections.

(c) Zones based on the above criteria but with time built in: chronozones. In chronozones, the boundaries of the biozone are extended as "time-parallel" surfaces into facies where the biozone itself cannot be recognized. In ISSC parlance that changed the unit from the biostratigraphic to the chronostratigraphic category (and confused me for a decade).

(d) In a further useful reduction of nomenclatural clutter, datums specify evolutionary events that seem to be especially consistent, clear and valuable.

The most important recent developments in biostratigraphy have emerged from a renewed scrutiny of the relationship between "organism" and "environment" in the context of a major paradigm shift. That shift, of course, has been from Lyellian gradualism to an episodic view of the way in which the world works, and the shift has pervaded everything from seafloor spreading and orogeny to speciation and phylogeny in organic evolution. There have been: (i) a return to the holistic stratigraphy that became anatomized during the rise of basin analysis in petroleum geology; (ii) a clarified perception of pattern-process and of hierarchy, both influenced by palaeontology and macroevolution; (iii) an extension of non-phyletic Quaternary-type biostratigraphy and physical stratigraphy into the pre-Quaternary. Thus:

(i) As the world changes, most notably from the e.g. Mesozoic "greenhouse" mode to the Neogene "icehouse" mode, it does so in sharp steps that are recorded in the stratigraphic record in various ways, of which the most apparent are sealevel change and climatic change. We search more closely now for allocyclic (and often global) signals among the local autocyclic signals. The recognition of geobiological, geochemical and stratigraphic signals and their integration into a rigorous chronology, in all environments and globally, constitutes the discipline christened systemic stratigraphy (3). The subdiscipline "chemostratigraphy" is based on variations in the isotopic ratios of carbon, oxygen and strontium (4).

(ii) Whereas the purest versions of classical biostratigraphy sought to base everything on speciation events - abjuring even extinction as a potentially diachronous phenomenon - we realize now that a lot of nonphyletic information has not been exploited thoroughly (2). Examples include biogeographic migrations, mysterious bulges in abundance, disjunct distributions. Acme horizons record rapid watermass shifts and make a case for resurrection of the hemera, proposed by Buckman in 1893 but never regarded as very respectable. Rapid environmental changes do not, in many cases at least, stimulate evolutionary changes within species but rather migration of the species which returns when the good times return: this is the Lazarus Effect of disjunct distribution in time. There is a case for rehabilitating the Oppel-zone as a multidisciplinary effort, as where there is parallelism between foraminiferal overturn, foraminiferal migration and expansion, and zones erected on events among terrestrial and marine palynomorphs: those biological signals were modulated in concert through climatic change and transgression/regression (5).

(iii) The stratigraphic record is perceived once more as occurring in natural packets - in "chronostratigraphic sequences" (6), in hierarchies of "transgressive-regressive units" (T-R)(7), from two for the Phanerozoic down to the Milankovitch time band where there are "punctuated aggradational cycles" (8) and, now, numerous records in epicontinental, oceanic, icehouse and greenhouse situations (9). The role of biostratigraphy in all this is sharpened in several ways. (a) Phylogeny (irreversible) provides the framework for (reversible, flip-flop) geomagnetic, T-R, and putative sealevel events. (b) Biostratigraphy is challenged to date specific events, especially the downlap surfaces in sequence stratigraphy. (c) Physical events are used to enhance the succession and calibration of biostratigraphic datums. (d) The chronological relationship of marine - sealevel - events to coals and to weathering profiles can be sharpened and tested through such notions as the "climate change surface" (Fig. 6, from (7)) between cool/arid and warm/humid modes, as also in the bimodal schema in Fig. 9 (2).

The durations of the third-order cycles from one maximum flooding surface (MFS) to the next (6) and of planktonic foraminiferal P-zones vary broadly in parallel (Fig. 2) through the early Tertiary. Integrated early Tertiary biostratigraphy for southern Australia hinges on the correlation of extratropical planktonic foraminiferal (Fig. 3) and coccolith events to the respective tropical standards (P-zones here are chronozones, sensu Fig. 1). Note the gap in early Middle Eocene (where resolution is coarsest in Fig. 2) in Figs. 3 and 4. A pot-pourri of later Eocene biostratigraphic events is shown in Fig. 5, and the potential for relating such events to sequence stratigraphy is high (Fig. 7 based on (12)). Thus, two MFS at Blanche Point are carried predictively to Browns Creek - from a low plankton to a high plankton regime; note probable correlations of nonphyletic events <u>a</u> to <u>f</u>, respectively, in which case "extinctions" (<u>i</u>) and (<u>ii</u>) are not coeval. Similarly, four peaks in very low numbers of <u>Guembelitria</u> at the Eocene/Oligocene boundary seem to correlate (Fig. 8, from (13)).

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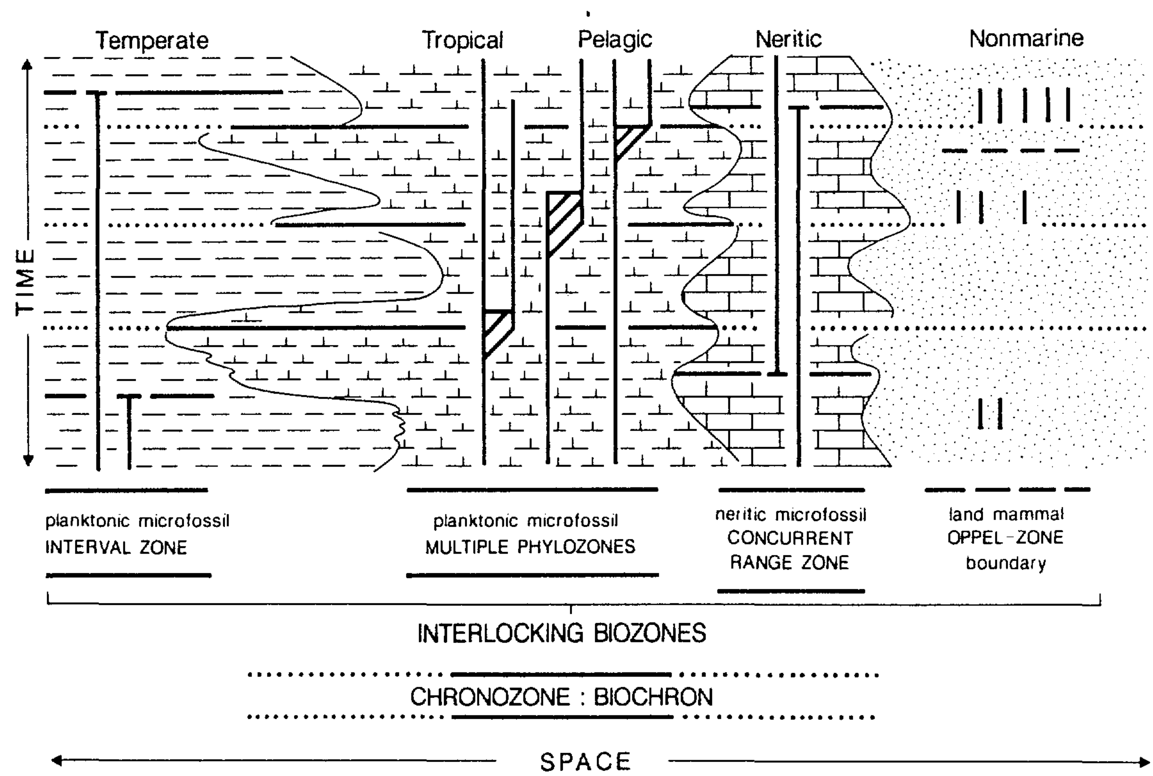

Fig. 1. Space-time-faciesdiagram (2) illustrating cross-correlation between different facies, with the aim of perceiving "chronozones" based on but extending well beyond the tropical standard.

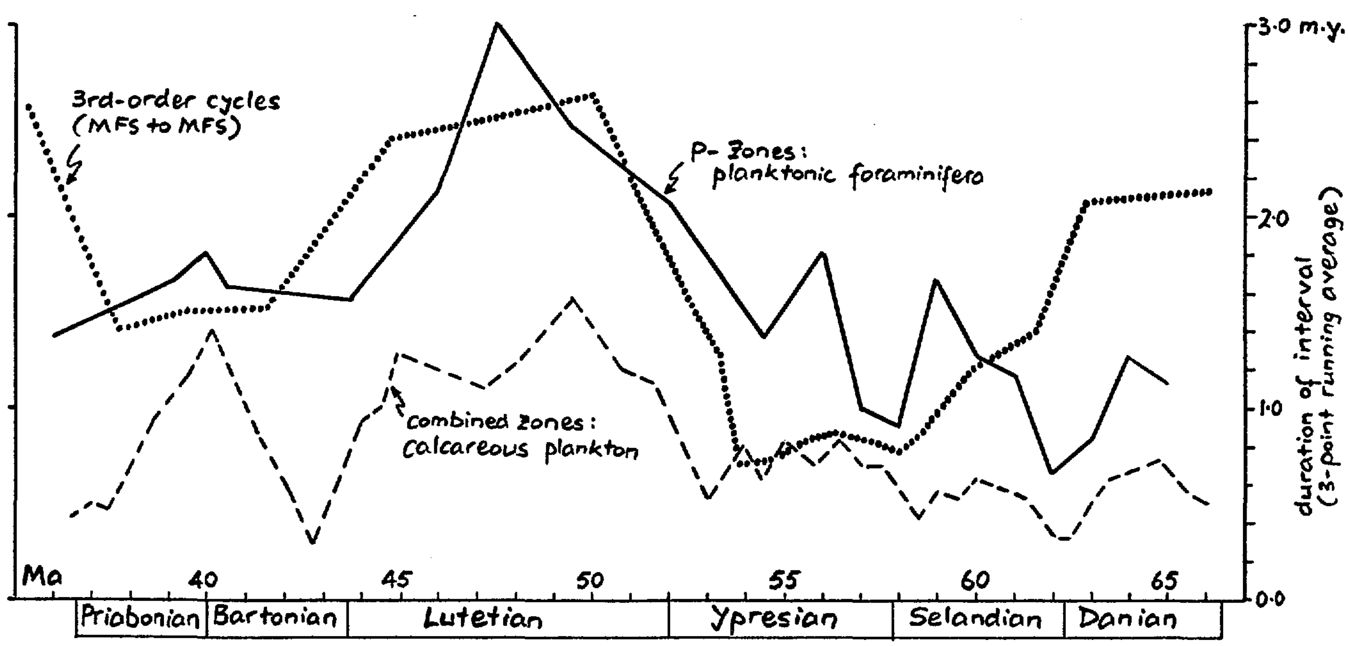

Fig. 2. Duration (three-point moving averages) of planktonic foraminiferal zones and combined foraminiferal and coccolith zones (10) compared with MFS spacings (6) based on calibration in (10).

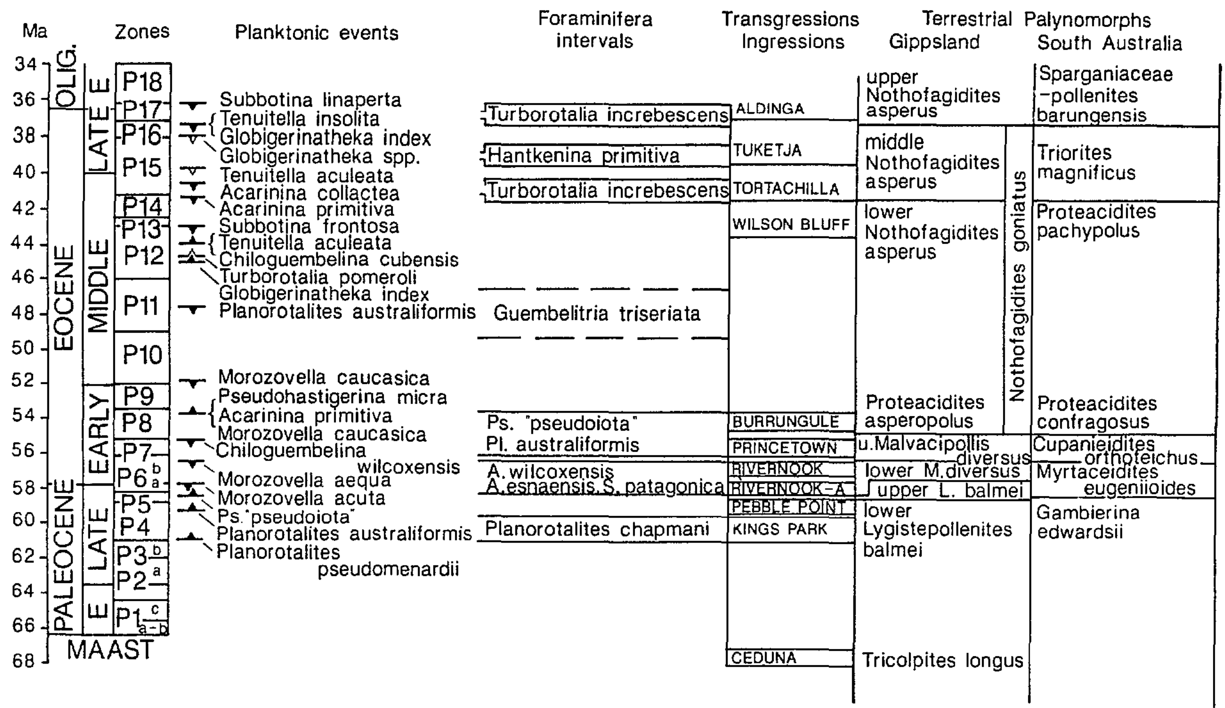

Fig. 3. Early Tertiary biostratigraphy, southern Australia (11).

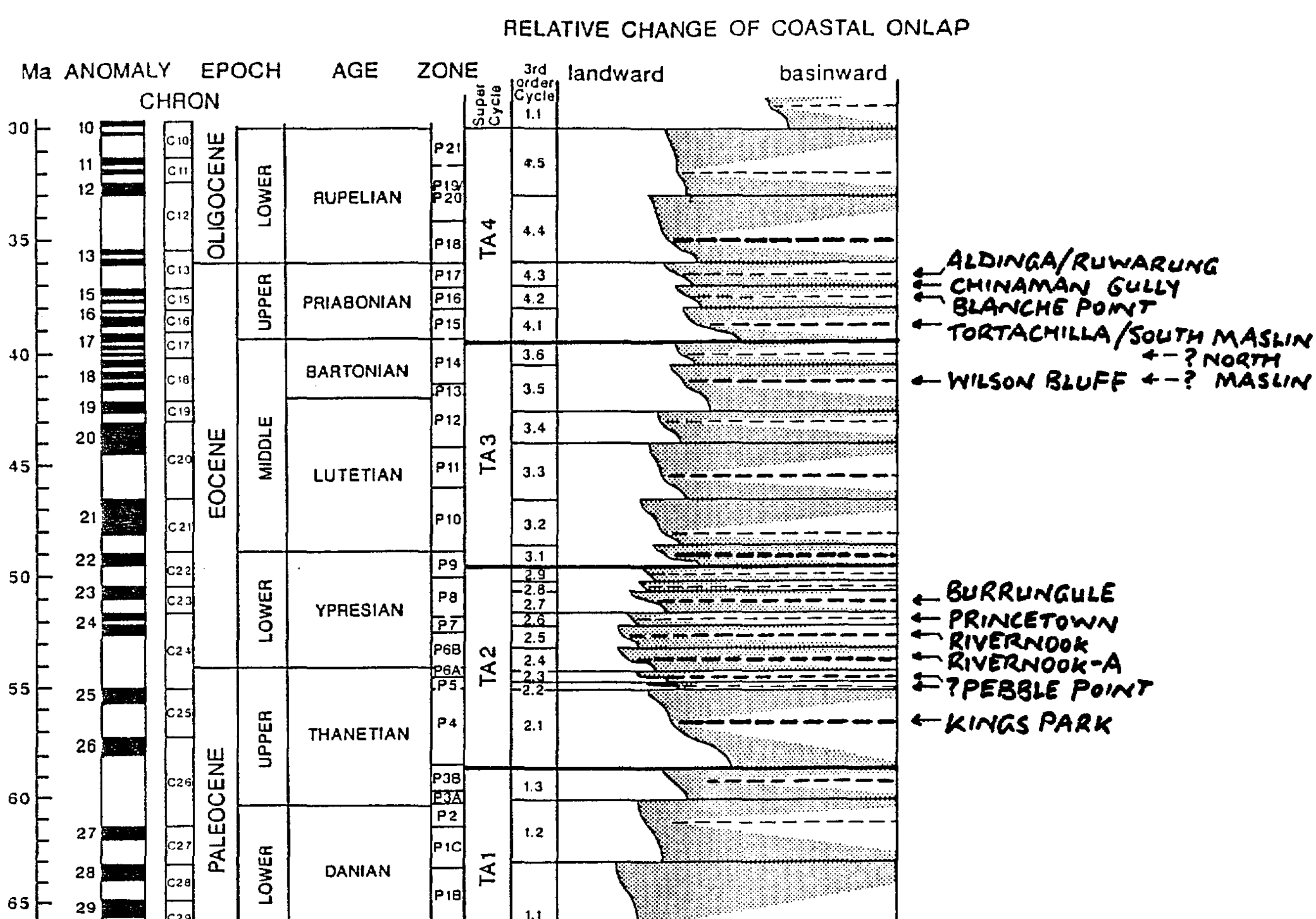

Fig. 4. Marine horizons, southern Australia (11) identified as MFS (6).

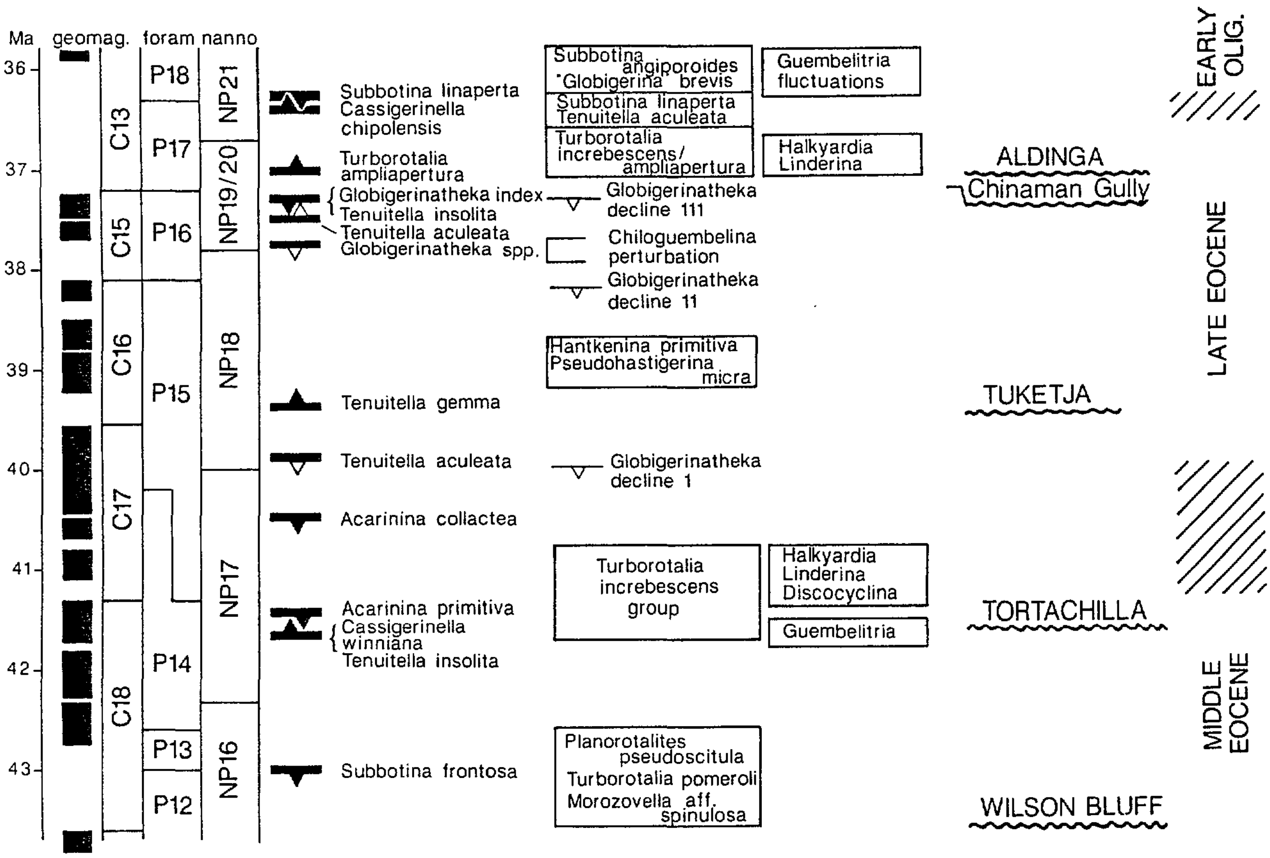

Fig. 5. Biostratigraphy, southern Australia (11), correlated with integrated geochronology (10).

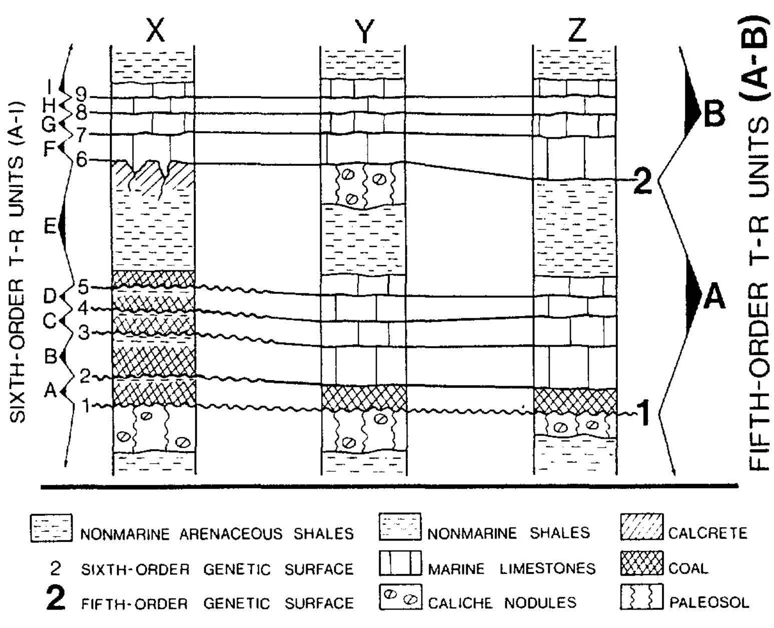

Fig. 6. Schematic relationship of climate change surfaces and transgressive surfaces at three hypothetical localities, from (7). Durations: fifth-order, ?300-500 x 10^3 years; sixth-order, ?50-130 x 10^3 years.

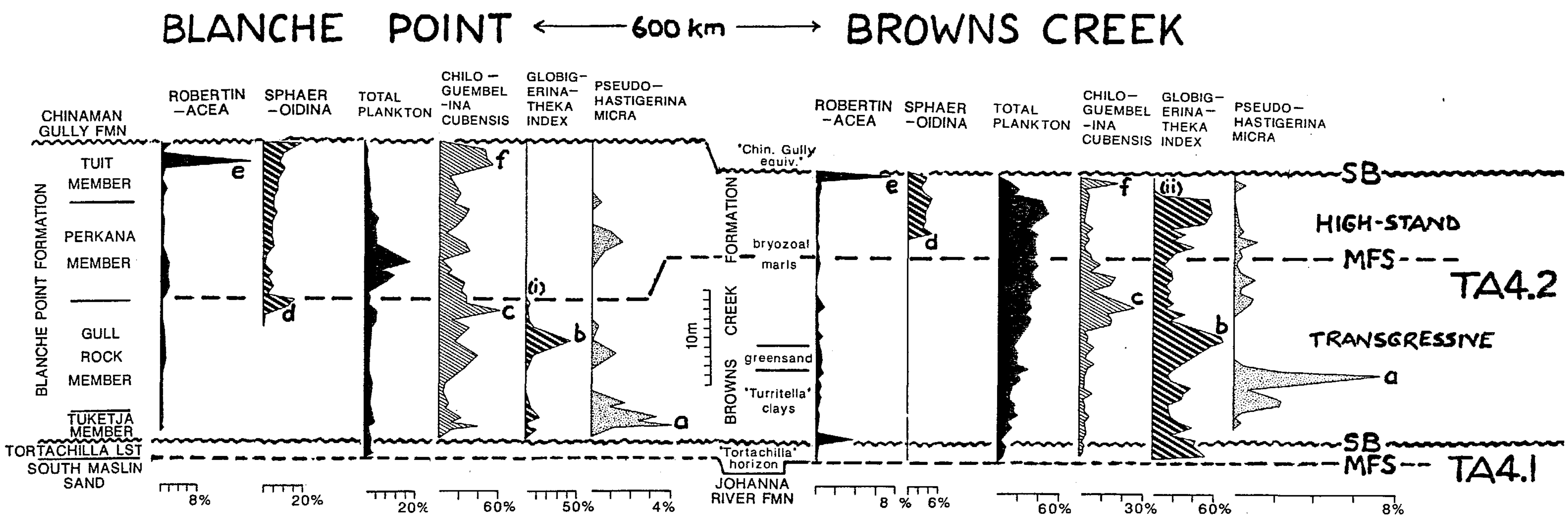

Fig. 7

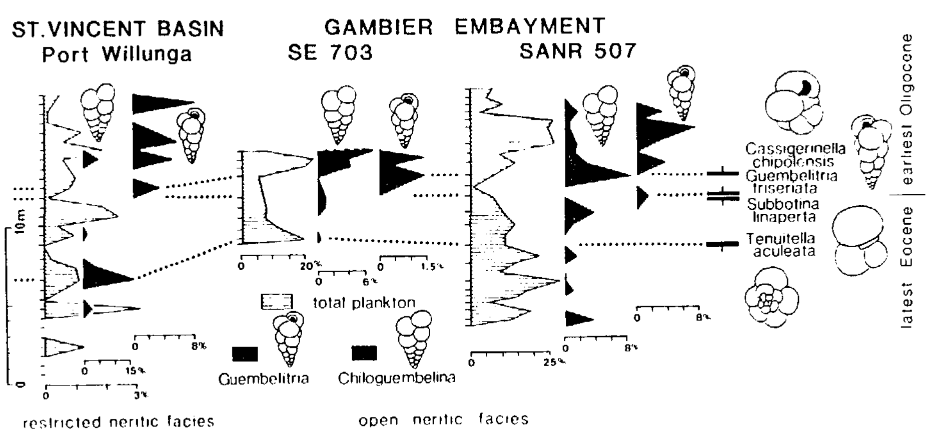

Fig. 8

Fig. 9

	TECTONISM		SEA LEVEL	CLIMATE		BIOTA	RECORD	DURICRUST	IN TERTIARY
MODE ONE	rapid seafloor spreading	amplified: uplift, subsidence, igneous activity, CO_2 exhalation	marine trans-gression	maritime climate, global warming, more humid, more equable	end result: 'greenhouse'	increased: habitat diversity, biotic diversity, evolutionary overturn	increased chance of sedimentary accumul-ation and fossilization (marine and nonmarine)	laterite and deep weathering	Middle to Early Miocene; Late to late Middle Eocene; Early Eocene to Late Paleocene
MODE TWO	slow seafloor spreading	subdued: uplift, subsidence, igneous activity, CO_2 exhalation	marine regression	continental climate, global cooling, more arid, less equable	end result: 'icehouse'	decreased: habitat diversity, biotic diversity, evolutionary overturn	decreased chance of sedimentary accumul-ation and fossilization (marine and nonmarine)	silcrete	Late Miocene; Oligocene; early Middle Eocene; Early Paleocene

Glacial controls on sea level

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Glacial eustatism and isostasy

Sea level varies sympathetically with the volume of land ice caps. This is known as glacio-eustatism. For a given change of ice volume, the actual change of sea level relative to each land mass is not the same throughout the world. This is because the figure of the solid earth tends to adjust isostatically to the water and ice loads, and therefore will alter when these change. Additionally, the hydrosphere is adjusted to the gravitation of masses above sea level (as well as below), which includes the ice caps.

Differences in relative sea-level changes are easily seen in the contrast between formerly glaciated regions and lands in low latitudes. The glacio-eustatic rise associated with ice cap melting is registered as a rise relative to all low-latitude lands. However, in formerly glaciated areas, isostatic uplift of the land can easily outpace the rising tendency of sea level, resulting in relative sea-level fall. This simple example illustrates the problem. In general, global variation of glacio-eustatic change reflects the earth's rheology, which affects its response to changes of ice and water loads. Clark et al. (1978) published a widely known analysis of the global problem; more recently, Nakada & Lambeck (1988) developed techniques for predicting differential sea-level changes with high spatial and temporal resolution.

Although relative sea-level changes vary, it is useful to think in terms of "global" averages, disregarding regions near ice caps. Present ice (mostly in Antarctica) represents about 50-60 m of sea-level equivalent. Ice which existed at the peaks of late Quaternary ice ages amounted to 100-130 m sea-level equivalent. Thus, the total amplitude of glacio-eustatic changes in the late Cenozoic is about 150-200 m. This is larger than the "second order" sea-level fluctuations which punctuate the Mesozoic and Cenozoic stratigraphic records (Vail et al., 1977, Haq et al., 1987). It is not much smaller than sea-level changes related to other geologic processes on longer time scales, such as to variations of sea-floor spreading rate (300-400 m; Pittman, 1978), and thermally induced changes of continental freeboard (340-500 m; Worsley et al., 1984). However, the distinctive feature of glacio-eustatism is its rapidity.

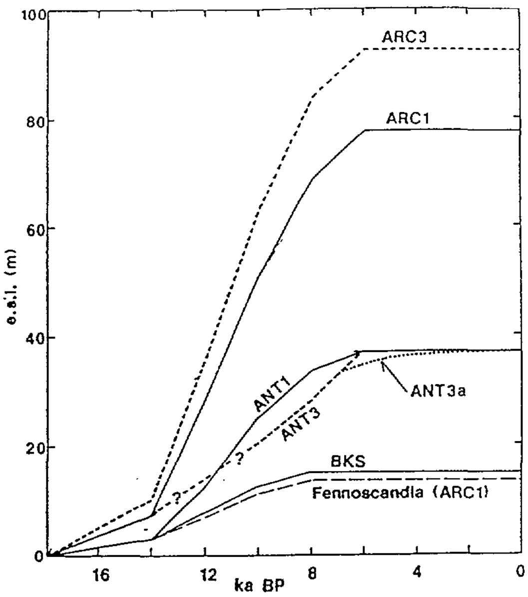
Direct evidence of glacial eustatism

Direct evidence that sea level quantitatively reflects ice cap growth and decay exists only within the radiocarbon-datable part of the Late Quaternary (about the last 35,000 years). Within this period, ice cap dimensions in North America and Fennoscandia are determined from well-dated series of ice-margin deposits. Sea levels are determined from coastal deposits, mostly drowned in estuaries and on continental shelves. The sea-level record since 11 Ka is sufficiently well determined in several areas for ice-melting history to be tested numerically. Figure 1 shows the melting history used by Nakada & Lambeck (1988), together with their comparisons of predicted sea-level change with data from Moruya (southern NSW) and Christchurch (New Zealand).

Records of sea-level changes over the last several hundred thousand years are derived from flights of coral reef terraces, dated by U-series methods, on islands which are rising rapidly through tectonic uplift. Uplift rates at such sites are determined from the elevation of reefs formed at 125 Ka, when sea level is known to have been similar to present, from independent evidence. Relative sea-level fluctuations, interpreted from the terrace sequences, are converted to "absolute" local curves by removing the uplift factor. For the last 300 Ka, the most detailed results come from Huon Peninsula, Papua New Guinea (Chappell, 1974; Bloom et al., 1974; Chappell & Shackleton, 1986) (Fig. 2). While a glacio-eustatic origin is "proven" only for the last 35 Ka, glacio-eustatism for the entire 300 Ka record is indicated by indirect evidence.

Indirect evidence - oxygen isotope curves

The oxygen isotope ratio, expressed as $\delta^{18}O$, varies in seawater directly with the quantity of land ice, owing to strong isotope fractionation in the hydrologic cycle. Changes of seawater $\delta^{18}O$ are represented in marine carbonate organisms, with a temperature-dependent overprint. Ice increase and temperature decrease both drive $\delta^{18}O$ more positive. Glacial advance is associated with generally lower temperatures. The $\delta^{18}O$ signal in foraminifera in deep-sea cores, therefore, is a composite ice volume/temperature record of ice ages. The temperature factor can be removed by comparing records based on planktic and benthic forms, which provides a record of ice volume variation (Shackleton 1987). $\delta^{18}O$ analysis of molluscs in the Huon Peninsula coral terraces shows that sea level corresponds with these ice volume changes (Aharon & Chappell, 1987), indicating that the curve in Figure 2 is glacio-eustatic. Figure 2 shows the direct comparison by Shackleton (1987) of ice volume (converted to sea level) based on composite planktic/benthic $\delta^{18}O$ data, and New Guinea sea levels, for the last 140 Ka.



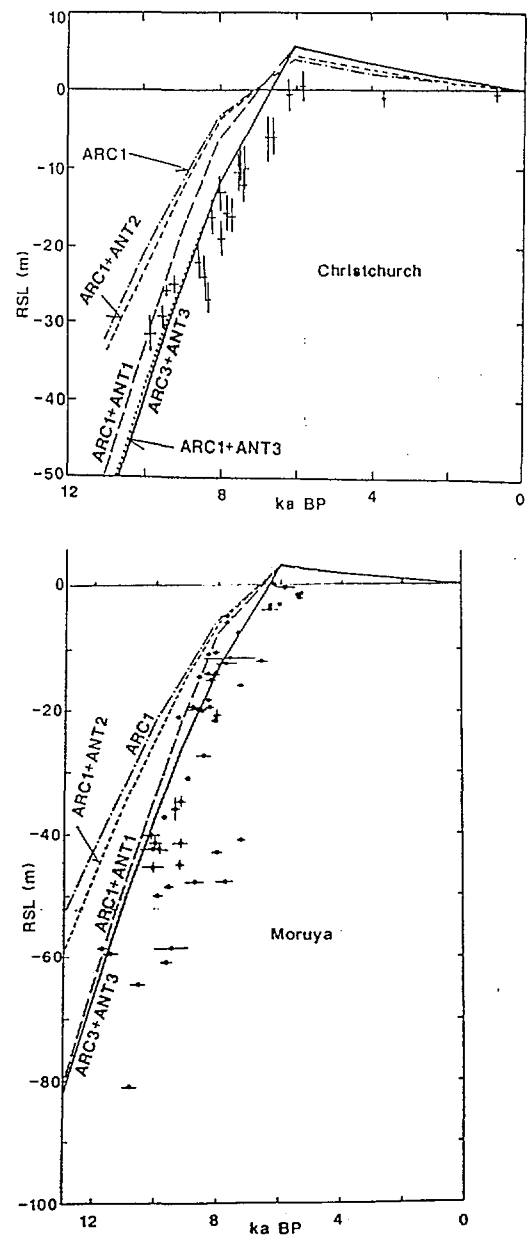
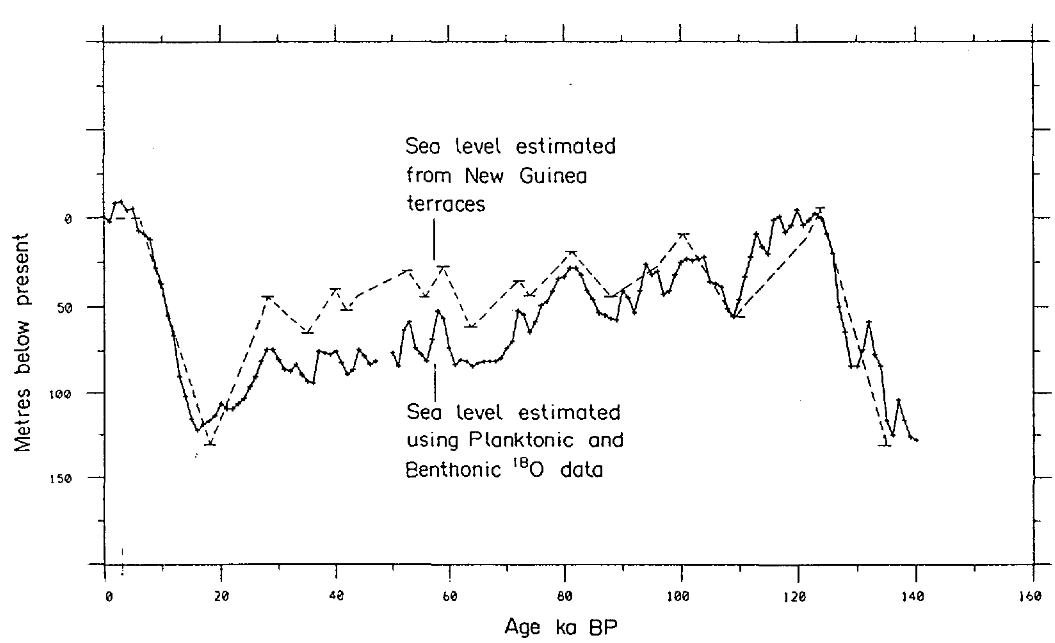


Figure 1. Ice melting curves, and predicted sea level curves compared with sea level data, from Nakada & Lambeck (1988).

Figure 2. Sea level changes of last 140 ka at Huon Peninsula (Chappell & Shackleton 1986), compared with sea level derived from deep-sea core oxygen isotope records (Shackleton 1987)



Tempo of Quaternary glacio-eustatism

The advent of long deep-sea core records, known through palaeomagnetic calibration to cover the Quaternary, showed that ice volume is strongly modulated by the earth's orbital variations, commonly known as "Milankovitch cycles" (Broecker & van Donk, 1970; Ruddiman et al., 1986; Martinson et al., 1987). Dominant peridocities (which can be perceived in Figure 2) are around 90-100 Ka, 40-50 Ka, and 20-25 Ka. Although mechanisms by which these regulate ice volume are not fully resolved, it is clear that their principal effect is on northern continental ice caps rather than the Antarctic. The fluctuating northern ice caps dominate the amplitude and tempo of Quaternary glacio-eustatism.

Pre-Quaternary glacial effects

Before the first advent of northern ice caps, 2.4 Ma ago (Kukla, 1987), growth of Antarctic ice since early the Oligocene doubtless caused glacio-eustatic fall - perhaps by 50-70 m, depending on the maximum size attained by the ice cap. Fluctuations at "Milankovitch" frequencies are likely to have been relatively small. The Antarctic cap is restricted by an ocean boundary and is unlikely to be as susceptible to climatic feedback as the Quaternary northern ice sheets, which were land-based at their lower latitude margins. However, the Antarctic cap may have fluctuated significantly, at lower frequency. Tertiary sea-level fluctuations with amplitudes from 20 m to over 200 m and periods of a few million years have been recognised stratigraphically ("third order" fluctuations of Vail et al., 1977; Haq et al., 1987). Although Tertiary glacio-eustatism may be inferred from oxygen isotope records (cf. Shackleton & Kennett, 1975), analysis comparable with the Quaternary record has yet to be done. In conclusion, glacio-eustatism may explain many of the Tertiary "third order" cycles, but this has to be proven.

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The influence of lithospheric stress on relative sealevel

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It has been established for more than a century that the oceans have advanced and receded across continental platforms, and that many of these relative sealevel changes may have occurred on a global scale. There has been less agreement on the causative mechanisms for these changes. Are they the result of volume changes in ocean water, are they the consequence of tectonic or structural change, or are they the result of displacement of water in the oceans by sediments? Different mechanisms contribute at different temporal and spatial scales, but only an incomplete and confused record of transgressions and regressions has been left. Only the shortest term effects (10-100 yr) have been have been directly observed; the rest must be inferred from exposed and submerged paleo-shorelines, and from the stratigraphic record. The most extensive record of these relative or apparent sealevel changes now seems to be contained in the patterns of sediment onlap and offlap imaged by seismic stratigraphy in coastal sedimentary assemblages. There appears to be a general acceptance of the principles underlying the construction and interpretation of these sediment sequences as markers of sealevel change and the challenge now is to interpret these features quantitatively in terms of the pattern of sealevel change and to establish the causative mechanisms.

Particular components in a relative sealevel record may be local, regional or global in character and may or may not be synchronous with other events preserved in the geological record. These two characteristics are nearly all we have to help us distinguish between causes of sealevel fluctuation. It is important to note, however, that many of the so called global curves are not truly global, but regional. For example, the Vail *et al.* (1977) sealevel curves for the Jurassic and younger time intervals are very much dominated by the stratigraphic records of North America and the North Sea, an area that has had a similar tectonic history for much of that time. In consequence, those sealevel curves would be more properly seen as regional curves rather than global. Even the most recent results (Haq *et al.*, 1987) remain dominated by the North Atlantic data.The causes themselves may be divided into structural effects which change the shape of the ocean basins or margins (tectonic mechanisms), volumetric effects which change the volume of the oceans (glaciation, global temperature changes, addition of juvenile water) and displacement effects which change the volume of sediment displacing water in the oceans. Most estimates agree that the latter will have little impact due the relatively small overall volume and slow accumulation of sediment in ocean basins and its continuing removal. Structural effects include changes associated with fluctuations in plate spreading rates, age of subducted lithosphere, ridge generation, and differentiation and cratonization of continental crust. These processes may produce up to 150 m sealevel fluctuations on a global scale but only at rates of about 1 mm/kyr. Tectonic mechanisms are well documented in the long period global and the short period local fields (fig.1), but until recently none were available in the intermediate field of variation inferred from seismic stratigraphy. The most important volumetric effect is produced by the exchange of water between the oceans and grounded ice sheets and this may produce magnitudes of up to 200 m over time intervals of a few tens of kyr. However, the inference of continuous fluctuations in sealevel due to glaciation cycles throughout the phanerozoic by Vail *et al.* (1977, 1987) presents problems because continental glaciation seems to have been inoperative for large parts of this era. Also, it is important to note that the rise in sealevel produced by the melting of continental ice sheets is not uniform because of self gravitation and earth deformation effects. These are particularly important in seas near the margins of the former ice sheets, such as the North Sea (fig. 2).

At least one tectonic mechanism now appears capable of producing relative sealevel fluctuations on at least a regional scale and of sufficient magnitude to leave its mark on the stratigraphic record. First discussed by Cloetingh *et al.*(1985), the mechanism involves the response of mechanical inhomogeneities in the lithosphere to variations in the level of inplane stress. In the situation where there is a sudden change in lithospheric thickness (fig.3a), such as may occur near continental margins, application of an inplane stress, or a change in the level of inplane stress, will induce bending moments which cause asymmetrical uplift and subsidence at the wavelength of flexural deformation. The mechanical inhomogeneity caused by a thick wedge of sediment filling a passive margin basin (fig.3b) will also act as the focus for bending moments causing broad scale vertical movements of the crust along the coast at the edge of the basin. Both effects can be expected to operate at passive margins. Analytical and numerical calculations confirm that relative sealevel fluctuations of 50-100 metres can be caused in this way by inplane stress changes of the order of a few hundred megapascals (fig.3c). The level of stress in the lithosphere is a poorly known quantity but this is within the plausible range inferred from seismic and geological evidence and physical modelling considerations. Certainly relative sealevel fluctuations of 20-30 metres due to this mechanism are to be expected at typical passive margins.

The mechanism is supported by the observation of a rough correlation between tectonic events likely to cause inplane stress variations in western Europe and the relative sealevel record around the margins of the North Sea (Lambeck *et al.*, 1987). Further support comes from observations of subsidence in the intracratonic basins of central

Figure 1: Rates and magnitudes of some mechanisms which have been seen as potential contributors to relative sealevel movements. Spatial scales are classified as local, regional or global (L,R,G). Events with clear global impact but with near-field / far-field variability are marked R-G.

Mechanism	Scale	Typical Rate (mm/kyr)	Maximum Magnitude (metres)	Characteristic Timescale
1. mid-ocean ridge volume	G	1-5	150	100 Myr
2. crustal differentiation	G	0.2	-	continuous
3. release of juvenile water	G	?	?	continuous? (related to 1 ?)
4. sediment accumulation	G	<1	indet.	continuous
5. continental accretion	R-G	1-2	50	variable
6. thermal welts	R-G	<0.2	10	variable
7. dessication and flooding of small ocean basins	R-G	1,000?	5-20	1-100 kyr
8. continental glaciation	R-G	10,000	200	10-100 kyr
9. mountain variable glaciation	R-G	5,000	1-5	1-100 kyr
10. inplane stress fluctuations	R	10-100	100	1-10 Myr
11. paleo-oceanographic circulation changes	R	?	?	?
12. thrusting at faulted margins	L	2,000	5,000	variable

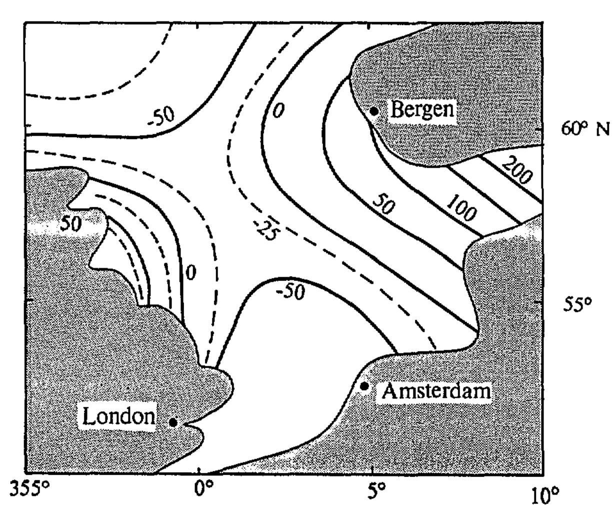
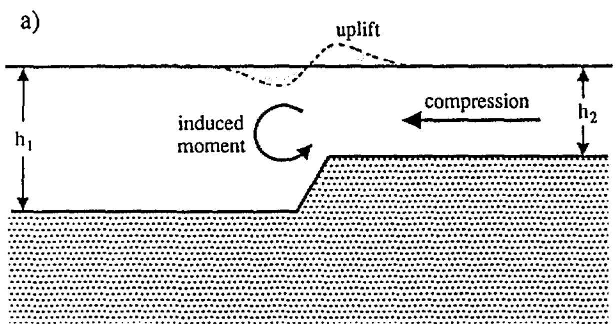


Figure 2:
Sealevel in the North Sea region, with respect to the present day value, at 18,000 years ago. The contours are generated from a model which uses a lithospheric thickness of 50 km and a uniform mantle viscosity of 10^{21} Pas to fit observed uplift patterns.



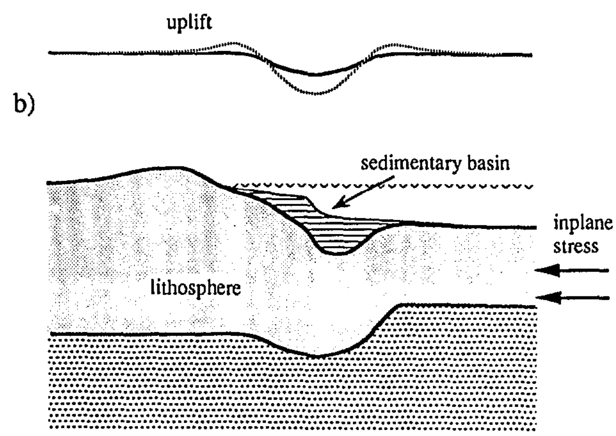
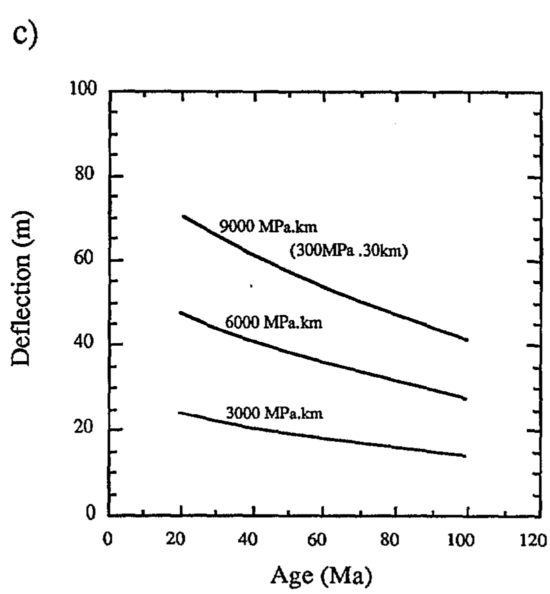


Figure 3: (a), (b) Two situations in which fluctuations in tectonically driven inplane stress levels will cause relative sealevel movements through coastal uplift or subsidence. (c) Magnitude of uplift produced by the mechanism (b) by inplane forces equivalent to a few hundred megapascals transmitted through a 30 km lithospheric layer. The variation in response as a function of the age of the margin is a consequence of assumed changes in the strength of the lithosphere and the thickness of offshore basin sediments with time. (modified from Cloetingh *et al.*, 1986)



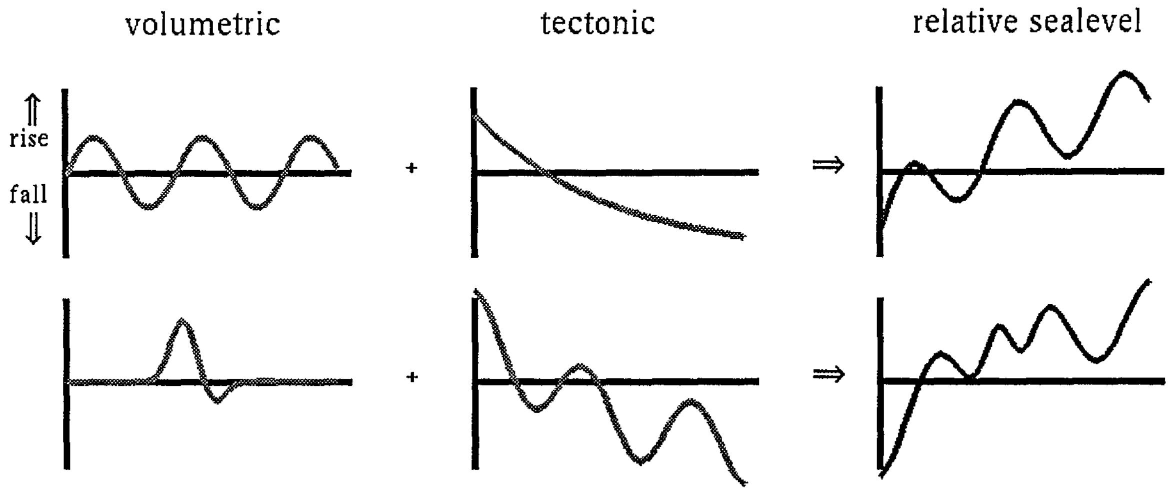


Figure 4a: Composition of volumetric and tectonic signals to produce an observed relative sealevel signal. The short term oscillations may come from either source, and probably both.

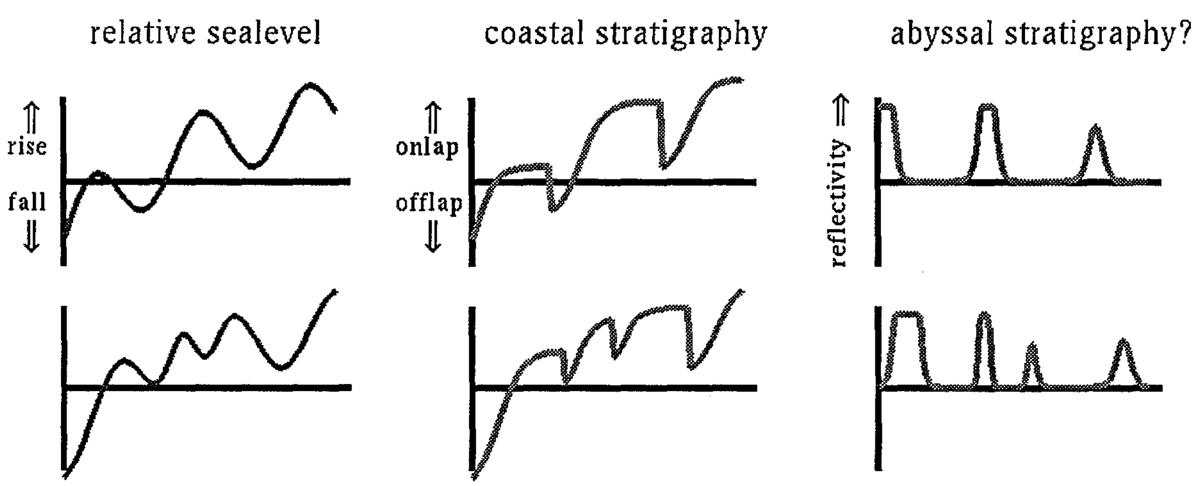


Figure 4b: Filtering of relative sealevel signals to produce onlap-offlap patterns and perhaps also variations in deep sea sediment seismic character

Australia where changes in subsidence rate occur synchronously over a number of basins, apparently at times of changes in tectonic regime at the plate boundary 1000 km or more away (Shaw *et al.*, 1988). It is important to emphasize that it is changes in stress level, rather than a transition from absolute tension to compression, that is required by this mechanism. By analogy, the tectonic cyclothems observed in the lower strata of foreland basins reflect a close relative of this mechanism and are generated in a continuing compressive stress regime by fluctuations in stress level. At least one caveat is in order, however. Geometrical complexity in the variation in thickness of the stress transmitting layers of the lithosphere may lead to local variations in the sense of uplift and subsidence. We cannot properly estimate this effect theoretically because so little is known about the detailed variation of mechanical strength in the lithosphere. There is no reason to believe that the flexural thickness is an appropriate measure of the thickness of the layer transmitting the inplane stress, as the stress distribution is different in the two cases, but even if it was, the depth of the strongest layers might vary across province boundaries without significantly affecting the flexural wavelength while it would have a significant effect on the vertical response to inplane stress variations.

While it is now clear that this is a plausible mechanism which probably contributes significantly to the relative sealevel record, a lot more evidence needs to be accumulated before we can begin to disentangle tectonic, glacial, and other possible mechanisms represented in relative sealevel records. The problem can be cast in signal processing terms (fig.4). Relative sealevel is the sum of several signals which cannot be distinguished without separate data or assumptions. The stratigraphic record of transgressions and regressions is then a further filtered representation of this composite signal, and the characteristics of the filter are still the subject of some debate. The acausal nature of this filter (erosion modifying previous deposits) and the likelihood of temporal variations due to sediment bypass make it impossible to reconstruct even relative sealevel unambiguously from the stratigraphic record alone. Separating the causative agents presents a further level of difficulty. Distinction on the basis of local or global character makes assumptions on the spatial character of the individual components which are not well founded as, for example, the deglaciation response is not wholly eustatic and the inplane stress consequences of global plate tectonic readjustments may well be global in character. It is therefore important to seek more sources of data. In this context, one promising line of enquiry is indicated by the observation by Mayer *et al.*(1986) of reflectors in equatorial pacific sediments marking some (but not all) of the events inferred by Vail. In addition, it is desirable that stratigraphic reconstructions of the local relative sealevel signal be undertaken at a wide variety of locations, preferably by different researchers.

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Unconformities and seismic reflectors in the Cretaceous-Cenozoic of eastern South Island, New Zealand

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A preliminary onlap curve for Canterbury has been derived through the correlation of unconformities and seismic reflectors. Intervals of the curve between the ages of the unconformities were extrapolated through consideration of palaeobathymetry inferred from foraminiferal palaeoecology and from sedimentary facies. Canterbury events are correlated with events outside the region to test for eustatic components. Though significant problems exist in the correlating these events with events of the northern hemisphere, it appears that most of the events in Canterbury were eustatic.

Events in the Cretaceous are generally dated too broadly to allow good correlation, though it is possible that regional events occurred in the Cenomanian (base UZA-3.1? - nomenclature of Haq et al.,1987), the Santonian (base UZA-3.4) and Maastrichtian.

Regional changes in sea level appear to have occurred at the Cretaceous-Tertiary boundary (base TA1.1), in the Late Palaeocene (base TA2.2), late Early Eocene (base TA2.7), early Middle Eocene (base TA3 or base TA3.1), late Middle Eocene (base TA3.4?), near the Eocene-Oligocene boundary (base TA4.4), and in the Middle Oligocene (base TB1), Early Miocene (base TB1.3 or base TB1.4), Middle Miocene (correlation uncertain) and Late Miocene (base TB3.4?). The envelope of the Palaeogene part of the onlap curve reflects post-rift subsidence.

The Canterbury onlap curve is a preliminary model that needs more rigorous testing through refinement of age and palaeobathymetric data.

Sea Level, Subsidence, Sediment Inputs and Slope -
Interacting Factors in Modelling Basin Formation

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Introduction

Sediment geometry, produced during basin evolution, results from the combined effects of shelf subsidence, shelf slope, eustatic changes in sea level, and sediment supply. Seismic stratigraphy is essentially the interpretation of such geometry, as seen in seismic sections. We have therefore attempted to model sediment geometry produced during a number of characteristic basin evolution scenarios, in order to test the validity and applicability of seismic stratigraphy to these cases.

Sediment geometry modelling

The geometry of sedimentary sequences, formed during basin evolution, has been examined experimentally, using initial values consistent with a number of depositional environments. The model variables and their assumptions are as follows:

1) a sediment budget, assumed to be constant in time, supplies sediment from a coastal plain, across a hinge line and onto a subsiding shelf;
2) the shelf is assumed to be subsiding at a constant rate in time, the amount of subsidence linearly increasing from zero at the hinge line to a maximum at the shelf edge;
3) the coastal plain and the shelf slope angles are specified (younger basins have steeper slopes than more mature basins);
4) the hinge line location, which separates the coastal plain from the shelf, is defined and can be seawards or landwards of the shore line;
5) the shelf width (hinge line to shelf edge) is specified; and
6) the rate of eustatic change in sea level is defined for time increments during the modelled subsidence history.

The model simulates continuous sediment accumulation by attempting to fill the volume made available during incremental time steps in the subsidence history. The lower surface of the possible volume created during each time step is determined by the combined effects of shelf subsidence and eustatic sea-level changes. The upper surface is defined by assuming that the shelf slope is preserved throughout the experiment - sedimentation continues to occur at grade. The amount filled during each time step is essentially controlled by the sediment budget and the shelf slope. Erosion and transportation of sediments, exposed during periods of relative fall in sea level, is taken into account.

Shelf subsidence and eustatic sea-level change

The relative effect of shelf subsidence and eustatic change in sea level is most sensitive when subsidence occurs with a falling sea level. When the rate of eustatic fall in sea level is faster than the shelf is subsiding, then the relative sea-level change is such that the water depth is decreasing and the shoreline is moving seawards (regression). Conversely, when the shelf is subsiding at a greater rate than the eustatic fall in sea level, then water depth is increasing and the shoreline is moving landwards (transgression). The amount of shelf subsidence varies with distance from the hinge line, resulting in complex interactions between shelf subsidence and eustatic sea-level changes.

Eustatic sea-level changes are presumed to occur as a result of essentially global phenomena (e.g. change in sea-floor spreading rates) and are therefore modelled as a gradual change from one level to another with the maximum rate of change occuring at the middle of the time period. The sea-level curve we use thus describes a sigmoid shape with respect to time.

Experiments

Experiments have been carried out for a variety of subsidence scenarios - we shall restrict ourselves to discussing those with the most significant results.

Typically, a falling sea-level curve is used representing an 80 m fall in sea level in a 20 my time period. Shelf subsidence rates are of the order of 10 m/my (1 cm per thousand years) at an initial shoreline located one third of the distance from the hinge line to the shelf edge. Two basin evolution environments are modelled with shelf slope gradients of 1:5000, representing mature basins, and 1:2000, for young basins.

The following interactions are observed between the shelf subsidence and eustatic fall in sea level.

In the earliest phase of sedimentation, subsidence is faster than the eustatic sea-level fall and hence water depth is increasing (relative sea level is rising) and the shore line is moving landwards. This results in a backstepping transgressive wedge sequence at the base of the section.

As the rate of eustatic sea-level fall increases and overtakes the rate of shelf subsidence, the relative sea level gradually changes from rising to falling and the shoreline position gradually changes from moving landwards to seawards. The backstepping transgressive sequence gradually converts to form a prograding wedge of sediments. Once the relative sea level has fallen past its original level, then sediment deposited earlier is exposed and eroded. This results in an increase in the supply of sediment (giving an increased rate of progradation) and the truncation of the top of the prograding sequence.

Towards the end of the modelled subsidence period, the rate of eustatic sea-level fall again becomes less than the shelf subsidence and thus the prograding sequence gradually reverts to a backstepping transgression, covering the truncated prograding sequence below.

The effects described above can be dramatically changed by providing different values for the model variables. In addition to the effects of different subsidence rates and eustatic sea-level curves, the most significant effects are observed by changing the shelf slope angles. The sediment geometry differs considerably for contrasting slope variables.

Discussion

The apparent timing of the changes from transgression to regression, and vice versa, can be interpreted from the sediment geometry. These times appear to be out-of-phase with those predicted from a simple combination of shelf subsidence and eustatic sea-level changes. This effect is particularly noticeable for steep shelves, representing basins at a young stage in their evolution.

The early backstepping transgressive wedge, at the base of the sedimentary sequence, can change to a prograding regressive sequence some 3 to 4 my before that predicted from the sea-level curve. The upper backstepping transgressive wedge, at the top of the sedimentary sequence, also begins to grow before transgression begins.

The differences in timing arise from the variation in the rate of shelf subsidence with distance from the hinge line and changing sediment availability, owing to erosion of exposed sedments.

Conclusions

The scenarios that we have modelled represent reasonable approximations to those occurring in real non-glacial situations. The experiments show that different sediment geometry will arise as a consequence of different subsidence rates and shelf slope angles. These conditions are most likely to vary on young margins and in new developing basins.

The degree to which the interpreted changes in sea level are out-of-phase with reality will vary with the changing conditions, but is particularly significant for steeper slopes. In these cases, time correlations may be misleading and great care will need to be given to their interpretation.

For shallower slopes, the effects are much less significant and time correlations can be expected to work reasonably well. It is perhaps coincidental that global seismic stratigraphy has been largely developed from studies of "old" margins.

Seismic Facies Distribution in the Central Great Australian Bight

H.M.J. Stagg & J.B. Willcox, BMR

The major Great Australian Bight (GAB) Basin (ca 400x200 km, up to 10 km thick) formed near the centre of a 4000 km-long Gondwanan rift system that extended from the Naturaliste Plateau in the west to the South Tasman Rise in the southeast. The rift was initiated by the Middle Jurassic and culminated in the breakup of Australia-Antarctic in the Cenomanian (ca 95 Ma; Veevers, 1986). While the central GAB has been the focus of a number of regional and industry surveys, the dearth of exploration wells (Jerboa-1 in the Eyre Sub-basin and Potoroo-1 in the northern GAB Basin) and the lack of modern or ancient analogue rift zones of similar width (ca 300 km) and setting, severely hinder the dating of seismic sequences and the determinaton of their facies relationships.

In this paper, we combine analysis of the seismic sequences in the central GAB with consideration of the tectonic setting and palaeoclimate to compile a preliminary estimate of the distribution of seismic facies in the region.

Tectonic Setting

The central GAB (Fig. 1) is interpreted to have formed when the 'lower plate' Australian margin was pulled out from beneath the 'upper plate' Antarctic margin (Lister & others, in press). Only highly extended remnants of the upper plate occur beneath the Magnetic Quiet Zone (MQZ) and the Ceduna Terrace on the Australian margin. The total amount of pre-breakup extension is estimated at 360 km (Veevers & Eittreim, 1988) and 280 km (Lister & others, in press), and is assumed here to be about 300 km. The azimuth of pre-breakup extension, assumed by early workers to be N-S, has been re-interpreted by Veevers & Eittreim (1988) to be NNE-SSW and by Willcox & Stagg (in press) to be NW-SE from the pre-Middle Jurassic to the Neocomian (Fig. 2). If the early extension was NW-SE, it follows that the Eyre Sub-basin in the western GAB is almost purely extensional, while the Ceduna depocentre is transtensional and may have formed as a strike-slip basin.

The main structures and sedimentary features within the central GAB are illustrated in Figure 3 on dip (line 6) and strike (line 7) seismic profiles recorded by BMR in 1986. The primary features of these lines include:

1) A 'perched' extensional basin (Eyre Sub-basin; line 6) containing synrift and post-rift sediments; extension is about 20%, and the basin has not undergone major subsidence;
2) Upper crustal basement blocks beneath the continental rise that become

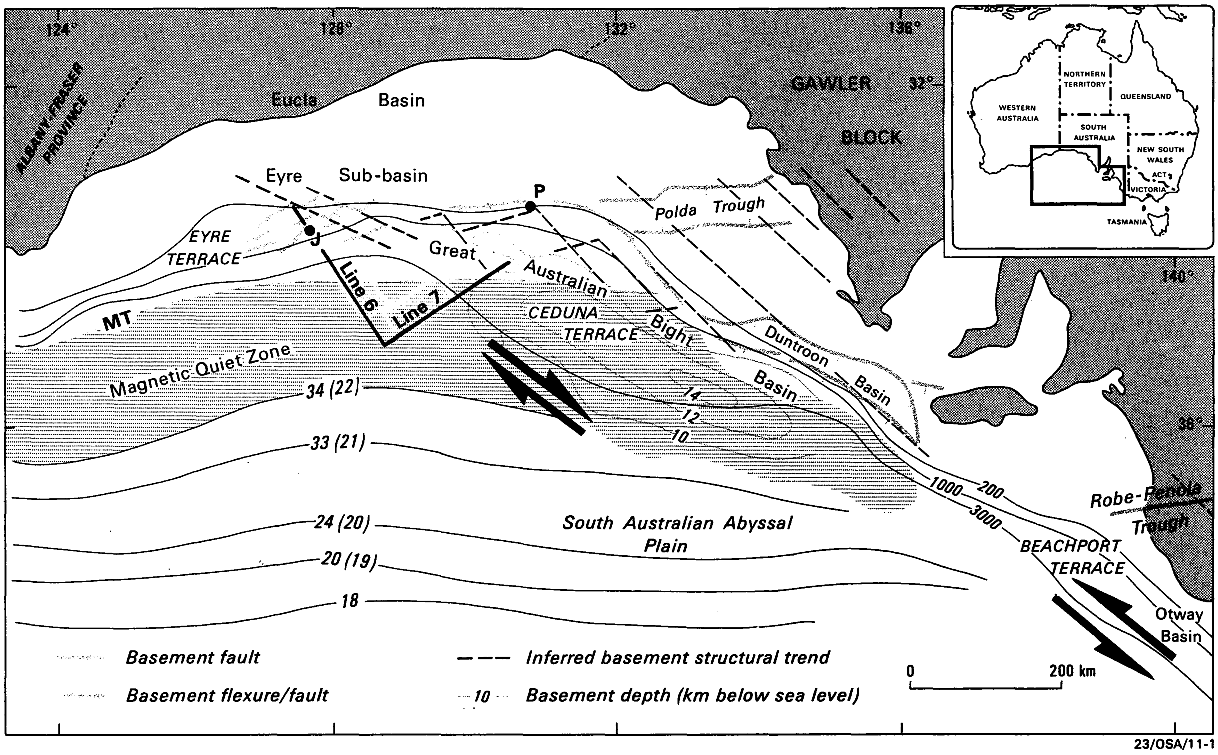

Figure 1: Southern margin of Australia (modified after Lister & others, in press) showing the gross bathymetry, major structural features, seafloor spreading magnetic anomaly traces, magnetic trough (MT), magnetic quiet zone, location of Jerboa-1 and Potoroo-1 exploration wells, and location of seismic sections shown in Figure 2. Heavy arrows indicate portions of margin considered to have been 'transpressional' or 'transtensional' in the pre-Late Jurassic.

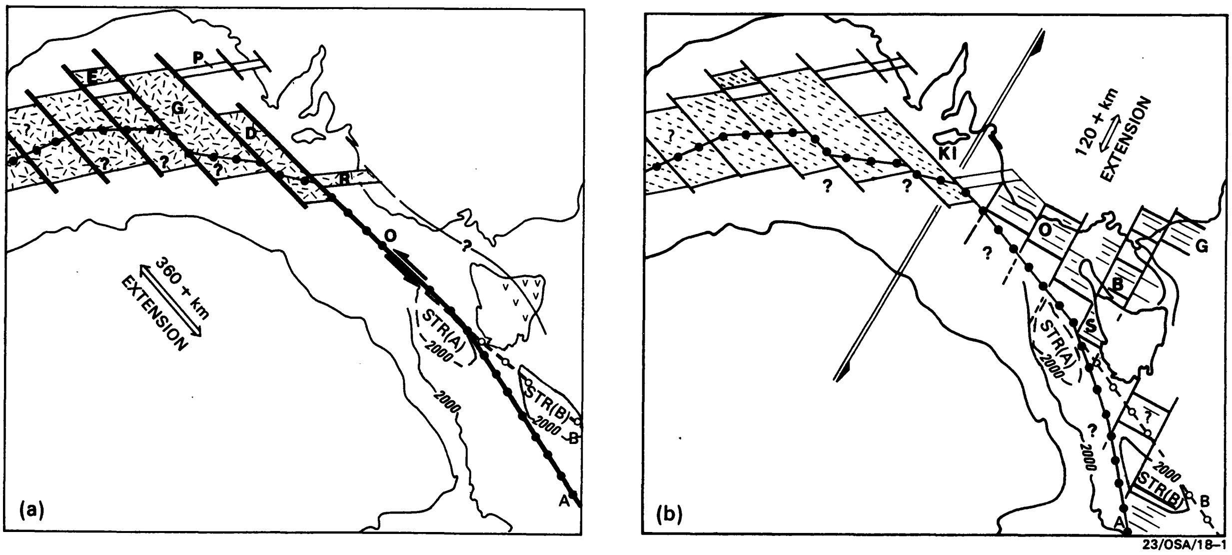

Figure 2: a) Plate configuration following pre-Middle Jurassic to Neocomian extension of 360 km on NW-SE azimuth in GAB. b) Plate configuration prior to Cenomanian breakup, following Early Cretaceous extension in SE Australian basins of 120 km on NNE-SSW azimuth. E = Eyre Sub-basin; G = GAB Basin; P = Polda Trough; D = Duntroon Basin; R = Robe trough; O = Otway Basin; S = Sorell Basin; B = Bass Basin; G = Gippsland Basin; STR(A) and STR(B) are alternative pre-extension positions of South Tasman Rise discussed by Willcox & Stagg (in press).

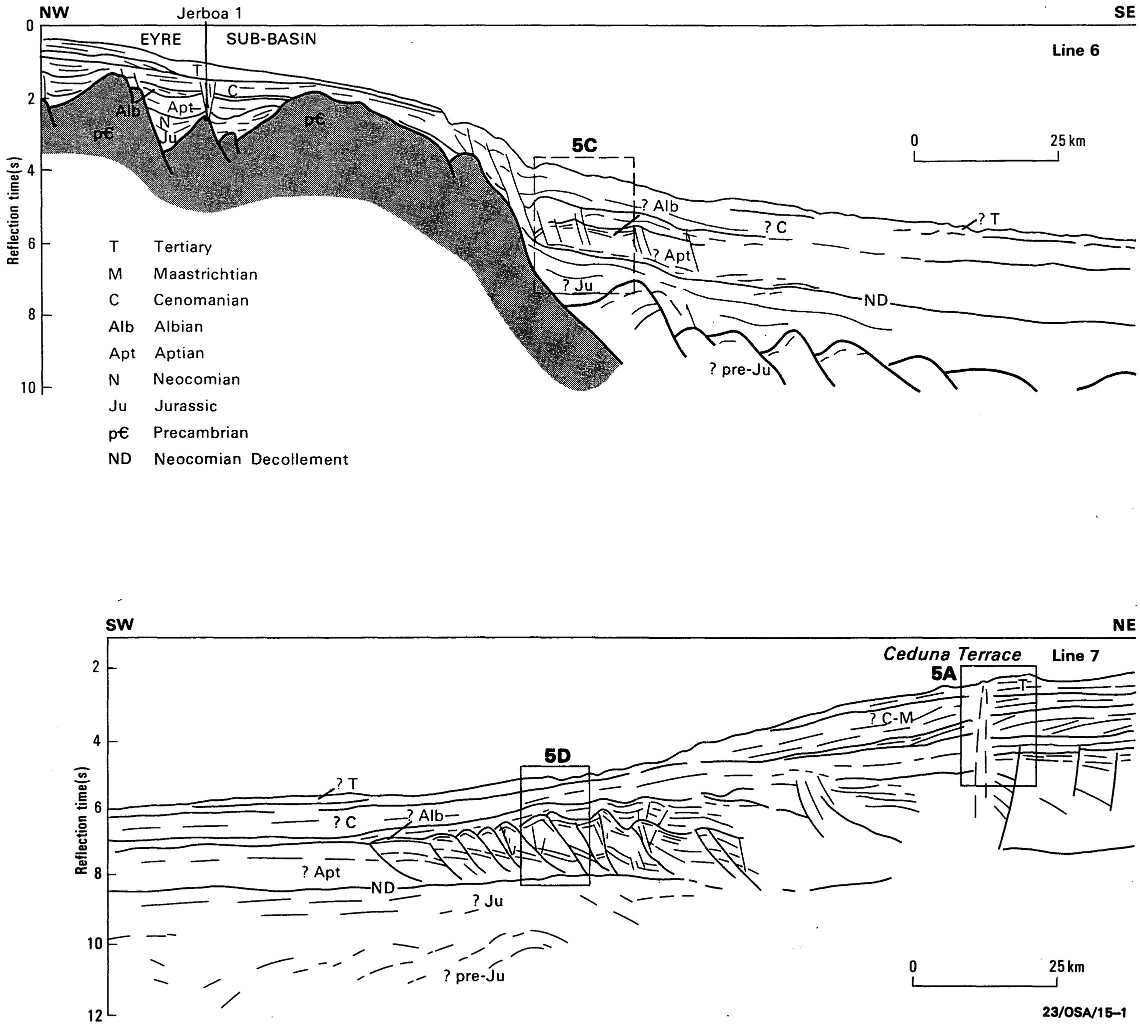

Figure 3: Line drawings of BMR Survey 65 seismic profiles on lines 6 & 7 (location in Fig. 1; after Willcox & Stagg, in press). Boxes indicate seismic detail in Figure 5.

progressively more strongly rotated southwards (line 6); extension is at least 200% (Lister & others, in press), and basement has subsided much further than in the Eyre Sub-basin;

3) A sedimentary layer on the continental rise (basement to horizon 'ND') that is seismically featureless (?indurated) except at the base of the continental slope where it may have synrift character (line 6; Figs 5B, 5D);

4) A sedimentary section above 'ND' ranging from 2.5 s (continental rise) to 4.5 s (Ceduna Terrace) two-way time thickness, of probable late Neocomian to Maastrichtian age. This section contains prominent sedimentary structures which include nappes (?Aptian; Fig. 5D) beneath the continental rise and a major delta (Cenomanian-Maastrichtian; Fig. 5A) beneath the Ceduna Terrace. The section is extensively faulted beneath the Ceduna Terrace, but apart from the nappes and syn-sedimentary listric faulting at the base of the continental slope (line 6), is essentially flat and unstructured beneath the continental rise. The layering within the continental rise sequences decreases with increasing distance from the continental slope;

5) A thin veneer of Tertiary carbonates, principally on the Eyre and Ceduna Terraces.

Palaeoclimate

Australian palaeolatitudes and palaeoclimates have been summarised by Embleton and Quilty (both in Veevers, 1984), respectively. For the central GAB, palaeolatitudes varied from about 50^{o} during the Jurassic, to the mid 60^{o}'s during the Cretaceous, with the most polar latitudes being reached at about the Cretaceous/Tertiary boundary (ca 68^{o}) during the period of slow drift between Australia and Antarctica. The climate during the Jurassic was less differentiated than now, and along the southern margin has been interpreted as varying from temperate around Tasmania (Townrow, 1964) to hot to arid and, later, hot to wet off Western Australia (Filatoff, 1975). Cretaceous climates in southern Australia showed considerable variation despite the high latitudes prevailing. During the Early Cretaceous, southern Australia appears to have been cool to cold (Quilty, in Veevers, 1984), while during the Late Cretaceous the climate was somewhat warmer. The major implication of the palaeoclimate is that the conditions for source rock deposition are more likely to be propitious during the Jurassic and Late Cretaceous.

Seismic Facies Distribution

Our initial interpretation of the gross distribution of seismic facies in the GAB Basin is summarised in Figure 6. The end members of this table are the exploration wells Jerboa-1 and Potoroo-1, while the western Ceduna Terrace and continental rise columns are compiled from our studies and those of Fraser &

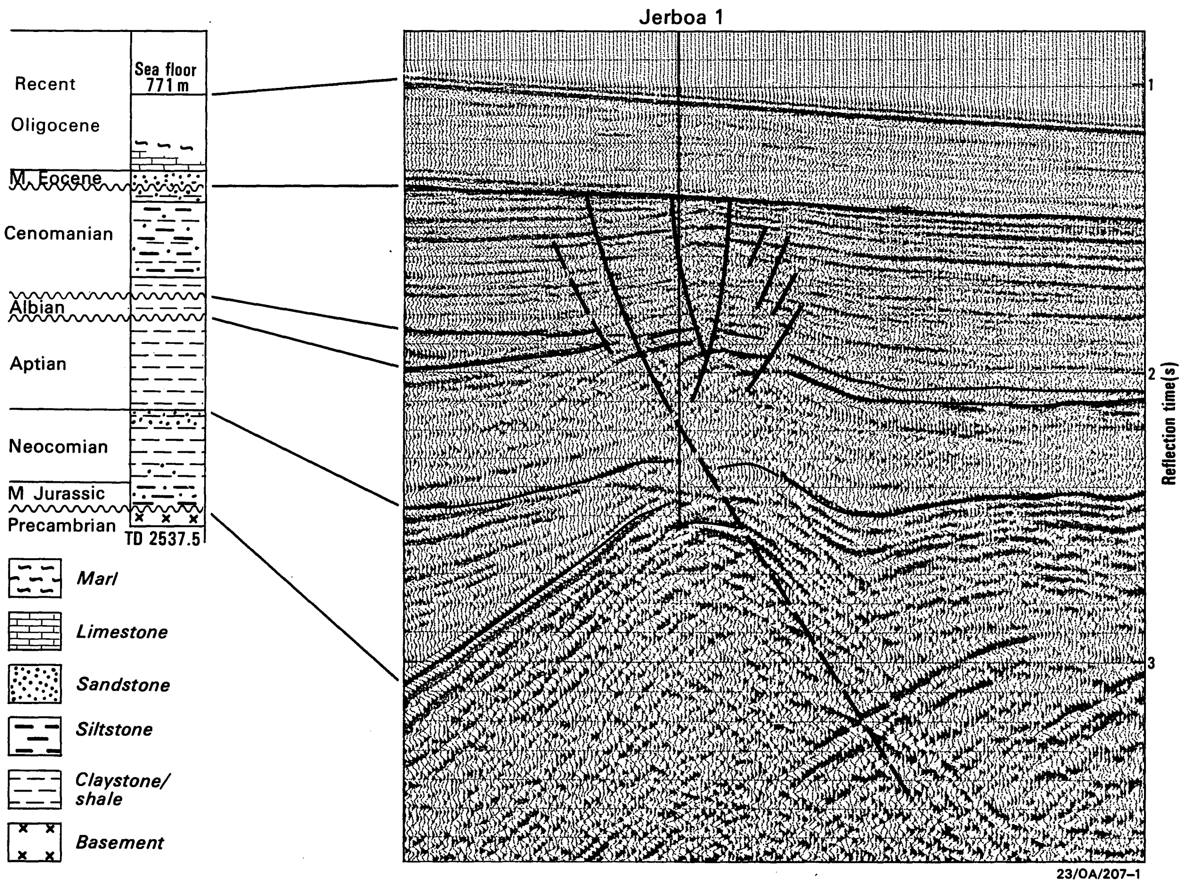

Figure 4: BMR Survey 65 seismic profile through Jerboa-1 exploration well, corelated with well stratigraphic column (after Willcox & others, 1988).

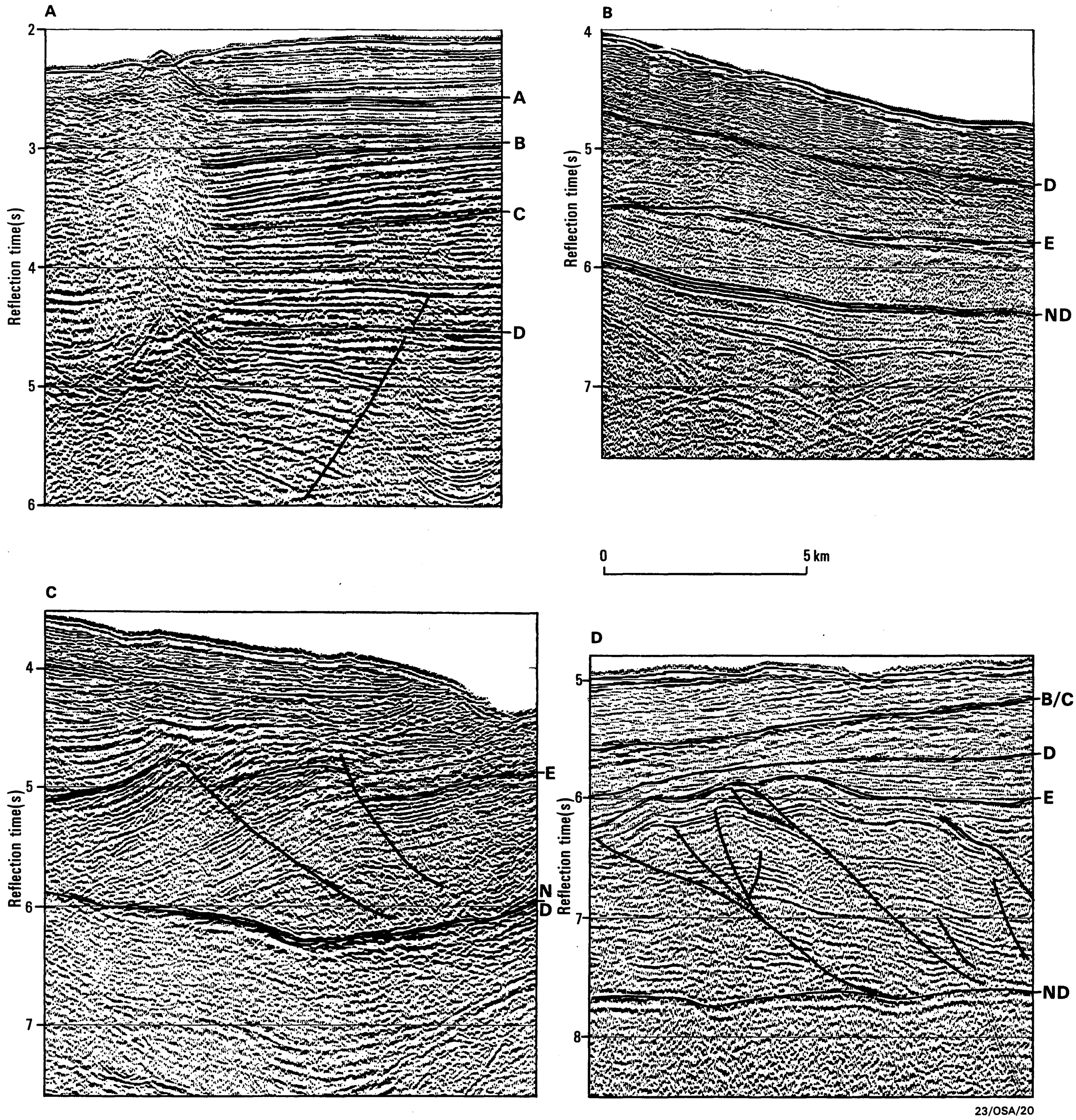

Figure 5: BMR Survey 65 seismic section details; location of sections shown in Figure 3; horizon identifications are as used in Figure 6. A) distal end of delta beneath Ceduna Terrace; B) Cretaceous sedimentary section on inner continental rise above Neocomian decollement (ND); C) As for B, showing synsedimentary faulting in ?Aptian section above ND; D) Cretaceous section above ND on outer rise, showing ?Aptian nappes.

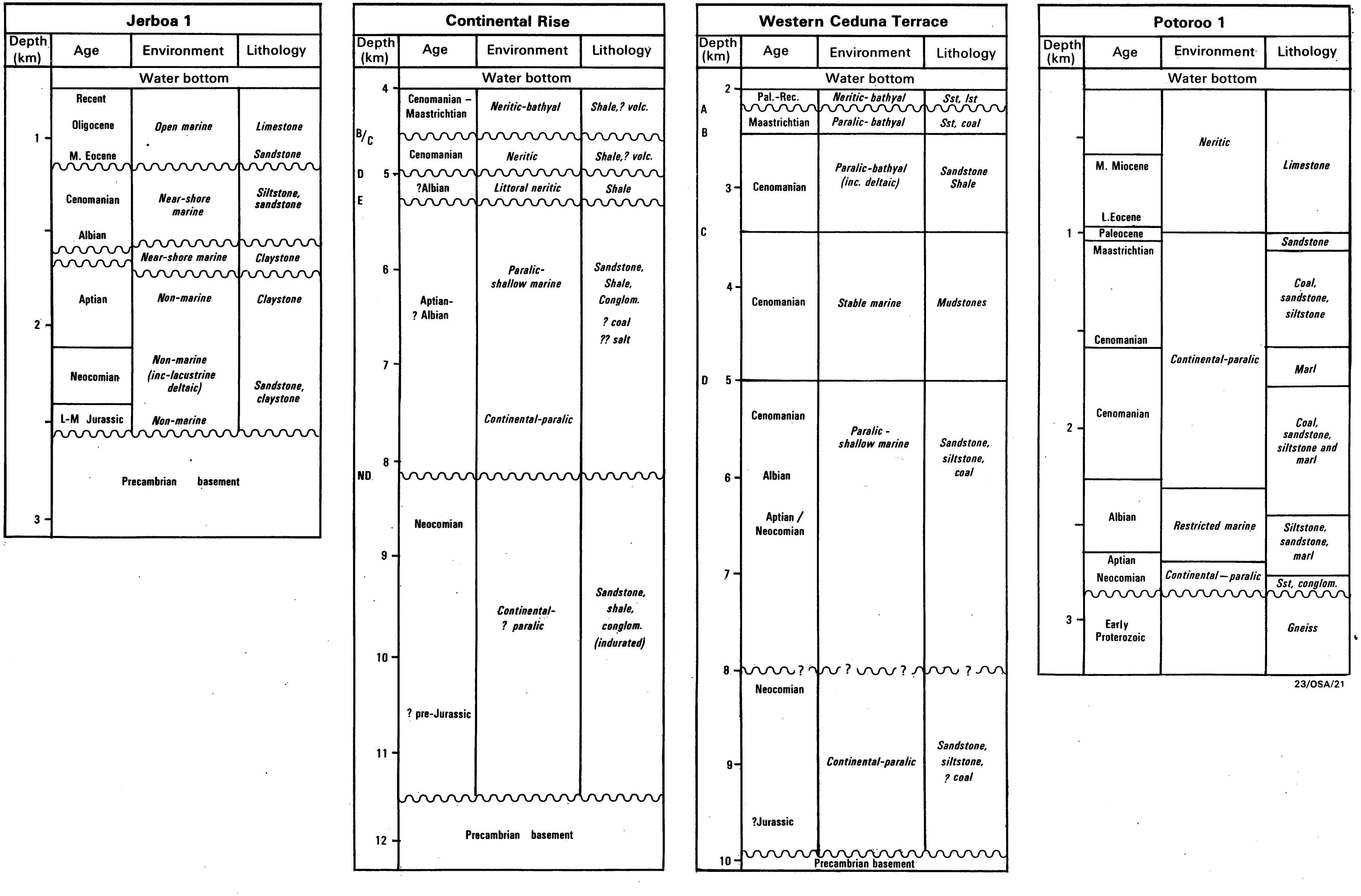

Figure 6: Facies distribution in the GAB. Jerboa-1 column based on Bein & Taylor (1981); Potoroo-1 and western Ceduna Terrace columns based on Fraser & Tilbury (1979); continental rise column based primarily on interpretation of seismic data. Note that vertical scale for continental rise and western Ceduna Terrace columns are twice the scale for Jerboa-1 and Potoroo-1.

Tilbury (1979). We agree with Fraser & Tilbury (pp62-64) in their assessment of the Cenomanian and younger geological history (with the addition of volcaniclastics on the continental rise), but would add the following comments to the earlier rift history:

Pre-Middle Jurassic to Neocomian - Rifting and continental extension began no later than Middle Jurassic, as seen in Jerboa-1. It is possible that rifting began before the Jurassic, or that the rift may have propagated along an older (?Permian) aborted rift, as may have happened off Western Australia; we note that Permian sediments underlie the Jurassic sediments in the Polda Trough, which appears from magnetic basement configuration (Stagg & others, in press) to be genetically related to the Eyre Sub-basin. Sedimentation was lacustrine at Jerboa-1 (Bein & Taylor, 1981), and was probably lacustrine and fluviatile along the northern margin of the GAB Basin. It is possible that increased subsidence near the rift axis (resulting from the greater crustal thinning) may have allowed limited marine influence. We suggest that high heatflow through the thinned crust has caused induration of these sediments and, hence, their lack of reflectivity.

Aptian to Albian - Seismic data suggest that continental extension was largely complete by the late Neocomian (Fig. 3; Bein & Taylor, 1981, fig. 4). Continued subsidence and rapid deposition in the Aptian caused listric faulting (line 6) and thrust faulting (line 7) which soles out on the Neocomian horizon 'ND'. Sedimentation continued to be continental at Jerboa-1 and continental to paralic at Potoroo-1. In the main rift valley, it is likely that seas encroaching from the newly-formed margin off Western Australia produced paralic to shallow marine environments by the Aptian though the marine influence did not reach the topographically higher Jerboa structure until the Albian.

Implications for Petroleum Exploration

Fraser & Tilbury (1979) have summarised the principal hydrocarbon plays beneath the Ceduna Terrace (tilted fault blocks and intra-delta). These plays are untested and are still valid. We believe that further exploration should concentrate on the N and NE margins of the GAB Basin where:

1) Neocomian and older sediments can be expected to have been deposited in deep lakes adjacent to the boundary fault, possibly providing source rocks;
2) Suitable reservoirs may be provided in the form of clastic aprons adjacent to the boundary fault and orthogonal transfer faults; and
3) Heatflow above highly-extended crust should be high enough to generate hydrocarbons (cf. the 'cool' Eyre Sub-basin).

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Oligocene-Miocene sea-level changes in the onshore Gippsland Basin, Australia.

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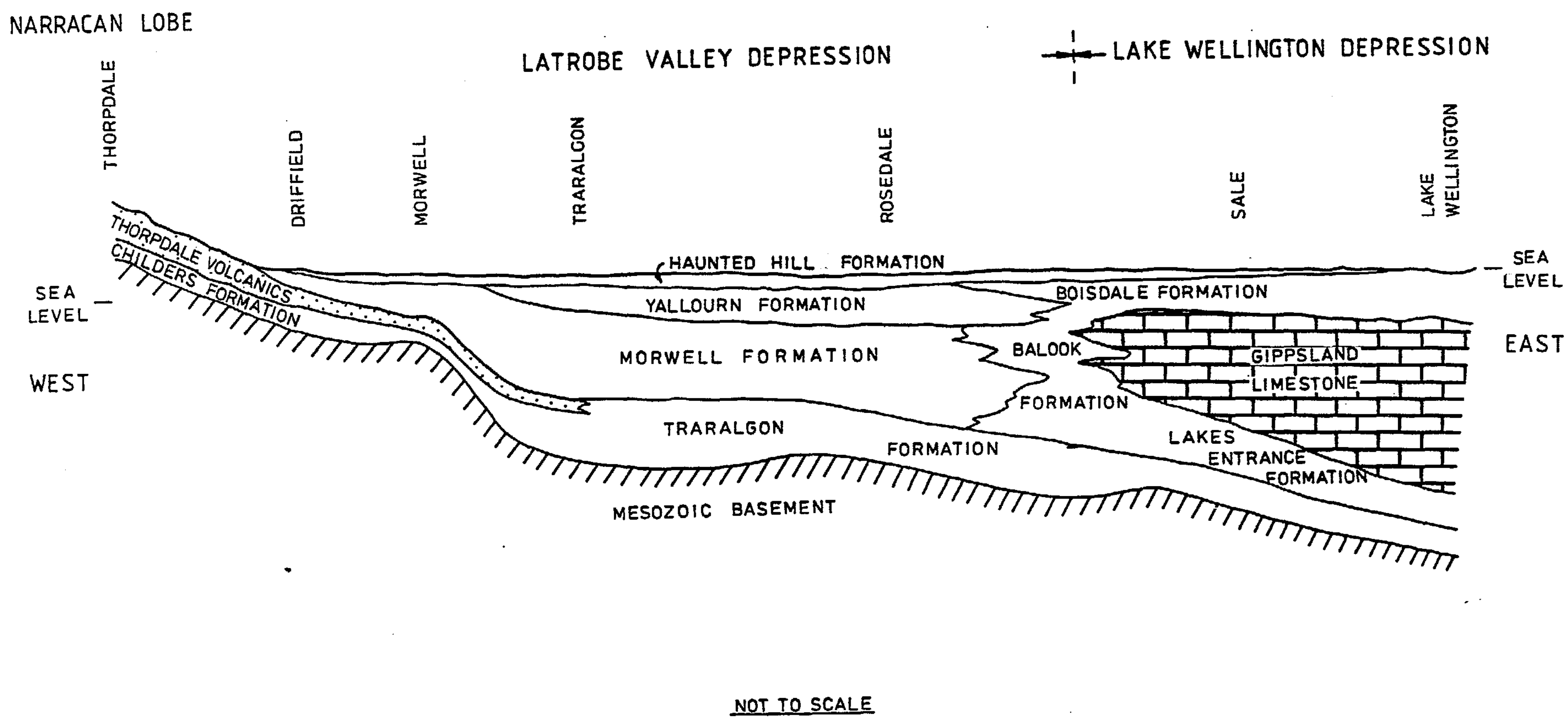
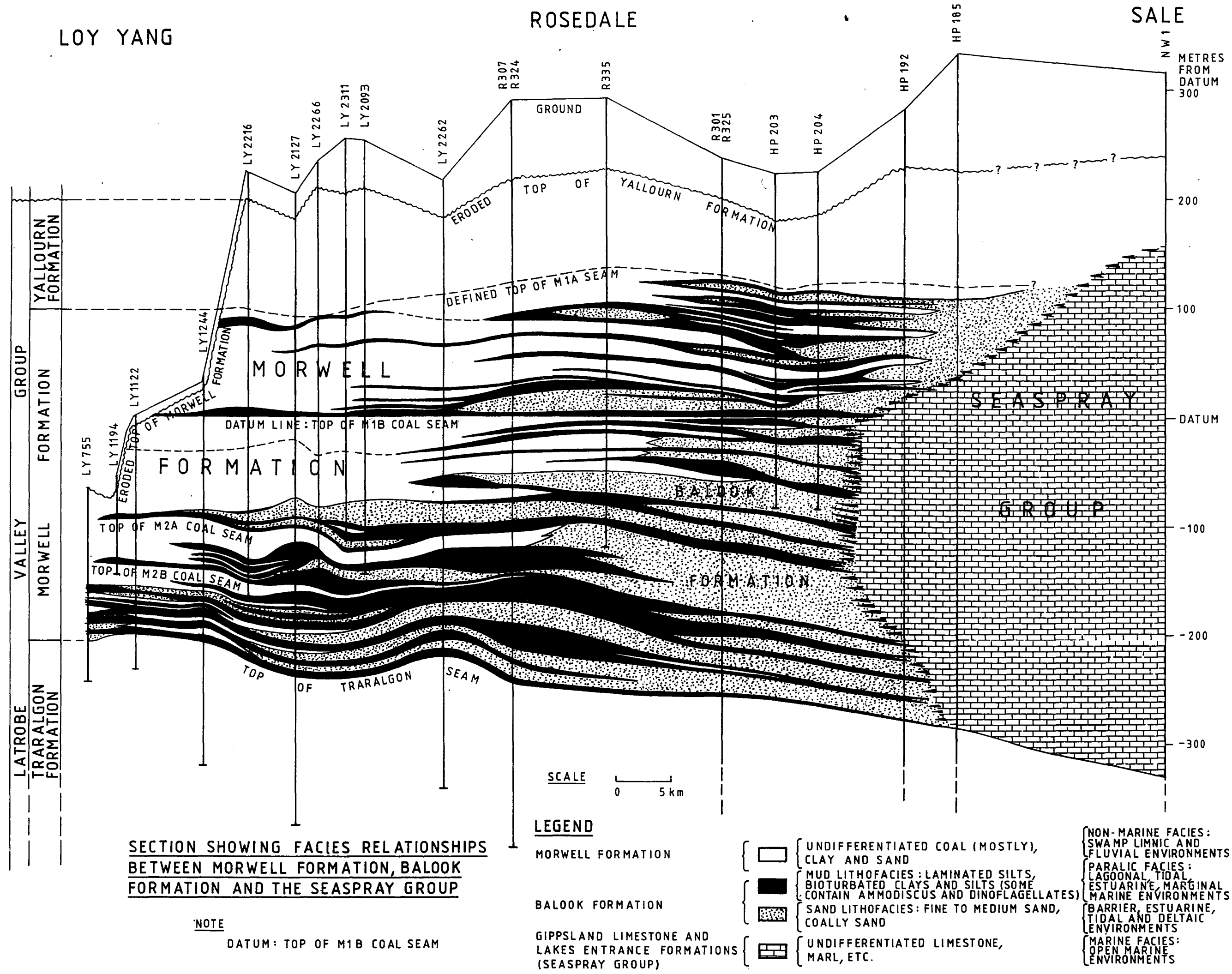
Oligocene-Miocene sedimentation within the onshore Gippsland Basin has traditionally considered to have been non-marine within the coal measure sequence of thef Latrobe Valley Depression to the west, and open marine in the Seaspray Group to the east (see Fig 1). Fossil evidence for marine and brackish water incursions within the Latrobe Valley Coal Measures have recently been reported Holgate and Sluiter (1987). The fossils include marine dinoflagellate cysts and brackish arenaceous water foraminifera which occur in a series of clay lithofacies (laminated silts, bioturbated clays and silts, and massive pyritic claystones) which interbed with the Morwell Formation coal seams east from Loy Yang brown coal open cut mine (see Fig 2). Six major interseam incursions comprise the principal seam boundaries, with more numerous partings representing incursions of lesser amplitude. A total of up to 22 inclusions are found in the Morwell Formation. The clays are interpreted to represent a paralic facies deposited in a complex of littoral environments including estuarine, tidal flats, lagoons and lakes, in a manner possibly akin to the present day Gippsland Lakes.

Each mud lithofacies grades seawards, or is overlain by a fine to medium grained sand and lignitic sand lithofacies The major



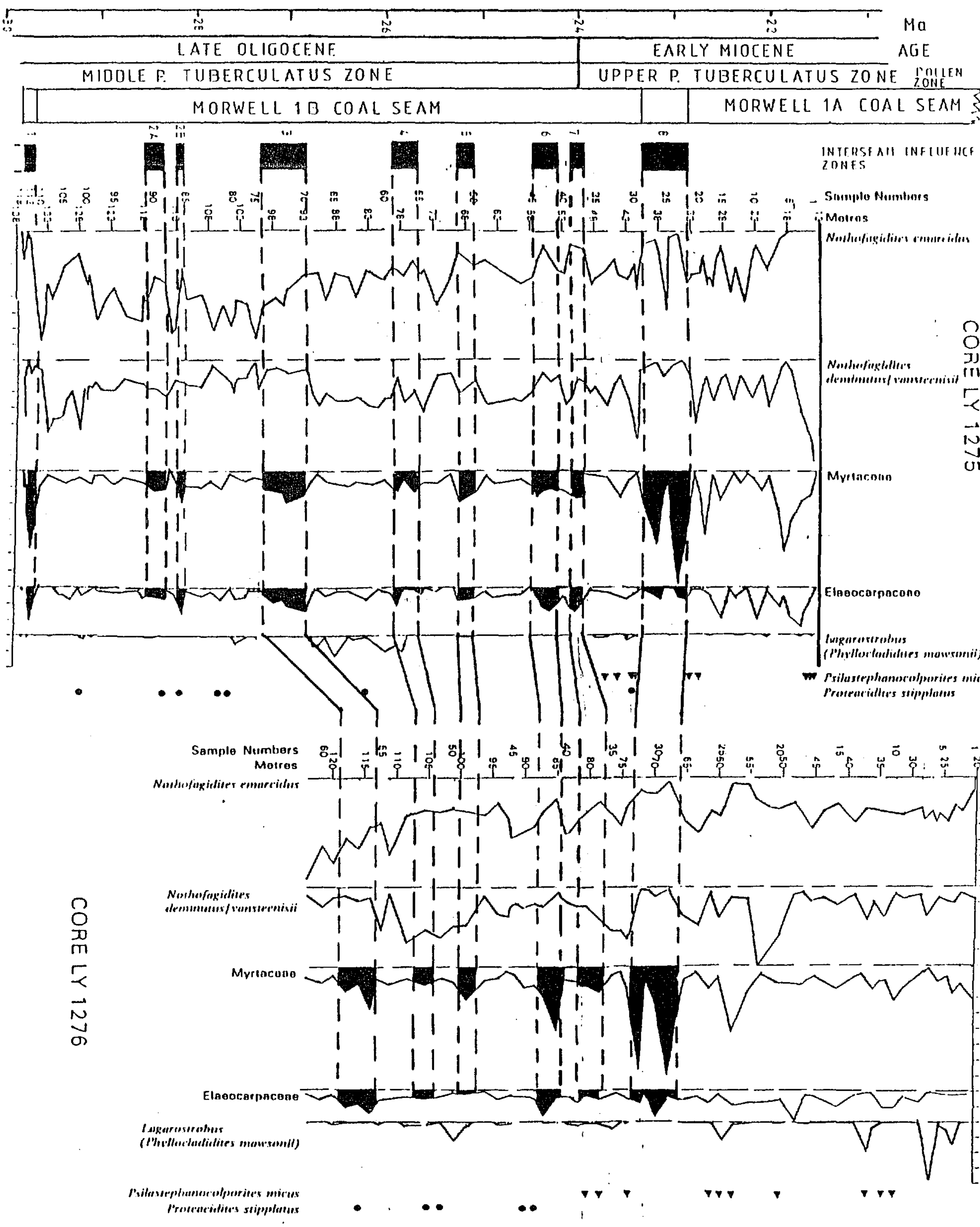
1. West to east cross section across the basin from the narracone Lobe to the Lake Wellington Dpression.



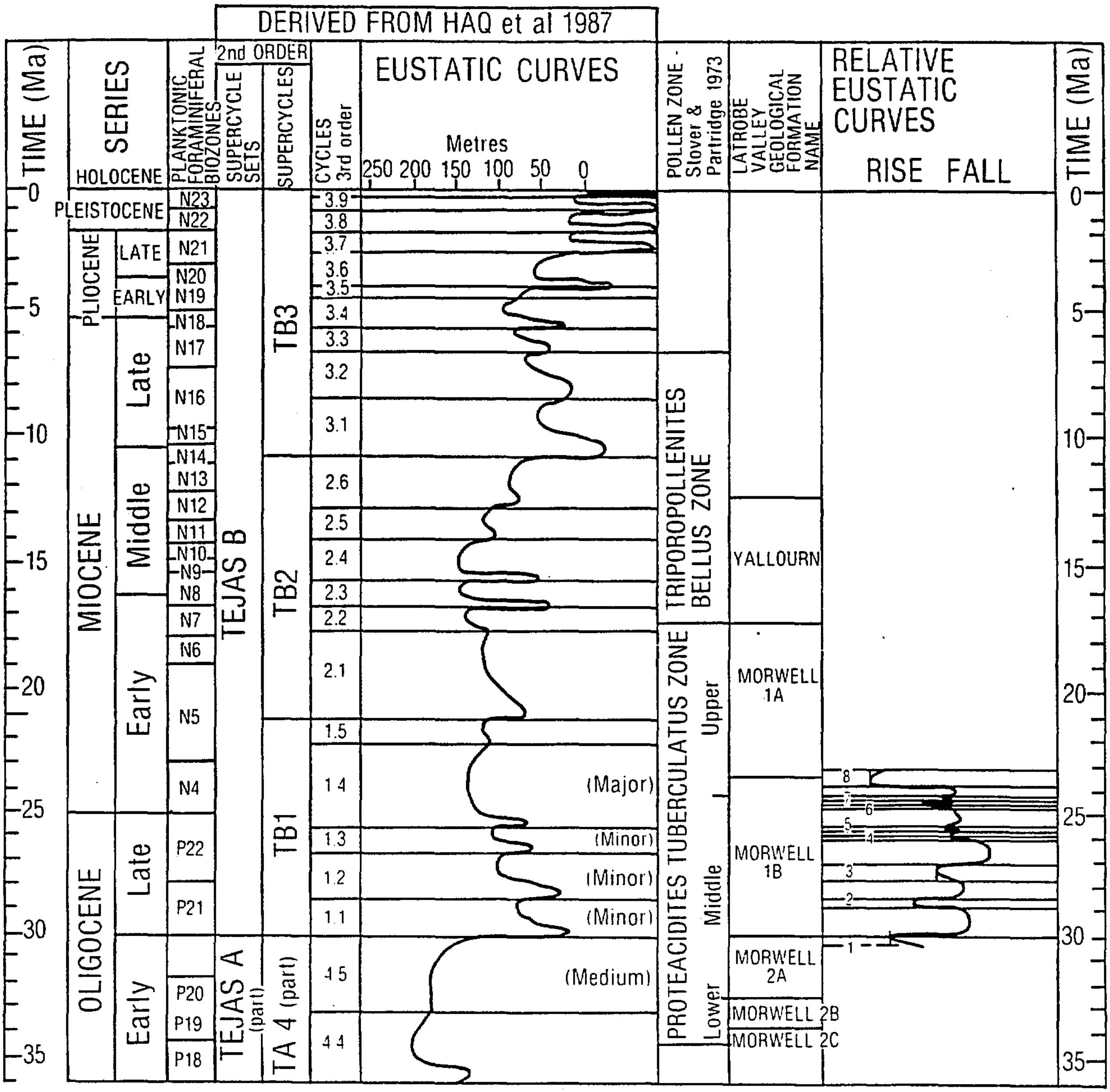
2. Section showing the facies relationships between the Morwell Formation, Ballok Formation and the Seaspray Group.

accumulations of these sands occur near the marine boundary of the Seaspray Group and are known as the Balook Formation. As these sands can extend for up to 30 km inland, depending on the amplitude of the sea-level oscillations, the concept of a barrier system fixed in the one area thoughout the coal forming period Thompson (1981) is no longer tenable. A more dynamic model is proposed where marine to marginal marine transgressive deposits (related to higher eustatic sea-levels) flooded former coastal swamps up to a distance of 30 km inland. Gradual stabilisation of the outer barriers allowed gradual desalinisation and sediment infill of the back-barrier littoral to supra-littoral systems, eventually leading to a re-establishment of the coastal and near-coastal swamp vegetation.

Pollen analysis of Morwell Formation coal seams at Loy Yang (Sluiter, 1984) of of basin-wide sediments Partridge (1971), Stover and Partridge (1973) has provided the framework on which a depositional chronology is based for the Late Oligocene to Early Miocene. Complete core sequences from all five Morwell coal seams and the Yallourn seam have been quantitatively analysed for palynological content Sluiter, 1984, Sluiter and Kershaw, (1982), Kershaw and Sluiter, (1982), Kershaw, Bolger, Sluiter, Baird and Whitelaw (in press) with the most detailed information existing for the M1B and M1A seams (see Fig 3). Periods of increase in pollen of Myrtaceae and Elaeocarpaceae occur at the expense of the pollen of the normally dominant Nothofagidites form taxa during phases of pronounced interseam influence within the Latrobe Valley. This is interpreted to indicate response to an



3. Composite relative frequency pollen diagram of selected taxa through the Morwell Formation coal seams, Latrobe Valley, Victoria.



4. The record of relative sea level change in the Latrobe Valley compared with the coastal onlap chronology of Haq etal 1987.

increase in palaeotemperature linked to probable eustatic sea-level rises.

Throughout the deposition of the Morwell 1B seam (ca. 30-23 million years B.P.) eight marine incursions of varying amplitude are recognisable and correspond to two major interseams and six other lesser partings. The resulting record of eustatic sea-level fluctuations is compared with the coastal onlap chronology of Haq et al. (1987), Haq, Hardenbol and Vail (1987), and acomparative chronology between the two studies is suggested (see Fig 4).

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Sequence stratigraphy: continental margin and basin sediment facies response to sea-level change

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The interpretation of sea-level fluctuations in marine sections, independent of seismic data, has been facilitated by the development of sequence-stratigraphic concepts. A depositional sequence, recognisable at the seismic resolution as well as in outcrops and well logs, is a relatively conformable succession of genetically related strata bounded by conformities, or their correlative conformities, deposited during a cycle of sea-level change. A complete cycle of sea-level change extends from the inflection point of the maximum rate of sea-level fall to the subsequent rise, followed by the next fall.

Sequence stratigraphy is that branch of stratigraphy which subdivides the rock record into a succession of depositional sequences of genetically related strata as regional and inter-regional correlative units.

Sedimentary patterns along continental margins are controlled by sediment supply, rate of subsidence, and sea-level change. The combined effect of regional tectonics and eustasy determine the accommodation potential for sediments and the distribution of facies within genetically related packages (systems tracts) that form during various phases of sea-level change.

The rate of fall of sea-level determines the type of sequence boundary that terminates the sequence. If the rate of eustatic fall exceeds the rate of subsidence at the depositional shoreline break, the entire shelf may be exposed, and a type 1 sequence boundary will result. In deep-water basins with a sand source, type 1 boundaries are commonly characterised by canyon-cutting on the slope, fluvial incision on the shelf, and the formation of basin-floor fans. When the rate of sea-level fall is less than the rate of subsidence at the depositional shoreline break, the shelf seaward of this break will not be exposed, and a type 2 sequence boundary will result. During a complete cycle of sea-level change, lowstand, transgressive, and highstand facies are all well defined, although lowstand and highstand facies are generally represented by relatively thicker sections, and transgressive facies by thinner sections.

Sequence-stratigraphic principles and the distribution of sediment facies along the margins and in the basins in response to changing sea-level will be discussed during this talk.

Late Mesozoic and early Cainozoic history of the Kerguelen Plateau: facies development, palaeogeography, and palaeoceanography

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Ocean Drilling Program Legs 119 & 120 Shipboard Scientists

The Kerguelen Plateau is a large structural high in the south-central Indian Ocean approximately equidistant from Africa and Australia. It is about 500 km wide by 2100 km long, the long axis trending northwest-southeast (Fig. 1) Houtz & others (1977) described the general structure of the plateau, and made a distinction between the northern and southern plateau sectors based on seismic reflection data, a conclusion later corroborated by Coffin & others (1986) on the basis of the Seasat gravity field and multichannel seismic reflection (MCS) data. The northern part of the plateau, which includes the volcanic Kerguelen, Heard, and McDonald islands, lies for the most part less than 1000 m below sea level. The southern plateau, south of 54°S, lies deeper, at 1000-3000 m. The depth of the sea floor surrounding the Kerguelen Plateau is generally 4000 to 4500 m, except on the northeastern and southern flanks, where depths range from 3000 to 4000 m towards the Southeast Indian Ocean Ridge and the Antarctic continental margin, respectively.

Seismic stratigraphic studies of the northern Kerguelen Plateau (Munschy & Schlich, 1987) and southern Kerguelen Plateau (Colwell & others, 1988; Schlich & others, 1988; Coffin & others, 1988a, 1988b) have revealed the presence of significant sediment accumulations interpreted as Cretaceous and early Tertiary in age. Nine sites on the Kerguelen Plateau were drilled during Ocean Drilling Program (ODP) legs 119 and 120 between December 1987 and April 1988 (ODP Leg 119 Scientific Party, 1988a, 1988b; ODP Leg 120 Scientific Party, 1988a, 1988b). The objectives of the drilling were to study the palaeogeography and palaeoceanography of the region, and to provide information on the origin and evolution of the plateau. Sites 736 and 737 were drilled on the northern plateau, and sites 738, 744, and 747 to 751 on the southern plateau (Fig. 1). Plate tectonic reconstructions derived primarily from marine magnetic data (Mutter & Cande, 1983) and satellite altimeter data (Royer & Sandwell, 1988) provide independent control on the palaeogeography of the Kerguelen

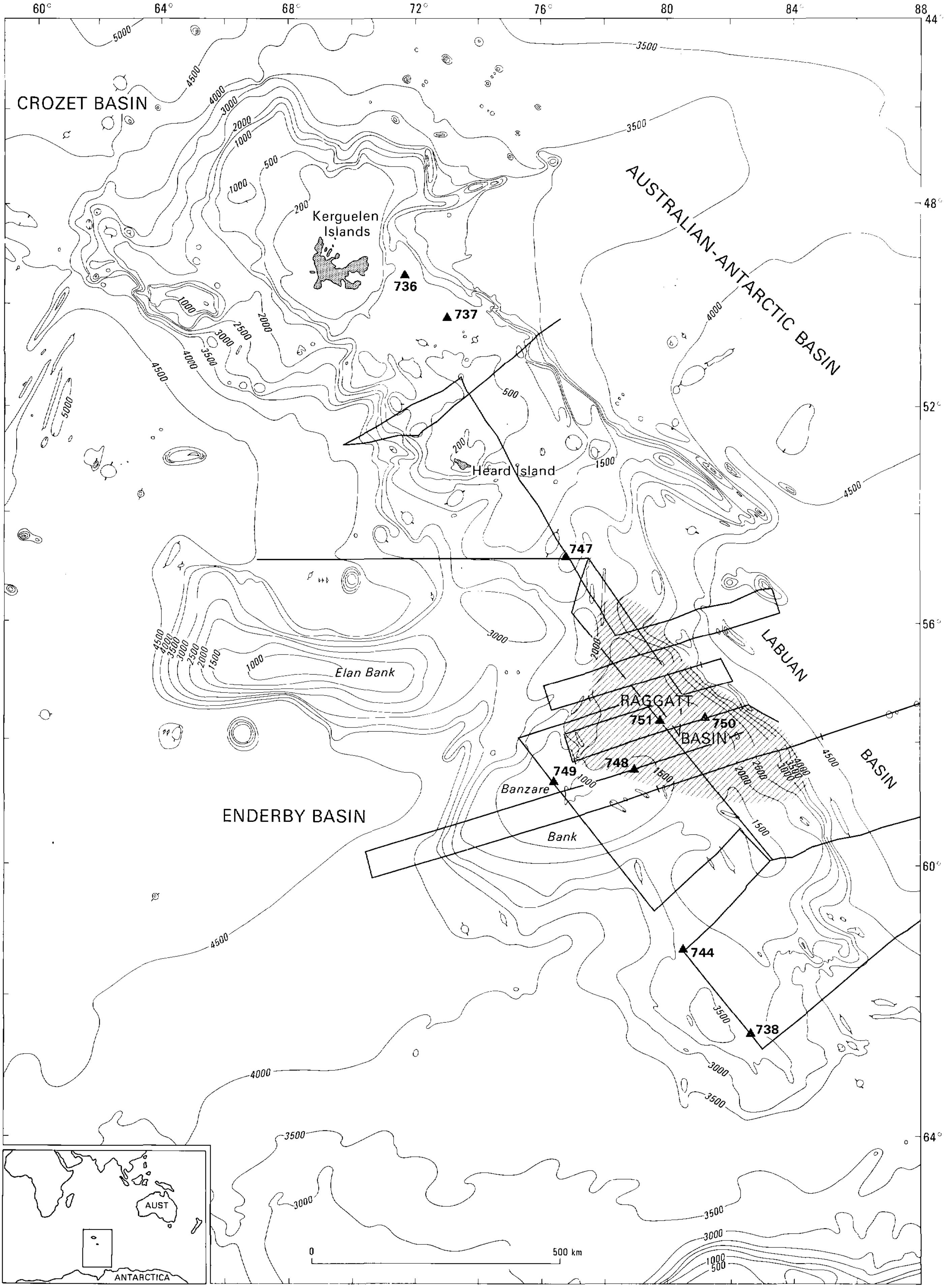
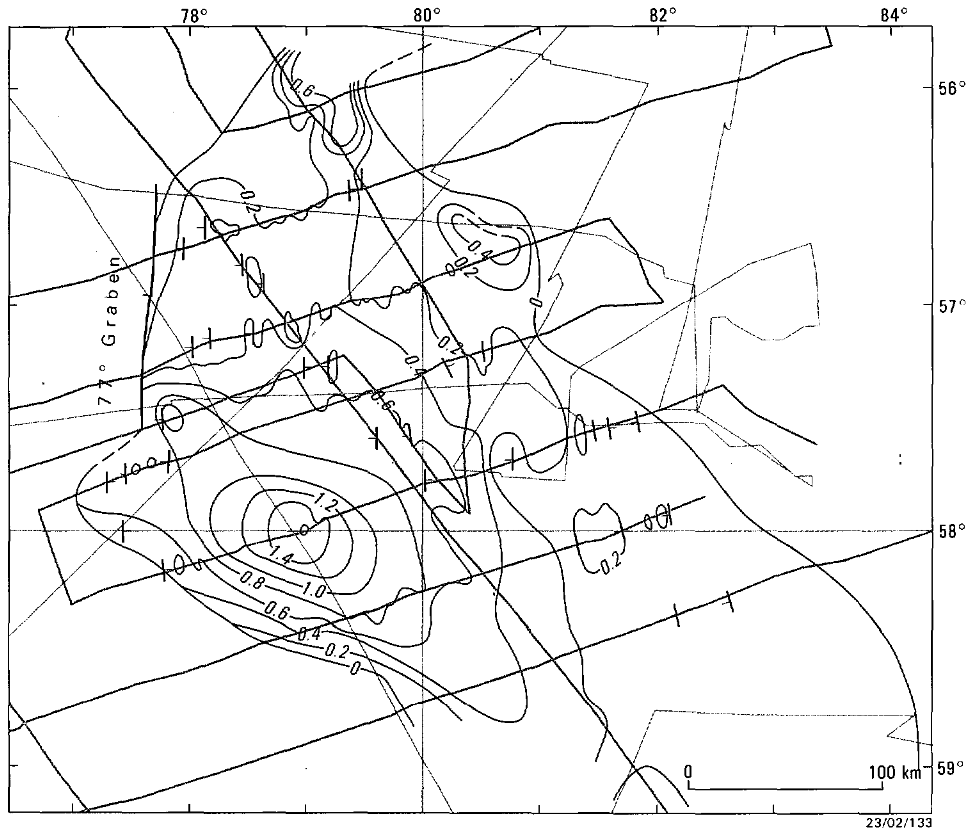
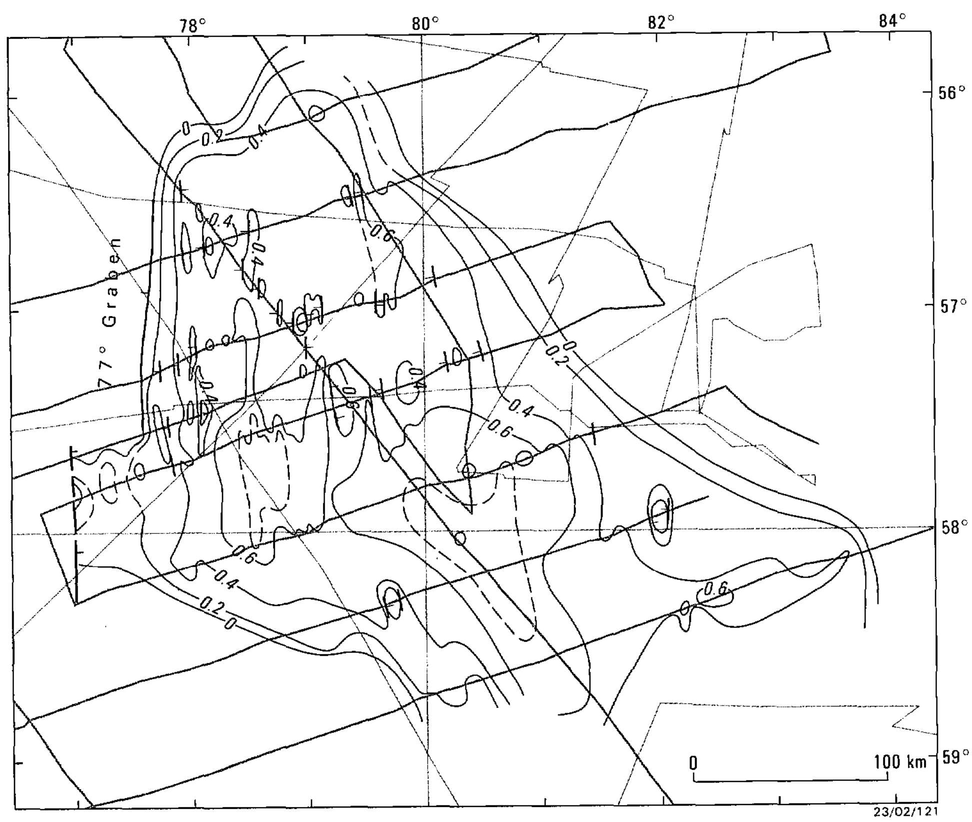


Figure 1. Bathymetry of the Kerguelen Plateau (Schlich & others, 1987). Contour interval is 500 m. Non-proprietary multichannel seismic data and Ocean Drilling Program sites are indicated.



a. Cretaceous sequences K1, K2, and K3.



b. Palaeogene sequences P1 and P2.

Figure 2. Sediment isopach maps of the Raggatt Basin, southern Kerguelen Plateau (Coffin & others, 1988b). Contours are in seconds of two-way travel time.

Plateau.

Cretaceous and early Tertiary sediment sequences have been mapped (Fig. 2) and drilled (Fig. 3) on the southern Kerguelen Plateau (Fig. 1). The age of the basement complex is probably Early Cretaceous (Leclaire & others, 1987; ODP Leg 120 Scientific Party, 1988a, 1988b). At ODP sites 748 and 750, which attempted to recover the oldest sediments from the southern plateau, the oldest dated sediments are Turonian and Cenomanian(?), respectively, in age. However, at both sites a significant thickness of sediment lies between basalt and other volcanics of the basement complex and the oldest dated sediment. This undated terrigenous sediment consists of smectitic/glauconitic claystone (Site 748) and ferruginous, kaolinitic, coal-rich claystone (Site 750). Clearly, the volcanic constructional phase culminated in or was followed by emergence and intense weathering in a warm temperate or subtropical environment. Rainfall was sufficient to weather volcanics to kaolinite, which accumulated in well-vegetated (possibly forested), subaqueous or subaerial environments, perhaps on marshy flood plains. The terrigenous facies correlates with seismic stratigraphic units K1 and part of K2, and has been mapped over the central portion of the Raggatt Basin on the southern Kerguelen Plateau (Fig. 2). Prior to and during mid-Cretaceous time (~95 Ma) the Kerguelen Plateau was situated relatively close to India.

During Cenomanian, Turonian, and probably Coniacian/Santonian time the western portion of the southern plateau remained subaerial or at very shallow water depths. Glauconitic sandstone, siltstone, and claystone, with rare silicified bioclastic debris and some pyritized wood fragments, were recovered from Site 748. The eastern part of the southern plateau subsided during this time; open marine deposits of chalk with dark, clayey interlayers were drilled at Site 750. During Campanian and late Maestrichtian time open marine conditions persisted to the east, with deposition of nannofossil chalk, chert, and intermittently silicified limestone, while in the west, the plateau subsided slowly; glauconitic sandstone, siltstone, and claystone gave way up section to intermittently silicified rudstone, grainstone, and wackstone. During the Late Cretaceous epoch the depocentre of the Raggatt Basin shifted to the east (Fig. 2), and the Kerguelen Plateau gradually became more isolated from continental influences on sedimentation (Fig. 4).

From Late Maestrichtian to Middle Eocene time open marine sediment (primarily nannofossil chalk and ooze with some chert) was deposited over the southern Kerguelen Plateau (sequences P1 and P2, Fig. 2). Nannofossil ooze without chert dominates the Middle Eocene to Pliocene section. Middle Eocene time marks the breakup between Broken Ridge and the Kerguelen Plateau (Mutter & Cande, 1983), and the initiation of the vigorous Circumpolar Current (Kennett & Watkins, 1976).

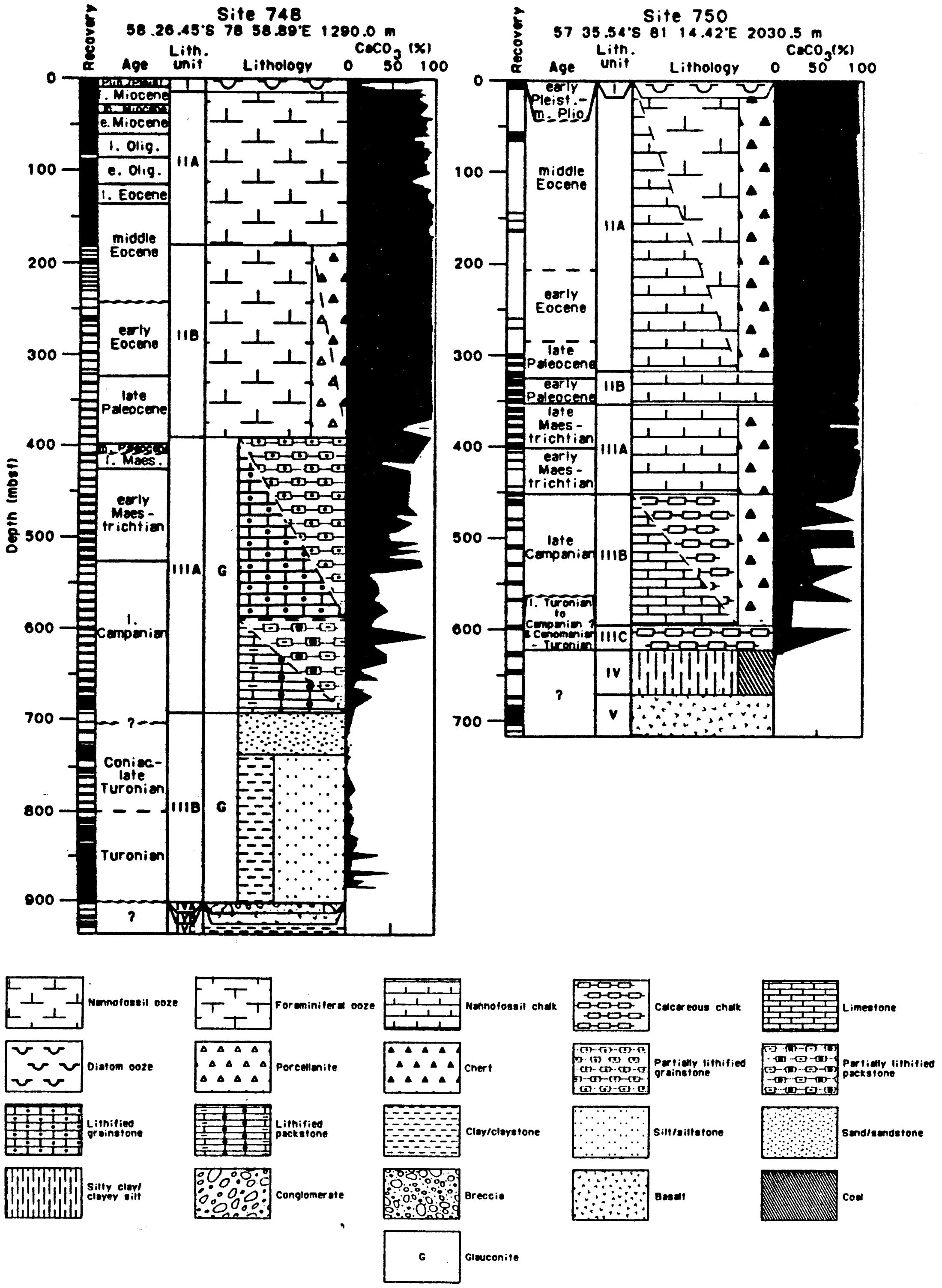


Figure 3. Ocean Drilling Program results, southern Kerguelen Plateau (ODP Scientific Party, 1988b).

a. Site 748 stratigraphic column.

b. Site 750 stratigraphic column.

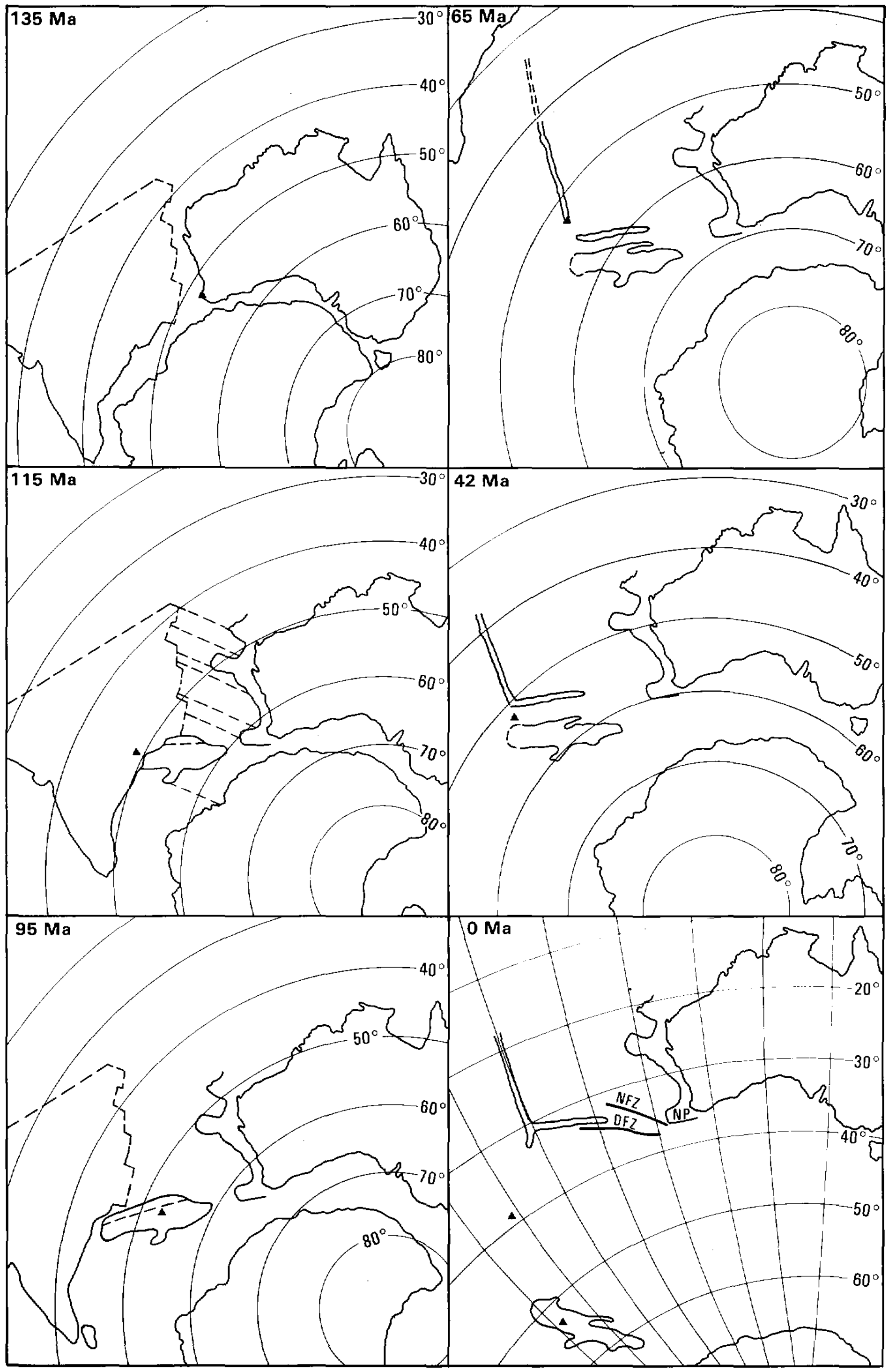


Figure 4. Plate reconstructions, 135 - 0 Ma (Davies & others, 1988).

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Sea level, climatic and tectonic implications of Mesozoic and Cainozoic sedimentary sequences in continuously cored ODP holes on the Exmouth Plateau

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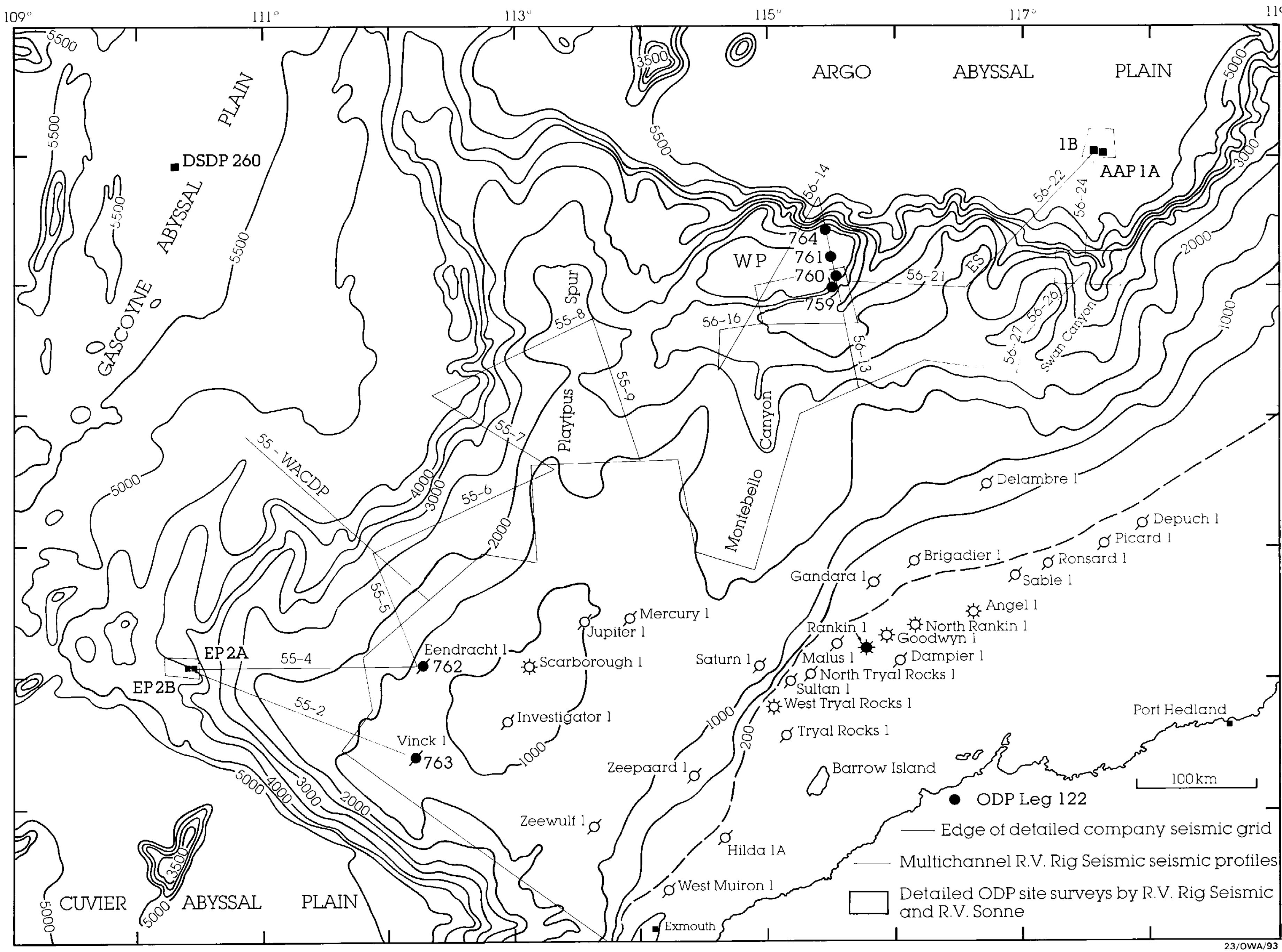
The Exmouth Plateau off Northwest Australia (Fig. 1) is part of one of the oldest oceanic margins in the world. It has relatively low terrigenous and high biogenic sedimentation, and so is ideal for comprehensive and integrated sedimentologic, biostratigraphic, paleobathymetric and tectonic studies of continuously cored holes. Such data are highly relevant to the understanding of the geologic development and hydrocarbon resource potential of the region. Two Ocean Drilling Program (ODP) legs were planned for this area mainly using site survey data obtained by the BMR vessel Rig Seismic in 1986. Leg 122 (Figs. 1 and 2) drilled a transect of four sites on the Wombat Plateau, and two on the western Exmouth Plateau (3500 m of drilling); Leg 123 planned to drill one site on the western continental rise of the Exmouth Plateau and another on the Argo Abyssal Plain. This paper reports the initial results of Leg 122, carried out in July-August 1988. A major aim of Leg 122 was to test the influence of tectonic movements, eustatic changes in sea level (Haq et al., 1987), and climate on the Mesozoic and Cainozoic sediments of the plateau. A particular objective was to establish sea level curves for some parts of the Exmouth Plateau sequence, and to test their fit with the global sea level curves establised from European and North American passive margins.

The Exmouth Plateau has water depths of 800 to 4000 m (Fig. 1). The results of extensive geological and geophysical studies including petroleum exploration have been summarized by Exon & Willcox (1980), Wright & Wheatley (1979), von Stackelberg et al. (1980), Exon et al. (1982), von Rad & Exon (1983), Barber (1988), and Exon & Williamson (1988). The plateau consists of rifted and deeply subsided continental crust, covered by 10 km of Phanerozoic sediments. It is separated from the Northwest Shelf by the Kangaroo Syncline, and is bounded to the north by Jurassic oceanic crust of the Argo Abyssal Plain, and to the west and south by Cretaceous oceanic crust of the Gascoyne and Cuvier Abyssal Plains.


109°
111°
113°
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119°
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19°
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ARGO
ABYSSAL
PLAIN
GASCOYNE
ABYSSAL
PLAIN
CUVIER
ABYSSAL
PLAIN
DSDP 260
1B
AAP 1A
764
761
760
759
WP
ES
Swan Canyon
Spur
Platypus
Montebello
Canyon
55 - WACDP
55-2
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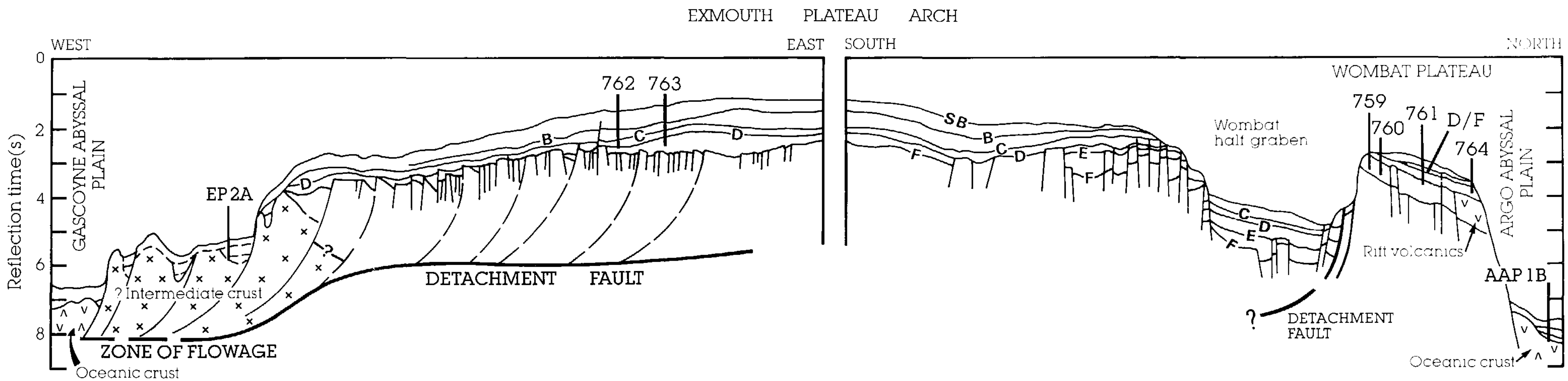
EP2A
EP2B
Eendracht 1
762
Vinck 1
763
Scarborough 1
Jupiter 1
Mercury 1
Investigator 1
Saturn 1
Zeepaard 1
Zeewulf 1
Hilda 1A
West Muiron 1
Exmouth
Gandara 1
Brigadier 1
Delambre 1
Depuch 1
Picard 1
Ronsard 1
Sable 1
Angel 1
North Rankin 1
Rankin 1
Goodwyn 1
Malus 1
Dampier 1
North Tryal Rocks 1
Sultan 1
West Tryal Rocks 1
Tryal Rocks 1
Barrow Island
Port Hedland
100km
ODP Leg 122
Edge of detailed company seismic grid
Multichannel R.V. Rig Seismic seismic profiles
Detailed ODP site surveys by R.V. Rig Seismic and R.V. Sonne
23/OWA/93

Figure 1.



	Reflector	Age and lithology
	SB	
Mature Ocean	B	Late Cretaceous and Cainozoic marine carbonates
	C	
		Mid Cretaceous marine detrital sediments
Breakup in south	D	
		Early Cretaceous deltaic sediments
Breakup in north	E	
		Jurassic coal measures and carbonates
Rifting	F	
		Triassic sandstones and shales

23/OWA/94

Figure 2.

The sediments beneath the Exmouth Plateau were deposited in part of the Westralian Superbasin (Bradshaw et al., 1988), which formed a north-facing Tethyan embayment in Gondwana and received detrital sediments from the west, south and east until Early Cretaceous time. In the central plateau region at least 4000 m of fluvio-deltaic to shallow marine detrital sediments were deposited from Permian to mid Cretaceous times (Fig. 3). Breakup of the southern and western margins of the plateau in the Neocomian reduced terrigenous input; hemipelagic shallow-marine sediment was deposited in the Early Cretaceous, followed by Late Cretaceous to Cainozoic pelagic carbonate.

The northern ODP sites (Fig. 4) on the Wombat Plateau (759, 760, 761, 764) drilled sequences whose maximum thickness were: Cainozoic 175m, Cretaceous 85m, Late Triassic 900m. The sites showed that presumed fluviodeltaic sediments of the Middle Triassic are overlain by Late Triassic sediments, of which 30% are shallow water carbonates and the remainder low-energy paralic to deltaic siliciclastics. Two shallowing upwards sequences were drilled in the Carnian, with sequence boundaries representing sea level falls above the middle and late Carnian. Seismic data suggest that the Carnian/Norian unconformity may be related to a period of rifting and extension prior to the formation of this margin of the Exmouth Plateau. Another shallowing upwards sequence, from shallow marine to coastal plain, characterizes the Norian; this too is capped by an unconformity which is a sequence boundary. A nearly complete marine Rhaetian section consists of reefal and shelf limestone, and open marine marl. A sequence boundary within the latest Rhaetian is overlain by shelfal limestones. At all four northern sites the Late Triassic is truncated by a major angular unconformity.

The southern sites (762, 763; Fig. 5) drilled sequences whose maximum thicknesses were: Cainozoic 550 m, Cretaceous 790 m. They yielded very complete Cretaceous and Cainozoic sequences. The southernmost hole (763) recovered an almost complete Valanginian to Campanian section (total sequence 1000 m), and the central hole (762) recovered an almost complete Maastrichtian to Quaternary section (total sequence 650 m). The oldest sediments drilled were part of a prodelta sequence of the Barrow Group equivalent, laid down during a period of tectonic activity related to breakup of the plateau's southern margin. Tectonic uplift provided abundant detrital material which was laid down very fast in the Berriasian. Sand bodies represent turbidites in a generally clayey sequence. The Berriasian sequence is capped by a condensed unit of Valanginian sandstone, limestone and claystone, which in turn is capped

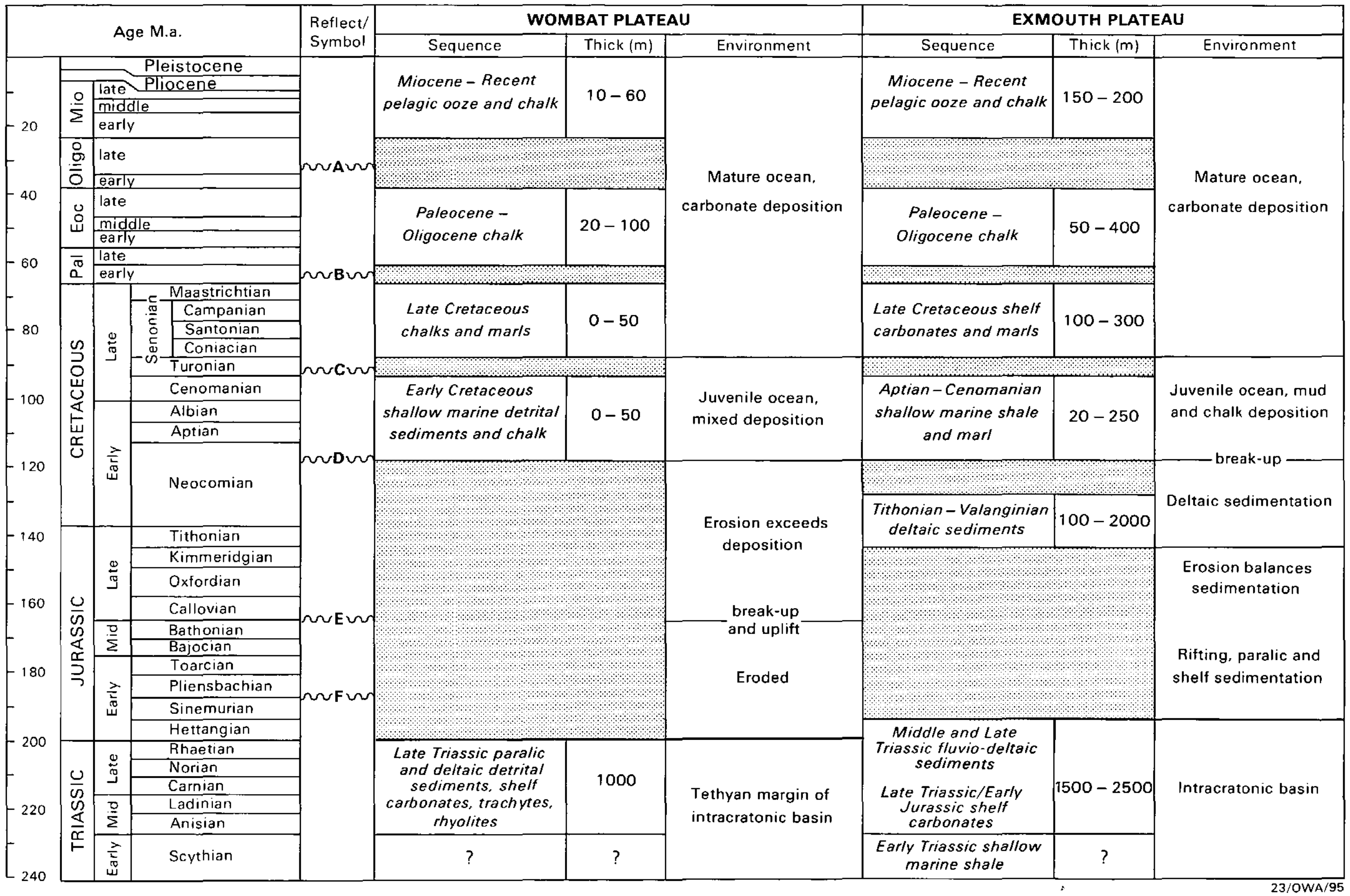


Fig. 3. Simplified stratigraphy of the Exmouth Plateau

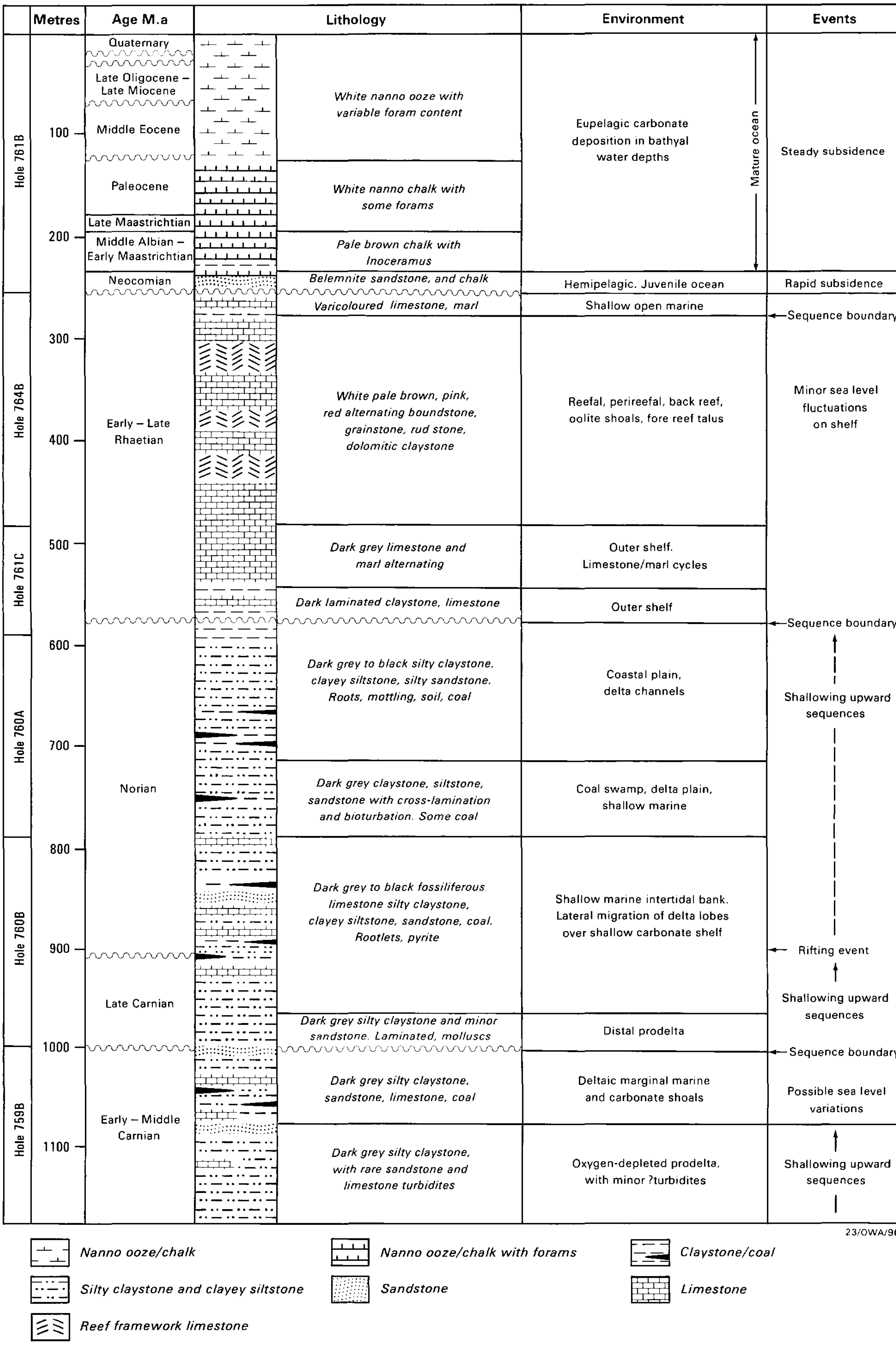


Fig. 4. Wombat Plateau
(Composite from Sites 759, 760, 761 and 764)

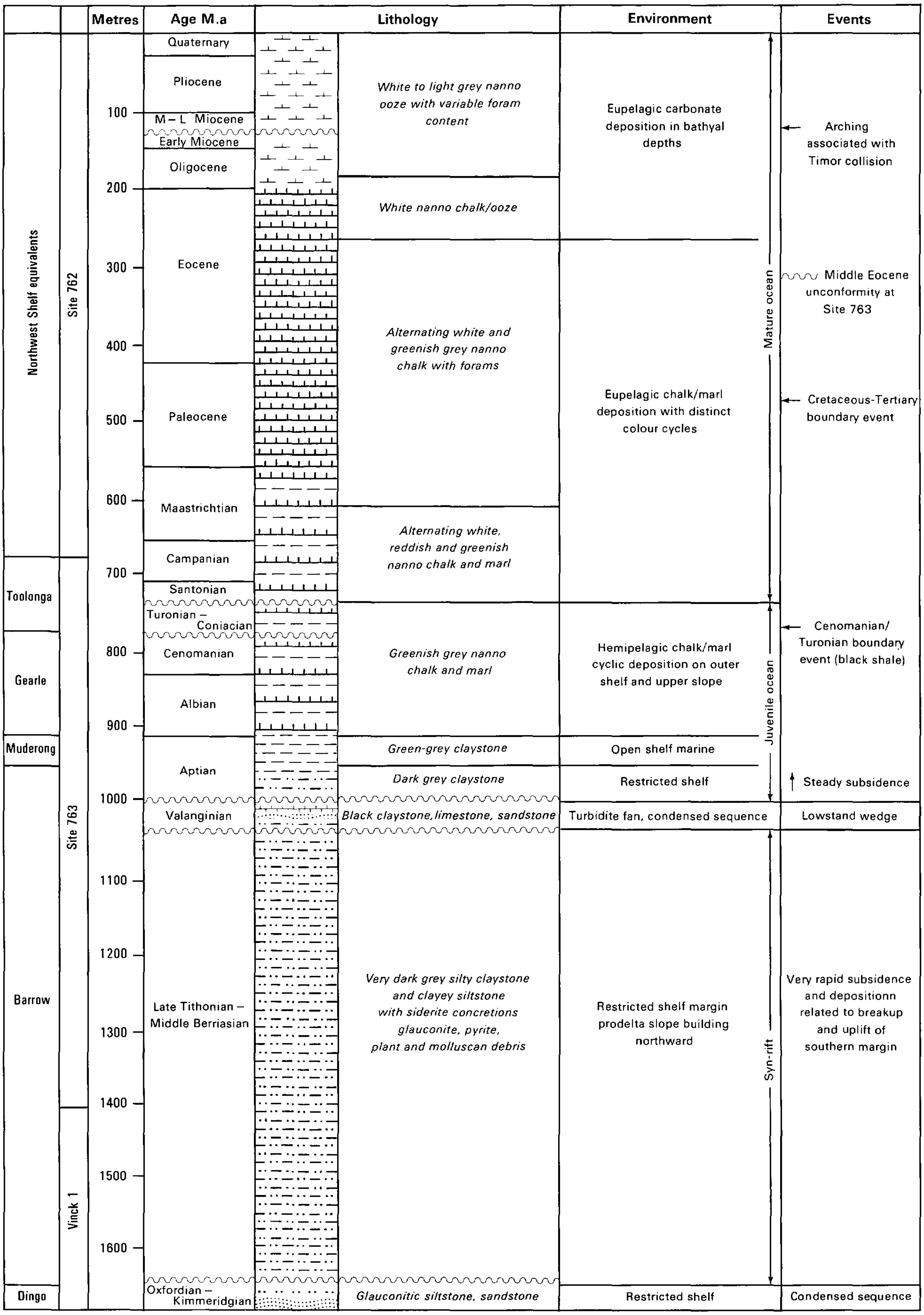


Fig. 5. Central Exmouth Plateau
(Composite from sites 762 and 763, and Vinck No 1)

by a prominent unconformity (the Neocomian "breakup unconformity"). Thereafter the plateau sank rapidly, and early Aptian silty claystone gave way first to middle Aptian to Cenomanian marls, and then to Turonian to late Campanian chalks. An anoxic event gave rise to thin black shales at the Cenomanian-Turonian boundary.

The Cainozoic sequence everywhere consists of pelagic chalks and oozes. Cyclic colour variations (green/red or green/white) in Cenomanian to middle Eocene chalks and marls occur on several timescales, the most obvious being about 100,000 years. They appear to be caused by variations in the proportion and colour of clay minerals. Such cycles often occur in early post-rift sediments in Mesozoic Atlantic basins, and are probably due to combined changes in surface productivity, the influx of organic matter, and the intensity of bottom circulation, all of which may be controlled by climate. The cycles may be related to Milankovich-type cycles, and hence are potentially correlatable with global eustatic cycles.

Where tectonic events can be isolated, sea level fluctuations can be deciphered from sequence stratigraphic analysis of seismic, litho- and biofacies, and well-log data. Marine regressions have formed important sequence boundaries on the Wombat Plateau between the middle and late Carnian, at the Norian/Rhaetian boundary, and in the latest Rhaetian, and their timing conforms well with the eustatic cycle chart (Haq et al., 1987). The sequence boundary and systems tracts recognised in the Barrow Group equivalent of the central plateau correspond reasonably well to the global cycle chart. The preliminary results suggest that we will be able to test in detail the validity of these parts of the eustatic model.

In terms of petroleum resources the drill results are very significant. The discovery of Rhaetian reefs on the Wombat Plateau suggests that reefal reservoirs of this age may be present elsewhere on the outer margin of the Northwest Shelf; reefs of similar Late Triassic ages are known to occur in Papua New Guinea, far to the north (Skwarko, Nicoll & Campbell, 1976). Rock Eval pyrolysis of the Cretaceous sediments on the central plateau indicates the organic matter to be land-derived. Organic carbon values are generally around 1% in the cored deltaic intervals, but increase to 15% in one of the thin black shale layers at the Cenomanian-Turonian boundary. Deep-sourced methane bypassed the Early Cretaceous clastic sequence along faults, and dissolved in the pore waters of the Cretaceous-Tertiary chalks, which also acted as a barrier to further upward migration of gases. Organic geochemistry suggests that the organic-rich marine claystones of the Barrow Group equivalent are almost in the oil window, beneath 1000m of overburden at Site 763. Further east, where the overburden is twice as thick, and in areas of higher heatflow, the basal part of this sequence or the underlying Late Jurassic Dingo Claystone could generate oil. These could conceivably charge reservoirs within the lower Barrow Group or at top Triassic levels.

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Relative sea level control on sequence development : examples from Cambrian and middle Proterozoic outcrops

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Principles of sequence stratigraphy including the concepts of sequences, parasequences and systems tracts, and the recognition of sequence boundaries and controls on sequence development are based largely on subsurface data. Few studies have applied these principles to outcrops in which sequences can be mapped out in three dimensions. The Hampton and Erwin Formations of the early Cambrian Chilhowee Group in the Appalachian Mountains and the middle Proterozoic lower Quilalar Formation and upper Mt Guide Quartzite in the Mount Isa Orogen are exposed in structural blocks that provide stratigraphic and sedimentologic data both parallel to and across depositional strike. These rock units thus are amenable to sequence analysis and the evaluation of relative sea level controls on sequence and parasequence development.

The Chilhowee Group in southern and central Virginia consists of the Unicoi, Hampton, and Erwin Formations. The lower Unicoi Formation comprises alluvial feldspathic sandstones and conglomerates and basalts deposited in a rift setting, whereas the upper Unicoi Formation consists of tide- and wave-influenced, shallow-marine shelf sandstones reflecting the incipient development of an east-facing passive margin bordering the Iapetus Ocean. The early Cambrian Hampton and Erwin Formations record siliciclastic shoreline and shelf sedimentation along this passive margin. The overlying Shady Dolomite reflects the evolution of the passive margin from a ramp to rimmed shelf geometry.

Occurrence of both the Hampton and Erwin Formations on a number of thrust sheets permits an across-strike reconstruction of the passive margin. The Hampton and Erwin Formations represent an overall offlap package consisting of up to five transgressive - progradational sequences bounded by unconformities and their correlative conformities. Sequences vary systematically between thrust sheets with replacement of shallow- by deeper- water depositional environments from west to east.

Two depositional systems are represented in the Hampton and Erwin Formations : tidal flat (TF) and storm-dominated shelf (SDS); the latter consists of four facies: outer shelf facies (OSF), distal inner shelf facies (DISF), proximal inner shelf facies (PISF) and shoreface facies (SF). Depositional systems and their constituent facies are associated in Systems Tracts that constitute 65 to 225 m - thick Sequences. Transgressive Systems Tracts developed during initial rise in sea level and consist of: 1) TF followed by SF → PISF, or SF → PISF above unconformities in western thrust sheets and 2) thin DISF with detrital glauconite, and OSF above conformable sequence boundaries in eastern thrust sheets. Associated with maximum rates of transgression, black mudstones (condensed sections) accumulated in distal inner - shelf and outer - shelf settings. Highstand Systems Tracts reflect a decrease in rate of sea level rise and are represented by : 1) PISF → SF, and OSF → PISF → SF in western thrust sheets, and 2) OSF → DISF → PISF, DISF → PISF, and OSF alone in eastern thrust sheets.

The Hampton and Erwin Formations reflect outbuilding of the Chilhowee passive margin related to a regression resulting from a decrease in rate of thermal subsidence. Sequences record lower - order sea level changes.

The Quilalar Formation in the Mount Isa Orogen either conformably overlies rift - related volcanics and sediments or nonconformably overlies basement. It represents a thermotectonic or sag phase of sedimentation between 1780 and 1740 Ma. Facies analysis of the lower siliciclastic member of the Quilalar Formation permits discrimination of depositional systems that are restricted areally to either north-south trending marginal 'platform' or central 'trough' paleogeographic settings.

Four depositional systems each consisting of several facies, are represented in the lower Quilalar Formation; these are categorized broadly as Storm-Dominated Shelf (SDS), Continental (C), Tide-Dominated Shelf (TDS) and Wave-Dominated Shoreline (WDS).

SDS facies are arranged mainly in 70 to 130 m - thick coarsening - upward and thickening - upward sequences that contain 5 to 10 m - thick parasequences. The vertical transition of facies reflects shoaling of a storm-dominated shelf from outer-shelf to inner-shelf to shoreface environments; the latter contains evidence of subaerial exposure. Basal black mudstones are interpreted as condensed sections that developed as a result of slow sedimentation in an outer-shelf setting starved of siliciclastic influx. Continental facies consist of fining-upward intervals of fluvial pebble conglomerates and stratified feldspathic arenites, and fine-grained cross-bedded arenites of aeolian origin.

TDS facies are represented by stacked tabular bodies of quartz arenite and rare mudstone. Cross-bedded cosets capped by thin-bedded rippled intervals, modified ripples, adhesion structures and/or desiccation cracks make up 0.5 to 5 m - thick parasequences. Vertical arrangement of facies in parasequences reflects flooding and establishment of a tidal shelf, followed by shoaling to intertidal conditions. WDS facies are preserved in ca 2 m thick, stacked parasequences. Vertical transition of facies reflects initial flooding with wave reworking of underlying arenites along a ravinement surface, followed by shoaling from lower shoreface to beach conditions.

Depositional systems are related in Systems Tracts that make up 50 to 140 m - thick Sequences bounded by unconformities and their correlative conformities. Transgressive Systems Tracts consist of TDS and WDS depositional systems on the 'platforms' and condensed section deposits in the 'trough' and are related to a gradual increase in rate of sea level rise. Succeeding Highstand Systems Tracts are represented by SDS depositional system in the 'trough' and coeval continental depositional system on the adjacent 'platforms' and developed during the subsequent decrease in rate of sea level rise.

Fischer plots of cumulative parasequence thickness (corrected for linear thermal subsidence) versus time for TDS parasequences in the upper Mount Guide Quartzite show deviations in thickness from that expected for linear subsidence. Relative changes of sea level or 'jerky' subsidence could account for such deviations; a sea level control is favoured because the deviations are systematic rather than random. Parasequence sets display thickening and thinning of TDS parasequences that reflect rapid rises followed by slow falls of sea level. Parasequences may record sea level variations within the Milankovitch Band superimposed on a higher-order sea level oscillation.

Cambrian shale-carbonate cycles, Amadeus Basin: High frequency ?Milankovitch sea level oscillations in an intracratonic setting

J M Kennard and J F Lindsay, BMR

The Middle to Late Cambrian Shannon Formation is characterized by metre-scale rhythmic alternation of poorly exposed siliciclastic mudrocks (shaly half-cycles) and carbonates (carbonate half-cycles) of great lateral continuity. The formation is readily subdivided into two units; a lower mudrock-rich unit 140-240 m thick, and an upper carbonate-rich unit 250-400 m thick. In both units, asymmetric carbonate half-cycles are sharply overlain by siliciclastic mudrocks, and their basal contact may be either sharp and erosional, or gradational over several decimetres. Shaly half-cycles are typically 1-8 m thick in the lower unit, and 1-5 m thick in the upper unit. They comprise red-brown micaceous mudstone, mudshale and minor siltstone, and locally contain desiccation cracks and runzel marks.

Carbonate half-cycles in the lower unit comprise dolostone, are typically 0.2-1 m thick, and are dominated by stromatolites of low synoptic relief (less than 20 cm). They commonly exhibit the following shallowing-upward sequence; 1) peloid or ooid grainstone, commonly wave-rippled with lenticular and wavy dolo-mudstone drapes, 2) wavy laminated and linked hemispherical stromatolite biostromes, 3) undulose or planar laminated stromatolite biostromes, and less frequently, 4) thinly interbedded dolo-mudstone, peloid grainstone and flake conglomerate. Silicified evaporite pseudomorphs commonly occur at the top of these cycles. Facies associations and microstructural analysis of stromatolites within these cycles (Kennard, in press) indicate that they record ecologic successions of lower intertidal (hemispherical, wavy and planar stromatolites) to upper intertidal (undulose stromatolites) benthic microbial communities. Thus these cycles have a thin subtidal base (grainstone) and a thicker intertidal-supratidal cap.

Carbonate half-cycles in the upper unit consist of limestone and subordinate dolostone, are typically 0.3-3 m thick, and are characterized by thrombolites of relatively high synoptic relief (30-100 cm) and stromatolites of moderate to low synoptic relief (less than 30 cm). They commonly exhibit the following shallowing-upward sequence; 1) trough cross-bedded peloid-ooid-intraclast grainstone, 2) relatively large thrombolite bioherms, 3) inter-biohermal peloid-intraclast grainstone, 4) columnar grading upward to wavy laminated stromatolites (these cap the thrombolite bioherms, and are flanked by),

5) intraclast conglomerate, 6) peloid-ooid grainstone with symmetrical wave ripples, and 7) undulose or planar laminated stromatolite biostromes and dolomudstone with desiccation cracks. These half-cycles are frequently incomplete, however, and any of the above lithotypes may be abruptly overlain by siliciclastic mudrock or, less frequently, truncated by a karst erosion surface. Facies associations and microstructural analysis of thrombolites and stromatolites within these cycles (Kennard, in press) indicate that they record ecologic successions of subtidal (thrombolites), shallow subtidal to lower intertidal (columnar and wavy stromatolites), and intertidal (undulose and planar stromatolites) benthic microbial communities. These half-cycles thus have a relatively thick subtidal base (grainstone and thrombolite) and a thin intertidal cap.

Based on estimates of the absolute age of the Shannon Formation (top 520 Ma, base 530-538 Ma, duration 10-18 Ma; Shergold, in prep.) and the number of cycles measured at five sections (136-219), the cycle period is estimated to be 45 000 - 130 000 years.

The cycles are interpreted to result from low amplitude, high frequency, sea level oscillations. Each cycle is initiated by a rapid sea level rise at which time peritidal carbonates of the underlying cycle are inundated by several metres of water. During a lag time before carbonate production is re-established, shoreward (westward) ponded siliciclastic muds are remobilised and distributed across the submerged carbonates. As the rate of sea level rise begins to decrease, the supply of siliciclastic mud wanes, siliciclastic deposition contracts to the west, and carbonate production reaches its full potential. Peloid-ooid shoals and benthic microbial communities are established, microbial carbonates build to sea level, and peritidal carbonate flats prograde rapidly westward. As sea level begins to fall, the peritidal carbonate flats are stranded and subaerially exposed, carbonate production is terminated, and siliciclastic muds are ponded in shallow waters shoreward of the exposed carbonate flats. The next sea level rise inundates the carbonate flats and heralds the beginning of a new cycle.

Quantitative modelling of eustatically controlled small-scale carbonate cycles (Read and others, 1986) indicates that the marked change from thin subtidal based cycles in the lower mudrock-rich unit, to thick subtidal based cycles in the upper carbonate-rich unit, could be generated by either; 1) an increase in amplitude of sea level oscillation, or 2) an increase in lag time in carbonate production following submergence. A third and perhaps more likely cause, however, is longer-term sea level variations. When the longer term rate of sea level change decreases, transgressive pulses of the shorter term sea level oscillations are minimized, and regressive pulses are accentuated. Thus transgressive pulses result in relative minor submergence, and very shallow subtidal to intertidal stromatolite-dominated facies are established. Enhanced regressive pulses result in evaporite deposition, prolonged emergence, and extensive dolomitization. Conversely, when the longer term rate of sea level rise increases, transgressive pulses are accentuated, submergence is greater, and relatively deeper subtidal thrombolite-dominated facies are established. Such longer term sea level variations are also thought to have generated other large-scale shallowing upward lithologic cycles recognized in the basin, which are comparable to the Cambrian "Grand Cycles" documented in North America by Aitken (1978) and Chow and James (1987).

Fourier spectral analysis of five sections of the Shannon Formation does not provide conclusive evidence of a spectrum of Milankovitch band signatures. One intuitively expects, however, that such signatures might easily be obscured by local noise or irregularly episodic autogenic sedimentation processes within this extensive, intracratonic, shallow marine environment.

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Ordovician Event Stratigraphy and the development of a Larapintine Seaway, Central Australia

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and J.D. Gorter (J.D. Gorter Pty. Ltd.)

Introduction

The name Larapintine Sea was first used by Keble & Benson (1939), and elaborated by Webby (1978), for a seaway that extended in the Ordovician from the Canning Basin, through the Amadeus Basin to the Warburton and Georgina Basins and the Tasman Geosyncline, thus bisecting the Australian portion of the Gondwanaland supercontinent (Figure 1). Webby (1978) in four maps showed the development of this seaway from its inception in the late Tremadoc through its trans-Australian development in the Arenig and Llanvirn, to its end in the Caradoc.

Recent detailed biostratigraphic and sedimentologic studies in the Amadeus Basin, and a re-interpretation of data from the Canning and Georgina Basins, has modified part of this earlier interpretation and has enabled comparative relative sealevel and onlap curves to be prepared for the three basins.

Intra-basin Correlation and Event Stratigraphy

With our improved age control of the stratigraphic units in the three basins we can now compare and correlate events between them. We are also able to compare the events within the basins to events recognised in extra-Australian basins and thus determine if the causative factors relate to global sealevel fluctuations or to regional tectonic events.

Comparative relative sealevel and onlap curves have been prepared for the three basins using outcrop rather than seismic evidence (Figure 2). Earliest Ordovician sedimentation was restricted to the Amadeus and Georgina Basins. In the Georgina Basin it was a time of continuous shallow water to inter-tidal carbonate deposition (the Ninmaroo Formation), but in the Amadeus Basin only two short periods of clastic sedimentation occurred (the lower part of the Pacoota Sandstone). Two world wide low sealevel events are recorded in this interval, the Lange Ranch Eustatic Event in the earliest Tremadoc, and the Black Mountain Eustatic Event in the middle Tremadoc (Miller, 1984).

A late Tremadoc transgression occurred in all basins, minor in the Georgina Basin but major in the other two with the return of marine sedimentation to the Amadeus Basin and the initial flooding of the Canning Basin. In the Amadeus Basin, where detailed control is available, minor fluctuations in sealevel can be recognised in the latest Tremadoc and earliest Arenig but in the Canning Basin our control is not yet adequate to detect any record of minor fluctuations. In the

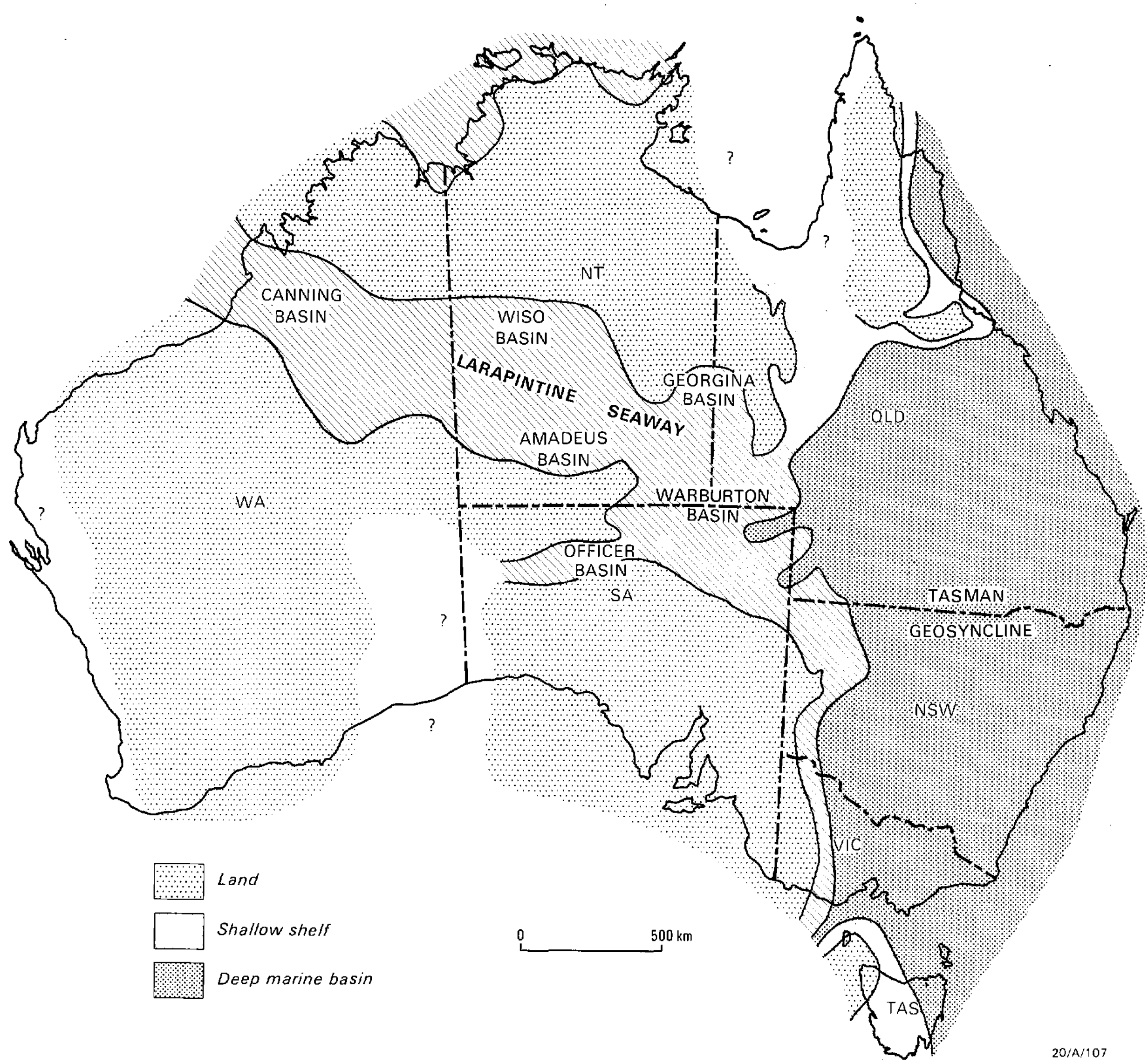

Figure 1. Location of the Ordovician Larapintine Seaway, central Australia.

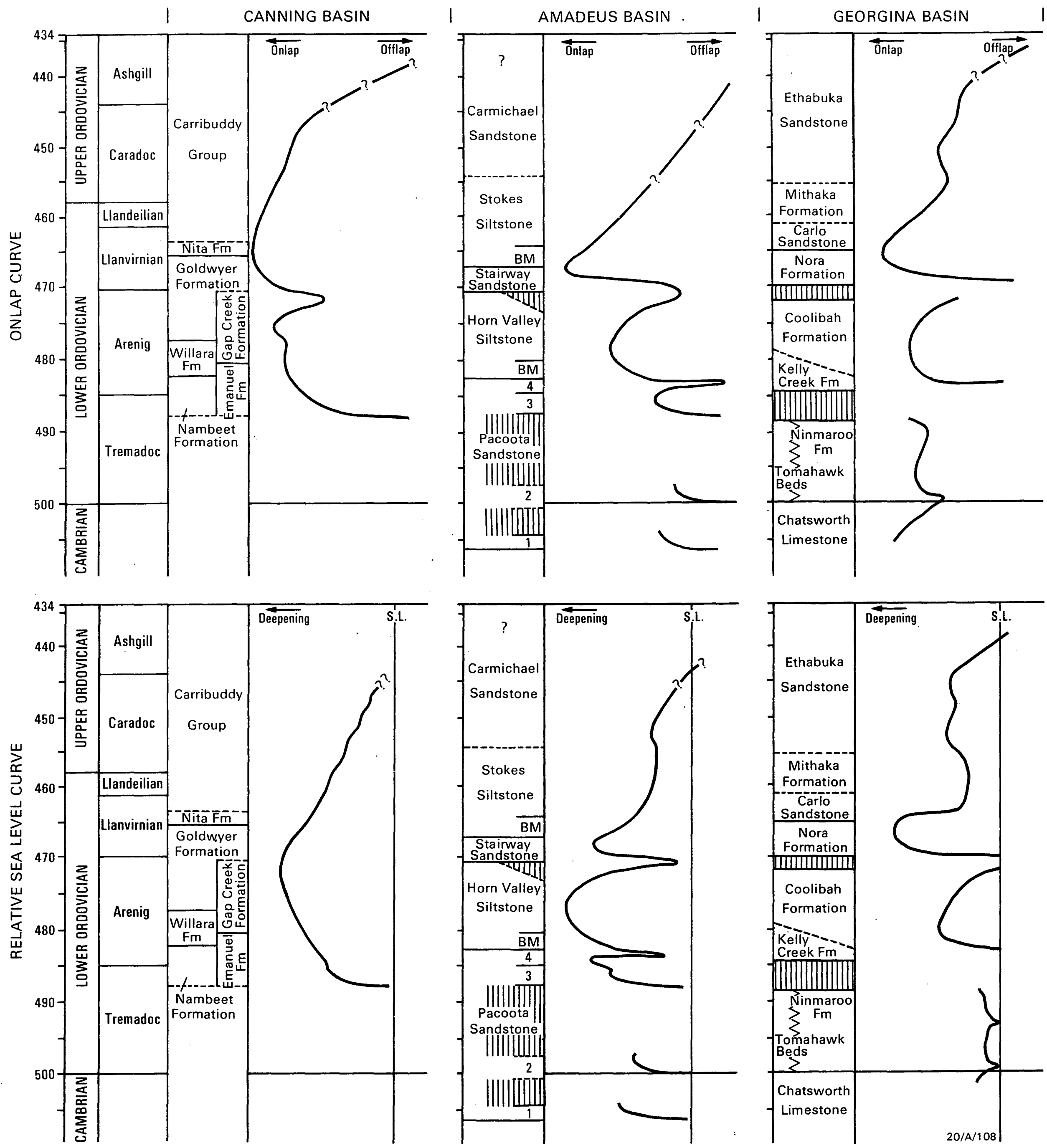

Figure 2. Onlap and relative sealevel curves for the Canning, Amadeus and Georgina Basins, Australia.

Georgina Basin an erosional break occurs in the latest Tremadoc (Kelly Creek Movement), which appears to reflect local tectonic influences rather than eustatic events.

The middle Arenig is a period of increasing relative sealevel in all three basins with expansion of the areal extent of the basins. However, in the late Arenig regression occurred with some erosion of earlier deposited units towards the margin of the Amadeus Basin and throughout the Georgina Basin. A major regression occurred on the Canadian (Barnes, 1984) and Scandinavian Cratons (Lindström and Vortisch, 1983) at about this time and it may represent a global eustatic rather than regional tectonic event.

In the late Arenig to early Llanvirn a transgression expanded all three basins to their maximum Ordovician areal extent, demonstrated by the distribution of the Nita Formation, upper Stairway Sandstone/basal Stokes Siltstone and the Nora Formation. In the Wiso Basin to the north of the Amadeus, the Hanson River beds were being deposited at this time and in the Officer Basin to the south the Indulkana Shale may represent the same transgressive event. This event may be of global significance since it has also been recorded from China (Chen, 1988).

In the Canning and Amadeus Basins the late Llanvirn depositional environment became restricted with a tendency to hyper-salinity. In the Amadeus Basin 500 metres of unfossiliferous mudstone were deposited in the upper Stokes Siltstone while in the Canning Basin 1500 metres of dolomite, mudstone and evaporites were deposited in the Carribuddy Group, a likely correlative of the upper Stokes Siltstone. A clastic influx (the Carmichael Sandstone) dated by fish plates as probably Caradoc, marks a transition to non-marine deposition associated with the Rodingan Movement in the eastern part of the Amadeus Basin, and is not reflected in the other basins. In the Georgina Basin this interval appears to be represented by more normal marine sediments with a clastic overprint: only at the top of the Ethabuka Sandstone does Draper (1980) note that consistent non-marine conditions developed. The lack of late Ordovician (Ashgill) marine sediments probably reflects lowered sealevels associated with major glaciation at this time (Sheehan, 1988).

The Larapintine Seaway

The Larapintine Sea developed in the late Tremadoc with the transgression of marine waters across the middle of Australia. The western end opened to a shelf, probably narrow, and open ocean. In the east it extended to the Tasman Geosyncline and deep water. The main axis of the seaway was through the Canning, Amadeus and the entirely subsurface Warburton Basins with the Georgina Basin representing the northern margin of the seaway.

Initiation of the seaway appears to have been by a eustatic rise in sealevel in the late Tremadoc, and through much of the existence of the Larapintine Seaway eustatic rather than regional events controlled its extent. In its initial history, uplift in the latest Tremadoc (Kelly Creek Event) may have broken the seaway in the east for a short period but the connection was soon re-established and deposition continued until the late Arenig when a sealevel fall may again have broken the connection in the east.

This sealevel low was followed in early Llanvirn times by the major Ordovician transgression during which the Larapintine Seaway reached its greatest extent on the Australian Craton. From the mid-Llanvirn onwards gradual regression due to falling sealevels led to the seaway shrinking in area with the development of restricted marine environments in the Amadeus and Canning Basins until, in the early Caradoc, tectonic uplift in the east of the Amadeus Basin finally severed the east-west connection across Australia. East of the barrier open marine conditions continued in the Georgina Basin, but west of the barrier, in the Amadeus Basin, non-marine conditions developed after a brief clastic marine phase while in the southern Canning Basin hypersaline conditions dominated.

The Larapintine Seaway therefore had a history spanning much of the Ordovician; for much of this time its development was controlled by sealevel changes which are mostly of eustatic significance. An understanding of the history of the seaway and of these sealevel changes is important for hydrocarbon prospectivity in the three basins discussed. Source rocks, linked to the presence of *Gloeocapsamorpha prisca* (Hoffman and others, 1987), are present in all the basins, and appear linked to relative sealevel highs, while suitable reservoir rocks appear linked to sealevel lows. A greater understanding of the Ordovician in all the basins, but particularly the Canning, is needed to better assess hydrocarbon potential.

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Middle Cambrian phosphogenetic system in Australia

J.H. Shergold, P.N. Southgate and P.J. Cook, BMR

During the late Precambrian and Cambrian, global phosphogenesis resulted in the deposition of economically important phosphate deposits in many parts of the world. In Australia, major deposits in the Georgina Basin were formed during the Middle Cambrian, in close association with global sealevel changes. Sealevel fluctuations characterise many deposits, even though the phosphorites themselves may form under very shallow marine conditions ranging from shallow subtidal to intertidal, and probably even supratidal.

From the time of their discovery until quite recently all the phosphate deposits of the Georgina Basin were considered to occur within the Beetle Creek Formation an assumed to have the same age - Templetonian (Middle Cambrian). First doubts on their contemporaneity arose from the recognition of a laterally widespread and persistent erosion surface (Bronco Stromatolith Bed) immediately overlying the phosphatic lithofacies suite of the Thorntonia Limestone and correlatable Beetle Creek Formation in the northeastern portion of the Georgina Basin. Disconformity surfaces or faunal hiatii identified at discrete stratigraphic intervals in the Basin have subsequently permitted the recognition of three disconformity-bounded sedimentary sequences, each containing repeated lithofacies associations which include phosphorites. Faunal differentiation may occur within these associations so that biofacies controls must now be assessed in spatial (environmental) as well as temporal contexts.

The earliest Georgina Basin phosphorites, of Ordian and/or earliest Templetonian age (Event 1)(Fig.1); occur in a complex facies mosaic directly related to gradual transgression over an irregular palaeotopography. Five facies suites are recognised : basal clastics and redbeds, sub-basinal and peritidal phosphatic carbonates and phosphorites, peritidal carbonates, deeper water finely laminated micritic dolostones and basinal black shales. The Ordian sequence rests unconformably on Proterozoic basement and is everywhere capped by a subaerial disconformity surface. Four types of shallowing-upward cycles, three phosphatic and one calcareous, each culminating in emergence, are recognised in the peritidal and sub-basinal portions of the Ordian sequence. In situ phosphatic hardgrounds, stromatolites, phoscrete profiles, and desiccated mudstone and fenestral phosphorites occur at the tops of the three phosphatic cycles. Calcrete crusts, laminoid fenestral dolostones, desiccation polygons and teepee structures typify the uppermost parts of the calcareous cycle. Sub-basinal and peritidal phosphatic carbonates and phosphorites developed in areas of sea-floor irregularities where basement palaeotopography controlled bathymetry. Peritidal carbonate facies developed on evenly sloping

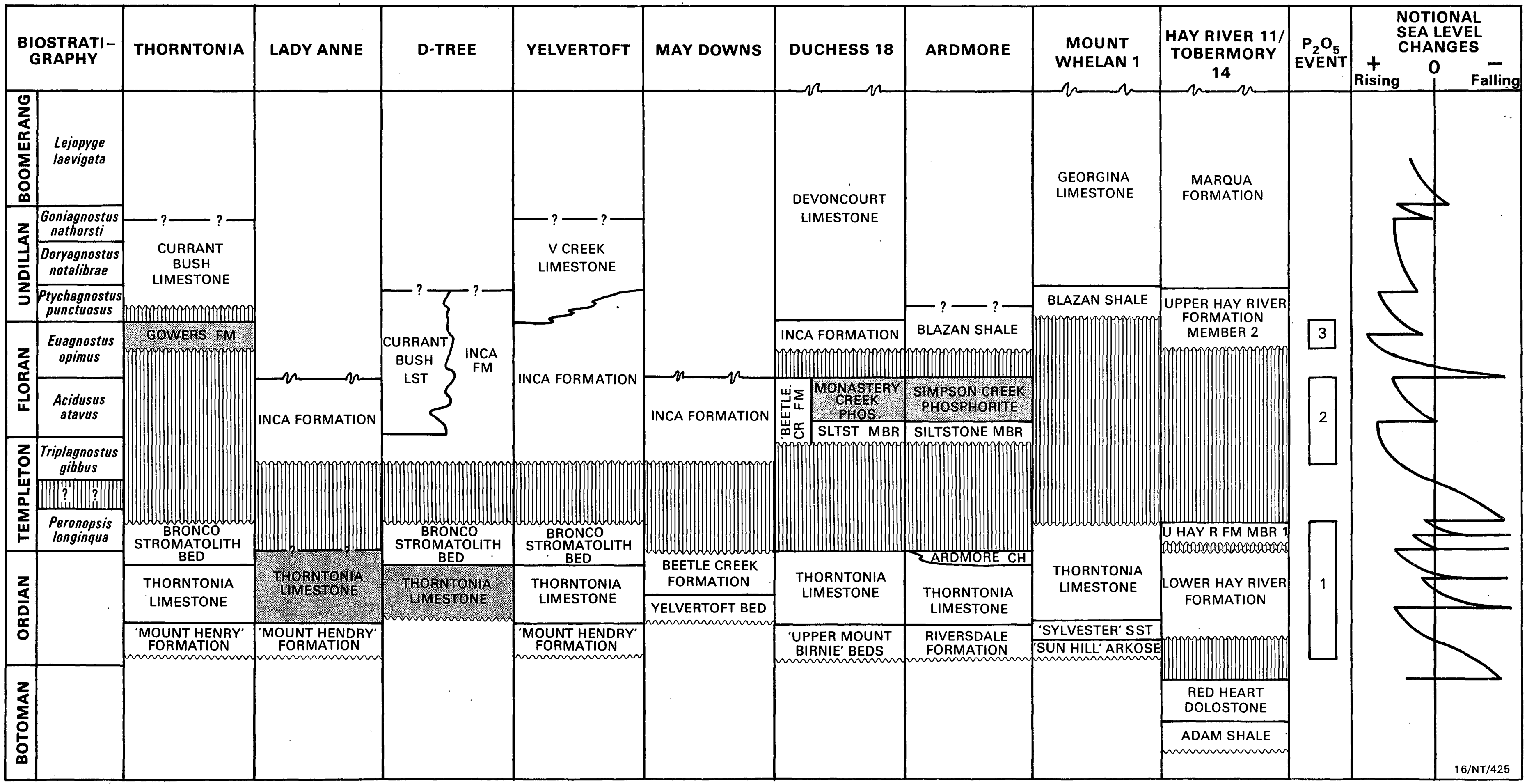

Figure 1: Correlation of phosphogenetic events in the Georgina Basin, northern Australia

platforms in areas of negligible sea-floor relief. In the northern and eastern parts of the basin gradually shallowing peritidal carbonates, phosphatic carbonates and phosphorites herald late Ordian regression and the development of a karst surface on top of the Thorntonia Limestone. Between Thorntonia and Yelvertoft phoscrete profiles, vadose cements and vertically-stacked trilobite conquinas are interbedded with laterally extensive sheets of stratiform stromatolites which accreted in a fresh water algal marsh. Peritidal carbonates underlie the disconformity in the Burke River Structural Belt and at Ardmore peritidal carbonates and evaporites mark it. In the southern parts of the basin, in the vicinity of Tobermory 14 and Hay River 11, gradually shallowing peritidal facies are absent. Instead a 1 metre thick interval of conquinite forms a sheet-like deposit capping deeper water and basinal, black shale and fine grained micritic carbonate.

During the Ordian/early Templetonian interval, three quite distinct trilobite biofacies are recognised and their occurrence related to environmental parameters such as basin salinity and anoxicity. The peritidal carbonates of the Thorntonia Limestone contain an association of the genera <u>Redlichia</u> and <u>Xystridura</u> representing the Ordian Zone of <u>Redlichia chinensis</u> as earlier reported by Öpik. Deeper subtidal environments, such as those of the Beetle Creek Formation at its type locality, are dominated by species of <u>Xystridura</u> to the virtual exclusion of <u>Redlichia</u> and other trilobites. This assemblage has been considered to represent the early Templetonian Zone of <u>Xystridura templetonensis</u>. A third biofacies, however, is also apparent and represented by a much more diverse assemblage of polymeroids, eodiscoids and a greater variety of agnostoid trilobites. This has been referred to the early Templetonian <u>Peronopsis longinqua</u> Zone, and are currently considered coeval based on the sedimentation cycles, lithofacies mosaics, and erosional events recognised in the Undilla area, and correlation accordingly of phosphatic and non-phosphatic lithofacies there, ie. the correlation of the non-phosphatic Beetle Creek Formation at its type locality with both phosphatic and non-phosphatic Thorntonia Limestone and the phosphate deposits of the Undilla Sub-basin. This has considerable palaeogeographic ramification as formations throughout the Georgina Basin are correlated within the reconstituted time slice.

Phosphate deposits occurring in the Ardmore Outlier and south of Duchess in the Burke River Structural Belt, eastern Georgina Basin (Event 2)(Fig 1), have also been referred to the Beetle Creek Formation, and assigned a Templetonian age because the trilobites which occur in the siltstone dominated lower part of the formation there represent a xystridurinid biofacies similar to that of the <u>Peronopsis longinqua</u> Zone. It does, however, contain other polymeroid trilobite genera and agnostoid trilobites, which relate it to a younger Middle Cambrian, probably early Floran, zone of overlap between Triplagnostus gibbus and Acidusus atavus. The phosphatic "Beetle Creek Formation" of the Burke River Structural Belt is therefore demonstrably younger than the Thorntonia Limestone and its correlatives. These younger phosphorites occur in a simpler lithofacies mosaic genetically related to tectonic subsidence of the Mt Isa Block. Sub-basinal and peritidal phosphatic carbonates and phosphorites (Monastery Creek Phosphorite Members) overlie black siltstones and cherts (Siltstone Member of the "Beetle Creek Formation") which locally interdigitate with the phosphatic sediments. A rich and diverse fauna occurs in the phosphatic carbonates and phosphorites. Shallowing in the early Foran Acidusus atavus Zone resulted in local subaerial exposure of phosphorites in the Burke River area and shallowing upward trends in the remaining sequence. This shallowing phase preceded a major relative rise in sealevel late in the zone of Euagnostus opimus that eventually drowned the platform and terminated phosphate deposition. Peritidal phosphatic carbonates and phosphorites (Gowers Formation) were deposited around palaeohighs during the early stages of this transgression (Event 3) in the northeastern part of the Georgina Basin. Continuation of the transgression during Undillan time produced an onlapping sequence in the Burke River Structural Belt, and eventually led to the accumulation of peritidal carbonates in the southwestern and northern parts of the basin, bordering a drowned platform or ramp on which the deposition of ribbon, parted and rhythmically laminated limestones continued.

The processes of phosphogenesis are complex and have been considered related to oceanic anoxic events. They are also closely related to palaeoclimatology, palaeobathymetry and proximity to appropriate upwelling oceanographic systems. These factors influence the basic geochemical ingredients and provide the geographic setting for the deposition of phosphorites. Global sealevel rise at the beginning of the Middle Cambrian is represented by the Ordian transgression which distributed phosphate enriched waters across the Georgina and conterminous basins. Late Templetonian to early Undillan transgression over a foundering Mount Isa Block gave rise to two further phosphogenetic events, each also related to globally rising sealevel and local sea floor topography.

Controls on Jurassic Non-marine Sedimentation in Eastern Australia:
Evidence from the Clarence-Moreton Basin

P E O'Brien & A T Wells, BMR

A large part of eastern Australia is covered by the Mesozoic fluvial and lacustrine rocks of the Eromanga, Surat and Clarence-Moreton Basins (Fig.1). Lithostratigraphic schemes in these basins reflect major changes in depositional style and sediment composition (Fig. 2, Table 1). This study examines sedimentation changes in the Jurassic Bundamba Group of the Clarence-Moreton Basin in order to understand the processes that caused them. In particular, the study aims to test the hypothesis that most sedimentation changes in the Jurassic sediments of the Surat, Eromanga and Clarence-Moreton Basins were caused by eustatic sea-level changes (Exon & Burger, 1981).

In order to recognise which processes were dominant in shaping depositional styles in the Bundamba Group, the study integrates facies analysis, palaeocurrent data, palynology, sandstone composition and the study of basin tectonics. These lines of evidence are interpreted in terms of drainage basin processes and fluvial sedimentology.

The major influences on fluvial sedimentation styles are:

1. Source area lithologies and topography that control the volume, composition and calibre of sediment supplied to the rivers (Grantham & Velbel, 1988).
2. Climate that controls discharge, sediment composition and volumes, and vegetation cover (Schumm, 1977).
3. Basin subsidence rates influence rates of deposition and river slopes, and avulsion to aggradation ratios determine sandstone - shale ratios and sandstone body geometry (Alexander & Leeder, 1987).
4. Base level changes related to sea level or tectonism, control stream long profiles and hence aggradation or erosion (Mackin, 1948).
5. Groundwater systems in the basin can draw off water from a river or crop out to produce lakes and swamps, so changing the fluvial style.

The Clarence-Moreton Basin formed by thermal relaxation of the crust after Permian to Triassic transtension. The large strike-slip faults that controlled the transtension episodes remained active throughout basin development introducing variations to subsidence rates. The Late Triassic to Early Jurassic fluvial sediments of the Bundamba Group in the Clarence-Moreton Basin contain abundant plant debris and thin coals and lack red palaeosols

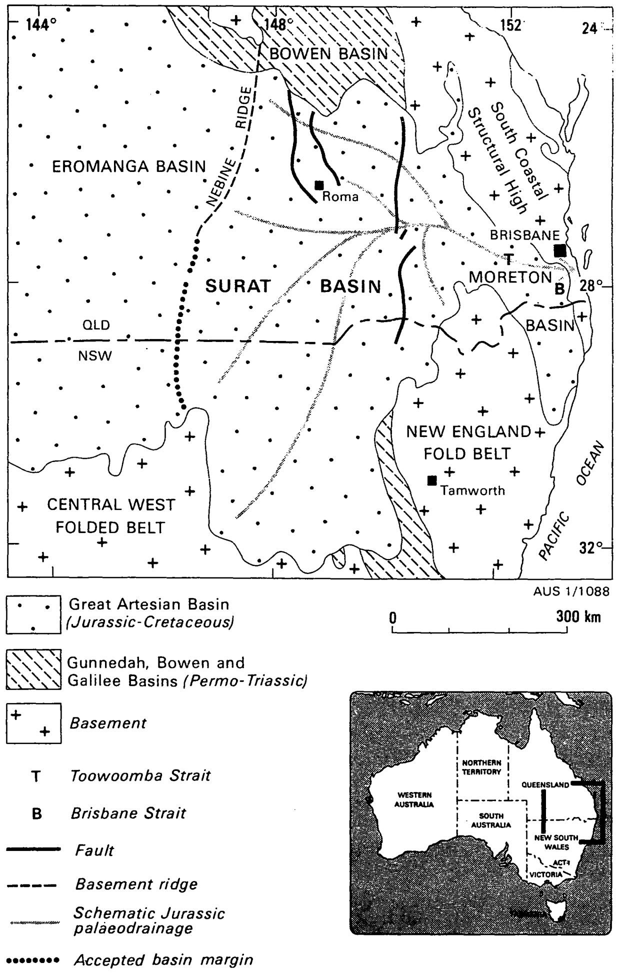

FIGURE 1. Regional setting of the Clarence-Moreton Basin from Exon & Burger (1981). Palaeocurrent data from the Clarence-Moreton Basin shows that Jurassic palaeodrainage did not flow through the Brisbane Strait as shown by Exon & Burger (1981) but flowed north to north-east across the South Coast Structural High.

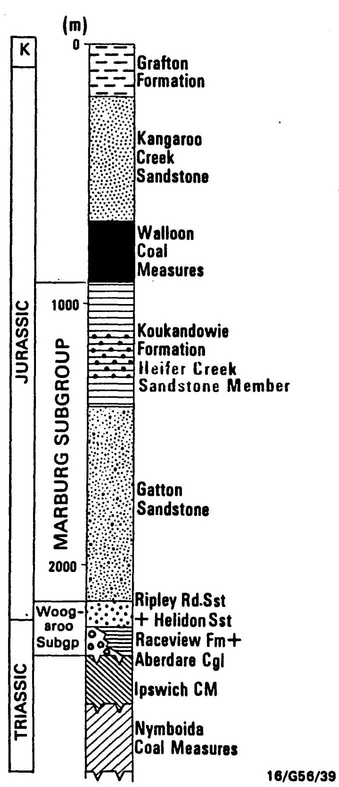

FIGURE 2. Stratigraphy of the Clarence-Moreton Basin.

indicating humid climates during deposition so that changes cannot be ascribed to large climatic fluctuations.

Most changes in sedimentation in the Clarence-Moreton Basin result from tectonic effects (Table 1). Tectonic rejuvenation is reflected in re-arrangement of palaeocurrent patterns, influxes of coarse detritus from uplifted basement blocks and increased proportions of lithic grains and feldspar in the sandstones because of steeper slopes in the basin hinterland. Erosional maturation of the hinterland is indicated by quartzose detritus replacing lithic grains in the sandstones.

Low sandstone-shale ratios in units indicate relative rises in base level because the rising base level reduces stream gradients favouring aggradation, so lowering the avulsion-aggradation ratio. Lower stream gradients also favour a change from braided streams to meandering and anastomosing patterns. Three rises in relative base-level occurred during Bundamba Group deposition, two resulting from tectonic subsidence affecting the Raceview Formation and the Koukandowie Formation in the Logan Sub-basin (Table 1). The third initiated the change from the Gatton Sandstone to the Ma Ma Creek Member of the Koukandowie Formation and caused simultaneous facies changes in the Surat, Eromanga and Nambour Basins. It probably stemmed from a eustatic sea level rise. However, palaeocurrent data indicates that any connection to the sea was well north of the Clarence-Moreton Basin so that tectonic damming of the distal part of the drainage system cannot be entirely ruled out. Facies assemblages associated with this sedimentation change make climatic change or variations in in-plane tectonic stresses unlikely causes.

The replacement of shaley units deposited in response to base level rises by sheet-like sandstone units (e.g. Ripley Road and Helidon Sandstones replacing Raceview Formation, Heifer Creek Sandstone Member replacing Ma Ma Creek Member) probably reflects the build up to steeper, near-graded stream profiles. After base level rises, streams aggrade to increase slope. Increased slope may cause a change from meandering to braided stream patterns and graded streams transport all their detrital load (Mackin, 1948) so that avulsion-aggradation ratios are relatively high, resulting in relatively high sandstone-shale ratios. Falls of regional base level cause regional down cutting. Large amounts of down cutting are only visible locally in the Bundamba Group suggesting that regional falls did not take place.

Therefore, sedimentation changes in the Bundamba Group of the Clarence-Moreton Basin

TABLE 1. Sedimentation changes in the Bundamba Group, Clarence-Moreton Basin.

FORMATION	CHARACTERISTICS	CONTROLLING PROCESSES
Aberdare & Layton's Range Congs. Raceview Fm.	Alluvial fan & valley fill conglomerates passing basinwards into mixed load fluvial sediments. Lithic sandstones. Radial palaeocurrents.	Initial rapid subsidence. Flat basin floor and steep edges.
Ripley Road & Helidon SS.	Sheet-like, bedload stream deposits. Quartzose sandstones. S to N palaeocurrents in E, W to E in the W.	Landscape matured and streams reach grade after initial subsidence. Subsidence possibly slow so high Avulsion/ Subsidence.
Gatton SS.	Sheet-like, bedload stream deposits. Diachronous change to lithic sandstones. Palaeocurrents all S to N. Some basement blocks emerge briefly.	Tectonic rejuvenation of basement areas, tilting of the W part of the basin.
Ma Ma Creek Mbr. Koukandowie Fm.	Lacustrine and suspended-load fluvial sediments. Chamositic oolite, brackish water acritarchs. Change mappable through adjacent basins.	Base level rise, probably sea level rise or tectonic damming of the distal end of drainage system.
Heifer Creek Mbr., Koukandowie Fm.	Sheet-like, bedload stream deposits. Quartzose sandstones. S to N palaeocurrents.	Re-establishment of graded system after base level rise. Mature landscape providing quartzose detritus.
Koukandowie Fm above Heifer Creek Member (East only).	Mixed-load & bed load stream deposits. Lithic sandstones. S to N palaeocurrents.	Tectonic rejuvenation and slightly increased subsidence in the east (Logan Sub basin).

indicate that eustatic sea-level changes can have a major influence on fluvial systems in intractonic basins. However, not every major change can be automatically ascribed to sea-level fluctuations. In the case of the Jurassic sediments of eastern Australia, tectonic changes were responsible for most changes in sedimentation.

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Palaeogeographic maps and their application

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If palaeogeographic maps are to be useful to the exploration industry they must be developed from a comprehensive data base that encompasses all available lines of evidence. They must also be as accurate as possible and this requires, as a starting point, the most precise biochronological framework, whether "snapshots" or "time slices" are used as a basis for mapping. Finally, it is necessary to be able to readily update the maps. Bearing these and other factors in mind, BMR developed a three-year palaeogeographic mapping project, the aim of which was to produce a complete series of palaeogeographic maps for the Phanerozoic of Australia. Through the provision of support from the Australian Petroleum Industry Research Association (APIRA), and the cooperation of the sponsoring companies and many individuals and groups within BMR, a complete set of maps has been compiled.

The first and most protracted phase of the project was the compilation of basic data from published and unpublished literature, and drillhole information etc. From the literature review it was possible to establish the minimum number of stratigraphic columns necessary to characterise the stratigraphy of the continent. For example, a total of 58 sections was needed to characterise the Cambro-Ordovician stratigraphy of the continent as a whole. Information compiled for each section included thickness, grain size, lithology, sedimentary structures, palaeontology, etc. Additionally, a separate interpretative sheet, including such information as inferred depositional environment, tectonic environment, provenance, and sea-level changes, was also compiled for each section.

The information from each of the detailed data sheets was summarised into a single column and then placed in a biochronological and isotopic age framework. It was then possible to make intra- and inter-basinal correlations, and to establish where the main time breaks or major lithological changes occurred for the continent as a whole. These were then used to "bracket" sedimentologically significant time slices, some of which may approximate to seismic sequences. Obviously, the finer the time intervals, the more accurate the resultant palaeogeographic maps. However, it was often difficult to extend time lines from the craton into the Tasman Fold Belt, because of the lack of fossils in many of the volcanic and flysch sequences of the latter. The complex deformational history of the fold belt added to the difficulties.

For each time slice, a data map was compiled. This includes information such as areas of outcrop, subcrop, well sites, lithology, thickness, and the presence of such environmentally significant minerals as evaporites (halite, trona, sulphates), phosphorites (collophane), glauconite, chert and organic matter. Igneous rocks and metamorphic events are also shown.

Before production of the palaeogeographic maps a "structural element" map was compiled showing tectonic features for each Period. The rationale for doing this was that major tectonic features were likely to have profoundly influenced the depositional framework and hence the palaeogeography. Unlike the data maps, this map was inevitably partly factual and partly interpretative. The fold belt features tend to be more problematical than those of the craton. However, the delineation of cratonic features is not without its problems, as exemplified by the inclusion of the Arunta Block in the category of basement, despite the fact that it underwent extensive uplift and deformation in the mid to late Palaeozoic. Additionally, in some areas of the craton there is no deep drilling information or preserved sequences, and any interpretation of depositional environment is highly speculative.

The next stage of the project was the production of palaeogeographic maps for the selected time slices. Lithologies are represented by broad patterning. Environmental interpretations (continental, marine, etc.) are superimposed upon lithology in colour. Ideally, a palaeogeographic map represents the continent-wide disposition of depositional environments and lithologies at an instant in time. The broader the time slice, the less precise the palaeogeographic map will be.

Organic geochemical data available in the public domain were compiled separately. Where possible, parameters such as total organic carbon, vitrinite reflectance, kerogen type and composition (H/C and O/C ratios, $\delta^{13}C$), extractable organic matter composition (abundance of saturates, aromatics, asphaltenes, n-alkanes, pristane to phytane ratios) were compiled.

Maps have now been compiled for 71 time slices throughout the Phanerozoic, representing intervals of time ranging from as little as 1 million years to as much as 30 million years. Taken together, these maps provide a graphic picture of the way in which the mosaic of depositional environments and sediment types, relative sea level, landforms, and climate have changed through time.

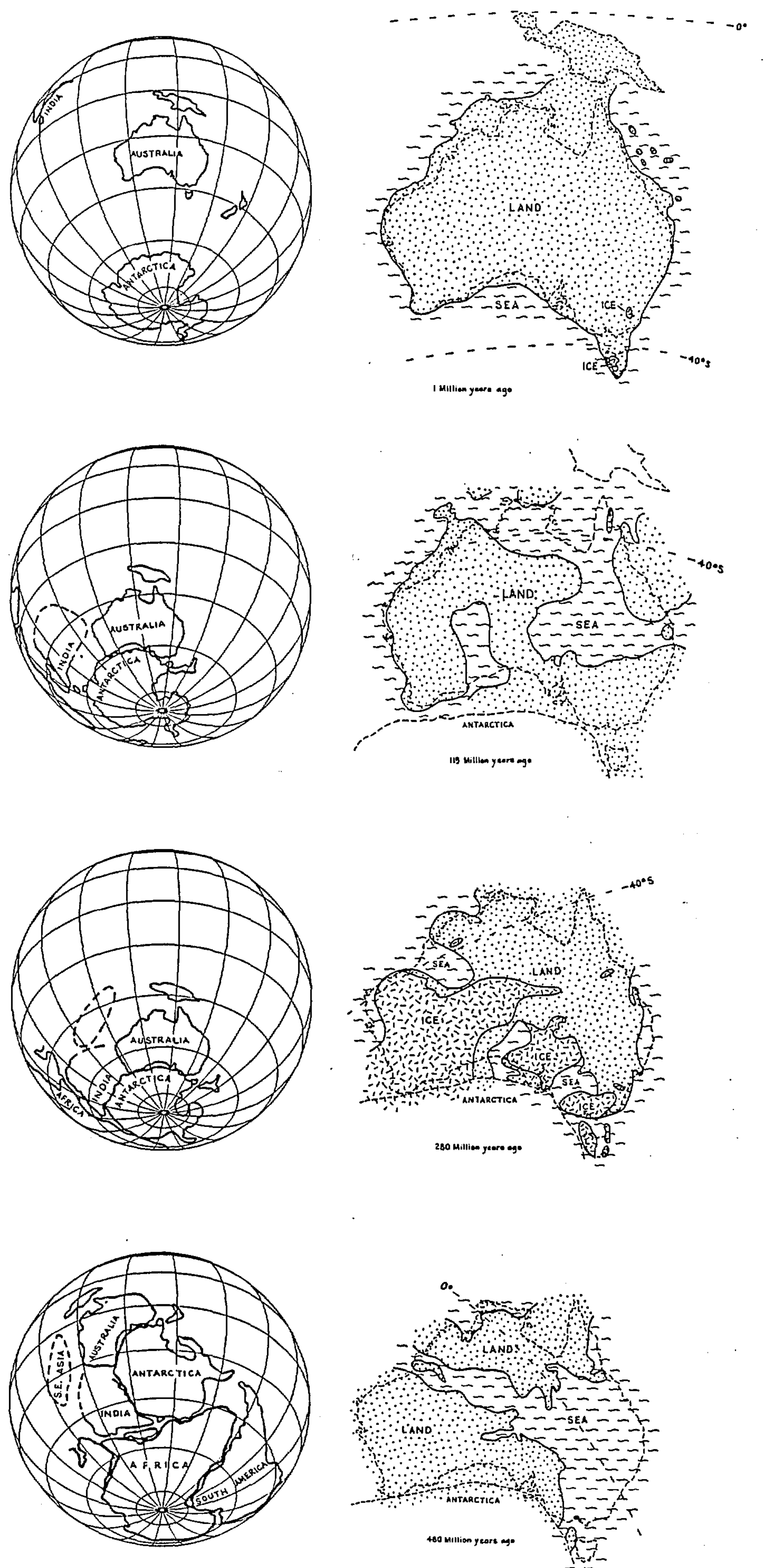

Figure 1: Summary palaeogeographic maps of Australia.
(a) 1 million years, (b) 115 million years, (c) 280 million years, (d) 480 million years.

Right at the start it was recognised that there would be, inevitably, shortcomings in the maps. Perhaps the most serious of these is that the maps are not on a palinspastic base. This is because there is no agreed set of reconstructions for the Australian Palaeozoic, and insufficient work has been undertaken to identify terranes in eastern Australia with confidence. Conversely, on the craton (other than in the Amadeus Basin) the lack of a palinspastic base probably does not matter greatly unless it is necessary to take into consideration the Kimberley transcurrent fault or the Gambier-Beaconfield Fracture Zone. Therefore, while we recognise there is a problem (and one that will be addressed in the next phase of the project) we consider that for much of the continent the maps do provide a useful portrayal of the palaeogeography. The second feature which some might feel constitutes a short-coming is opting for a time slice rather than a snapshot approach. Obviously, any map of a time slice represents a generalisation of the palaeogeographic conditions over a period of several million years. However, this is the best that we (or anyone else) can currently do on a continent-wide basis. In addition, taking a time slice approach provides us with the opportunity to address the vertical dimension more readily, because sediment thicknesses deposited within time slices were compiled, thus enabling us in the next phase of the project to use our data sets for undertaking broadscale geohistory modelling. However, for the present we have completed only the compilation of the maps. A few of these are produced in summary form in Figure 1, to show some of the more notable features of Australian palaeogeography.

In conclusion, the maps we have compiled to date are seen as only a starting point for Australian palaeogeography in that they have not been compiled on a palinspastic base. They nevertheless represent a major step forward in our understanding of the history of the continent and provide for the first time a comprehensive set of Phanerozoic maps that can be used for the development of exploration concepts and the assessment of undiscovered resources.

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In addition, folios of the following Periods are in preparation and will be published over the next 1-2 years.

Cainozoic	:	Wilford
Cretaceous	:	Bradshaw
Jurassic	:	Bradshaw
Triassic	:	Yeates
Permian	:	Brakel
Carboniferous	:	Brakel
Devonian	:	Yeates
Silurian	:	Yeates
Ordovician	:	Cook & Totterdell.

PALAEOGEOGRAPHIC EVOLUTION OF THE NORTH WEST SHELF REGION

Bradshaw, M.T., Yeates, A.N., Beynon, R.M., Brakel, A.T., Langford, R.P., Totterdell, J.M., & Yeung, M.

The BMR/APIRA Palaeogeographic Maps Project has produced environmental reconstructions of Australia for seventy time slices, from the Cambrian to the Recent. The comprehensive coverage allows the geological history of the North West Shelf to be viewed in the context of the wider region, as Australia evolved from part of Gondwana to the island continent (Bradshaw et al., 1988).

The southwest-northeast trend of the present coastline mirrors the structural grain of the series of sedimentary basins underlying the North West Shelf. All share a similar geological history and can be considered as parts of one superbasin, the Westralian Superbasin (Yeates et al., 1987).The superbasin is distinguished from the older onshore basins by having opposing structural trends and a thick Mesozoic sequence in contrast to a thick Palaeozoic section with a thin drape of younger sediments, that characterises the onshore basins. The sedimentary fill(c. 10km) of the superbasin ranges in age from Permian to Early Cretaceous, and is composed of fluvio-deltaic to marine clastics, with minor carbonates. The predominantly rift phase superbasinal sequence is overlain by a seaward thickening wedge(over 4km in places) of carbonate and minor clastics of Cretaceous to Recent age, deposited as a marine passive margin sequence.

The region's palaeogeographic evolution reflects a history of changing tectonic regime, climate and sea level. Since the Late Palaeozoic there has been a progression from intracratonic rift (Fairbridge, 1982) to passive margin (Falvey, 1974) with a late phase of collision, paralleled by a shift in climatic regime from glacial conditions in the Permian to the tropical seas of today. Superimposed on these major controls was an alternating pattern of transgression and regression, which produced a shifting mosaic of environments.

The initial rift was a southern arm on the periphery of Tethys, partly enclosed by continental fragments, the last of which rifted off in the Late Jurassic as seafloor spreading commenced in the Indian Ocean (Veevers, 1988). Deep narrow fault-bounded troughs were superimposed on the broad, southwest-northeast trending Triassic depoaxes in response to continental breakup (Veenstra, 1985). Subsidence of the margin followed, with some indications of wrench movements during the Cretaceous (Williams and Poynton, 1985). The regional northwest tilt of the margin continued through the Cainozoic, though Miocene to Recent faulting, interpreted as strike-slip (Forrest & Horstman, 1986) disrupted the gradual subsidence pattern, forming several en echelon anticlines. This tectonic activity may reflect the Pliocene continent - arc collision along the northern margin of Australia (Veevers, 1984).

Since the Permian, the North West Shelf has experienced an amelioration of climate from glacial conditions, through the humid regime of the Mesozoic into the tropical, and increasingly arid climate of the Cainozoic. This progression is the result of the shift in palaeolatitude northward, changes in continent and ocean configuration and fluxes in the global climate. The sediments reflect this change, ranging from Permian tillites, through Mesozoic fluvio-deltaic sands and marine shales, up into Cainozoic carbonates with only minor intermixed clastics.

Cycles of sea level change have imposed their rhythms on the North West Shelf region. The world-wide transgressive peaks of the Early Triassic, Late Jurassic and Early Cretaceous are well represented by the landward shift of marine facies, sometimes hundreds of kilometres. These peaks often correlate with the deposition of organic rich sediments, as in the Early Cretaceous and Late Jurassic. The Oligocene regression is also evident within the stratigraphy as a major unconformity.

Despite these eustatic oscillations there has been, from Permian to Cainozoic, a steady progression towards more marine facies, in response to the tectonic development of the region, from intracratonic rift to passive marine margin. Apart from imposition of this broad trend, the local tectonic regime has strongly influenced the lithology, geometry and distribution of sediments by determining the configuration of troughs and high platforms.

The interplay of changing climate, tectonics and sea level has controlled the palaeogeographic evolution of the North West Shelf and thus, its hydrocarbon potential. The major oil and gas reservoirs are in Triassic and Cretaceous fluvio-deltaic sands. Late Jurassic marine shales deposited during an episode of high sea level in narrow fault-bounded troughs provide the source rocks for these accumulations. A regional shale seal was deposited across the North West Shelf during the Early Cretaceous marine transgression, and the Cainozoic carbonate wedge has been important in the thermal maturation of the underlying sequence. Most traps are structural - fault blocks related to rifting and continental breakup, and anticlines formed in response to later compressional regime.

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Climatic and sea-level controls on the distribution of Mesozoic source rocks

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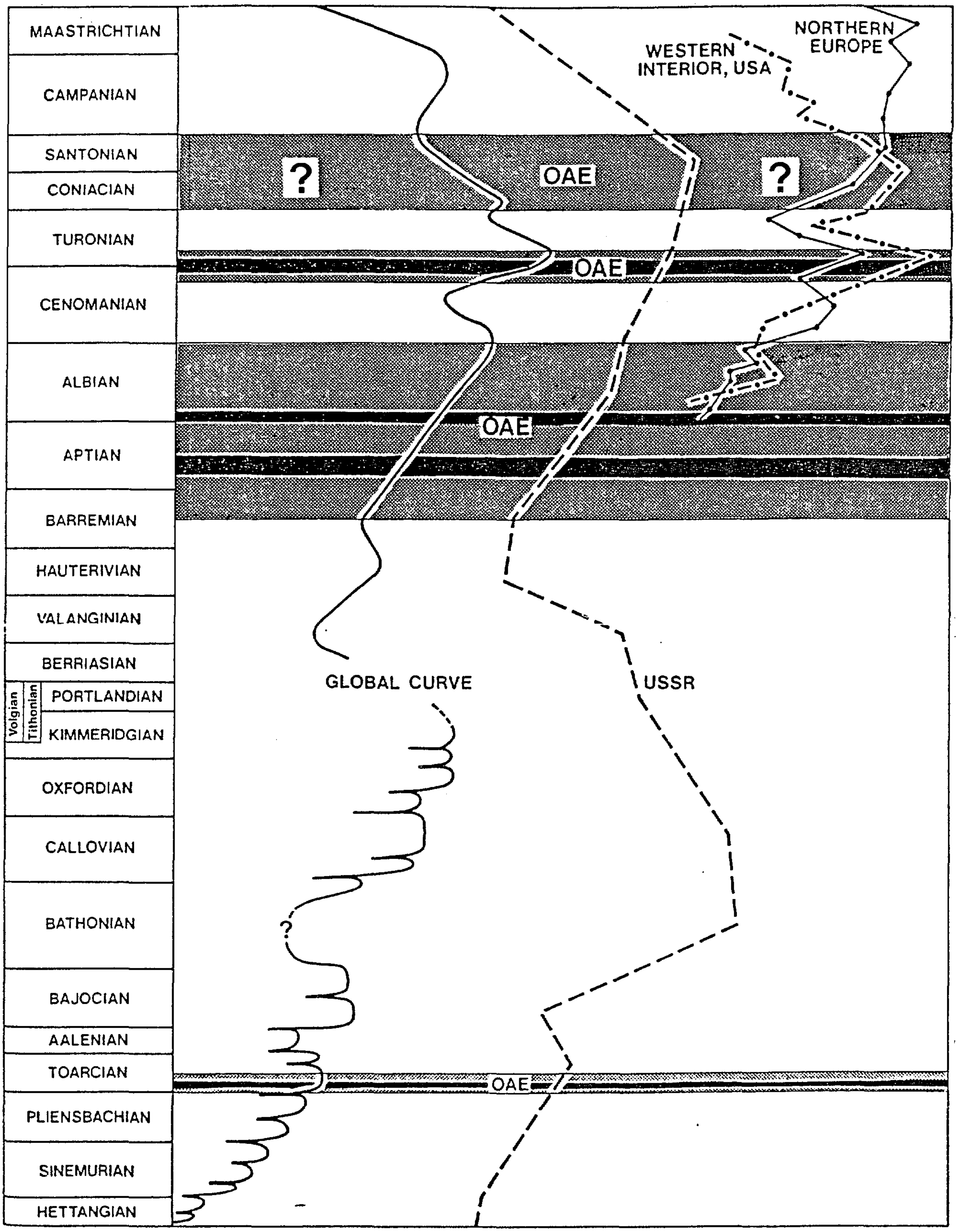
Organic matter in sediments of the Mesozoic is strongly concentrated globally in four time intervals: 1) Toarcian 2) Aptian-Albian 3) Cenomanian-Turonian boundary and 4) Coniacian-Santonian, as quantified by volume and delta C studies (Arthur et al., 1988). These Oceanic Anoxic Events (OAEs) are coincident with many petroleum source rocks in giant fields and are strongly correlated with major rises or peaks in sea-level as defined by both coastal onlap and continental inundation curves. On this basis OAEs, and global concentrations of organic matter might be expected but have not yet been demonstrated for other high stands, e.g. Bajocian, Oxfordian. One effect of high sea-levels which may have played a role in these cases is the inhibitation of clastic dilution of organic sediments. Correlations with climatic optima are less certain owing to the general scarcity of good time-series measurements of climatic data in the Mesozoic and there is the further complication that many good source rocks are related only to local or regional palaeogeographic or palaeoenvironmental controls.

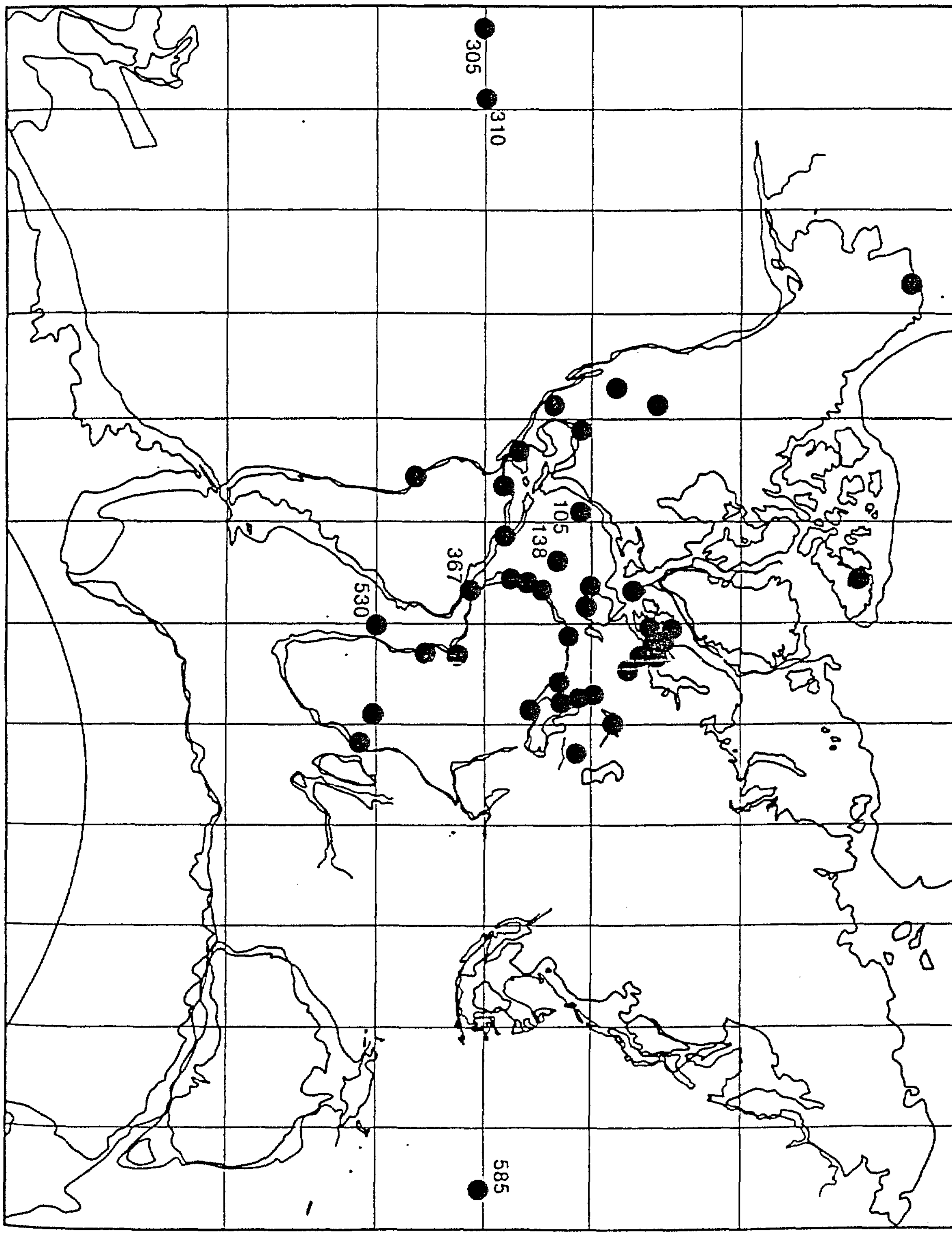
OAEs in fact correspond to variable climatic conditions; the Toarcian to a slight warming trend, the Aptian-Albian to late phrases of a coolish interval, and the C-T boundary and Coniacian-Santonian to near-peak warmth on a global basis. The latter two events took place during one of the warmest episodes in earth history, the Mesozoic "Ulti-thermal". Whereas the Toarcian was a relatively arid time, the Cretaceous OAEs occurred when the earth was becoming more humid. As deduced from organic geochemistry, the origin of organic matter at these critical times was also variable, reflecting increased organic productivity both on continents and in the deep sea. Possibly the only factor which could explain these varying relationships would be increased CO_2 fluxes to the ocean-atmosphere, thus enhancing biological growth and fertility.

On continents, warm humid mid to late Mesozoic climates generated abundant vegetation as shown in studies of fossil vegetation, and coincident



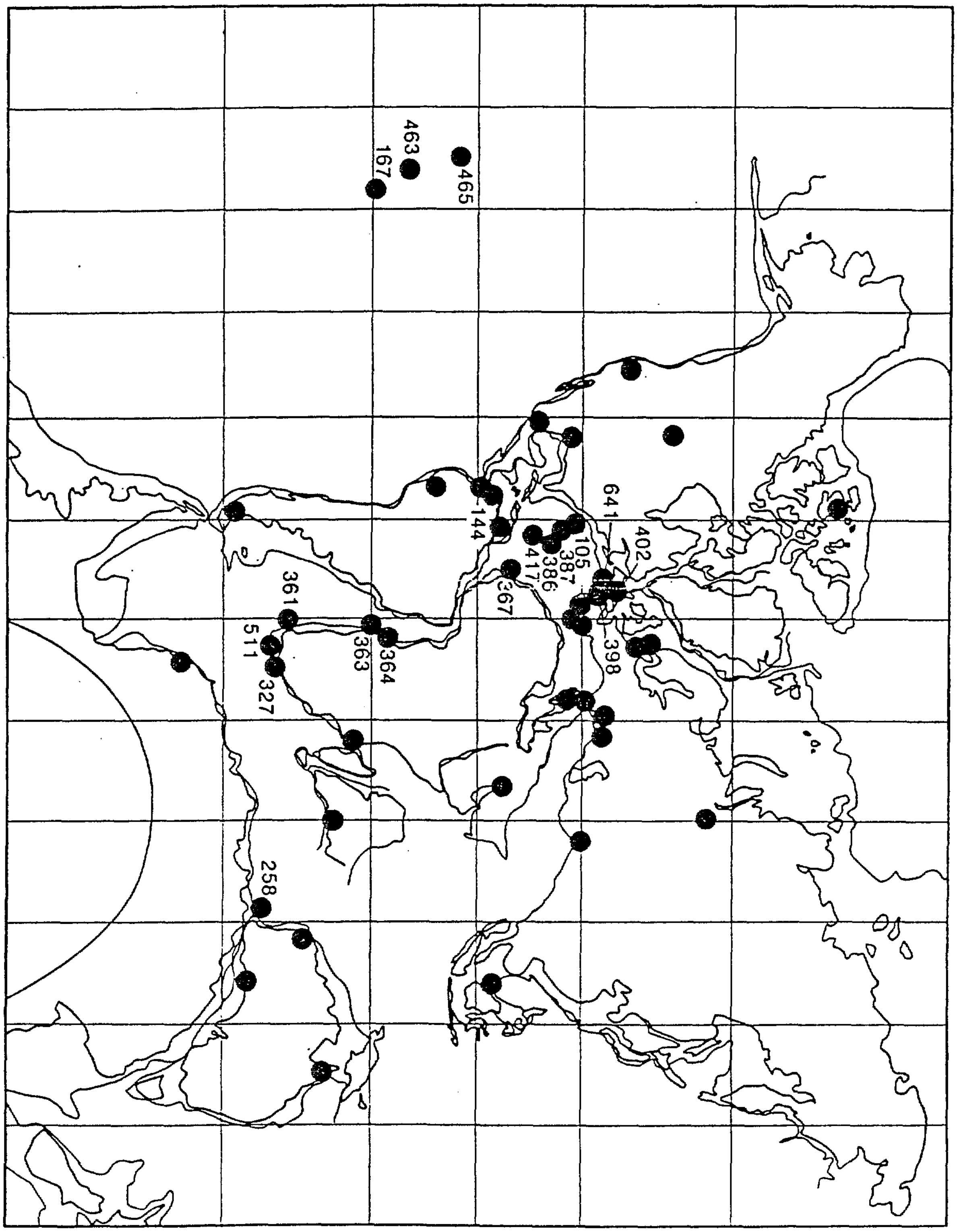
Jurassic and Cretaceous stages showing approximate timing of OAEs (Oceanic Anoxic Events); broad envelopes as defined by Schlanger and Jenkyns (1976) shown in stippled pattern, and proposed subevents or short-term organic carbon burial episodes.

(From Arthur et al., 1988)



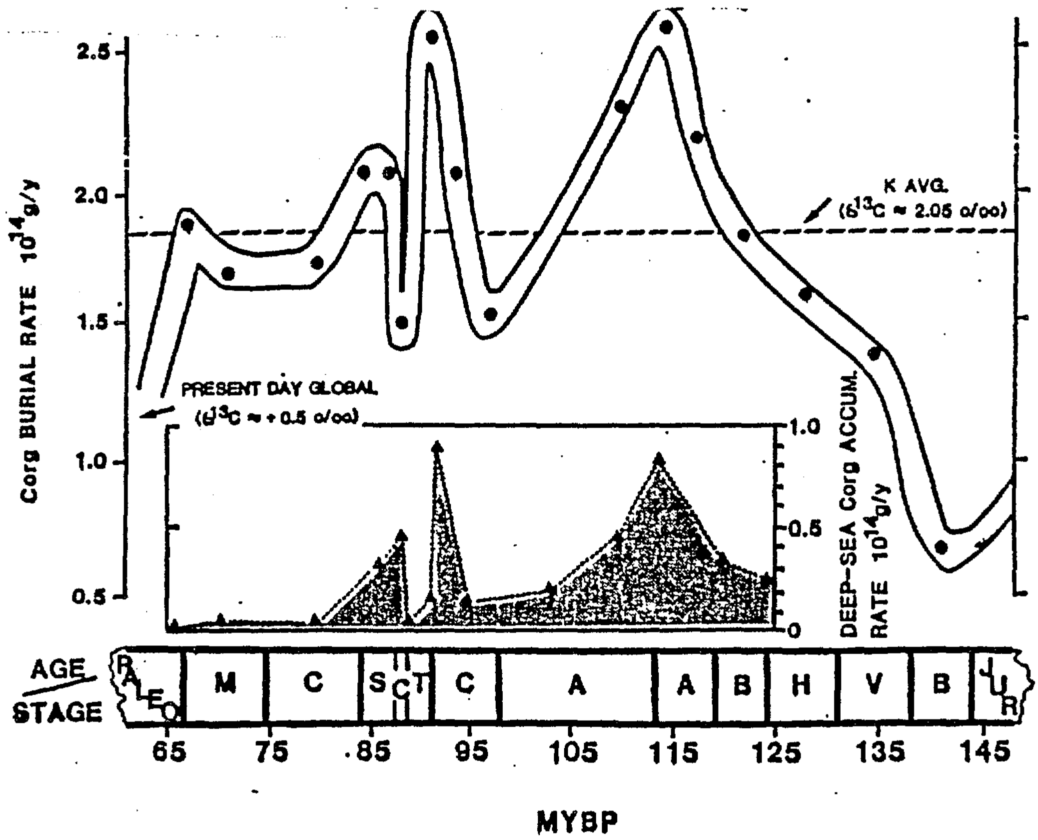
Continental reconstruction (see Barron, 1987) for early Turonian (90 myBP) time showing localities where organic-carbon rich strata of Cenomanian-Turonian age (OAE-2) have been documented. Numbered localities are Deep Sea Drilling Project Sites.

(From Arthur et al., 1988)



Continental reconstruction (Barron, 1987) for Albian time showing localities from which Aptian-Albian black shales are known. Numbered localities are Deep Sea Drilling Project Sites.

(From Arthur et al., 1988)



Estimated burial rates of Corg by stage or substage during the Cretaceous. Top curve is burial rate in 10^{14} g C yr^{-1}; the values were obtained using stage or substage carbon isotope averages, a modern $\partial^{13}C$ of +0.5 o/oo, and the model of Garrels and Lerman (1981) as corrected by Berner and Raiswell (1983). Inset shows average deep-sea Corg burial rates for stages or substages computed from Corg data for DSDP holes from Legs 1 through 48 (Arthur, 1982). Time scale is DNAG (1983).

(From Arthur et al., 1988)

intracratonic basins were sediment-starved due to high stands of sea-level (Western Interior Basin of North America, Eromanga Basin of Australia). Marine fertility also was high and the abundance of this organic material plus that derived from basin margins contributed to oxygen depletion and dysaerobia or anoxia in basins, particularly in those with restricted access to the open sea (e.g. Toolebuc Formation, Eromanga Basin). Numerical modeling has shown the liklihood of extensive monsoonal patterns along the margins of the Tethys during the Mesozoic, which may have contributed to extensive plant growth in northern Australia. Triassic and Jurassic source rocks of the North West Shelf apparently reflect this in being derived dominantly from terrestrial plant material (Locker Shale, Mungaroo Formation).

The southern Australian margin underwent an entirely different history. Residing mostly in high latitudes (>55^{o}) the region was segregated into several basins mainly in the early Cretaceous when cool but humid conditions prevailed. Possibly this, and heavy clastic dilution, hindered the development of extensive source rocks at this time except perhaps in the southern Gippsland Basin and parts of the Great Australian Bight Basin. There may be correlations between organic-rich shales of the Otway Basin and Oceanic Anoxic Events recognized globally.

The effects of eustatic sea-level change on sedimentary sequences, whether coincident with climate change or not, can give rise to the optimum combination of source, reservoir and seal rocks. For this to occur it would appear that regressions (perhaps reflecting falls of sea-level) are best suited to generate a petroleum source horizon overlain by reservoir rocks. Whereas seals may be developed internally within regressive sequences, they may also originate as fining upward sequences due to transgressive conditions (or sea-level rise). An effective source rock therefore is stratigraphically linked to reservoir and seal, and transgressive-regressive cyclicity provides an excellent mechanism for providing this. The added effect of climate varying in concert with sea-level rises and falls would be to increase the concentration or organic matter in sediments during high stands (due to increased plant growth and decreased sediment transport during warm intervals), and to increase the possibility of reservoir formation during low stands, due to lowered base level thus increased erosion in the hinterland.

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Depositional Controls on Source Quality, Composition and Distribution

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Studies of the depositional conditions favouring the preservation of organic matter have led to the development of the organic facies concept which allows prediction of the likely occurrence of source rocks as a function of depositional environment (Demaison & Moore, 1980) and particularly in the marine environment (Demaison et al. 1984). Recent developments open the possibility that these concepts can equally be applied to terrestrial source sequences (Powell, 1984; 1986). It has also long been known that one of the primary controls on the composition of crude oil is the depositional environment of the source bed. This can be related first to the nature of the primary source material (algal, bacterial or higher plant) and secondly to the depositional conditions which control the extent and nature of bacterial reworking prior to burial. There is a link therefore, between the source material and conditions of preservation of organic matter. This transcends the classification of organic matter as oil-prone or gas-prone and of oils as marine or non-marine. It enables the prediction as to whether the primary oil product is paraffinic, paraffinic-naphthenic or aromatic-asphaltic and the likely distribution of hydrocarbon biomarkers in oils from both marine and non-marine sequences.

Conditions favouring the deposition of organic-rich sediments in marine environments include:

A Anoxic or micro-oxic bottom conditions brought about by
- (i) silled basins
- (ii) impingement of oxygen minimum zone on the shelf particularly in upwelling areas. This may become particularly important at times of global warm-ups and major transgressions when expanded oxygen minimum zones may result.

B High relative sea level stands and maximum coastal onlap. This results in the lowering of base level and minimises the opportunity for dilution of a potential source material by clastic debris and terrestrial organic matter.

These factors often work in concert to produce major source rock sequences. In turn the combination of climatic, lithological and palaeogeographical controls serves to develop a series of distinctive organic source lithofacies in the marine environment (Table I) as follows.

A Clastic source facies
- (i) low to moderate sedimentation rates eg. Kimmeridgian N. Sea.
  - high TOC; homogeneous laminated mudstones

TABLE I

Possible correlation between source rock and oil characteristics with depositional setting in marine sequences

Environment	Source Rock				Oil Composition								Example (ref)
							Biological markers						
							Land	Bacteria				Algal	
salinity/clastic supply	Lithology	Org. C %	Kerogen type	Type	Pr/Ph	I/N	plant	A+I	Ipr	Hop	ArI	steranes	
Restricted Basin or depression													
normal/low	Calc shale	1 to >10	II low S	PN low S	0.8–2.0	0.4–0.8	*	*	*	**		***	Jur.–N. Sea
normal/high	Shale	<5	II/III v. low S	PN-P v. lowS	>3.0	0.4–0.8	**	*	*	**		**	Jur.-Carnarvon Basin
normal/v. low	Carbonate	1 to >10	II high S	PN-A high S	0.8–2.0	0.4–0.8		*	*	**	*?	***	Dev.-Alberta Basin
hypersaline/ v. low	Carbonate-evaporite	<1 to 5	II v. high S	AAS v. high S	0.4–0.8	0.6–1.5		*	**	**	***	***	Dev.-Alberta Basin
Upwelling-Restricted Basin?													
normal/v. low	Diatomite phosphatic carbonate/ shale	1 to >10	II V. high S	AAS v. high S	0.4–0.8	0.8–1.5		*	*	**	?	***	Mio-California

Pr/Ph = pristane to phytane ratio; I/N-pristane to n-heptadecane ratio or phytane to n-octadecane ratio where pr/ph <1; PN = paraffinic naphthenic; A = aromatic; AAS = aromatic asphaltic; S = sulphur; *** = dominant; ** = present; * = trace; A + I = anteiso- + iso-alkanes; Ipr = extended acyclic isoprenoids; Hop = hopanes; ArI = aryl isoprenoids; Land Plant = C_{29} steranes only and diterpenoids; Algal Steranes = C_{27} to C_{29} steranes.

(ii) high sedimentation rates eg. Kimmeridgian Lewis Trough, Carnavon Basin
- moderate TOC; thick mixed source facies of mudstones and siltstones.

B Carbonate and mixed source facies - Toarcian, Paris Basin; Devonian Alberta.
- organic-rich laminated micritic carbonates to argillaceous carbonates.

C Pelagic source facies - Monterey Formation, Miocene Califonia.
- organic-rich laminated micritic to argillaeous carbonates interbedded with cherts.

D Hypersaline facies - Middle Devonian, Alberta.
- interbedded organic-rich dolomite and evaporites.

In the case of non-marine environments the primary controls are the tectonic setting, climate and where terrestrial organic matter contributes to the preserved organic matter the stage of evolution of the land plants. Consideration of these factors serves to develop a series of distinctive organic source facies in the non-marine environment (Table II).

A Tectonic lakes - subsidence > sedimentation

(i) Deep lake facies, humid to semi-humid climate - Songliao Basin, China.
- thick mudstones and siltstones to varved calcareous sediments often oil shales. Deposited in deep fresh-brackish lakes which are eutrophic but may be oligotropic in early stages

(ii) Deep lake facies, semi-arid climate Uinita Basin, USA.
- varved calcareous sediments often oil shales may become interbedded with gypsiferous shales and occasional salt beds. Deposited in deep to shallow saline eutrophic lakes

(iii) lake facies arid climate - Jianghan Basin, China; Officer Basin, Australia.
- mudstone/carbonates interbedded with gypsum, salt or alkaline evaporites. Deposited in hypersaline and possibly playa lakes.

B Flood or delta plain - sedimentation = subsidence eg. Gippsland Basin, Eromanga Basin, Cooper Basin, Australia.
- coals and shales alternate and oil shales are rare. Deposited in ephemeral oligotropic or dystrophic lakes and peat bogs. Climate varies from humid to dry, warm to cool temperature.

TABLE II

Possible correlation between source rock and oil characteristics with depositional setting in non-marine sequences

Environment	Source Rock†		Oil Composition†									Example
							Biological markers					
							Land	Bacteria			Algal	
productivity/salinity	Org C %	Kerogen type	Type	Wax %	Pr/Ph	I/N	plants	A+I	Ipr	Hop	steranes	
Floodplain and Delta swamp	1 to >10	III to II/III	P	5-20	>3	0.4-0.8	***	***	?	**		Gippsland Basin-Aust.
	1 to >10	III to II/III R	NA	<5	>3	0.8-1.5	*** R	*	?	***		Mackenzie Delta-Canada
Floodplain Lake												
oligotrophic/fresh	1 to >10	II/III	P	5-20	>3	0.4-0.8	***	***	?	**		Eromanga Basin-Aust.
eutrophic/fresh	1 to >10	I to II/III B?	P	5-20	>3?	0.4-0.8	**	**	?	**	** b?	
Tectonic Lakes												
oligotrophic/fresh	1 to >10	I to II/III	P	>20	1-3	<0.1	**	***	*	*	*?	Uinta Basin-USA
eutrophic/fresh	1 to >10	I to II/III Pd, B	P	>20	1-3	0.1-0.3	**	*	*	**	** b?C?	Songliao Basin-China
eutrophic/saline	1 to >10	II Pd?	P?	5-20	<1-3	0.1-0.3?	*	*	**	**	*** C	Uinta Basin-USA
eutrophic/hypersaline												
sulphate	<1	II S	AAS S	5-20?	<1	0.5-1.5		*	**	**	***	Jianghan Basin-China
alkaline	<1	I to II	PN to A	<5	<1	0.5-1.5		*	***	**	***	Officer Basin-Australia

† Kerogens and oils are very low in sulphur except where indicated.
Pr/Ph = pristane to phytane ratio; I/N = Pristane to n-heptadecane ratio or phytane to n-octadecane where Pr/Ph <1; A+I = anteiso- + iso-alkanes; Ipr = extended acyclic isoprenoids; Hop = hopanes; R = resin and resin compounds present; B = *Botryococcus* present; Pd = *Pediastrum* present; S = sulphur-rich; P = paraffinic; N = naphthenic; A = aromatic; AS = asphaltic; b = botryococcane present; C = carotane present; *** = dominant; ** = present; * = traces. Land Plant = C_{29} steranes only and diterpenoids; Algal Steranes = C_{27} to C_{29} steranes.

There is now a considerable body of knowledge on the chemistry of source rocks and petroleum which can be related to specific geological settings (Tables I and II). At the same time conditions favourable for organic matter accumulation and preservation can be prediced from palaeogeography, geomorphological features and sea level considerations. Integration of this date with climatic and lithological information will enable a predictive and comprehensive model of source rock occurrence and composition to be achieved.

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Palaeoenvironmental and geological controls on the quality of the Toolebuc Formation oil shale, Queensland

S. Ozimic, BMR

The widespread Early Cretaceous oil shale-bearing Toolebuc Formation in the northern Eromanga and southern Carpentaria Basins (Fig. 1) consists of various proportions of calcareous oil shale and coquinite. To the south the Formation passes laterally into time equivalent sequences lacking oil shale; they are the Wooldridge Limestone Member of the Oodnadatta Formation and the Urisino Beds, which consist of coquinite, limestone, siltstone and sandstone.

The Toolebuc basin formed about 100 million years ago in a region 40^{o} to 70^{o} south of the Early Cretaceous palaeo-equator. The available geological and geophysical data show that the known Early Cretaceous sediments including the Toolebuc Formation were deposited in a single depression that constituted the Eromanga and Carpentaria Basins. Structure contours of the top Toolebuc Formation and time-equivalent units (Fig. 2) illustrate the present structural style in the two basins. Major structures affecting the depositional and post-depositional history of the Toolebuc Formation and time-equivalent units appear to be the Nebine Ridge and 'Canaway Fault Zone' (Fig. 2). The Nebine Ridge is postulated to have risen spasmodically during the Cretaceous and to have influenced sedimentation intermittently (Exon & Senior, 1976). This hypothesis is supported by pinch-out of the Toolebuc Formation against the western flank of the Nebine Ridge (Ozimic, 1981b), indicating that the transgressive Toolebuc sea lapped on but did not cross the Nebine Ridge into the Surat Basin. The 'Canaway Fault Zone' consists of a line of faults and fault-induced anticlines trending northeast along the Canaway Ridge, Canaway Fault, Stormhill Fault and Beryl Anticline (Fig. 2).

The Toolebuc Formation consists wholly of facies A and facies B (Fig. 1), which are each characterised by common lithologies, age, sedimentary and biogenic features, and boundary characteristics. However, a marked difference between the two facies in the ratio of coquinite to oil shale is the basic criterion for their differentiation. The totally marine fauna, presence of fine laminations and lack of sharp erosional boundaries indicate quiet marine conditions during deposition of the Toolebuc Formation. The great extent of the Toolebuc Formation (0.484×10^6 km^2), and absence of sand bodies or reef structures that could have formed lagoon barriers, suggest deposition in a large body of water. The nature of the organic matter which it contains, and the presence of regular fine laminations, suggest that the formation could not have developed on the bottom of a 'Toolebuc sea' in which the water was agitated by waves or currents. Preservation of organic matter was possible because of poor oxygenation. The coquinite layers represent recurrent conditions suitable for the establishment of specialised, low oxygen-tolerant, large-sized benthonic shelly faunas. Periodic

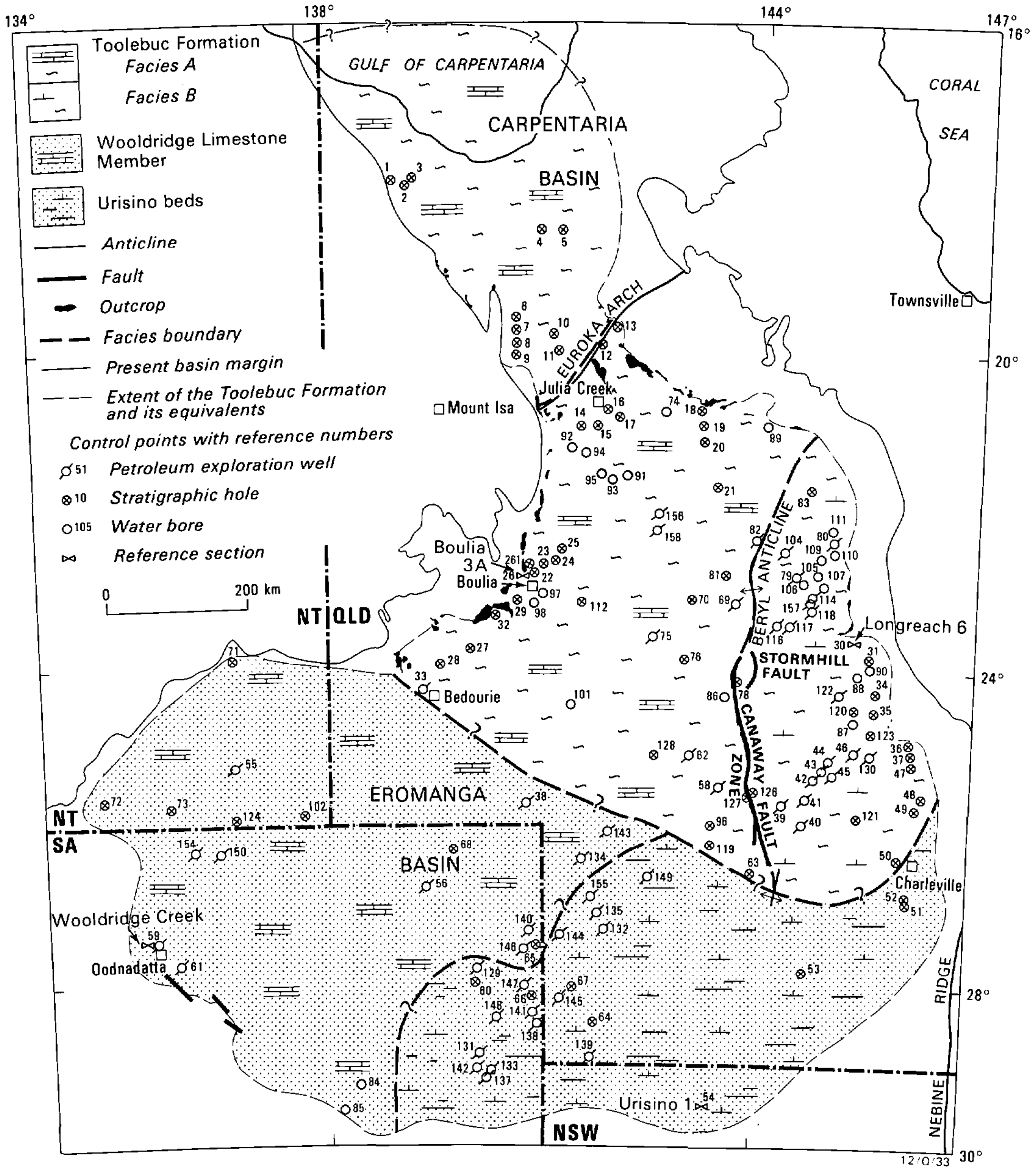


Fig. 1. Location and facies map, Eromanga and southern Carpentaria Basins (refer Table 1 for borehole references).

disappearance of those faunas is speculatively attributed to increased productivity of phyto- and zooplankton, which might have further depleted oxygen levels in the lower water column, and, or contaminated the water column with plankton debris, so that conditions were unsuitable even for low oxygen-tolerant filter feeders, such as <u>Inoceramus</u> and <u>Aucellina</u>. The organic matter in the Toolebuc Formation is of extremely uniform composition and is primarily sourced from marine matter which is largely algal or modified algal remains. In particular the abundance of coccolith remains strongly suggests that a large component of the organic matter was of planktonic origin (Boreham and Powell, 1987). Glickson and Taylor (1986) have identified filamentous remains which they ascribed to cyanobacterial mats. Sherwood and Cook, in their organic petrological study (1986), observed lamalginite representing up to 10 per cent of the rock. The precise affinities of cyanobacterial mats and the lamalginite are uncertain. Recognition of telalginite and lamalginite (Hutton & Cook, 1983)

TABLE 1. Stratigraphic control points

TABLE 1. Stratigraphic control points

Control Point No.	Borehole	Control Point No.	Borehole	Control Point No.	Borehole
1	Westmoreland 1	54	Urisino 1	107	RWB 1653
2	Westmoreland 2	55	Hale River 1	108	RWB 2348
3	Westmoreland 3	56	Pandieburra 1	109	RWB 3860
4	Croydon 1	57	Budgerygar 1	110	RWB 13234
5	Croydon 4	58	Thunda 1	111	RWB 13944
6	Dobbyn 1	59	Oodnadatta 1	112	Ooroonoo 1
7	Dobbyn 2	60	Gidgealpa 1	113	Belmore 1
8	Dobbyn 3	61	Toodla 1	114	Glenaris 1
9	Dobbyn 4	62	Barcoo Junction 1	115	Saltern Creek
10	Millungera 1	63	Eromanga 1	116	Longreach Oil 4
11	Millungera 2	64	Naryelco 1	117	Longreach Oil 1
12	Millungera 4	65	Innamincka 1	118	Marchmont 1
13	Millungera 5	66	Dullingari 1	119	Cumbroo 1
14	Julia Creek 1	67	Orientos 1	120	Fairlea 1
15	Julia Creek 2	68	Putamurdie 1	121	Carlow
16	Julia Creek 3	69	Penrith 1	122	Barcoo 1
17	Julia Creek 4	70	Fermoy 1	123	Boree 1
18	Richmond 1	71	Hay River 12	124	Colson 1
19	Richmond 2	72	Finke 2	125	Canary 1
20	Richmond 3	73	McDills 1	126	Yongala 1
21	Manuka 1	74	RWB 391	127	Yongala 1
22	Boulia 1	75	Mayneside 1	128	Galway 1
23	Boulia 2	76	Newlands 1	129	Merrimelia 1
24	Boulia 3	77	Stormhill 1	130	Bury 1
25	Boulia 4	78	Ban Ban 1	131	Kumbarie 1
26	Boulia 3A	79	Muttaburra 1	132	Karmona 1
261	Boulia 10B	80	Thunderbolt 1	133	Gurra 1
27	Springvale 6	81	Clyde 1	134	Gilpeppee 1
28	Springvale 6	82	Beryl 1	135	Durham Downs 1
29	Springvale 6	83	Tangorin 1	136	Coongie 1
30	Longreach 6	84	Clayton Bore	137	Cherri 1
31	Jericho 11	85	Well C.K. Bore	138	Brumby 1
32	Springvale 5	86	RWB 1474	139	Binerah Downs 1
33	The Brothers 1	87	RWB 378	140	Yanpurra 1
34	Tambo 37	88	RWB 2977	141	Toolachee East 1
35	Tambo 41	89	RWB 1043	142	Tinga Tingana 1
36	Tambo 42	90	RWB 2655	143	Tanbar 1
37	Tambo 44	91	RWB 3260	144	Tallalia 1
38	Betoota 1	92	RWB 2552	145	Roseneath 1
39	Cothalow 1	93	RWB 379	146	Packsaddle 1
40	Gumbardo 1	94	RWB 2549	147	Nappacoongee 1
41	Leopardwood 1	95	RWB 3268	148	Murteree 1
42	Gilmore 1	96	Chandos South 1	149	Mt Howitt 1
43	Log Creek 1	97	RWB 1674	150	Mokari 1
44	Etonvale 1	98	RWB 1676	151	Witcherrie 1
45	Stafford 1	99	RWB 4333	152	Warbrecan 1
46	Bonnie 1	100	RWB 4339	153	Hulton 1
47	Augathella 5	101	RWB 14486	154	Purni 1
48	Augathella 6	102	Thomas 1	155	Barrolka 1
49	Augathella 7	103	Towerhill 1	156	Weston 1
50	Charleville 5	104	Brookwook 1	157	Rand 1
51	Charleville 6	105	RWB 1645	158	Lovelle Downs 1
52	Charleville 7	106	RWB 1652		
53	Toompine 1				

suggests algal productivity in the euphotic zone and growth of algal mats on the seabed. The preservation of dead algal matter can be related to an oxidising-reducing boundary probably situated immediately below the base of the living algal mat layer, and keeping pace with its upward growth. Bubela (1980) found experimentally that algal mats constitute an effective boundary between the oxidising environment of the water in which they grow and the strongly reducing environment of the substrate (e.g. sediments or dead algal mats). Mat destruction can, however, result from environmental stresses such as salinity, temperature, and light changes.

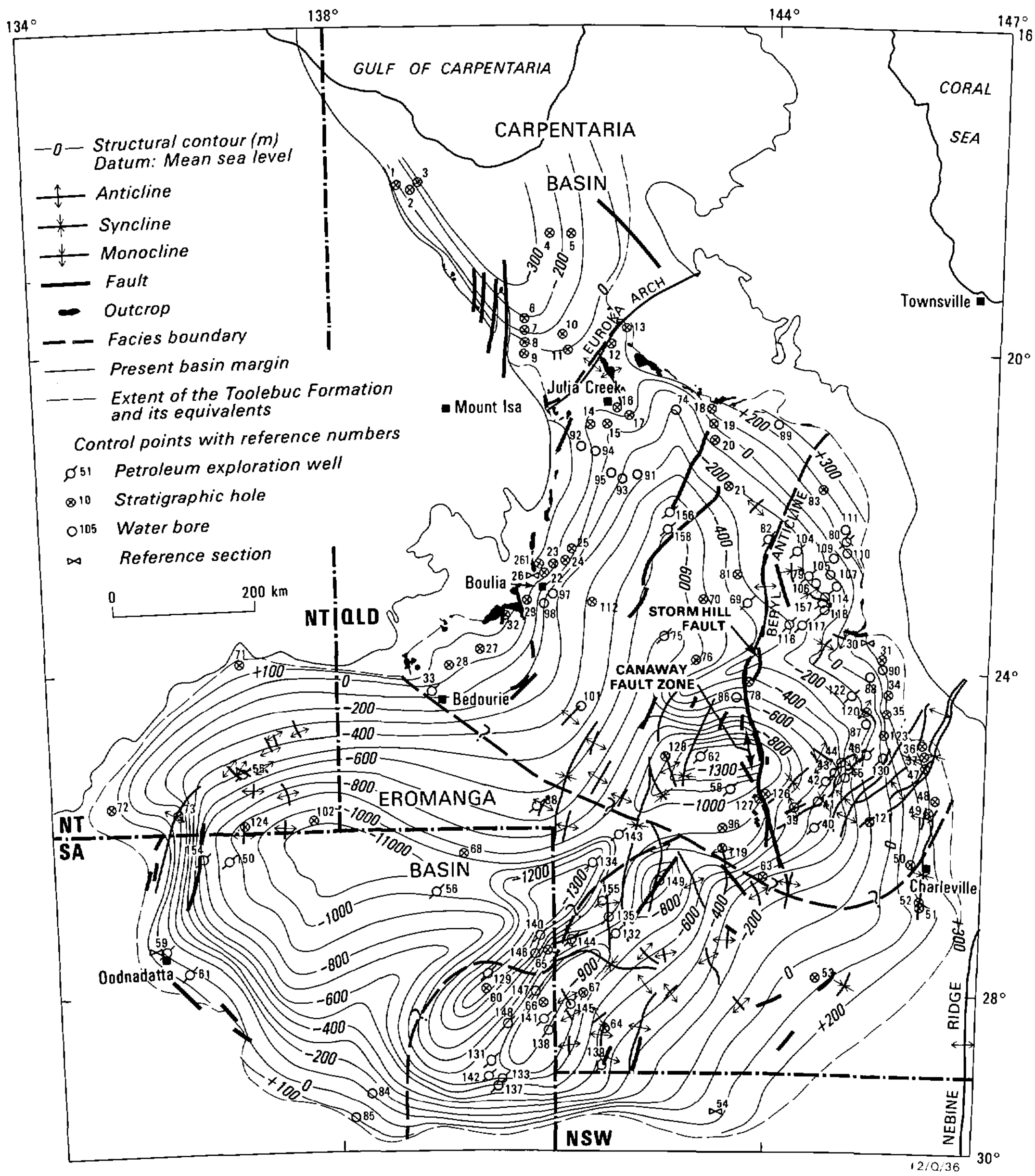
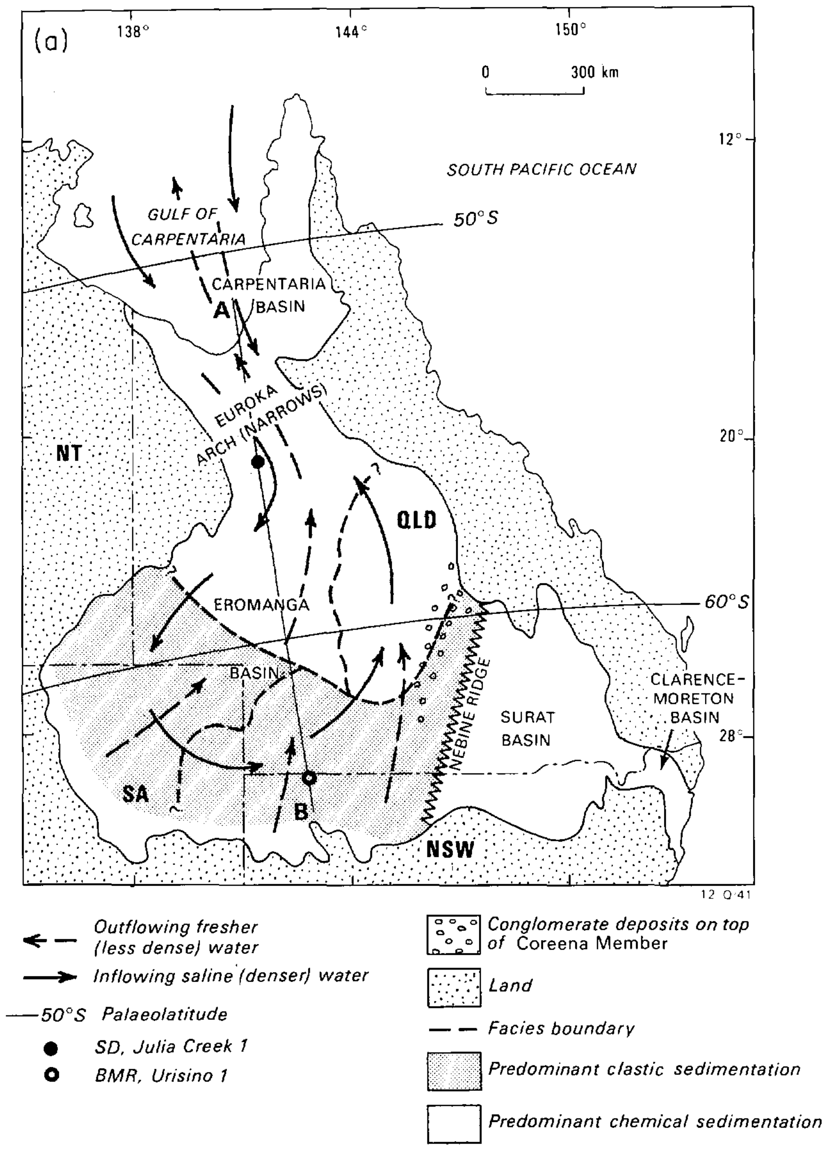


Fig. 2. Structure on top of Toolebuc Formation Wooldridge Limestone Member and Urisino beds.

Larger scale variations in depositional conditions in the Toolebuc Formation are noted along the southeastern and southern margins. According to Boreham and Powell (1987) organic preservation is poor in the lower part of the formation and oxygen contents of the kerogen are high. In this region the redox boundary lay below the sediment water interface and substantial oxidation of the organic matter has occurred. The Charleville No. 6 hole (Table 1) represents a point close to the paleo-shoreline where terrestrial organic matter has contributed to the sediment. A higher sea level may have existed during the later stages of deposition of Toolebuc Formation because both at Augathella No. 6 (Table 1) and Charleville No. 5 organic carbon contents are higher, and kerogen quality improves in the upper part of the formation, an observation which is in agreement with palynological studies (McMinn and Burger, 1986). A deep water re-entrant may have existed in the area where Tambo Nos. 37, 41, 42 and 44 boreholes are located (Table 1) as there the carbon contents and Hydrogen Indices are consistently higher throughout the formation reflecting a probable deep water environment with less circulation of oxygen-rich water (Boreham and Powell, 1987). The evaluated coquinite/kerogenous shale ratios and their areal variation suggest that living conditions for the growth of shelly fauna were more favourable along the western basin margin than along the eastern basin margin where growth was severely restricted, probably due to very low oxygen levels. The change to progressively more oxygenated conditions can also be seen along the southern margin of the Toolebuc Formation where there is a decline in the amount of organic carbon. This reflects more pervasive oxidation and bacterial reworking of the organic matter. The Urisino Beds represent a low lying coastal environment dominated by terrestrial organic matter. In contrast the Wooldridge Limestone Member represents a shallow sea deposit. The small amount of organic matter present appears to be very similar to that in the Toolebuc Formation, but is extensively oxidised and bacterially degraded.

Before the sediments of the Toolebuc Formation facies were deposited, and following a major middle Albian marine regression from the Eromanga and Carpentaria Basins, there was an onset of fresh-water conditions during which the regressive sequences of the upper part of the Coreena Sandstone Member of the Wallumbilla Formation were subaqueously and, or subaerially irregularly eroded and reworked (Day, 1969). Conglomeratic deposits at the top of the Coreena Sandstone Member occur mainly along the eastern margin of the Eromanga Basin (Fig. 3) and are interpreted to have been derived from the adjacent and rising Nebine Ridge. Absence of conglomeratic deposits at this stratigraphic level elsewhere in the Eromanga and southern Carpentaria Basins possibly indicates that the Nebine Ridge had only local structural influence. The sea re-entered the basin from the north in the early part of the late Albian (Burger, 1980), but did not cross the Nebine Ridge. The conditions envisaged are those of a 'positive water balance basin' (Demaison & Moore, 1980) in which saline water entered from the north and circulated anticlockwise, while fresh water from the hinterland flowed northwards out of the region (Figs 3a, b). The sea was most likely stratified, with a permanent halocline below a layer of fresh water. At the same



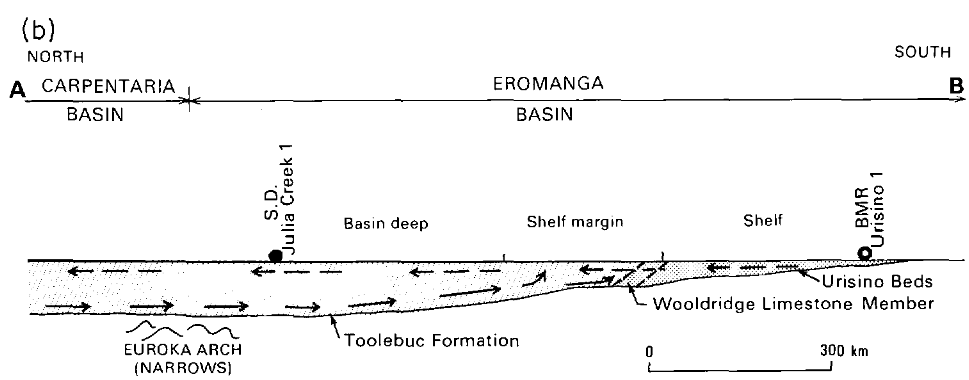


Fig. 3. (a) 'Toolebuc Sea', palaeolatitudes and current patterns.
(b) Hypothetical cross-section showing possible conditions during deposition of the Toolebuc Formation and time equivalents. (After Ozimic & Saxby, 1983)

time, the uranium which is the major source of the gamma-ray anomaly associated with the Toolebuc Formation (Fig. 4), was probably transported into the depositional area in a soluble state by run-off waters from adjacent landmasses that were flowing into the 'Toolebuc Sea'.

Such palaeogeographic conditions would have:

(1) enhanced prolific productivity in the euphotic zone;

(2) favoured permanent or intermittent oxygen depletion in the lower parts of the sea water;

(3) limited the establishment of normal benthonic marine fauna;

(4) favoured the preservation of organic matter;

(5) enhanced reduction of uranium (from the soluble hexavalent state to the insoluble tetravalent precipitate), and absorption of the radioactive precipitate by organic matter in the prevailing anaerobic environment.

Conditions which favoured oil shale deposition were apparently terminated by an increase in saltwater inflow into the depositional basin as a result of rising sea level, and possibly as a result of variations in atmospheric conditions limiting productivity in the euphotic zone.

Deposition of the Toolebuc Formation in an oxygen-deficient environment would appear to coincide with similar deposits in other ocean basins that existed within the same general mid-Cretaceous period (Schlanger & Jenkyns, 1976). The widespread global distribution of these blackish sediments in various palaeo-oceanographic and palaeobathymetric settings required that different processes were responsible for black shale formation at different places. However, if these black shale events were the consequence of a single overriding factor, then it was most likely an ultimate response of the increase of both terrestrial and marine biota to changes in atmospheric climate (Habib, 1982).

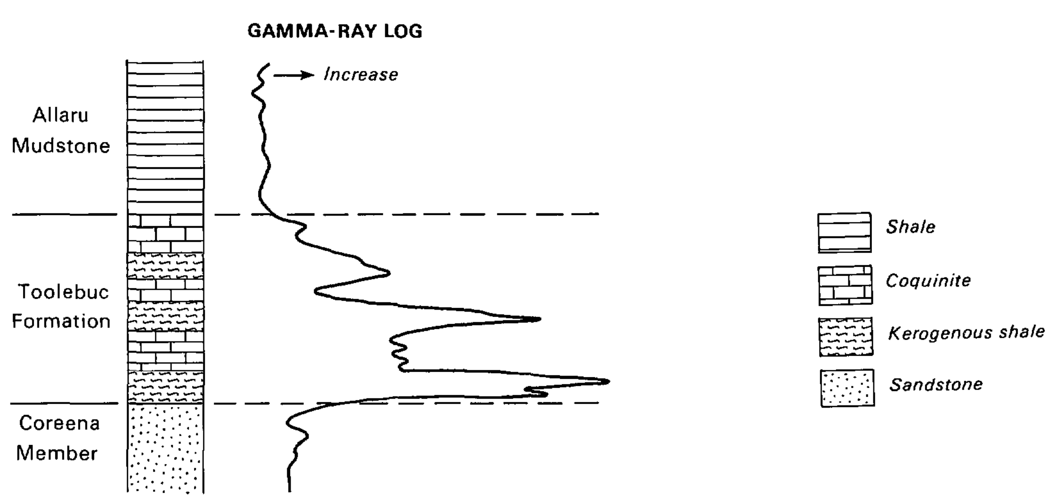


Fig. 4. Toolebuc Formation, typical gamma-ray log response.

The Toolebuc Formation productive oil shale covers an area of 0.484×10^6 km^2 (Fig. 1) (excluding the weathered, non-productive zone from surface to 50 m). The oil shale ranges in thickness from 6.5 to 7.4 m, has a specific gravity of 1.7, and yields on average 37 litres of oil per tonne. On this basis the total potential shale oil resources of the Toolebuc Formation have been estimated at 245×10^9 m^3 (Ozimic, 1983). Approximately 20 per cent could possibly be produced by open-cut mining at depths from 50 to 200 m. The remainder could potentially be produced by in-situ retorting at depths greater than 200 m.

The quality of Toolebuc oil shale appears therefore to be only moderate. The formation's average oil yield is regarded as a lower economic limit for possible conventional or in-situ production methods. Economic factors at a particular time will decide how much (if any) of the total potential shale oil can be viably recovered.

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PALAEOGEOGRAPHY AND THE GENERATION OF PLAY CONCEPTS IN AUSTRALIA

M.T. Bradshaw.

Palaeogeography, in its simplest form, is concerned with the distribution of land and sea at various times in the past. Outcrop, well and seismic data provide information for the reconstruction of these ancient landscapes. The discernment of a variety of environments and reconstruction of a number of time intervals adds to the sophistification of the palaeogeographic analysis. The understanding of processes and sedimentary products in modern environments and detailed biostratigraphy provide an essential framework. Palaeogeographic maps can be produced at a variety of scales - local, regional, continental or global, depending on their ultimate use.

Petroleum exploration is a major use of palaeogeographic maps, and was the major impetus for the BMR-APIRA Palaeogeographic Maps Project. These maps (Cook, 1988), identify over a dozen different environmental categories, have a continent-wide coverage, and provide a resolution of seventy time slices for the Phanerozoic.

A petroleum play is a concept or model which directs the search for hydrocarbons. To be successful a play requires the coincidence of a porous and permeable reservoir unit, with access to a mature source rock, enclosed by an impermeable seal facies, and in a trap configuration.

The primary depositional environment is a major control on these factors of reservoir, seal and source; and to some extent on trap, especially if there is a stratigraphic component, as in a reef or unconformity play. Thus, palaeogeographic maps are an important tool in play analysis as they provide a reconstruction of the pattern of past environments. For example the mapped trend of an ancient shoreline can be used to predict the occurrence of porous reservoir sands, now deeply buried. Using palaeogeographic maps, it is also possible to extrapolate and interpolate from limited data. For example, the distribution of associated fluvial sands and prodelta muds can be predicted from the occurrence of deltaic deposits.

Post-depositional processes are crucial to the success or failure of a petroleum play. These include maturation, migration, entrapment and preservation of the hydrocarbons, and the effects of diagenesis. Palaeogeographic analysis is also useful when considering the post-depositional factors controlling a play. For example, evaporitic solutions generated in a playa environment can dolomitse underlying limestones and increase porosity in a potential reservoir; and exposure of former shelf areas during major regressions may cause intrusion of bacteria-contaminated meteoric waters into hydrocarbon pools. Thus, when analysing a play the palaeogeography of a number of time intervals should be reconstructed, not just the depositional episodes of the source, reservoir and seal facies, but also critical times in the succeeding history of the area.

New petroleum plays can be generated in a number of ways, using empirical, analogue and analytical methods. Palaeogoegraphy is a stimulus to new ideas in all approaches.

Experience teaches that oil is where you find it, and a most successful way of discovering a new play area is to extend an old one. Thus a series of anticlines in a structural trend may be drilled after one has been found to contain oil. With more knowledge of the geology controlling a play, a palaeogeographic trend may be followed, such as reef prospects along an ancient shelf edge.

Once a petroleum play is well understood it is possible to begin the search for repetitions of the same geological conditions. The hunt for analogues of a successful play is greatly aided by palaeogeographic maps which show the environmental configuration of the known play area and of its potential analogues. For example, the deep restricted marine troughs of the Barrow-Dampier Sub-basin in the Late Jurassic provided the correct conditions for the accumulation of organic-rich shales which are the source rocks for the giant gas fields of the Rankin Trend and the oil at Barrow Island and associated smaller fields. A palaeogeographic reconstruction of the North West Shelf in the Late Jurassic (Bradshaw et al. 1988) shows that the same environmental configuration of narrow deep water troughs is repeated to the north in the Timor Sea area, and the recent discoveries of the Jabiru and Challis fields (MacDaniel, 1988) indicate that a similar hydrocarbon potential is being realised.

Within a single time interval, the analogue method can be successful across a single basin or across the globe. The Devonian reef play is an example of a North American analogue transplanted, with some success, to Australia. The small Blina oil field, in the Canning basin, is contained in Late Devonian carbonates (Moors et al., 1984) that have some affinity to the prolific oil reservoirs of Western Canada (Playford, 1969; Lehmann, 1984). However, a careful comparison of age equivalent geological analogues shows that none are exactly the same. Consideration of the differences often prompts incisive questions that can identify the critical factors that separates a billion barrel play from one that appears to have all the right factors but has not fulfilled its promise.

Evaporites are closely associated with the productive reefal facies in the Devonian of Western Canada, and enhanced accumulation of organic matter under a hypersaline water column (Kirkland & Evans, 1981) may have played a role in the deposition of a rich source rock facies in basin areas adjacent to the reef trend. The Canning Basin also has evaporites in the sequence but they were deposited in an earlier depositional cycle than the reefs. Western Canada escaped the major Late Carboniferous/Early Permian Gondwanan glaciation, which produced a significant erosional unconformity in the Canning Basin and potential for destruction of early formed oil pools.

Consideration of the Late Jurassic palaeogeography of the North West Shelf shows that the Vulcan Sub-basin differs from the Barrow-Dampier Sub-basin in being less enclosed by surrounding uplands (Bradshaw, 1988). There is a large contribution of terrestrial organic matter, washed in from the adjacent land areas, in the Barrow-Dampier source rocks, and hydrocarbon discoveries to date suggest that the sub-basin may be gas prone. However, further north, in the Vulcan Sub-basin and adjacent troughs, more oil prone source rocks may have been deposited, with a reduced terrestrial component, owing to more distant and lower relief land areas.

Continental breakup and an episode of high sea level created the right environments for source rock deposition in many parts of the world in the Late Jurassic, including the North Sea (Demaison et al., 1984) and the offshore Jeanne D'Arc Basin of eastern Canada (Powell, 1985). In both cases source beds with organic carbon contents as high as 10 per cent were deposited in similar deep water troughs to those on the North West Shelf. A source rock interval with the same richness has not however, been intersected to date, on the North West Shelf. This may be due to the lack of drilling in basinal locations, or it may indeed be lacking. A global reconstruction for the Late Jurassic (Scotese, 1986) shows that the North Sea and eastern Canada, though in similar latitudes to the North West Shelf, had considerably more restricted seaways. The Atlantic was only starting to open, while the North West Shelf was facing onto the expanse of Tethys, perhaps partially barred by a thin continental sliver (Veevers, 1988). Thus different palaeo-oceanographic conditions may have been the crucial factor in determining source rock quality.

An increased number of time slices improves the power of the analogue method in generating new play concepts. Broad time intervals smear important distinctions and ideally time slices should approximate individual cycles of transgression and regression. Precise biostratigraphical zonations are required for the fine resolution of time slices. In the Australian Ordovician there are two units recognised as oil source rocks:- the Goldwyer Formation in the Canning Basin (Foster, et al., 1986) and the Horn Valley Siltstone in the Amadeus Basin (Gorter, 1984). Both are of similar age and facies, deposited during a period of elevated sea level in the Early Ordovician. Careful analysis shows that the Horn Valley Siltstone is slightly older than the Goldwyer Formation (Nicoll et al., 1988) and two intervals of enhanced source rock quality are now recognised in both basins; in the Willara Formation underlying the Goldwyer in the Canning Basin, and in the Stairway Formation overlying the Horn Valley in the Amadeus Basin. The Early Ordovician is another example of the analogue approach identifing plays on a global scale. The Goldwyer Formation has age equivalents with similar source rock characteristics in the Baltic and Williston Basins (Foster, et al., 1986), all of which shared a palaeogeographic location close to the equator in the Ordovician (Scotese, 1986).

Analogues of a successful play can be searched for in a different time slice that has a similar configuration of environments. From the above discussion episodes of high sea level in the Early Ordovoician and Late Jurassic have been shown to be associated with enhanced conditions for source rock deposition. Another time of high sea level world-wide was in the Early Triassic, which should provide a fruitful time interval for repeats of play types that have been successful in other transgressive episodes. Palaeogeographic maps indicate a number of places along the North West Shelf where Early Triassic basal transgressive sands are sealed by overlying marine shales which may provide a hydrocarbon source facies (Bradshaw et al., 1988).

Palaeogeography combined with seismic stratigraphy and the sea level cycle concepts of Vail et al., (1977) are powerful tools for the development of new play concepts using the analogue approach. Just as episodes of high sea level have been shown to be influential in controlling the hydrocarbon potential of an area, low sea level stands are also critical periods. During low sea level times reservoir facies, such as submarine fans, may be deposited farther basinward than usual, where they may closely interfinger with source facies and have a greater likelihood of being overlain by a seal. The Flag Sandstone reservoir in the Harriet field (Howell, 1988) is an example of a "low stand fan" related to an Early Cretaceous (Valanginian) regression on the North West Shelf. This play may occur in the Papuan Basin where Valanginian fan deposits may be found basinward of the front of the Toro Sandstone delta.

Palaeogeographic maps are a major tool for the generation of new play concepts using a strictly analytical approach. Areas of reservoir, seal and source facies are identified on time slice maps, and potential play areas can be recognised where there is an overlap of these facies on different time slice maps. Plays can be discovered on a series of sequential time slice maps, such as where deltaic reservoir sands prograde over older pro-delta muds, and are then onlapped by marine shales. Analysis of palaeogeographic maps of vastly different ages can identify plays across major unconformities. For example palaeohighs may provide the reservoir for much younger source and seal facies, as in the Sirte Basin of Libya (Williams, 1972).

The empirical, analogue and analytical methods are the end members of a continuum of approaches that are used to generate new play concepts. Palaeogeographic analysis is an important step in all these attempts to develop a new plays. The chances of success are enhanced if there is a fine resolution of time slices and a comprehensive coverage, in space and time, of the maps.

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Late Palaeozoic Glacial Facies in Australia and their Petroleum Potential.

A.T. Brakel, P.E. O'Brien & J. Totterdell

Late Palaeozoic glacial sediments are widespread throughout Australia. Localized possible glacial deposits in the Carnarvon Basin and eastern Australia may be Namurian. Stronger evidence for glaciation, but not extensive ice sheets, is found in the Late Carboniferous, especially in south-eastern Australia. The glacial maximum occurred at around the Permian-Carboniferous boundary, when three major ice sheets existed which may have linked at times. The glaciation ended near the end of the Sakmarian, but local ice masses reappeared during the Kungurian.

Glacial depositional systems can be divided into zones (Boulton & Jones, 1979):

1. Core Zone: Occupied by ice even during interglacials and is a zone of net erosion.
2. Intermediate Zone: Occupied by ice during interstadia within glacial epochs. Ice sheets leave behind thin deposits in this zone.
3. Outer Zone: Occupied during stadia, the coldest times of a glacial period. It is a zone of net deposition and is the site of thickest diamictite accumulation.
4. Periglacial Zone: Beyond the furthest limit of grounded ice, ice sheets still control sediment supply and sea level, so strongly influencing sedimentation.

Near the Permian - Carboniferous boundary, core zones probably covered the Yilgarn, the Pilbara and parts of central and southern Australia (Fig. 1). Intermediate zones flanked these areas and covered parts of Victoria and Tasmania. Outer zones rimmed the intermediate zones, with major depositional areas in Victoria, and the Cooper, Pedirka, Officer and southern Canning Basins. Where ice sheets discharged into the sea in the Carnarvon Basin and southern Australia, floating ice shelves were established. Terrestrial periglacial sediments accumulated in the Cooper Basin, and glaciomarine sediments in marine basins adjacent to glaciated areas.

The outer and periglacial zones receive most sediment and are thus of most interest. Facies within the outer zone can be classified as ice-contact or proglacial. The characteristic ice-contact facies are subglacial and supraglacial tillites which show variable but very poor sorting. Englacial stream and lake sediments are usually small deposits, except for tunnel valleys that are steep sided, up to several kilometres across, and several hundred meters deep. They are cut by catastrophic subglacial drainage and are typically filled by sand or gravel with a clay plug at the top.

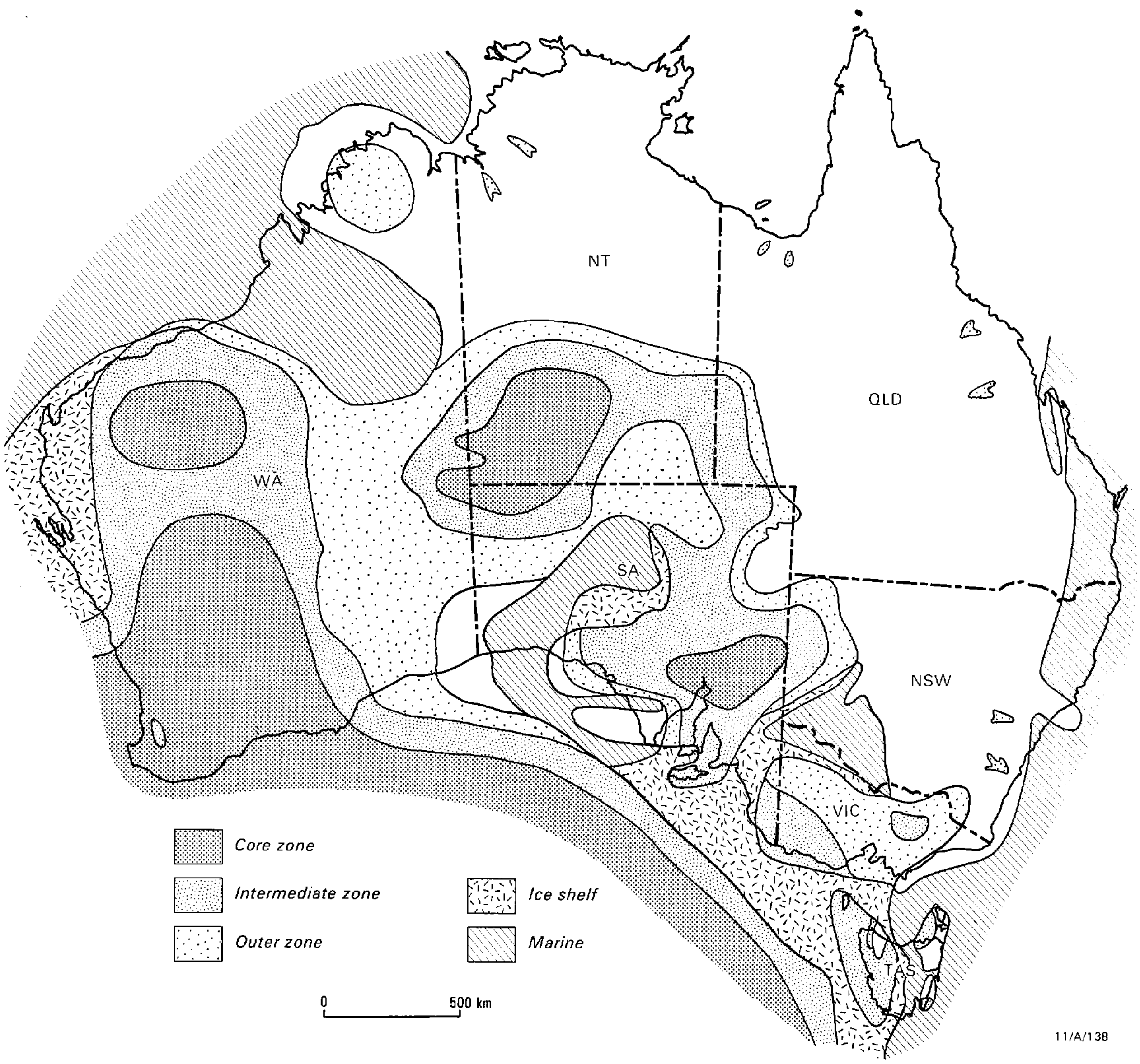

Fig.1 Interpreted glacial zones in Australia during the earliest Permian.

Proglacial sediments are typically preserved in ice-retreat sequences that start with subglacial diamictites overlain by progressively more distal proglacial facies. Proglacial sediments include fluvial deposits, eolian dune and sheet sands, deltaic sediments and subaqueous outwash fan deposits. Ice-rafting of detritus into standing water bodies is also important in the outer zone.

Proglacial streams are typical braided streams depositing sheet-like conglomerate and sandstone. Proglacial eolian deposits consist of well-sorted sands in extensive sheets 1 to 2 m thick, or thick but areally restricted dune fields. Fluvially-dominated proglacial deltas display topsets of braided distributary channels passing downslope into rhythmically bedded sandy foresets and fine-grained bottomsets. Wave-dominated deltas containing abundant well-sorted sand also develop in large proglacial lakes and marine settings. Subaqueous outwash fans form where englacial tunnels disgorge into standing water. They consist of a central core of coarse sediment that passes out into sandy foresets and finer bottomsets. Both subaqueous fans and deltas may feed subaqueous channels.

Sedimentation in the periglacial zone, though beyond the limits of glacial ice, shows strong glacial influence. Temperate glaciers provide heavy sediment loads to surrounding environments whereas polar ice sheets can cause sediment starvation. Glacioeustatic sea-level changes also have widespread effects.

Glacial rocks are traditionally regarded as lacking porosity, but proglacial fluvial and deltaic rocks produce hydrocarbons in the Cooper Basin (Williams & Wild, 1984) and in Oman (Levell & others, 1988). Also, Williams & others, (1985) demonstrated excellent porosity and permeability in Palaeozoic proglacial eolian sandstone in the Cooper Basin. Therefore, any sandstone or conglomerate facies deposited in the outer or periglacial zones may have good reservoir characteristics, although tunnel valley infills are the only ice-contact deposits large enough to be considered potential targets.

Diamictite and mudstone facies can be good seals (e.g. Levell & others, 1988) but generally have low hydrocarbon source potential. However, Domack (1988) shows that a time of sediment starvation follows the retreat of a polar marine ice shelf so that organic-rich sediments can accumulate. He cites the organic-rich shales and "Tasmanite" pelagite of the Quamby Mudstone in Tasmania as Palaeozoic a examples of such deposition. Glacioeustatic falls in sea level might also restrict circulation in some basins, resulting in organic-rich deposits. Coals and organic-rich mudstone also accumulate on the distal parts of glaciofluvial outwash plains (Boothroyd & Ashley, 1975; Thornton, 1979).

In conclusion, sediments of the outer and periglacial zones have potential reservoirs and seals. Source rocks may be present but are unlikely to be abundant (Table 1). Therefore, glacial sequences in Australian sedimentary basins should not be ignored but treated on their merits as potential hydrocarbon targets.

TABLE 1. Potential reservoir, source and seal facies in glacial sediments.

POTENTIAL RESERVOIRS	SOURCE ROCKS	SEALS
Tunnel valleys.	Transgressive shales deposited after polar ice shelf retreat.	Lacustrine & marine shales.
Fluvial outwash.	Basins barred by sea level fall.	Tillites.
Eolian dune sandstone.	Coals and non-marine carbonaceous mudstone.	Glaciomarine diamictites.
Deltaic sandstone and conglomerate.		
Subaqueous outwash fans.		

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Sealevel, tectonics and climate - determinants of reservoirs and source rocks off northern Northeast Australia and Papua New Guinea.

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Rifting, drifting, subsidence, collision, sealevel change and palaeo-oceanography have combined to control the prospectivity of northeast Australia. This paper examines the processes that have affected the extreme north of the region and predicts the relations between these processes and potential sources, reservoirs and seals. Finally, it defines two tests of th exploration predictions the results of which radically change and upgrade the exploration potential of a large part of northern Australia and southern Papua new Guinea.

Palaeogeographically, New Guinea represents the northern leading edge of the craton and northeast Australia its eastern rifted margin. Little is known about the architecture of the northern cratonic margin. In the Palaeogene we presume it to have been an originally gently sloping margin with a gradual transition to a gently dipping continental slope. Early rifting of the eastern margin in the Cretaceous -Palaeocene defined a margin architecture at a very early stage which consisted of thick elongate depocentres adjacent to north -south trending basement highs. Mesozoic-Palaegene depocentres in the wstren Papuan Basin and beneath the pandora Trough to the east contain up to 2-3 seconds of section. The Papuan Basin depocentre was flanked by the Borabi hinge zone and the Pasca Ridge, while the Pandora Trough is flanked by the Ashmore -Pandora High and the Eastern Plateau.

Palaeogeographic and palaeolatitude reconstructions indicate that the Palaeogene is typified by open marine conditions along the northern margin and restricted circulation along the eastern margin. Palaeoclimatic reconstructions suggest distinctly cool temperate conditions for the latter part of the Paleogene. Ocean productivity was therefore probably relatively high. Sealevels throughout much of the Palaeogene are thought to have been high. Conversely, subsidence of the margin at this time appeasr to have been relatively low with sediment supply at a minimum. All these conditions combine to indicate that the Palaeogene was a period in which extensive source rocks could have been deposited: such source rocks would have been thickest in the north - south trending rift troughs and on the continental slope of the northern cratonic margin.

These conditions prevailed until the craton approached the tropics as a consequence of northward Cainozoic drift. The early Miocene marked a change in the nature and geometries of the shallow water sedimentary facies from temperate bryozoan/foram dominated biostromes and sheets to sub-tropical red algal/foram dominated reef type buildups. The Neogene is therefore essentially a period of reservoir development with progressive northward drift and increasing surface water temperatures giving rise to true reef buildups overlying sub-tropical red algal buildups. Subsequent development of such reservoirs along both the northern and eastern margins of the craton owes much to the collision that initiated the development of the new Guinea orogen which began about 25-30 million years BP. Collision caused the development of a foreland basin with a flexural wavelength 500-700km wide and with the position of the downwarp migrating south throughout the Neogene as the orogen evolved. Immediately after collision the foreland basin consisted of a proximal deep 100-200km across and a distal epicontinental shelf 300-500 km wide. Thick(> 5km) clastic sediments, and associated continental derived and marine organics were deposited in the proximal deep while the distal shelf was the site of tropical carbonate buildups both parallel to the axis of the foreland basin and at right angles to it along fault controlled highs on the eastern margin of the craton.

The growth response of the tropical buildups was dependent upon their initial orientation relative to the axis of flexure. Reef growth parallel to the collision front formed a continuous tract of thin reefs on the flexural hinge of the foredeep: as the basin axis migrated to the south the locus of reef growth migrated towards the craton. In contrast the location of reefs along the eastern margin remained fixed along the north-south trending highs eg the Pasca, Borabi, Ashmore-Pandora and Eastern Reef highs. The response of reef growth to foreland basin development and the concomitant subsidence was accelerated vertical growth and the contraction of the initial barrier reefs to a series of smaller and smaller pinnacles. The eastern margin of the Fly Platform in the Torres Shelf area and the northern margin of the Great Barrier Reef are currently undergoing an evolution comparable to that of the early to middle Miocene reefs of the Borabi platform.

Continued convergence throughout the Neogene resulted first in the incorporation of the early Miocene slope facies and foredeep clastics into the foreland fold belt, and secondly clastic infill of the proximal deep with subsequent progradation across the shelf carbonate reservoirs, causing a marked reduction in the area of carbonate deposition and encasement of carbonate reservoirs in clastic seals. A Pliocene fall in sealevel exposed the northern and eastern platform margins allowing the clastic sediments derived from the emerging mountains in the north to spread far to the south. This outpouring of detritus was so great that it produced an inimical environment which terminated all carbonate deposition even during subsequent high sealevels.

As a consequence of the above events two distinct exploration scenarios have been identified, (1) stacked tropical reef and subtropical biohermal reservoirs along well defined north-south trending fault controlled highs, sourced by adjacent Palaeogene and older basinal sediments or Neogene foreland basin clastics and sealed by prograding Neogene foreland basin clastics, and (2) latitude parallel discrete Neogene reef reservoirs progressively backstepping to the south, sourced by early foreland basin marine bathyal sediments and sealed by later prograding foreland basin sediments. Recent exploration has successfully tested both these two scenarios. Drilling by the International Petroleum Corporation at Pandora Reef defined stacked reefs tightly sealed in prograding fluvioclastics, the carbonates forming a reservoir for a mega gas field. Seismic exploration by Santos south of the thrust belt onshore New Guinea has identified a series of east to west orientated buildups encased in fluvioclastics. Future drilling will further test this hypothesis.