The palaeogeographic and palaeoenvironmental evolution of a Palaeogene mixed carbonate–siliciclastic cool-water succession in the Otway Basin, Southeast Australia

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Abstract

The Otway Basin in southeast Australia contains a thick sequence of Cenozoic shelfal carbonates and siliciclastics that preserve signals relating to the progressive opening of the Southern Ocean since the Palaeogene. This multidisciplinary study integrates outcrop and subsurface well data from over 100 wells and bores throughout the Otway Basin with micropalaeontological analyses to constrain the age and palaeoenvironments of the Nirranda Group (Late Eocene to Middle Oligocene) and the Heytesbury Group (Late Oligocene to mid Miocene). These data were used to deduce the Late Eocene to Late Oligocene palaeogeographical evolution of the area. During the Late Eocene paralic high energy siliciclastic shoreline to shelf facies dominated the region, deepening southwards where mid to outer shelf conditions preserved high energy sandy carbonate facies. Above the Eocene–Oligocene boundary low energy inner to mid shelfal silt and muddy sand persisted to the north, deepening southward to carbonate-dominated low energy outer shelf to bathyal marls. The change from siliciclastics to carbonates at the Eocene–Oligocene boundary in the Otway Basin may relate to regional tectonics. In the Early Oligocene, high energy inner to outer shelf sand bodies formed in front of marine to inner shelf mudstone facies; the sand units are likely to have been influenced by strong local longshore drift and ocean swells that increased as the Southern Ocean widened to create a larger fetch. In the eastern half of the basin, later in the Early Oligocene, mixed paralic to inner shelf siliciclastic and carbonate facies were deposited passing to inner to mid shelf marl and mudstone and outer shelf to bathyal marls basinward. During this time, low to high energy shelfal calcarenite, chalk and marl dominated the westerly edge of the basin. The contrast in facies from west to east in the basin is inferred to be due to contrasting terrigenous input, environmental energy and ramp/shelf geometry. By Late Oligocene times (the Clifton Formation) the Otway Basin was dominated by high energy carbonate facies deposited in mid to outer shelf palaeoenvironments. The base of the Clifton Formation preserves a shift in facies and foraminiferal faunas that correlates to the major sea level fall at the Early–Late Oligocene boundary. This sea level fall is related to a major ice advance in Antarctica that corresponds to mid-Oligocene unconformities globally. The switch from low to high energy facies across the Early–Late Oligocene boundary in the Otway Basin suggests that the Southern Ocean swells experienced by the modern Otway coast were well established by Middle Oligocene time, evidence of the strengthening ‘proto’ Antarctic swell regime. By Early Miocene times, with final deepening of the Drake Passage, the Antarctic Circum-Polar Current formed and predominantly inner to outer shelf marls and limestones were deposited in the Otway Basin. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Otway Basin in southeast Australia (Fig. 1) contains a thick sequence of Late Eocene to Miocene marine neritic siliciclastic and carbonate sediments that record the Palaeogene to Neogene history of events surrounding the progressive opening of the Southern Ocean. Owing to its position on the west side of Tasmania, the Otway Basin was exposed to the full force of the Southern Ocean swells throughout most of the Tertiary. In addition, hundreds of bores and wells drilled for water and hydrocarbon exploration containing Cainozoic marine sediments exist for the Otway Basin; this subsurface data supplemented with surface outcrops makes this basin one of the best sampled Cenozoic successions along the southern margin of Australia. These factors make the Otway Basin an ideal setting for studying the neritic record of changes in the Southern Ocean during the Tertiary.

The Otway Basin is an onshore basin containing a thick sequence of Mesozoic and Cainozoic sedimentary and volcanic rocks. It is located on the southern coastland of Eastern Australia, extending between L acepede Bay in South Australia and the eastern side of Port Phillip in Victoria over a distance of 400 km. The Otway Basin constitutes one of approximately eight discrete basins developed along the southern seaboard of the Australian continent. These basins include from east to west: the Gippsland, Port Phillip, Torquay, Otway, Murray, St. Vincent, Eucla and Bremer Basins. All eight basins have a common basin-filling history, and were initiated by events leading up to and following the Gondwana continental rifting, breakup and northwards drifting of the Australian continent from Antarctica. A common theme through all eight basins is the gradual transition from essentially non-marine Early Cretaceous sediments becoming more marine with time in the Tertiary period. This is considered to reflect the progressive opening of the Southern Ocean from Late Cretaceous times. By the Late Eocene most of these basins had become predominantly marine in character.

The Otway Basin covers an approximate area of 60,000 km$^2$ and is delimited to the north (onshore) by outcropping Palaeozoic basement rocks, and to the south (offshore) at the toe of the present continental slope (Fig. 1). The onshore part of the basin constitutes approximately half the total area, and has been subdivided into a series of intra-basinal structural troughs and highs, some of which have localised effects on the Late Cretaceous and Tertiary sedimentary thicknesses and facies. For example, in the Portland Trough, Tertiary-aged siliciclastic and carbonate sediments can exceed 2500 m, whereas on the Warrnambool Ridge they are less than 700 m.

The Otway Basin siliciclastic sedimentary sequences comprise the Late Cretaceous Sherbrook Group and the Palaeocene to Middle Eocene Wangerrip Group. During the Late Eocene the sediments became increasingly dominated by cool water carbonates that persist through to the Late Miocene. The predominantly carbonate sediments include the Late Eocene to Early Oligocene-aged Nirranda Group and Clifton Formation. In the offshore part of the basin, Tertiary siliciclastic and carbonate sediments exhibit a progradational geometry on offshore petroleum seismic lines, and downlap onto a Late Cretaceous unconformity surface. Wangerrip Group sediments thin offshore, whereas progressively thicker and younger carbonate wedges extend the modern-day shelfal area southwards into the Southern Ocean.

The palaeogeographic and palaeoenvironmental evolution of the Late Eocene to Oligocene Nirranda Group and Clifton Formation siliciclastic and carbonate sediments are the focus for this paper. They record the Palaeogene to Neogene history of events surrounding the progressive opening of the Southern Ocean.

2. Stratigraphy

2.1. Nirranda Group

The Nirranda Group includes all the Late Eocene to Oligocene marine siliciclastic and car-
Fig. 1. Location of the sections and wells and bores analysed in this work. Sections A–A¹–A² (Fig. 4) and B–B∞/C–C∞ (Fig. 5) are indicated along with the location of Glenelg-1 Bore.
bonate units of the Otway Basin (Fig. 2). The Group, first defined by Bock and Glenie (1965), was later relegated to subgroup status by Glenie (1971) because of the difficulty in distinguishing it from the overlying Heytesbury Group in the western Otway Basin. In this paper the original group status is preferred, as the new data from this study redefine the more westerly facies with greater certainty. The Nirranda Group includes two formations: a lower mixed carbonate and siliciclastic Mepunga Sand Formation conformably overlain by a mainly carbonate Narrawaturk Marl Formation. The Mepunga Sand Formation conformably overlies and is readily distinguished from the underlying siliciclastic paralic facies of the Lower Eocene-Paleocene Wanggurrup Group (Dilwyn Formation). Some minor localised Early to Middle Eocene siliciclastic marine units sometimes overlie the Dilwyn Formation and are referred to as the Burrungule Member (Harris, 1966) and the Sturgess Point Member (Tickell et al., 1992). Contiguous strata to the Narrawaturk Marl Formation in the South Australian part of the western Otway Basin have variously been referred to whole or part of the Gambier Limestone (McGowan, 1973; Moss and McGowan, 1993), with equivalents to the Mepunga Sand Formation referred to in Abele et al. (1976, 1988) and in this paper. More recently, new members of the Gambier Limestone have been proposed by White (1996).
(for the South Australian section), but the basin-wide stratigraphic utility of these units remains doubtful. For most of the Otway Basin the Nirranda Group is a subsurface unit only. Outcrops of the Nirranda Group occur at the eastern end of the Otway Basin, in the Johanna River-Glen Aire Districts (Carter, 1958a). The original local nomenclature for this district has since been redefined into the general Otway Basin nomenclature by Abele et al. (1976, 1988) and Tickell et al. (1992). In this paper, data from the subsurface are primarily used, with reference to the sections in the Aire District described more fully by Abele (1994).

2.2. Heytesbury Group

The Heytesbury Group comprises Late Oligocene to Late Miocene carbonates, which occur throughout the Otway Basin. The focus of this paper is mainly on the Late Oligocene to Early Miocene part of the Heytesbury Group, including the basal Clifton Formation and the lower beds of the overlying Gelibrand Marl. We do not extend the study much above the Oligo-Miocene boundary. The Clifton Formation usually is regarded as the basal part-clastic, part-carbonate formation of the Heytesbury Group, with the remaining units allocated to the carbonate dominated Gelibrand Marl. In the western Otway Basin, the typical characteristic features of the basal Clifton Formation are poorly expressed, leading to the previously cited nomenclature problems. In this paper, redefined biostratigraphic ages and a new event stratigraphic approach have been used to carry these units across the whole onshore part of the basin. This includes the South Australian section, providing for the first time a more uniform approach to the whole Otway Basin. The Clifton Formation is also recognised in this western area. Outcrops of the Clifton Formation and lower Gelibrand Marl are mainly confined to the eastern end of the Otway Basin at a type section located in coastal cliff outcrops near Princetown (Fig. 1). Similarly aged outcrops can also be viewed in the northeastern part of the Port Campbell area, and in quarries in the Mount Gambier area in South Australia. Outcrops of rocks above and below the Oligocene-Miocene boundary occur in Glenelg River cliff sections located at the South Australian-Victorian border. In this paper, both outcrop and subsurface data have been used to provide a uniform approach to the whole basin stratigraphy.

3. Methods

This study incorporates an interpretation of outcrops and subsurface well data (cores, cuttings, geophysical logs) from over 100 wells and bores throughout the Otway Basin (Fig. 1). In addition, 144 micropalaeontological samples were studied from cores from 30 wells and bores (which were continuously cored and representative samples were retained by the drillers every 2 to 3 m) and outcrops to constrain the age and palaeoenvironment of each unit (Tables 1–3). Binary presence/absence faunal data were collected, although where a particular sample contained over 15% of a particular benthic taxon its abundance was noted. A detailed quantitative foraminiferal and facies analyses of the Glenelg-1 Bore and the Clifton Outcrops can be found in Gallagher et al. (1999). The biostratigraphic datums used for dating each unit are illustrated on Fig. 3. These follow the biostratigraphic schemes outlined in Lindsay (1985), Abele (1994), Holdgate and Gallagher (1997) and McGowan et al. (1997). The palaeoenvironmental interpretations are based on comparisons with extant forms with reference to Murray (1991), Jones and Yassini (1995) and Li et al. (1996a,b), see Table 3. This detailed multidisciplinary integrated study forms the basis of palaeogeographic reconstructions for the Palaeogene of the Otway Basin.

4. Results

Three stratigraphic cross-sections (Figs. 4 and 5) were compiled to illustrate basin-wide relationships between units. The cross-sections are reduced to datum along the base of the Clifton Formation (top Nirranda Group), close to the Early–Late Oligocene Boundary. The east–west section along the present Otway coast illustrates the relationship between facies and structure (Fig. 4). Stratal
Table 1

Planktonic foraminiferal distribution in the Eocene to Oligocene of the Otway Basin. The data for Heywood-10 are adapted from Reed (1965). Note: *r* = reworked,
*cf* = cf. A more detailed quantitative foraminiferal and facies analyses of the Glenelg 1 Bore and the Clifton Outcrops can be found in Gallagher et al. (1999). See Fig. 14 for illustrations of these taxa.
Table 2
The distribution of benthic foraminiferal species in the Eocene to Oligocene of the Otway Basin. The data for Heywood-10 are adapted from Reed (1965). Note: these data are primarily binary presence/absence (the grey boxes), although the black boxes denote samples with more than 15% of that taxon in benthic assemblages. In addition, b=biconcava, ch=chapmanni, d=dehiscens, k=karreriformis, L=lingulata, P=planoconcava, p=papillata, s=sp., w=wilsoni. See Fig. 15 for illustrations of some of these taxa.
Table 3

The distribution of palaeoenvironmentally significant benthic foraminifera in the Eocene to Oligocene of the Otway Basin. The data for Heywood-10 are adapted from Reed (1965). The shading on the left-hand side of the table relates to the relative abundance of that taxon or its equivalents in the modern offshore Southeast Australia; white = absent, light grey = rare, dark grey = common, black = abundant. Note: these data are primarily binary presence/absence (the grey boxes), although the black boxes denote samples with more than 15% of that taxon in benthic assemblages. In addition: A = australis, B = bulloides, ca = conviva, L = large, N = novomezianus, S = sp., se = seminula, si = singletoni, st = stelligerum, T = tasmanensis, un = unilatera, ve = venusta. See Fig. 15 for illustrations of some of these taxa.
Fig. 3. The plankton foraminiferan zonation scheme used in this study plotted beside sequence chronostratigraphic coastal onlap chart of Haq et al. (1988). Note: The italicised dates (in brackets) of age boundaries in the epoch column are those of Berggren et al. (1995). This zonation is adapted from Moss and McGowran (1993), Abele (1994), Holdgate and Gallagher (1997) and McGowran et al. (1997).

geometries of the Mepunga Sand Formation and the Clifton Formation are illustrated using isopach maps (Fig. 6). Fig. 7 gives the lithological key for the detailed core logs shown in Figs 8 and 9 for five typical bores in the Victorian section of the Otway Basin (Glencly-1, Heywood-10, Narrawaturk-2, Portland-3, and Timboon-5); Figs. 8 and 9 also show the main geophysical log characteristics. Core logs from the Mount Gambier area in South Australia have also been used for comparison with the Victorian data (Blanche-145, Fig. 4); these are adapted from James and Bone (1989). The following stratigraphic nomenclature and descriptions slightly alter previously published nomenclature. The sedimentary succession is divided into two groups: the Nirranda Group, including the Mepunga Sand Formation and the Narrawaturk Marl Formation (Fig. 2); the Heytesbury Group, including the Clifton and Gellibrand Marl Formations (Fig. 2).

4.1. Nirranda Group: distribution and lithostratigraphy

The three principle Nirranda Group units in the Otway Basin are the Mepunga Sand
Fig. 4. An east-west stratigraphic section from Cape Otway to South Australia (see Fig. 1 for locality).
Fig. 5. Two north–south stratigraphic sections of the Otway Basin (see Fig. 1 for localities).
Fig. 6. Isopach maps of important stratigraphic units in the Otway Basin.
Fig. 7. Lithological key to Figs. 8 and 9.
Fig. 8. Sample lithologs and wireline logs from the Narrawaturk-2, Portland-3, Timboon-5 and Heywood-10 bores (see Fig. 1 for locality). Note, the vertical scales are in feet. See Fig. 7 for key to symbols.
Formation, the Narrawaturk Marl Formation and the Wangoom Sand Member (here defined, Fig. 2). In the deeper troughs (Figs. 4 and 5) the Wangoom Sand Member and Mepunga Sand Formation are generally present, separated by the lower part of the Narrawaturk Marl Formation. The Wangoom Sand Member is conformably overlain by the upper part of the Narrawaturk Marl Formation.

On structural highs such as the Warrnambool Ridge, and at the eastern end of the Port Campbell Embayment, the Wangoom Sand Member may be absent, or is poorly developed as thin beds of sandy dolomite within the Narrawaturk Marl Formation. In these instances a thickening of the Narrawaturk Marl Formation records a facies change in the Wangoom Sand Member from sandstone to marl. The north-south section down the axis of the Port Campbell Embayment (Fig. 5) illustrates a facies change from sandstone to marl near the present coastline (see Narrawaturk-2: Fig. 8). Wells in the offshore area contain predominantly marly facies. In the western end of the basin the two sand units are well developed within the Portland Trough, although in some bores the intervening lower part of the Narrawaturk Marl Formation may be absent. On the north-south section through the Portland Trough (Figs. 4 and 5) the Wangoom Sand Member becomes increasingly marly towards the present coast, where a log of the Portland-3 bore shows the interval as mainly limey marl and limestone (Fig. 8).

Further west in the Mount Gambier area of South Australia, the Mepunga Sand Formation is the only sand unit present. The Wangoom Sand Member pinches out on the western edges of the Portland Trough (Fig. 4). In addition, much of the Narrawaturk Marl Formation in the Mount Gambier region is present as dolomitic limestone (the Lower Gambier Limestone equivalent), whereas marly facies dominate the nearby Glenelg-1 bore (Fig. 9) and further to the east. The pervasive dolomitisation around Mt Gambier extends into Victoria for some 20-30 km, but the controls on its distribution are not well understood. Cochrane (1952) postulated a fault control to the dolomitisation, whereas James and Bone (1989) considered the dolomites to be post-depositional phenomena that may be related to the younger volcanism in the region, although James et al. (1993) now believe that the dolomites formed soon after deposition mainly by the interaction of the limestones with seawater.

An isopach map of the Mepunga Sand Formation and Wangoom Sand Member sands throughout the Otway Basin is shown on Fig. 6. This isopach includes the lower part of the Narrawaturk Marl Formation between the two units (this unit was incorporated since it is generally less than 10 m thick where the sand units are usually thicker than 20 m). Two major depocentres with a maximum thickness of 160 m occur within the Port Campbell Embayment and Portland Trough. The sands appear to thin into the offshore area and onto the northern basin margins, and to thin locally over intrabasin highs.

The central offshore area of the Otway Basin has no well data, but the thinning trends shown offshore to Portland, where well data are better, are probably repeated.

4.2. Age of the Nirranda Group

(1) Mepunga Sand Formation. Planktonic foraminifera are rare in this unit (Table 1) and consist of *Subbotina linaperta* and *Globigerinatheka index* with rare *Globorotaliinaea euapertura*, *Globorotaloides nauteri*, *Chiloguembelia cubensis*, *Paragloborotalia ampliapertura* and *praetenuitella*. No *Praetenuitella aculeata* or *Hamulinia primitiva* were found, although the LAD of the former taxon is often unreliable (Abele, 1994). In the absence of any mid Eocene indicators, a Late Eocene P15-P17 age is assigned to this unit. A K/Ar radiometrically defined oldest age of 36.5 ± 1 million years for the Mepunga Sand Formation can be obtained from the underlying basalt date in the Cobboboonee-2 bore (Fig. 4), although it is not absolutely certain whether some Mepunga Sand Formation units may also underlie this basalt. However, assuming the basalt date reflects the age of extrusion (and is not an intrusive age), then the date is in broad agreement with the biostratigraphic age.

(2) Narrawaturk Marl Formation. A diverse plankton fauna occurs in this unit (Table 1). The lower part rarely contains *G. index* and, therefore,
occasionally it may be Late Eocene (P15–P17) in age. The majority of the lower section of this unit (incorporating the Wangoom Sand Member) lies above the LAD of G. index. Subbotinina angiporoides, S. linaperta, Tenuitella gemma, C. cubensis, tenuntellids and the textularid Bolivinopsis cubensis are common in the lower Narrawatuk Marl Formation; based on these data an Early Oligocene (P18) zonal age is assigned to this part of the unit. An Early Oligocene (P19/20 zonal) age is assigned to the upper part of the Narrawatuk Marl Formation (above the Wangoom Sand Member) based on the LAD of Guembelitria triseriata and FAD of S. angiporoides. The LAD of C. cubensis occurs near the top of the Narrawatuk Marl, giving an upper Early Oligocene (P21a subzonal) age, although occasionally this taxon may be reworked into younger overlying units.

4.3. Foraminiferal assemblages and facies of the Nirranda Group

Diverse benthic foraminifera and facies occur in the Nirranda Group (Tables 2 and 3), representing palaeoenvironments from high energy inner shelf to low energy upper slope to bathyal. The biofacies evolution of the Nirranda Group with time is shown in Figs. 10–12. Foraminiferal assemblages and facies of the Nirranda Group include burrowed shelly siltstone (not sampled) and mudstone with glauconite in the northern part of the basin, and shelly pyritic marls in the southern part. Planktonic and benthic foraminifera are common in this interval (Figs. 13, where macrofaunas would have been winnowed and sorted by wave action. The carbonate content of this shelf facies increases southwards to Voluta-1.

(2) Narrawatuk Marl Formation. For descriptive purposes, this unit can be subdivided into three: lower Narrawatuk Marl Formation, Wangoom Sand Member and its equivalents and the upper Narrawatuk Marl Formation.

(a) Lower part of the Narrawatuk Marl Formation. Fine-grained facies characterise the lower part of the Narrawatuk Marl Formation and include burrowed shelly silstone (not sampled for microfossils) and mudstone with glauconite in the northern part of the basin, and shelly pyritic marls in the southern part. Planktonic and benthic foraminifera are common in this interval (Figs. 14 and 15). A diverse mixed rotaliid and textularid fauna occurs (Tables 2 and 3). Robertinids such as Globocassidulina subglobosa, Anomalinoides macroglabra and Cibicidoides perforatus. Cibicidids such as Cibicides and Heterolepa also occur with rare Alabamina, Cerobertina and Ceratocancris. Miliolinids such as Pyrgo and Quinqueloculina occur in Panmure-2 and Timboon-5 associated with low diversity benthic assemblages. Planktonic foraminifera are rare. Ferruginous sandstone and sandy limestone facies occur in Voluta-1 with rare Sphaeroindina bulboides, Pullenia bulboides and Cyclammina incisa. Glauconite is common in the Mepunga Sand Formation.

Palaeoenvironment. Most of the Mepunga Sand Formation is interpreted to have been deposited in mid to outer shelf palaeoenvironments based on the presence of P. bulboides, S. bulboides, G. subglobosa, A. macroglabra and C. perforatus. Inner to mid shelf conditions prevailed in the eastern part of the basin preserving restricted calcareous faunas and miliolinids. The coarse-grained ferruginous and glauconitic sandstones of the Mepunga Sand Formation probably formed in a continuum of environments ranging from a high energy shoreline to the north to outer shelf siliciclastic facies to the south during the Late Eocene (Fig. 13), where macrofaunas would have been winnowed and sorted by wave action. The carbonate content of this shelf facies increases southwards to Voluta-1.

Fig. 9. A log of the Glenelg-1 bore showing important biostratigraphic datums; note, the vertical scale is in feet. A more detailed quantitative foraminiferal and facies analyses of the Glenelg-1 can be found in Gallagher et al. (1999). The stratigraphic and faunal data for the Dilwyn Formation are adapted from Crespin (1954). See Fig. 7 for key to symbols.
subglobosa and A. macroglabra. Abundant infaunal taxa such as Uvigerina proboscidea and G. subglobosa occur in Timboon-5. The marly facies of Voluta-1 contains abundant Gyroidinoides allani, P. bulloides and G. subglobosa with Oridorsalis umbonatus. Palaeoenvironment. The siltstone facies in the northern part of this basin is interpreted to have
Fig. 11. The palaeogeography of the Early Oligocene sequences in the Otway Basin.

been deposited in a low energy marginal marine palaeoenvironment. The fauna in the burrowed mudstones in the eastern part of the basin was deposited in a low energy inner to mid shelf palaeoenvironment. The low energy marly facies in this interval contains typical mid to outer shelf foraminiferal faunas, including *G. subglobosa* and *P. bulloides*. In addition, it is possible that an
Fig. 12. The palaeogeography of the Early to Late Oligocene sequences of the Otway Basin.

Fig. 13. The sequence stratigraphy of the Otway Basin and its correlations with other Eocene to Oligocene units in SE Australia. The evolution of the Southern Ocean and Tasman Sea from Middle Eocene to Early Miocene times is adapted from Veevers et al. (1991). The palaeoceanographic features of the Southern Ocean are adapted from Kennett (1977), Kennett and von der Borch (1986) and Kamp et al. (1990). Note: the italicised dates (in brackets) of age boundaries in the epoch column are those of Berggren et al. (1995).
upwelling in a mid to outer shelf palaeoenvironment [like those described from Gippsland by Holdgate and Gallagher (1997) and McGowan et al. (1997)] may have occurred to produce the fauna observed in Timboon-5. The occurrence of *O. umbonatus* in Volata-1 is significant because this taxon typifies outer shelf to bathyal palaeoenvironments.

(b) Wangoom Sand Member and its equivalents. The facies in the Wangoom Member and its equivalents is summarised in Fig. 11. Two laterally discontinuous horizons of coarse ferruginous sandstone (around Portland and Warrnambool) separate the northern mudstone facies from marly facies to the south of the basin. The fine-grained marly and mudstone facies in this interval often contains sandy and silty material with laterally discontinuous sand bodies. Agglutinated foraminifers dominate the siliciclastic facies of the Wangoom Member and its equivalents (Fig. 11 and Table 2). The fauna is rich in *Ammodiscus parri* and *Cyclammina*, including the species *C. incisa*, *Cyclammina rotundata* and *Cyclammina pauhera*. This interval in Mepunga-7, Warrain-7 and Narrawaturk-2 is typified by abundant rotalids *G. subglobosa*, *C. perforata*, *Cibicides lobatus*, *Cibicides pseudocorn spaces* and *A. macroglabra*. *Spirillina* and miliolinids such as *Quinqueloculina* and *Pyrgo* are common in Yangeri-1 and Codrington-1. Heywood-10 contains few rotalid species and common agglutinated forms.

Palaeoenvironment. The ferruginous sandstone of the Wangoom Member is interpreted to represent offshore sand bodies reworked and deposited in a high energy palaeoenvironment. These sands formed offshore from the northern part of the basin where low energy marginal to fully marine mudstones were deposited. The facies to the south of the sand bodies becomes marly basinward. The presence of sandy and silty material in the fine-grained facies may indicate intermittent transportation of siliciclastic material into low energy environments. The discontinuous layers of sandstones and sandy limestones may represent shallow marine channels or small deltas that are the source of the siliciclastics to form the sand bodies (Fig. 11). Foraminiferal assemblages in the mudstone facies contain abundant inner shelf indicators such as *Quinqueloculina* and *Spirillina*. The most easterly sand unit of the Wangoom Member is inferred to have been deposited in a mid to outer shelf palaeoenvironment based on the presence of abundant *G. subglobosa* and *A. macroglabra*. A similar fauna occurs in the adjacent marly facies. The assemblage of textulariid taxa such as *Ammodiscus* and *Cyclammina* in this interval seems to have lived in inner to outer palaeoenvironments. In the absence of a probable depth control on this textulariid fauna, these foraminifers are inferred to be controlled by the substrate, with the most diverse assemblages prevailing on sandy facies.

(c) Upper part of the Narrawaturk Marl Formation. Carbonates dominate the facies of the upper Narrawaturk Marl Formation (Fig. 12). The marly limestones [calcarenite, marl and chalk described by James et al. (1993)] of the lower Gambier Limestone in South Australia and western Victoria pass into predominantly marls and mudstones of the Narrawaturk Marl Formation towards the east of the basin in Victoria. Ferruginous sandstones and sandstone facies to the south of the basin. A discontinuous sandy marl unit occurs near Port Campbell. Infaunal foraminifera such as *Astrononion*, *U. probuscidea,*
Gyroidinoides Marl Formation is primarily due to the predominant palaeoenvironments.

Parrellina crespinae Narrawaturk Marl Formation. In addition to these benthic foraminiferal assemblages can be distinguished in the 34 samples analysed in this unit (Table 3).

1. Miliolids such as Quinqueloculina lamarkii, Quinqueloculina singletoni and Pyrgo are common with the rotaliid Notorotalia howchini in Yangeri-1, Wangoom-2/6, Tanang-1 and Pannure-2 in the sandy and muddy facies North of Port Campbell. Rare C. incisa and A. parri occur in sandy facies. Other common textularid forms include Textularia hayi, Textularia lysthostrotia and Gyridiopsis creespae. Gyridiopsis problematica, C. perforatus and G. subglobosa are also abundant in some of the samples with this assemblage.

2. Parrellina crespinae, N. howchini and S. bulloides commonly occur in Palpara-4, Laang-1, Mepunga-7/10, Heywood-10, Portland-3 and Trewalla-5 (Table 3).

3. With the exception of Timboon-5 (with abundant Quinqueloculina sp.), miliolids, Notorotalia and Parrellina and textularids are absent or rare in Narrawong-13, Port Campbell-1, Tyrrendarra-13, Gorae-2/4 and Voluta-1. The assemblage in these samples contains common to abundant S. bulloides, G. subglobosa, A. macroglabrum, P. bulloides and Gyroidinoides. Cassidulina laevigata occurs sporadically in this assemblage.

Palaeoenvironment. The abundance of infaunal foraminifera in the upper part of the Narrawatur Marl Formation is primarily due to the predominance of low energy fine-grained facies in this unit. On coarser sandy substrates rare Cyclammina and Ammonitiscus occur in an association similar to the underlying Wangoom Member. The three faunal associations listed above are interpreted to have been deposited in inner, mid to outer shelf palaeoenvironments respectively. Assemblage (1) contains common inner shelf foraminifera, including a diverse assemblage of miliolids. Occasional, typically mid to outer shelf taxa such as G. subglobosa, S. bulloides and A. macroglabrum occur in these samples. These are interpreted to reflect either faunal mixing due to reworking or bioturbation, fluctuations in sea level up section in particular wells or marine upwelling (see Holdgate and Gallagher, 1997). If upwelling has occurred then one may expect typically mid to outer shelf foraminifera to extend their depth ranges into shallower facies. Assemblage (2) is interpreted to represent a mid shelf palaeoenvironment, although this palaeoenvironmental range may extend from mid to outer shelf where S. bulloides and Gyroidinoides are abundant in a sample; alternatively, this faunal variability may be due to the factors outlined for Assemblage (1). Assemblage (3) is interpreted to have been deposited in an outer shelf palaeoenvironment, based on the presence of common to abundant P. bulloides and S. bulloides and the absence of any inner to mid shelf forms (with the exception of Timboon-5, see below). The presence of abundant Quinqueloculina in Timboon-5 possibly reflects occasional across shelf transportation of inner shelf taxa into outer shelf palaeoenvironments.
4.4. Heytesbury Group: distribution and lithostratigraphy

The Clifton and Gellibrand Marl Formations comprise the Oligocene to Early Miocene Heytesbury Group in the Otway Basin. The three stratigraphic cross-sections (Figs. 4 and 5) illustrate basin-wide relationships between these formations, and are tied to a datum along the base of the Clifton Formation (top Nirranda Group). The typical geophysical wireline log responses and core logs for four key wells are illustrated in Fig. 8. The east to west section along the present Otway coast, and the Clifton Formation isopach map (Fig. 6), illustrate the relationship between thickness and structure. In the deeper depocentres, such as the Portland Trough and Port Campbell Embayments, the formations are thicker and tend to thin towards the basin margins and over intra-basin highs, such as the Warrnambool Ridge. In the offshore Otway Basin the trends are less certain due to the low density of well data, but evidence from wells off Portland suggests the Clifton Formation thins. Near the continental shelf margin the Clifton Formation appears to be truncated by younger Miocene-Pliocene carbonates. Disconformities occur at the base and top of the Clifton Formation: they are thought to represent sequence boundaries and are discussed later. Recognition of the Clifton Formation in the South Australian sector of the Otway Basin is based on electric log correlations and biostratigraphy. Because the underlying and overlying carbonates are more limey in this area, the characteristic Victorian features of the Clifton Formation are less well expressed. However, sufficient subsurface data now provide good control to carry the Victorian nomenclature into South Australia, providing evidence that the Middle Gambier Limestone of McGowran (1973) [the Camelback Member of White (1996)] is largely equivalent to the Clifton Formation, and the Upper Gambier Limestone [the Green Point Member of White (1996)] is equivalent to the Oligocene part of the Gellibrand Marl (Fig. 2). Because of stratigraphic precedent, the Victorian nomenclature should take priority over the more localised South Australian nomenclature, and is used throughout this paper.

Detailed core logs for five typical cored bores in the Otway Basin (Glenelg-1, Heywood-10, Narrawaturk-2, Portland-3, and Timboon-5), together with their main geophysical log characteristics, are shown in Figs. 8 and 9, and include the Clifton Formation and the lower part of the Gellibrand Marl Formation. Continuous core through the Clifton Formation and Gellibrand Formation equivalents in the Glenelg-1 bore (Fig. 9) provides most of the detailed biostratigraphic basis for this paper, from which is derived the sequence stratigraphy. This can be compared with the outcrop data (Table 1), providing a basin-wide correlation. The lower part of the Gellibrand Marl Formation is also exposed in a series of river cliff sections along the Glenelg Gorge at the South Australian–Victorian border (Fig. 1).

4.5. Age of the Heytesbury Group

(1) Clifton Formation. Planktonic foraminiferal content varied greatly in this unit. The lower part of this formation, exposed at Clifton Beach (Fig. 1, Table 1) and in the subsurface (at Glenelg-1, Fig. 9) contains a poor plankton fauna with no particularly age diagnostic forms. The LAD of *C. cubensis* occurs below this unit in the Glenelg-1 bore (Fig. 9) and near the base of the unit in Korot-10 and Kentbruck-3 (Table 1). Towards the middle of the Clifton Formation, plankton diversity and abundance increase with FADs of *Globigerina ciperoensis* and *Tentatulinella angusti-umbilicata* and LAD of the textularid *B. cubensis*. The FAD of *Globoturborotalia angulaturatula* is followed closely by the LAD of *G. triseriata* and LAD of the Camelford Member of White (1996) [the Camelback Member of White (1996)] is largely equivalent to the Clifton strata underlying the Clifton Formation. In the absence of other diagnostic indicators a P21b zonal age is assigned to the Clifton strata underlying P22 faunas and overlying the LAD of *C. cubensis*, top P21a.

(2) Gellibrand Marl Formation. Planktonic foraminifera are abundant and several key LADs and FADs occur (Fig. 9). The LAD of *G. triseriata* is followed closely by the LAD of *G. eapertura* that defines the base of the N4a subzone in this unit. The FAD of *Globoturborotalia woodi* defines
the base of the Early Miocene N4b subzone. At this level an influx of *Globorotalia kugleri* occurs. Other important zonal taxa that first appear in the Early Miocene part of this unit are *Globoturborotalia connecta* (base N5 zone, Fig. 9), *Globigerinoides trilobus* (base N6, Figs. 4 and 5), *Globigerinoides bisphaericus* (base N7). The first appearance of the *Orbulina* lineage is used to define the zones and subzones of the Mid Miocene (shown in Figs. 4 and 5). Therefore, the Gellibrand Marl Formation is predominantly Late Oligocene to Early Miocene, and may be as young as the Mid Miocene.

4.6. Foraminiferal assemblages and facies of the Heytesbury Group

Diverse benthic foraminifera and facies occur in the Heytesbury Group (Tables 2 and 3), representing palaeoenvironments from high energy inner shelf to low energy outer shelf. The biofacies evolution of the Clifton Formation of the Heytesbury Group is shown on Fig. 12.

(1) Clifton Formation. Limestones (calcisiltites and calcarenites) are the dominant facies of the Clifton Formation (Figs. 8, 9 and 12). On the northern margin of the basin these limestones are sandy and ferruginous and this coarse-grained siliciclastic facies may contain thin horizons of phosphate and limonite nodules (up to 0.2 m thick). Ferruginous sandy marl facies occur to the northeast. The most southerly subcrop of this formation in Voluta-1 has a silty marl facies. The Clifton Formation was sampled for foraminifera in four wells (Glenelg-1, Panmure-2, Timboon-5 and Narrawaturk-2) and one outcrop section (at Clifton, Fig. 1), the data are shown in Tables 1 to 3. A diverse benthic foraminiferal fauna was recovered from these samples. Plankton percentages were low in the majority of samples (0 to 5%), although they range up to 30% in samples in Glenelg-1 (Fig. 9). The sandy limestone facies in Panmure-2 and Timboon-5 contain common miliolinids such as *Triloculina* and *Quinqueloculina* and a relatively low diversity benthic rotalid fauna. Similar sandy facies in Narrawaturk-2 yields abundant *G. subglobosa* and *C. perforatus* with rare miliolinids. The coarse-grained ferruginous sandy limestones of the Clifton outcrop samples common textularids, *Discorbis*, *Parrellina* and *Notorotalia* with abundant *C. perforatus* and no miliolinids. The calcisiltite facies of Clifton Formation in the Glenelg-1 bore overall has a similar fauna to the Clifton outcrop samples except that *G. subglobosa* and *Heterolepa brevoralis* are not common and textularids are rare.

Palaeoenvironment. The sandy limestones of the Clifton Formation around Pannure-2 and Timboon-5 are inferred to have been deposited in relatively high energy inner shelf palaeoenvironments. The sandy limestones not sampled for foraminifera further north of these wells may also preserve paralic, coastal deposition. Further south the sandy limestones of the Clifton Formation outcrops and the subcrop in Narrawaturk-2 preserve a high energy mid to outer shelf foraminiferal biofacies. The occurrence of phosphate horizons in the Clifton Formation in this area is inferred to be hardgrounds representing occasional depositional breaks. High energy mid to outer shelf biofacies prevail around Glenelg-1 bore, where the relative lack of textularids is probably due to the lack of siliciclastic input to the basin in this region. Although not sampled for foraminifera, the marly sandy facies to the east of the basin may have been deposited in a sheltered inner shelf to paralic palaeoenvironment. The silty marls around Voluta-1 may represent low energy outer shelf to bathyal deposition.

(2) The Gellibrand Marl Formation. As the name suggests marl dominates the facies of this unit, although in Glenelg-1 occasional horizons of calcarenite, chalks and calcisiltites (Fig. 9) occur in the western part of the basin. For the purpose of palaeoenvironmental interpretation, only the Late Oligocene to earliest Miocene samples of the Gellibrand Marl Formation are included in this study; further work on the younger strata will be reported elsewhere. Infaunal foraminifera such as *Trifarina, Bolivina* and *Uvigerina* are common in the Gellibrand Marl Formation. *C. incisa* occurs in several wells near Port Campbell (Table 2). As with the faunas from Narrawaturk Marl Formation, the 15 wells that sample this unit can be divided into three principle assemblages (Tables 2 and 3): (1) a textularid- and miliolinid-rich
fauna occurs with common *Textularia, Quinqueloculina, Triloculina* and *Pyrgo, Notorotalia, Spirillina* and *Discorbinella* are also common in this assemblage; (2) a diverse rotalid assemblage with *Notorotalia* and *Spirillina* and rare milioloids; (3) a rotalid assemblage dominated by common *Anomalainoides procolligeri, A. macroglabra, S. bullosa* and *U. proboscidea*. This fauna lacks milioloids and *Notorotalia*.

Palaeoenvironment. The high infaunal content in this unit is directly related to the low energy marly facies. The three assemblages in the Gellibrand Marl Formation above are interpreted to represent inner, mid and outer shelf palaeoenvironments respectively (see explanation of the Narrawatuk Marl Formation above). Inner shelf faunas occur north of Port Campbell (Fig. 1) in Wangoom-2, Nirranda-3 and Mepunga-7-10, where the occurrence of *Cyclammina* in some of these wells may reflect siliciclastic input into these marls. The outer shelf biofacies occurs mainly around the Portland area (Gorae-4, Narrawong-13, Trewalla-5 and Cobbobbonee-2). The palaeogeography and palaeoenvironments of the full thickness of Gellibrand Marl are still being compiled and will be reviewed elsewhere.

5. Palaeogene to Neogene non-marine sediments of the Otway Basin

The non-marine sediment equivalents to the dominant marine carbonates of the Nirranda and Heytesbury Group probably exist within the basal fill of the palaeo-valley filling ‘deep lead’ systems that flowed south from the dividing range toward the Otway Basin. Such ‘deep leads’ comprise fluvial gravels, sands and lignitic clays infilling a series of channel systems, which usually are overlain and sealed in-place by Plio-Pleistocene-aged Younger Volcanics basalt flows. Three main lead systems have been mapped trending south from the present dividing range towards the Otway Basin (Canavan, 1988). They include the Langi Logan group of leads trending south from Ararat towards the Port Campbell area of the Otway Basin, and the Pittfield Plains and Durham leads trending south from Ballarat towards the eastern end of the Otway Basin (Figs. 9, 10 and 11). Several smaller leads are also present in the eastern Otway Rokewood area, including the Hanlon and Spring Creek leads that are dated at their marine junction as Oligocene–Early Miocene (Carter, 1958b). Although none of the south-trending leads is directly dated by palynology, similar leads north of the Dividing Range vary in ages from the Early Oligocene through Miocene and Pliocene (Martin, 1977; Partridge and Wilkinson, 1982). Bishop and Li (1997) re-interpret many of the most placer gold-rich leads in the Ballarat area to have flowed south at the time of deposition.

Channel-filling gravels and sands of the deep leads would provide a source for the coarse-grained siliciclastics that accumulated in the Nirranda Group and Clifton Formation nearshore areas during the Late Eocene and Oligocene. The lobate form of the sand isopachs (Figs. 6 and 9) suggests point sources occurred at deluge inputs to the shoreline at the basin margins. The larger siliciclastic supply required to produce the 1000 km$^3$ of underlying Dilwyn Formation in the Portland Trough was postulated to have been sourced from a proto-Murray River system that crossed the dividing range at a low point north of Hamilton (Holdgate, 1982). This source may also have continued at a diminished rate into the Late Eocene and Early Oligocene prior to uplift of the dividing ranges in this area.

6. Palaeogene to Neogene palaeogeographic evolution of the Otway Basin

Based on the detailed bio-, lithostratigraphic, facies and foraminiferal palaeoenvironmental analyses and inference about Tertiary Leads in the area, a series of palaeogeographic and biofacies maps were compiled for the Late Eocene to Late Oligocene strata of the Otway Basin (Figs. 10 to 12).

(1) The Late Eocene, Mepunga Sand Formation. The palaeogeography of the Otway Basin towards the end of the Eocene was dominated by paralic high energy siliciclastic shoreline to shelf facies (Fig. 10). Paralic facies quickly gave way to mid to outer shelf conditions south of the
shoreline, where high energy sandy carbonate facies prevailed. The source of the coarse-grained sandstone is inferred to be from the north, where high energy rivers fed into different parts of the shoreline (where lobes of sand are mapped into the subsurface).

(ii) The earliest Oligocene, lower part of the Narrawaturk Marl Formation. The biofacies data suggest that the palaeogeography of the area at this time (Fig. 11) was dominated by a low energy silty and muddy siliciclastic shoreline, deposited in the inner to mid shelf in the northern part of the basin, passing laterally southward to carbonate-dominated low energy outer shelf to bathyal marl. The source of the fine-grained siliciclastics is inferred to have been low energy rivers to the north of the basin.

(iii) The Early Oligocene, Wangoom Sand Member and its equivalents. The palaeogeography of the area during this time (Fig. 11) was dominated by high energy inner to outer shelf sand bodies fed by marine channels or small deltas; the morphology of these sand units is likely to have been controlled by longshore drift. Marginal marine to inner shelf mudstone facies formed behind these sands. Mid to outer shelf marly facies (often with a significant siliclastic content) was deposited basinward of the sand units. Similar to the underlying units, fluvial input from the north is inferred, with the source of the coarse sandy facies being high energy rivers.

(iv) The Early Oligocene, upper part of the Narrawaturk Marl Formation. Based on the biofacies data, the palaeogeography during upper Narrawaturk times can be subdivided into two principal regions (Fig. 12).

(i) The eastern and northern part of the basin consisted of a complex of siliciclastic and carbonate facies where paralic to inner shelf sands and sandy limestones to the north passed southward to inner to mid shelf limy marl and mudstone. A sandy marly unit near Port Campbell is inferred to have been a mid to outer shelf sand body, similar to the sand units of the underlying Wangoom Member. This sandy body may have sheltered the easterly part of the basin, thus allowing mudstone to be deposited. Southwards of the present shoreline mid to outer shelf marls were deposited.

(ii) The mid to outer shelf siliciclastic-poor calcareous, chalk and marl dominated the westerly edge of the basin.

The contrast in facies from west and east in the basin is inferred to be due to contrasting terrigenous input, environmental energy and ramp/shelf geometry. Low to high energy shelf facies predominated to the west, the prevalence of carbonate in this area reflecting a lack of siliciclastic supply and/or sediment starvation. To the east, low energy mainly outer shelf conditions prevailed with a relatively high terrigenous input, although most of the siliciclastics were deposited close to the shoreline in the northern paralic to inner shelf facies. The source of these siliciclastics is inferred to have been low energy rivers to the north.

(v) The Late Oligocene, Clifton Formation. Based on the biofacies data, the palaeogeography of the Clifton Formation in the Otway Basin during this time (Fig. 12) was dominated by high energy carbonate facies deposited in mid to outer shelf palaeoenvironments. Siliciclastic input from high energy rivers to the north and eastern part of the basin led to the deposition of high energy sandy limestone. The sandy facies were deposited around the margin of the basin and deepened from paralic to outer shelf conditions southwards. The sandy facies may have also formed an offshore barrier separating the siliciclastic poor limestone to the south and west from the marly sandstone to the northeast.

7. Otway Basin stratigraphic events and Southern Ocean evolution

The correlation between the Otway Basin, the Torquay Basin and the Gippsland Basin stratigraphies is shown on Fig. 13, where these units are correlated with the Haq et al. (1988) curve [modifed slightly to include the chronology of Berggren et al. (1995)]. It is clear from the data presented in Fig 13 that the Paleogene to Neogene neritic strata of the Otway Basin and other basins in Southeast Australia preserves signals relating to the initiation of glaciation in East Antarctica and
the evolution of the Antarctic Circumpolar Current in the Southern Ocean (Li et al., 1996a).

Marginal marine siliciclastics are preserved in the late Middle Eocene (45 Ma) of the Otway Basin. During this time no Antarctic Circumpolar Current existed due to the presence of the Tasman Rise and closed Drake Passage (Fig. 13A) and the region was bathed in warm surface currents (Murphy and Kennett, 1986; Kamp et al., 1990). Mackensen and Ehrmann (1992) observed that δ18O values in Antarctic sites increased from a maximum during early Middle Eocene times towards the Late Eocene, corresponding to a global cooling trend. They inferred warm bottom water masses with temperatures between 5 and 7°C in an ‘ice-free’ Antarctica and cool sea surface temperatures of less than 10°C during the late Middle Eocene. Dieter-Haass and Zahn (1996) estimated palaeoproductivity in the Maud Rise during the late Middle Eocene and inferred increasing mixing in a stratified ocean and that warm or temperate terrestrial conditions persisted near Antarctica during this time. Extratropical incursions of larger foraminifera into southeastern Australia associated with these warm conditions also occurred (Adams et al., 1990; McGowran et al., 1997). Evidence of these incursions is preserved in the Sturgess Point Member (see Fig. 13) where the large foraminifers Halkyardia bartrumi and Linderina glaesneri last occur (Port Campbell-1 at 1478 ft; planktonic foraminiferal zones P13/14, Fig. 4). The absence of larger foraminifers above the Sturgess Point Member in any well or bore sampled in the Otway Basin suggests cooler marine conditions toward the Middle–Late Eocene boundary. Abreu and Anderson (1998) suggested glacial events occurred on East Antarctica from Middle Eocene times based on preserved glacial sediments and erosive events on the Antarctic continental shelf and the correlation of δ18O peaks and sea level changes, although, their compiled DSDP/ODP data suggest no significant ice rafted debris in East Antarctica until the Late Eocene. Therefore, it seems that the warm currents around the Antarctic prevented the build up of sea ice or ice shelves during the Middle Eocene.

Late Eocene marginal to open marine shelf siliciclastics unconformably overlie the Middle Eocene strata of the Otway and Torquay Basins (Fig. 13); these are followed by predominantly carbonate sediments across the Late Eocene–Early Oligocene boundary. This change in sediment type may relate to uplift in the region at the end of the Eocene, generating the siliciclastic supply and subsequent tectonic quiescence in the Early Oligocene. The change also coincides throughout the area with the LAD of the diagnostic end Eocene taxon G. index and a switch to cooler water foraminiferal assemblages (without any larger foraminifera). Using δ18O values, Zachos et al. (1994) estimated that across the Eocene–Oligocene boundary, Southern Hemisphere sea surface temperatures cooled between 1 and 2°C accompanied by a cooling of deep sea temperatures by around 3°C at sites south of 56°. This cooling was accompanied by a rapid build up of the East Antarctic ice sheet, which lasted around 300 kys (Miller et al., 1987; 1991; Mackensen and Ehrmann, 1992; Zachos et al., 1994; Dieter-Haass and Zahn, 1996; Robert and Kennett, 1997, Abreu and Anderson, 1998).

A sand unit (the Wangoom Sand Member) formed parallel to the Otway coast during the Early Oligocene (Fig. 11), its morphology probably influenced by strong local longshore drift; these local oceanic conditions may reflect the increasing influence of the Antarctic Circumpolar Current in the Southern Ocean during this time.

The base of the Clifton Formation in the Otway Basin preserves a shift in facies (marl to limestone) and foraminiferal faunas that correlate to the major sea level fall at the mid–Late Oligocene boundary (Haq et al., 1988; Fig. 13). This sea level fall is related to a major ice advance in Antarctica (Kennett, 1977; Prothero, 1994) that corresponds to middle Oligocene unconformities globally (Poag and Ward, 1987). The switch from low energy marl and mudstone to high energy limestone and sandy limestone across the Early–Late Oligocene boundary (Fig. 13) in the Otway Basin suggests that the Southern Oceans swell experienced by the modern Otway coast (see Boreen and James, 1993) was well established by middle Oligocene time. This is further evidence of the increasing strength of the ‘proto’ Antarctic Circumpolar Current during this time. By Early Miocene times, with
final deepening of the Drake Passage the Antarctic Circumpolar Current wind and wave regime formed (Mackensen and Ehrmann, 1992) and predominantly highstand marl and limestone were deposited in the Otway and Gippsland Basins.

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