DEPARTMENT OF MINES
SOUTH AUSTRALIA

AUSTRALIA - ANTARCTICA SEPARATION AND THE EOCENE TRANSGRESSION IN SOUTHERN AUSTRALIA

BRIAN McGOWRAN
Senior Palaeontologist

CONTENTS — PAGE

FIGURES

G.S. No. 4655
Rept.Bk.No. 71/78
D.M. No. 622/71
Pal. Rept. 10/71

24th May, 1971.

DEPARTMENT OF MINES
SOUTH AUSTRALIA

AUSTRALIA - ANTARCTICA SEPARATION AND THE EOCENE TRANSGRESSION IN SOUTHERN AUSTRALIA

G.S.No.4655
Rept.Bk.No.71/78
D.M.No.622/71
Pal.Rept.10/71

ABSTRACT

Stratigraphic evidence points to a major change in the sedimentary regime beginning in the Middle Eocene, i.e. close to the inferred onset of continental separation. Deep sea evidence for an Antarctic ice-sheet overlaps this event in time whereas Australian and New Zealand data indicate warm conditions in the Upper Eocene and (New Zealand) Lower to Middle Eocene as well. It is concluded that diverse lines of evidence do not integrate convincingly as yet.

INTRODUCTION

Tertiary stratigraphy in all its aspects is basic to the ramifying enquiries into the youngest thick slice of earth history, and equally to attempts at their reconciliation. A firm foundation in correlation and age determination - in the cross-relationships of biostratigraphy, geochronology and geomagnetic polarity reversal chronology - is indispensable in the big questions of Tertiary geology, such as continental drift history related to orogeny and polar wondering, or tectonics related to climatic change on the global scale. Stratigraphic correlations and attempts at synthesis in Australasia have obvious relevance to (and need frequent re-assessment in the light of) attempts to write the region's climatic and tectonic and geographic history; nor can the studies classified as "economic geology" (in this case, petroleum exploration) be kept neatly apart. The present paper looks from the stratigraphic standpoint at some recent ideas on and pertaining to the Australasian region in the Eocene.

STRATIGRAPHIC RECORD OF TRANSGRESSION

Tertiary strata around the margins of southern Australia were deposited in two major and successional sedimentary regimes. In the older of these regimes accumulated thick clastic units which are often carbonaceous and contain little glauconite or carbonate. The environment was nonmarine to paralic, with arenaceous foraminifera and noncalcareous phytoplankton; periodic marine ingressions (Taylor 1967, 1971), mostly shortlived, are evidenced by calcareous benthonic and planktonic foraminiferal assemblages and shelly megafaunas, but calcareous nannofossils are absent or very rare. This is Bock and Glenie's "Cycle 2" (1965, fig.1; also published as fig. 10.5 in Brown et al. 1968). The age is Paleocene to Early Eocene (Bock & Glenie's Cycle 1 in the Upper Cretaceous is rather similar in overall aspect.

The second Tertiary "cycle" is very different, as may be seen on inspecting the diagram by Bock and Glenie (1965). The sediments mostly are highly fossiliferous marine shelf carbonates (marls and limestones) with variable, generally subordinate clastic content. The transgressive lowest part of this sedimentary phase consists of the following elements in various combinations or successions: carbonaceous clays and silts, limonite pellets and iron-stained sands, glauconite which is often pelletal, and fine to coarse carbonate bioclastics. The glauconite-to-carbonate sequence comprises Bock and Glenie's Cycles 3 and 4, subsequently modified (Glenie et al. 1968) to Cycle 3 introduced by Subcycle 3a. The age of the bulk of the known sediments is Middle Eocene to

Middle Miocene, but widespread shallow neritic Pliocene sediments undoubtedly belong to the phase as do the biogenic carbonates accumulating now (Wass et al. 1970). The section is more complete offshore (zones erected by D.J. Taylor are included in McGowran et al. 1971).

The contact between the main Tertiary phases of sedimentation is shown in the Eocene correlations outlined in fig.2. A system of planktonic foraminiferal zones based on tropical faunal successions and placed against a radiometric scale (Berggren 1969) is used as main reference. Local planktonic foraminiferal zones (Ludbrook and Lindsay 1969, slightly modified) are related to these zones; other systems erected in southeastern Australia and problems in correlation are discussed by McGowran et al. (1971). Correlations shown in fig.2 vary considerably in precision and confidence; there is doubt about how some planktonic microfaunal horizons relate to tropical zones (McGowran et al. 1971) and evidence other than planktonic foraminifera must be used locally. Solid lines in fig.2 therefore indicate only relatively more confidence, but margins of error above the earlier Middle Eocene do not matter greatly in the present context. Upper Eocene nautiloids (Cimomia, Aturia, Deltoidonautilus) seem to occur within an important, shortlived "ingressional interval" at about the same time as Hantkenina primitiva ("alabamensis") and occurrences are shown for their consequent, probably correlational value. Diachronism of local contacts is known but not shown here, nor is the marginal paralic to nonmarine facies found coevally in several basins. Fig.3 includes New Zealand data and other data used in this discussion.

The heavy line in fig.2 marks the base of the Eocene transgression and the onset of the second phase of Tertiary sedimentation in southern Australia. This horizon is accepted as an unconformity (Leslie 1967, Reynolds 1967, Wopfner 1969, Richards and Hopkins 1969). The boundary is not a point of cyclic reversal, in the usual sense of depositional cycles, but marks a change in basic sedimentational style. Relatively well dated beds on either side of the contact are closest in the Gambier Embayment of the Otway Basin. The Burrungule Member of the Knight Formation is dated as earliest Middle Eocene with the distinct possibility that it is late in the Lower Eocene (McGowran et al. 1970). This unit is the highest marine ingression with planktonic foraminifera (Planorotalites australiformis zone; fig.2) known in the earlier phase of sedimentation. The base of the second phase (Kongorong Sand and Lacepede Formation) extends down approximately to the Globigerapsis kugleri zone of early Middle Eocene age. In the Eucla Basin the base of the Wilson Bluff Limestone onshore is close to this level (McGowran and Lindsay 1969) and can be correlated with the Globorotalia centralis zone beneath the Orbulinoides beckmanni zone in Italy (Baumann 1971). To the west of the Eucla Basin, to the east of the Gambier Embayment, and toward more intracratonic situations (St. Vincent and Murray Basins) the base of the transgression, as known, moves upwards in time: there is widespread evidence for Upper Eocene age but no good evidence for Middle Eocene. Diachronism at the base of consistent facies successions within the Upper Eocene in the Otway Basin in Victoria has been analysed by Taylor (1971). The base of the glauconite-carbonate phase appears to extend as high as the Oligocene in the

Gippsland Basin as manifested in the Lakes Entrance Formation (Hocking and Taylor 1964): it is not clear whether Upper Eocene marine sediments (Taylor 1965, James and Evans 1971) should be classified as the basal part of the younger phase or as ingressions near the top of the older. Oligocene units in the Otway Basin (Compton Conglomerate, Nelson Formation) are still younger evidence of strongly diachronous transgression onto local highs, forming the base of Cycle 3 proper, above the Nirranda Group in Subcycle 3a, sensu Glenie et al. (1968). It should be noted that the transgression is not a simple phenomenon. Taylor (1967, 1971) has distinguished a variety of patterns in Upper Eocene environment and transgressional mode on the basis of detailed microfaunal analysis. There is a "pulse" at the base of the Kongorong-Lacepede section in the Gambier Embayment, where an ingression in the Globigerapsis index zone precedes and is separated by a thin, almost barren interval from the main transgression at the base of the "Turborotalia" aculeata zone. However, there is no doubt that the ingression lies above the major contact; the pattern is similar in Upper Eocene sequences (Taylor, 1967, 1971).

With reference to radiometric estimates (Berggren 1969) the transgression appears to have begun about 48 m.y. ago. Evidence for the transgression became geographically widespread after about 45 m.y. ago.

CLIMATIC INDICATORS, SOUTHERN AUSTRALIA AND NEW ZEALAND

Warm conditions in the Carnarvon Basin during the Upper Eocene are clearly indicated by the tropical Indo-Pacific assemblage of "larger" foraminifera: Nummulites, Discocyclina and related genera, Pellatispira, Biplanispira (Edgell, in McWhae et al. 1958; pers. obs.). Although these fossils were not known from the south coast of the continent, evidence (McGowran and Wade 1967) appeared to be consistent with warm water conditions suggested by O^{18}/O^{16} data from Ostrea in the Aire District (Dorman 1966). Subsequently, the larger foraminifer Asterocyclina has been found on the south coast of Western Australia (Cockbain 1967). It is not known further east, but the genera Halkyardia and Linderina (Ludbrook 1961, Lindsay 1969) indicate warm conditions. None of these foraminifera are known from the Otway Basin, but the nautiloid Aturia and the planktonic foraminifer Hantkenina have been suggested as possible warm water indicators by Cockbain (1968) and Jenkins (1968) respectively; both are present here, with the Aturia records being additional to Cockbain's list of Australian localities. Cockbain (1969) has identified the dasyclad alga Neomeris in southern Western Australia and suggested that this indicates, with reference to Recent distribution, a southern shift of the 20°C isochryme of at least 600 miles (about 10° lat.) in the Upper Eocene.

New Zealand evidence has been assessed as pointing to a warming from a "low" in the Porangan (early Middle Eocene) to a "high" in the Upper Eocene: O^{18}/O^{16} data (Devereux 1967), calcareous nannoplankton (Edwards 1968), planktonic foraminifera (Jenkins 1968). The curve shown in fig.3 is taken from an estimate based mainly on benthonic marine fossils but taking account of all other evidence (Hornibrook 1971).

Hornibrook judges the climate to have been not less than subtropical (20°C at Wellington, 41°S) throughout the Eocene. Evidence for warm water conditions is stronger in New Zealand than in southeastern Australia. Thus, Asterocyclina occurs in the Upper and Middle Eocene and is abundant in the Mangaorapan (Lower Eocene) (Hornibrook 1971), and the trans-Tasman difference in O^{18}/O^{16} values (Dorman 1966, 1968, Devereux 1967) has suggested to Cockbain that there is a northward swing in his 20°C isochryme in the vicinity of the Otway Basin. This is consistent with the presence of the nannofossil Isthmolithus recurvus in the Otway Basin (McGowran et al. 1971): according to Martini (1970) this species is "rare or not present in the tropical region". Nevertheless, if the sparseness of "tropical indicators" in the known Middle Eocene of southern Australia (with more in the Eucla than in the Otway Basin; McGowran and Lindsay 1969) has any meaning as negative evidence, then the Middle-to-Upper Eocene warming trends here and in New Zealand would seem to be similar. Again, the Eocene-Oligocene drop in New Zealand (Devereux 1967, Hornibrook 1971) is paralleled in southern Australia (Dorman 1966, 1968, McGowran and Wade 1967), and Hamilton's (1968) statement that the early Tertiary (including Eocene) was markedly colder than the middle Tertiary in Australasia is rejected.

CONTINENTAL SEPARATION AND DRIFT

Sproll and Dietz (1969) have produced a quantitative morphological fit of Australia with Antarctica. They have suggested that steplike downdropping of the thick offshore sedimentary section in the Otway Basin, presumably by normal faulting, represents "taphrogenic relaxation associated with rifting and continental drift". Mesozoic faulting consistent with their time-sequence diagram (see also von der Borch et al. 1970) is developed strongly in marginal southeastern Australia (Richards and Hopkins 1969). Griffiths (1971) has shown how this faulting might be interpreted as an "Otway Rift Valley" opening between Antarctica and Australia during the Jurassic to early Cretaceous (see also Carey 1970) and acquiring a nonmarine clastic fill, and widening in the Upper Cretaceous with marine influence coming from the northwest. The Mesozoic sediment shown on the Australian plate margin by Sproll and Dietz, von der Borch et al. and Griffith will include also the Paleocene-Eocene sedimentary unit, i.e. Bock and Glenie's (1965) Cycle 2.

The actuall separation of Australia from Antarctica, considered to be the latest episode in the fragmentation of Gondwanaland, is dated as occurring at about the time of seafloor magnetic anomaly 18 (Le Pichon 1968). Heirtzler et al. (1968) show anomaly 18 lying at about 45 m.y. ago in their time scale, or at about the Middle/Upper Eocene boundary (Berggren 1969). However, Wellman et al. (1969) have found that their studies of palaeomagnetic reversals in lava sequences in New South Wales, consistent in frequency and timing with the Heirtzler et al. scale at around 34 m.y., are not consistent at 52 m.y. They note that the time scale shows an increase in reversal frequency at about 45 m.y., and they suggest from their land-based results that the oceanic scale loses detail downwards at this time. This adds to the uncertainty in chronology already noted by Le Pichon (1968) in revising the estimated age of anomaly 32 from 77 m.y. (Heirtzler et al. 1968) to 60 m.y. Although this revision restores the frequency of reversals to something comparable to the post-45 m.y. level, the date of continental separation based on the identification of anomaly 18 at the foot of the Australian continental rise is not fixed firmly.

The anomaly pattern over the south-east Indian Ocean rise is interpreted to indicate that Antarctica and Australia have drifted 30° apart along an approximately north-south line since the time of anomaly 18 (Le Pichon and Heirtzler 1968). If the ridge is assumed fixed, the pre-drift (early Tertiary) latitude of Canberra (presently about 35°S) was about 50°S, which is very close to an early Eocene (51.6 m.y.) figure of 52°S (Wellman et al. 1969). A palaeolatitude closer to 60° is used in various reconstructions (e.g. Irving 1967, Le Pichon 1968, Dietz and Holden 1970, 1971, McElhinny 1970); the Eocene situation of Australia is similar in Wegener's reconstruction (e.g. Carey 1970, fig.2). Tarling (1971) has stated that Antarctica seems to have remained in polar latitudes since the Permian; "it has remained almost fixed with the other continents doing most of the drifting" (Dietz and Holden 1971). Lack of a subduction zone around the Antarctic plate (Carey 1970) would support this, requiring northward migration of the rise and suggesting that a figure of 15° latitude drift for Australia is a minimum. Irving and Robertson (1969, fig.7) on the other hand have shown how spreading rates and palaeomagnetic data might be consistent with a northward movement by Australia of only about 10° during the Tertiary. Although this model includes a fixed rise and a Mid-Tertiary episode of rapid polar wandering, since refuted (Wellman et al. 1969, McElhinny and Wellman 1969), polar wandering of 10-15° since the Eocene (McElhinny and Wellman 1969) can be accommodated. New Zealand is also at a high latitude in pre-drift Gondwanaland configurations (Le Pichon 1968, Dietz and Holden 1971, Jones 1971). Caution in reconstructing Gondwanaland and the motions of its fragments in relation to each other and to the ridge systems rather than to the geographic poles until adequate palaeomagnetic data are available for east Antarctica (Veevers et al. 1971), certainly is justified. However, high latitudes and the mutual juxtaposition of Australia-Antarctica-New Zealand are the inferences of importance to discussion of early Tertiary palaeoclimatic evidence.

DISCUSSION

Smith and Hallam (1970) list geological criteria for dating continental fragmentation, including "the first appearance of neritic marine sediments along the continental margin after a long period of non-marine sedimentation or absence of sedimentation". The change in sedimentation outlined here (fig.2) is such an event, and is the most marked change in the Mesozoic and Tertiary record in southern Australia. The Middle to Upper Eocene transgression probably is congruent with the Eocene transgression in North America (Damon 1968, fig.1) and with the early Tertiary "kick" based on widespread data (Fairbridge 1967, fig.15). To postulate that the transgression is tectono-eustatic rather than glacio-eustatic would be in agreement with recent inferences (von der Borch et al. 1970, Jones 1971, Veevers et al. 1971) apart from dating of the events. There are at least three possible variants of the cause-and-effect relationship. Increased subcrustal convection might lead to formation of new oceanic crust in a mid-ocean rise which would displace water from the ocean basins and be marked stratigraphically by transgression (Russell 1968, Valentine and Moores 1970). Frerichs (1970) has suggested seemingly in opposition to this that deep water sedimentation on continental plates corresponds to periods of convective quiescence and that convective activity is marked by regression. This refers, however, to plate margins rising or falling very close to a convection axis. If this effect is significant, then the transgression on the trailing edge of the Australian plate took place only when the water-displacing influence of the new oceanic rise became dominant. In a third model (von der Borch et al. 1970) transgression occurs when the trailing edge, thinned by erosion during initial uplift, has moved significantly away from the rise and sinks isostatically.

The early Middle Eocene transgression in the Eucla Basin and Gambier Embayment is, as noted above, basically similar to the more widespread Upper Eocene manifestation.. Therefore, the postulated relationship to intercontinental tectonics requires that the onset of drift about the southeast Indian Ocean ridge predate early Middle Eocene, or about 48-49 m.y. ago. And if anomaly 18 is the oldest recorded in the new oceanic crust south of Australia, then it is perhaps 5 m.y. older than the 45m.y. suggested by Heirtzler et al. (1968). The change in sedimentary style, which was rapid at least in the Gambier Embayment (fig.2), gives less control to a lower limit on drift chronology, because the paralic regime could have been "carried" during early drift, as in the von der Borch et al. model. A date is not available but the compressing of anomalies 18 to 32 into perhaps 10 m.y. suggests that the transgression followed the new episode of sea floor spreading rather closely. In accepting a late Eocene date for this set of events Jones (1971) has not considered the Middle Eocene stratigraphic record. Also, it would seem that late Eocene-early Oligocene seaward slumping in the Otway Basin and orogenic events in New Guinea (i.e. on Australia's northern continental margin), which Jones has linked with the major tectonics/transgression, are evidence instead of a distinctly younger historical phase. The diachronous base of the transgression (early Middle Eocene to Oligocene) may support Russell's (1968) suggestion that transgression depends on heating and expanding of a rise plus sea floor spreading, and is slow compared to regression depending only on cooling and retraction.

According to Adams (1967) the larger foraminifera occupied a latitudinal belt roughly 50°N - 50°S during most of the Tertiary. In Fairbridge's (1967) model neritic carbonate sediments with larger foraminifera extend to 60°N in the nonglacial situation, i.e. when shallow seas are most widespread and warmest (thalassocratic condition). These figures are acceptable more readily for the Northern Hemisphere. Warm oceanic water is centred approximately on the equator during the northern winter, but offset strongly to the north during the northern summer (e.g. Meyerhoff 1970a). This asymmetry about the equator, and the influence of continental configuration and the Gulf stream and Kuroshio current, are seen in distribution maps of living planktonic foraminifera (e.g. Bé 1969, fig.1).

That evidence for variably warm water influence in the Tertiary of New Zealand is paralleled but weaker in southern Australia is in keeping with deflection of the south equatorial current. But if Australia lay substantially further south during the Eocene than it does now, then Meyerhoff's (1970a) conclusion based on present geographic configuration that "warm climate brought by equatorial current systems cannot extend into higher southern latitudes" would seem to be reinforced. Larger foraminifera of early Eocene age in northwest Europe and Britain occur at about the same high latitude as in Canterbury and on Chatham Island on the New Zealand plateau, according to reconstructions by Le Pichon (1968). The high northern records can be explained by warm water influence from the Tethys seaway but an Eocene south equatorial current, if it existed, would have passed more completely to the north of Australia than it does now. For water temperatures in New Zealand to be comparable in the Eocene and Miocene (Devereux 1967, Hornibrook 1971) the Eocene climatic regime must have been very warm with very weak horizontal and vertical thermal gradients in the oceans. Similarly, in a more tropical situation, the Eocene and Miocene (possibly including Upper Oligocene) microfaunas in the Carnarvon Basin indicate similar conditions but are "separated" by drift of up to 15° latitude in the interim, and this basin is on the "southern" side of any anticlockwise circulation system in the Indian Ocean. A flat statement cannot be made yet on how far essentially nonquantitative climatic data from extinct organisms can be stretched to agree with quantitative inferences on palaeolatitudes and crustal spreading rates. The Palaeogene radiation in larger foraminifera, including the Discocyclinidae, achieved a level of diversity not matched since the Middle Miocene, and it is almost certain that niches occupied by marginal, endemic forms like Asterocyclina speighti cannot be circumscribed in actualistic terms. Even so, it would seem that the evidence of fossils encourages conservative estimates of Eocene palaeolatitudes and post-Eocene drift to the north.

If there is difficulty in reconciling these lines of evidence, then it is exacerbated by recent suggestions of a south polar ice cap during the Eocene. South Pacific deep-sea cores contain quartz grains with surface morphological features indicating glacial derivation and ice rafting (Geitzenauer et.al. 1968, Margolis and Kennett 1970). Different cores are dated as Lower Eocene (Globorotalia rex and nannofossils) and Middle Eocene (Acarinina primitiva with Globigerapsis index). The latter association defines the Globigerapsis index zone in South Australia (fig.2) and thus is no older than the base of the transgression discussed here. All cores are estimated from sea-floor spreading rates to be no more than 3^{o} of latitude from their original positions, and glaciation had to be extensive enough for ice rafting to carry into present day sub-Antarctic regions (Margolis and Kennett 1970). Similar conclusions were reached for the Oligocene; there were no Upper Eocene data.

The inferred existence of a polar ice cap means that thermal gradients in the oceans were strong in the Lower and Middle Eocene - much stronger than is indicated above for the Upper Eocene. Its presence as late as the Globigerapsis index zone also is evidence that the transgression in Australia was initiated by crustal tectonism rather than by ice-melting, but the latter effect may have contributed to the increase in transgressional extent discernible in the stratigraphic record at about the Middle/Upper Eocene boundary (fig.2). Similarly, the Kaiatan transgression extends beyond the Bortonian in New Zealand (Brown et al. 1968). A suggested Oligocene glaciation (Frerichs 1970) is not inconsistent with Margolis and Kennett's observations, but its extension back through the Upper Eocene inferred by Frerichs is not supported by the evidence discussed here. Glenie et al. (1968) conclude that stratigraphic fluctuations and palaeoclimatic evidence in the Otway Basin strongly support a eustatic origin and climatic control of inferred sea-level changes. This control requires an ice-cap; Glenie et al. do not consider tectonic control of eustasy. A model of deglaciation from Middle to Upper Eocene requires that Australia and New Zealand be further removed from Antarctica at the time than sea floor spreading and palaeomagnetic evidence would seem to allow. A better fix on an early Tertiary position of Antarctica than is presently available would not resolve the conflict between, on the one hand, evidence of glaciation contemporaneous with fossil evidence of warm conditions particularly in the New Zealand Lower Eocene (fig.3), and geophysical evidence of rather high latitudes and closeness to Antarctica on the other.

Unexplained inconsistencies aside, the data do not contradict suggestions of some link in cause and effect between crustal tectonics (and tectono-eustasy) and climatic change (Irving and Robertson 1969, Valentine and Moores 1970, Crowell and Frakes 1970, Frerichs 1970). Curves of transgression-regression and evaporite-glaciation are used to support different arguments but tend to be similar (see Fairbridge 1967, Grasty 1967, Damon 1968, Russell 1968, Meyerhoff 1970a,b, Frerichs 1970). Questions such as the old "climate (i.e. extraterrestrial cause) versus tectonics", or whether ice-cap formation and thus glacioeustatic phenomena can be controlled by and therefore reinforce tectono-eustasy, provide adequate stimulus for attempting to integrate palaeontological, sedimentological, palaeomagnetic and plate-tectonic research.

SUMMARY

(1) The transgression beginning in the Middle Eocene is the main change in Mesozoic-Tertiary sedimentation in southern Australia. The regime changes from nonmarine-paralic, with marine ingressions, to a neritic carbonate facies with variable clastics and a glauconitic/limonitic base.

(2) Sea floor spreading data have implied separation of Australia from Antarctica before marine magnetic anomaly 18. An episode of drifting with increased subcrustal convection leading to tectono-eustatic sea level rise would be consistent with the evidence of major stratigraphic change, but this suggests that anomaly 18, if it is the first record of new oceanic crust, is distinctly older than its estimated 45 m.y. age.

(3) There is good evidence for warm water, though not tropical, conditions in the Upper Eocene in southern Australia and New Zealand. To reconcile this evidence with geographical configurations derived from palaeomagnetism and pre-drift assembly, according to which Australia has moved north 15° or more since the early Tertiary, the Upper Eocene oceans must have been very warm with very weak thermal gradients. Yet a Lower and Middle Eocene ice-cap has been inferred from deep sea core data - at a time when New Zealand and Australia were very close to Antarctica.

(4) A model of tectono-eustatic transgression in the Middle Eocene, reinforced by deglaciation toward the Upper Eocene, fits

most data, if not comfortably; it does not fit Lower Eocene records of larger foraminifera in New Zealand. More study is needed to integrate the results of various lines of enquiry.

B. McGowran

BMcG:MFV:CH
24.5.1971

Adams, C.G., 1967. Tertiary foraminifera in the Tethyan, American and Pacific Provinces. In: C.G. Adams and D.V. Ager (Editors), Aspects of Tethyan Biogeography. The Systematics Association, Publication No.7: 195-217.

Baumann, P., 1970. Mikropaläontologische und stratigraphische Untersuchungen der obereozänen-oligozänen Scaglia im zentralen Appennin (Italien). Eclogae Geol. Helv., 63 (3): 1133-1211, pls. 1-7, text-figs. 1-27.

Be, A.W.H., 1969. Planktonic Foraminifera. In: Distribution of selected groups of marine invertebrates in waters south of 35°S latitude. Folio II, Antarctic Map Folio Series, American Geographical Society: 9-12.

Berggren, W.A., 1969. Cenozoic chronostratigraphy, planktonic foraminiferal zonation and the radiometric time scale. Nature, 224: 1072-1075.

Bock, P.E., and Glenie, R.C., 1965. Late Cretaceous and Tertiary depositional cycles in south-western Victoria. Proc. Roy. Soc. Victoria, 79: 153-163, figs. 1-2.

Brown, D.A., Campbell, K.S.W., and Crook, K.A.W., 1968. The Geological Evolution of Australia and New Zealand. Pergamon Press, Commonwealth International Library, Geology Division, 409pp.

Carey, S.W., 1970. Australia, New Guinea and Melanesia in the current revolution in concepts in the evolution of the earth. Search, 1:178-189, figs. 1-18.

Cockbain, A.E., 1967. Asterocyclina from the Plantagenet Beds near Esperance, W.A. Aust. J. Sci., 30:68.

Cockbain A.E., 1968a. Distribution of the nautiloid Aturia in the Eocene. J. Paleont., 42.

Cockbain, A.E., 1968b. Eocene foraminifera from the Norseman Limestone of Lake Cowan, Western Australia. W. Aust. Geol. Surv. Ann. Rept., 1967: 59-60.

Cockbain, A.E., 1968c. The stratigraphy of the Plantagenet Group, Western Australia. W. Aust. Geol. Surv. Ann. Rept., 67: 61-3.

Cockbain, A.E., 1969. Dasycladacean algae from the Werillup Formation, Esperance. W. Aust. Geol. Surv. Ann. Rept., 1968: 92-93, figs; 10,11, pls. 23,24.

Crowell, J.C., and Frakes, L.A., 1970. Phanerozoic glaciation and the causes of ice ages. American J. Sci., 268: 193-224, figs. 1-7.

Damon, P.E., 1968. The relationship between terrestial factors and climate. In: J. Murray Mitchell Jnr. (Editor), Causes of climatic change. Am. Meteorol. Soc., Meteorol. Monographs, Vol 8, No.30: 106-111, figs. 1-3.

Devereux, I., 1967. Oxygen isotope paleotemperature measurements on New Zealand Tertiary fossils. N.Z. J.Sci., 10: 998-1011, fig1.

Dietz, R.S., and Holden, J.C., 1970. Reconstruction of Pangaea: break-up and dispersal of continents: Permian to Present. J. Geophys. Res., 75: 4939-4956, figs. 1-8.

Dietz, R.S., and Holden, J.C., 1971. Pre-Mesozoic oceanic crust in the eastern Indian Ocean (Wharton Basin)? Nature, 229: 309-312, figs. figs. 1-3.

Dorman, F.H., 1966. Australian Tertiary paleotemperatures. J. Geology, 74: 49-61, figs. 1-3.

Dorman, F.H., 1968. Some Australian oxygen isotope temperatures and a theory for a 30-million year world temperature cycle. J. Geology, 76: 297-313, figs. 1-6.

Edwards, A.R., 1968. The calcareous nannoplankton evidence for New Zealand Tertiary marine climate. Tuatara, 16: 26-31, fig.1.

Fairbridge, R.W., 1967. Carbonate rocks and paleoclimatology in the biogeochemical history of the planet. In: G.W. Chilingar, H.J. Bissell, R.W. Fairbridge (Editors), Carbonate rocks, origin, occurrence and classification. Elsevier, Amsterdam, pp.399-432.

Frerichs, W.E., 1970. Paleobathymetry, paleotemperature and tectonism. Geol. Soc. America, Bull., 81: 3445-3452, figs. 1-9.

Geitzenauer, K.R., Margolis, S.V., and Edwards, D.S., 1968. Evidence consistent with Eocene glaciation in a South Pacific deep sea sedimentary core. Earth Planet. Sci. Letters, 4: 173-177, figs. 1-11.

Glenie, R.C., Schofield, J.C., and Ward, W.T., 1968. Tertiary sea levels in Australia and New Zealand. Palaeogeogr., palaeoclimatol., palaeocol., 5: 141-163, figs. 1-5.

Grasty, R.L., 1967. Orogeny, a cause of world-wide regression of the seas. Nature, 216: 779-780, figs.1-3.

Griffiths, J.R., 1971. Continental margin tectonics and the evolution of south-east Australia. Aust. Petrol. Expl. Assoc. J., 11: 75-79, figs. 1-7.

Hamilton, W., 1968. Cenozoic climatic change and its cause. In: J. Murray Mitchell Jnr. (Editor), Cause of climatic change. Am. Meteorol. Soc., Meteorol. Monogr., vol.8, no.30: 128-133, fig.1.

Heirtzler J.R., Dickson, G.O., Herron, E.M., Pitman, W.C., and Le Pichon, X., 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. J. Geophys. Res., 73: 2119-2136, figs. 1-11.

Hocking, J.B., and Taylor, D.J., 1964. The initial marine transgression in the Gippsland Basin, Victoria. Aust. Petrol. Expl. Assoc. J., 1964: 125-132.

Hornibrook, N. de B., 1968. Distribution of some warm water benthic foraminifera in the N.Z. Tertiary. Tautara, 16: 11-15, fig.1.

Hornibrook, N. de B., 1969. Report on a visit to the U.S.A. to attend the I.U.G.S. Working Group for a biostratigraphic zonation of the Cretaceous and the Cenozoic. N.Z.G.S., Rept.No. 42 (unpublished).

Hornibrook, N. de B., 1971. New Zealand Tertiary climate. In: R.P. Suggate (Editor), The geology of New Zealand. N.Z. Geol. Surv. (in press).

Irving, E., 1967. Palaeomagnetic evidence for shear along the Tethys. In: C.G. Adams and D.V. Ager (Editors), Aspects of Tethyan biogeography. The Systematics Association, Publ. No. 7: 59-76, figs. 1-8.

Irving, E., and Robertson, W.A., 1969. Test for polar wandering and some possible implications. J. Geophys. Res., 74: 1026-1036, figs. 1-8.

James, E.A., and Evans, P.R., 1971. The stratigraphy of the offshore Gippsland Basin. Aust. Petrol. Expl. Assoc. J., 11: 71-74, figs. 1-4.

Jenkins, D.G., 1968. Planktonic foraminiferida as indicators of New Zealand Tertiary palaeotemperatures. Tuatara, 16: 32-37, fig.1.

Jenkins, D.G., 1971. New Zealand Cenozoic planktonic foraminifera.

Geol. Surv. N.Z., Paleontol. Bull. 42: 1-278, pls. 1-23, figs. 1-2.

Jones, J.G., 1971. Australia's Caenozoic drift. Nature, 230: 237-239, figs. 1-3.

Le Pichon, X., and Heirtzler, J.R., 1968. Magnetic anomalies in the Indian Ocean and sea-floor spreading. J. Geophys. Res. 73: 2101-2117, figs.1-9.

Le Pichon, X., 1968. Sea-floor spreading and continental drift. J. Geophys. Res., 73: 3661-3697, figs. 1-11.

Leslie, R.B., 1966. Petroleum exploration in the Otway Basin. Proc. 8th Comm. Mining Congr., 5: 203-216.

Lindsay, J.M., 1967. Foraminifera and stratigraphy of the type section of Port Willunga Beds, Aldinga Bay, South Australia. Trans. Roy. Soc. S. Aust., 91: 93-109, figs. 1-2, pl.1.

Lindsay, J.M., 1969. Cenozoic foraminifera and stratigraphy of the Adelaide Plains Sub-basin, South Australia. Geol. Surv. S. Aust. Bull., 42: 1-60, figs. 1-6, pls. 1,2.

Ludbrook, N.H., 1961. Stratigraphy of the Murray Basin in South Australia. Geol. Surv. S. Aust. Bull., 36: 1-96, figs. 1-36, pls. 1-8.

Ludbrook, N.H., and Lindsay, J.M., 1969. Tertiary foraminiferal zones in South Australia. In: P. Brönnimann and H.H. Renz (Editors), Proc. 1st. Internat. Conf. Planktonic Microfossils, Geneva 1967, vol.2. E.J. Brill, Leiden, pp.366-375, pls. 1-2, figs. 1-2.

Ludbrook, N.H., 1969. Tertiary Period. In: L.W. Parkin (Editor), Handbook of South Australian Geology. Geol. Surv. S. Aust., Ch.5, pp. 172-203, figs. 83-101.

McElhinny, M.W., and Wellman, P., 1969. Polar wandering and sea-floor spreading in the southern Indian Ocean. Earth Planet. Sci. Letters., 6: 198-204, figs. 1-4.

McElhinny, M.W., 1970. Formation of the Indian Ocean. Nature, 228: 977-979, figs. 1,2.

McGowran, B., and Wade, M., 1967. Latitudinal variation in the foraminiferal content of biogenic sediments. Aust. N.Z. Assoc. Adv. Sci, 39th Congr. Melbourne, 1967, Sect. C, Abstr.:A9-A11.

McGowran, B., and Lindsay, J.M., 1969. A Middle Eocene planktonic foraminiferal assemblage from the Eucla Basin. Quart. Geol. Notes. Geol. Surv. S. Aust., 30: 2-10, fig.1, pls. 1-2.

McGowran, B., Harris, W.K., and Lindsay, J.M., 1970. The Maslin Bay flora, South Australia. 1. Evidence for an early Middle Eocene Age. N. Jb. Geol. Paläont. Mh., Jg.1970, H.8: 481-485.

McGowran, B., Lindsay, J.M., and Harris, W.K., 1971. Attempted reconciliation of Tertiary biostratigraphic systems, Otway Basin. In: The Otway Basin in southeast Australia. Spec. Bull. Geol. Survs. S. Aust. Victoria (in press).

McWhae, J.R.H., Playford, P.E., Lindner, A.W., Glenister, B.F., and Balme, B.E., 1958. The stratigraphy of Western Australia. Geol. Soc. Aust. J., 4: 1-161, text figs. 1-10.

Margolis, S.V., and Kennett, J.P., 1970. Antarctic glaciation during the Tertiary recorded in sub-Antarctic deep-sea cores. Science, 170: 1085-1087, figs. 1-2.

Martini, E., 1970. Standard Paleogene calcareous nannoplankton zonation. Nature, 226: 560-561, fig.1.

Meyerhoff, A.A., 1970a. Continental drift: implications of paleomagnetic studies, meteorology, physical oceanography, and climatology. J. Geology, 78: 1-51, figs. 1-35.

Meyerhoff, A.A., 1970b. Continental drift, II: high latitude evaporite deposits and geologic history of Arctic and North Atlantic Oceans. J. Geology, 78: 406-444, figs. 1-13.

Quilty, P.G., 1969. Upper Eocene foraminifera from Albany, Western Australia. J. Roy. Soc. West. Aust., 52(2): 41-58, figs. 1-7.

Rade, J., 1970. Otway Basin, Australia: use of calcareous nanno-plankton and palynology to determine depositional environment. Amer. Assoc. Petrol. Geol. Bull., 54: 2196-2199, fig.1.

Reynolds, M.A., 1967. A comparison of the Otway and Gippsland Basins. Aust. Petrol. Expl. Assoc. J., 7: 50-58, figs. 1-4.

Richards, K.A, and Hopkins, B.M., 1969: Exploration in the Gippsland, Bass and Otway Basins, Australia. E.C.A.F.E. Symp. Dev. Petrol. Resources Asia and Far East, Canberra.

Russell, K.L., 1968. Oceanic ridges and eustatic changes in sea level. Nature, 218: 861-2, figs. 1-2.

Singleton, O.P., 1968. Otway Region. In: J. McAndrew and M.A.H. Marsden (Editors), A Regional guide to Victorian Geology. Geol. Dept. Univ. Melbourne: 117-131, figs: 1-4.

Smith, A.C., and Hallam, A., 1970. The fit of the southern continents. Nature, 225: 139-144, figs. 1-2.

Sproll, W.P., and Dietz, R.S., 1969. Morphological continental fit of Australia and Antarctica. Nature, 222: 345-348, figs. 1-4.

Stuart, W.J., 1970. The Cainozoic stratigraphy of the south eastern coastal area of Yorke Peninsula, South Australia. Trans. Roy. Soc. S. Aust., 94: 151-178, figs. 1-7.

Tarling, D.H., 1971. Gondwanaland, palaeomagnetism and continental drift. Nature, 229: 229: 17-21, figs. 1-3.

Taylor, D.J., 1966. Esso Gippsland Shelf No.1: the mid-tertiary foraminiferal sequence. Bur. Min. Resour., Australia, Petrol. Search Subsidy Acts.

Taylor, D.J., 1967. Marine transgressive patterns in Victoria. Aust. N.Z. Assoc. Adv. Sc., 39th Congr. Melbourne 1967, Abstr. Sec.C: A3-A4

Taylor D.J., 1971. Foraminifera and the Cretaceous and Tertiary depositional history in the Otway Basin in Victoria. In:: The Otway Basin in southeast Australia. Spec. Bull. Geol. Survs. S. Aust. Vict., Ch.10 (in press).

Valentine, J.W., and Moores, E.M.,1970. Plate-tectonic regulation of faunal diversity and sea level:a model. Nature, 228: 657-659, fig.1.

Veevers, J.J., Jones, J.G. , and Talent, J.A., 1971. Indo-Australian stratigraphy and the configuration and dispersal of Gondwanaland. Nature, 229: 383-388, figs. 1-7.

Von der Borch, C.C., Conolly, J.R., and Dietz, R.S., 1970. Sedimentation and structure in the vicinity of the Otway Basin, southern Australia. Marine Geol., 8: 59-83, figs. 1-13.

Wass, R.E., Conolly, J.R., and MacIntyre, R.J., 1970. Bryozoan carbonate sand continuous along southern Australia. Marine Geol., 9: 63-73, figs. 1-6.

Wellmann, P., McElhinny, M.W., and McDougall, I., 1969. On the polar-wander path for Australia during the Cenozoic. Geophys. J.R. Astr. Soc., 18: 371-395, figs. 1-10.

Wopfner, H., 1969. Mesozoic Era. In: L.W. Parkin (Editor), Handbook of South Australian Geology. Geol. Surv. S. Aust., Ch.4: 133-171, figs. 60-82.

TEXT - FIGURES

Fig.1. Australia-New Guinea, Antarctica and New Zealand Plateau - New Caledonia (shading: shoreline to 2,000m). Australian basins contain Eocene sections (fig.2). Southern Australia also shown (dotted) in approximate early Tertiary (pre-Middle Eocene) position assuming minimum subsequent latitudinal drift of 15° (see text); this indicates a fit with the New Zealand Plateau, before opening of Tasman Sea, as proposed by Jones (1971) (see also Le Pichon 1968). Deep sea cores with clastics of inferred glacial and ice-rafting derivation, of Lower Eocene (open circles) and Middle Eocene (solid circles) ages, after Margolis and Kennett (1970).

Fig.2. Correlation of Eocene strata on Australian margin (excluding New Guinea). Data sources and symbols as shown.

Fig.3. Summary of biological and physical data discussed in text.

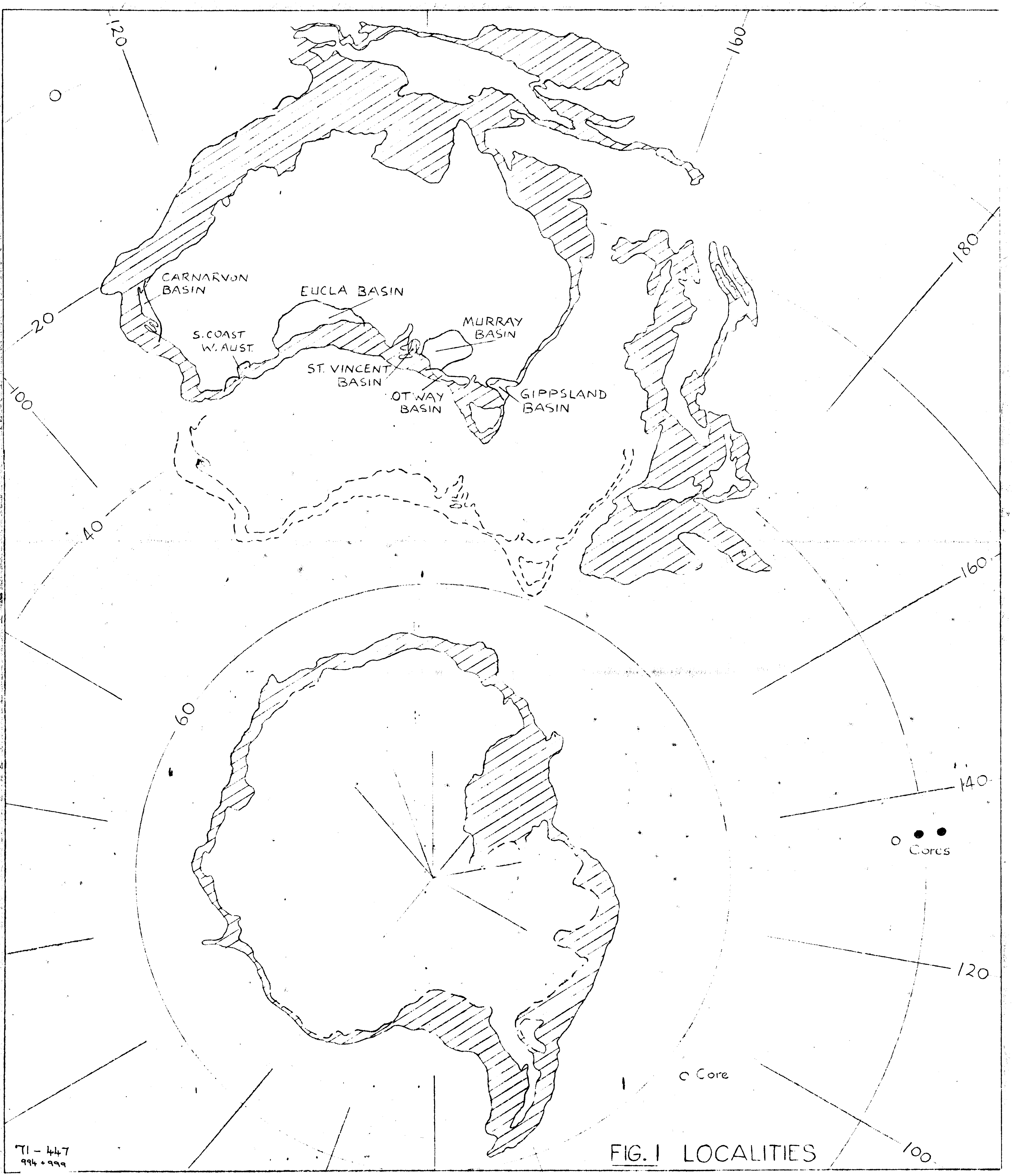
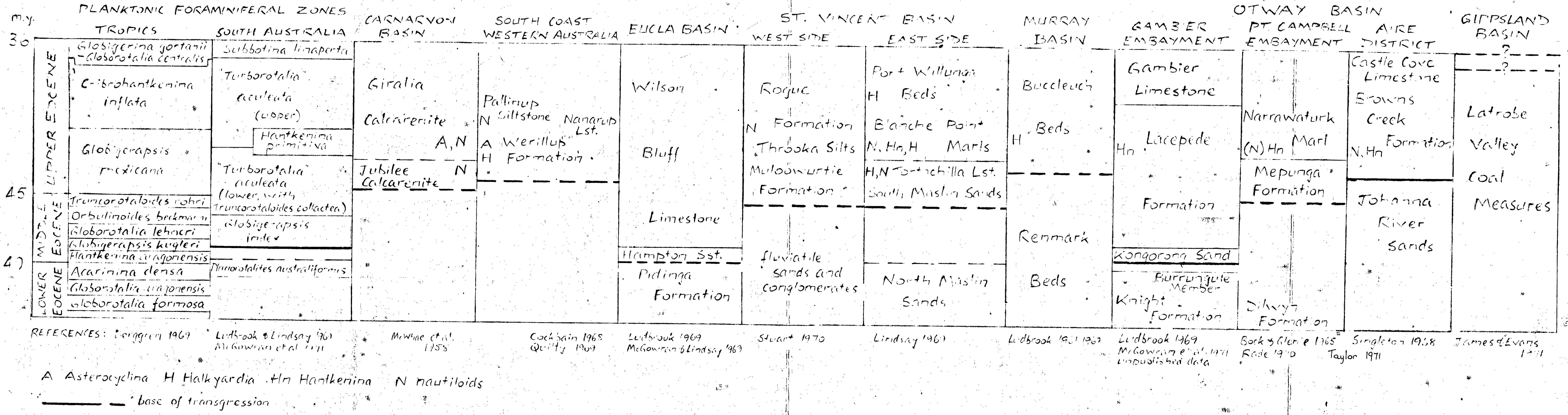
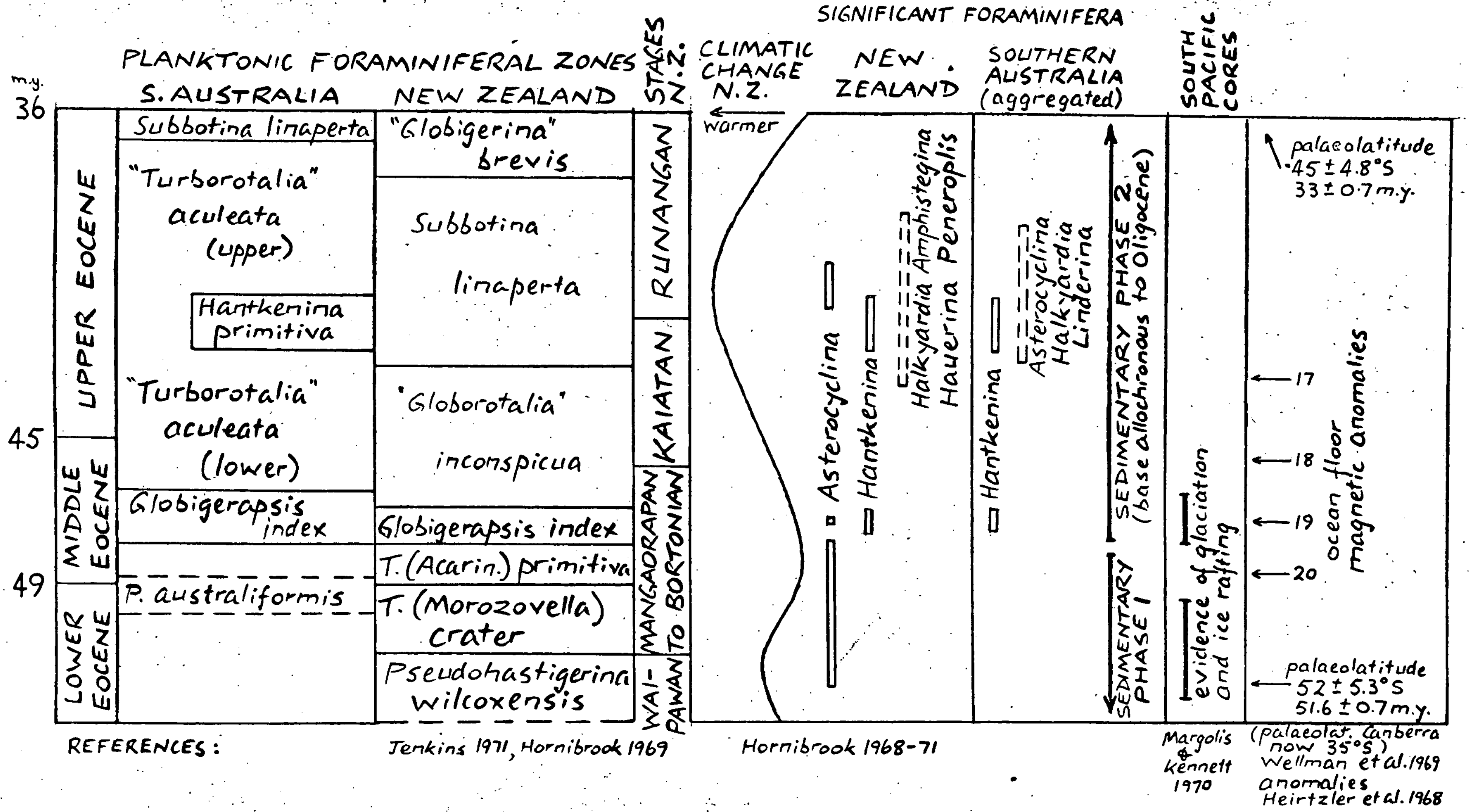


FIG. 1 LOCALITIES



71 – 448

FIG. 2 CORRELATION OF EOCENE STRATA ON AUSTRALIAN MARGIN



71 - 449
994 + 999

FIG. 3 SUMMARY OF BIOLOGICAL AND PHYSICAL DATA