ABSTRACT: An unconformity is present close to the Miocene–Pliocene boundary in the onshore and nearshore portions of the Otway, Port Phillip–Torquay, and Gippsland basins of southeast Australia. The unconformity is angular (generally < 1–5° angularity), with the underlying Miocene units having been deformed (gentle folding and reverse faulting) and eroded prior to deposition of the Pliocene succession. The unconformity also marks a change from Oligocene–Miocene deposition of cool-water carbonate sediments and brown coal-bearing successions to the accumulation of more siliciclastic-rich sediments in Pliocene time. The Miocene–Pliocene boundary therefore represents an interval of significant regional uplift in the southeast Australian basins. The amount of section removed is greatest around the Otway and Strzelecki ranges in Victoria, where up to a kilometer of section may have been removed. In most onshore sections of the Victorian basins hundreds of meters of section have been eroded. In distal offshore locations the boundary becomes conformable. The timing of uplift and erosion is best constrained in the Otway and Port Phillip basins, where late Miocene (N16 ~ 10 Ma) sediments underlie the unconformity and earliest Pliocene (~ 5 Ma) sediments overlie it. This timing coincides with a change in the dynamics of the Australian plate, beginning at around 12 Ma. Southeast Australia is currently under a NW–SE compressional regime, and this has probably persisted since the late Miocene. In the basins (as opposed to the basement-dominated highland areas), the late Miocene uplift event is more significant than later Pliocene–Recent uplift.

INTRODUCTION

Determining the relative importance of eustasy versus tectonic phenomena in controlling a sea level by analysis of the geometry of sedimentary packages. Regional and global correlation of such data should distinguish between tectonically and eustatically controlled sea-level change. However, widespread, short-lived tectonic events can easily be confused with eustatic events, particularly when the additional problem of age resolution is considered. The Miocene–Pliocene boundary is an example of an event (or events) where tectonism is apparent widespread across the globe (e.g., Mercier et al. 1987; Dewey et al. 1989; Amano and Taia 1992; Walcott 1998; Hill and Raza 1999), and potential exists for considerable confusion between eustatic and tectonic events.

There has been much discussion of the tectonic or eustatic significance of the Miocene–Pliocene unconformity in the southeast Australian basins (Gippsland, Port Phillip, and Otway basins; Fig. 1; e.g., Mallett 1978; Carter 1979). Unconformities of late Miocene–early Pliocene age (commonly associated with phosphatic clasts) from several localities across Victoria have long been recognized as being stratigraphically significant markers (Coulson 1932; Keble 1932; Singleton 1941; Gill 1957; Bowler 1963). However, little research has been carried out on the regional significance of this Miocene–Pliocene unconformity.

In this paper, we attempt to synthesize paleontologic, stratigraphic, and structural data from the various Tertiary basins across southeast Australia in order to assess the timing and origin of these Miocene–Pliocene unconformities. Through this we highlight the importance of independent interpretation of sequences rather than systematic correlation with templates for a sea-level curve (e.g., Haq et al. 1988). We suggest that a major interval of regional uplift and exhumation began in southeast Australia during the late Miocene. Exhumation in localized areas was on the order of several hundreds of meters to a kilometer or more (e.g., Otway Ranges). This and later Pliocene uplift is probably largely responsible for the present topographic relief of the southern Cretaceous Highlands (Otway and Strzelecki ranges; Fig. 2) of Victoria.

The recognition of late Miocene uplift in southeast Australia has some important economic implications. These include the erosion of cover sequences from the giant Oligocene–Miocene brown coal deposits of the Latrobe Valley, making large volumes of coal economic for mining, and structures offshore produced in the late Miocene provide favorable targets for petroleum accumulation (e.g., the Nerita structure, Torquay sub-basin).

REGIONAL GEOLOGY

The southeast Australian basins occupy an area along the southern margin of the Australian continent. The basins developed during the rifting of the Australian continent from Antarctica, Lord Howe Rise, and New Zealand during the Cretaceous to early Tertiary (Etheridge et al. 1987), resulting in a common structural and stratigraphic history. Consequently, all the basins contain a largely nonmarine Lower Cretaceous rift-fill succession overlain by an Upper Cretaceous to Recent nonmarine and marine post-rift deposits.

The margins of the basins are partly defined by blocks of Lower Cretaceous sediment (forming the southern Cretaceous Highlands), bounded by reverse faults that form structural highs and define the present limit of Tertiary sediments. The Otway basin is separated from the Torquay Embayment and Port Phillip basin by the Otway Ranges, which is in turn separated from the Gippsland basin by the Mornington Peninsula High and Strzelecki Ranges (Fig. 2). The northern margin of the basins is defined by the Western and Eastern Highlands, whilst the southern margin extends offshore (Fig. 1).

The Oligocene to Recent marine sediments of the Otway, Port Phillip and Gippsland basins are dominated by cool-water and temperate-water carbonates. The sedimentology and diagenesis of these nontropical carbonates has been the focus of several recent studies (e.g., James et al. 1992; Boreen et al. 1993). The Oligocene–Miocene carbonates that make up the bulk of the onshore marine sections are characterized by high-energy bryozoa such as little or no siliciclastic material. Nonmarine Oligocene–Miocene onshore sediments are characterized by extensive accumulation of brown coal, again with little or no siliciclastic content. Conversely, the Pliocene succession is typified by calcareous and unconsolidated sand deposits which contain a significant proportion of siliciclastic material, including quartz-rich pebble formations. Deposition of brown coal largely ended in the late Miocene, and there have been no significant Pliocene coal deposits discovered to date. Pliocene–Quaternary basaltic lavas, known as the Newer Volcanics (Douglas and Ferguson 1988), generally overlie the marine Pliocene.

Oligocene to Recent sediments in the onshore areas of the Otway and Gippsland basins are variously folded and faulted. Oligocene–Miocene sections commonly have gentle dips (generally < 10°) with monoclinal and open folds dominating. Reverse faults are also common in some regions, particularly surrounding the Cretaceous Highlands. Tertiary sediments in close proximity to reverse faults rarely have steep dips (up to vertical). Pliocene and younger sections are generally less deformed, but some faults and monoclins do affect these sediments. In the offshore portions of these
basins, some reverse faults and folding are also present, but deformation is generally less intense than in the onshore sections. In the offshore Gippsland basin, Oligocene–Recent deformation has produced large-scale structural traps that play host to giant oil and gas fields.

There are numerous structures with evidence of relatively young (Neogene) activity in southeast Australia. In the southern parts of Victoria, northeast oriented reverse faults of Neogene age bound the Otway Ranges, the Mornington Peninsula, and the Strzelecki Ranges, which are similarly oriented (Fig. 2). Farther north, in the Murray basin, Neogene faults have a NNE orientation. In South Australia, Neogene reverse faults are present
in the Flinders Ranges, Mount Lofty Ranges, and St. Vincent basin and they trend N–NNE. This is consistent with the predominantly W–WNW oriented compressional stress field to which southeast Australia appears to be currently subject (Coblentz et al. 1995).

The onshore parts of the southeast Australian basins contain a major stratigraphic break within the late Miocene–early Pliocene at the change from carbonate-rich to more clastic-rich sediments (Fig. 3). Phosphatic clasts and vertebrate remains are commonly present at this unconformity (Coulson 1932; Keble 1932). This regional unconformity has previously been interpreted as being due to tectonic, eustatic, or climatic effects (e.g., Bowler 1963; Carter 1978a; Mallett 1978). In this paper, we discuss the nature and significance of this stratigraphic break at various localities in the onshore and nearshore parts of the southeast Australian basins.

**METHODS**

Stratigraphic data were obtained through detailed sections taken at locations in the Otway, Port Phillip, and Gippsland basins. Borehole data were used from Sorrento (Mallett and Holdgate 1985) and from coal bores in the Gippsland basin (Bolger 1991; unpublished Rural Water Commission data). Paleontological samples were disaggregated by hydrogen peroxide and foraminifera picked, sorted, and identified for qualitative biostratigraphic purposes.

All $^{87}$Sr/$^{86}$Sr measurements were made on calcitic and unaltered aragonitic molluscs. Samples were cleaned with concentrated hydrochloric acid to remove any potential surface overgrowths and rinsed with distilled water. Dissolution of powdered samples was carried out in 10% acetic acid. Chemical separations were performed using 1N HCl and 2.5N HCl as eluents through AG 50W-X8 ion-exchange resin in 15 ml quartz columns for Sr separation. The Sr isotope composition of the separate was measured for Sr separation. The Sr isotope composition of the separate was measured using Howarth and McArthur’s (1997) Sr isotope Look-Up Table Version 3:10/99 (Table 1). Time–depth conversion of interpreted seismic sections from the Torquay basin was carried out using Seismic Plugin v. 3.0 (Jay Lieske, Jr.) for Adobe Photoshop™. Sonic velocities used were 1500 m/s, 1800 m/s, and 2200 m/s for sea water, Pliocene–Quaternary sediments, and Miocene Torquay Group sediments, respectively.

**MIOCENE–PLIOCENE BOUNDARY IN THE OTWAY BASIN**

Where the boundary between Miocene and Pliocene sediments is exposed in the Otway basin, it is generally an unconformity (Fig. 3). The unconformity is marked by a planar erosional surface with no evidence of oxidation and a significant change in the lithology. The underlying Miocene strata exhibit a shallowing-upward (more calcareous upward) character. Gray fossiliferous marls (Gellibrand and Muddy Creek marls) and bryozoan-rich fine-grained white limestones (Port Campbell and Bochara limestones) with a nominal siliciclastic content typify the sequence. The overlying Pliocene succession represents a prograding quartz-carbonate barrier system with the initial marine incursion marked at the base by quartz-rich shallow marine silts and shelly sands (Whalers Bluff and Grange Burn formations) and subsequent deposition of yellow flaggy calcarenites (Werrikoo Limestone).

**Glenelg River Section**

In the Dartmoor region (Fig. 4) along the Glenelg River valley, Pliocene–Quaternary quartzose calcarenites of the Werrikoo Limestone unconfor-

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**Table 1.** Measured $^{87}$Sr/$^{86}$Sr ratios of calcitic carbonate material from stratigraphic sections used in this study.

<table>
<thead>
<tr>
<th>Location</th>
<th>Stratigraphic height (m)</th>
<th>Age (Ma)</th>
<th>$^{87}$Sr/$^{86}$Sr</th>
<th>Std error $\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamilton</td>
<td>2.90</td>
<td>4.94</td>
<td>0.709039 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.90</td>
<td>5.03</td>
<td>0.709036 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.90</td>
<td>5.32</td>
<td>0.709061 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.60</td>
<td>10.86</td>
<td>0.708865 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>10.86</td>
<td>0.708865 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>11.13</td>
<td>0.708844 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td>Batesford</td>
<td>7.00</td>
<td>4.86</td>
<td>0.709041 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.60</td>
<td>4.21</td>
<td>0.709052 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td>Coghill</td>
<td>0.50 m below unconformity</td>
<td>10.26</td>
<td>0.70882 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td>Beaumaris</td>
<td>4.30</td>
<td>4.52</td>
<td>0.709048 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.80</td>
<td>5.24</td>
<td>0.709028 $\pm$ 12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.50</td>
<td>5.67</td>
<td>0.709011 $\pm$ 14</td>
<td></td>
</tr>
</tbody>
</table>

* All results are normalized to the SRM-987 standard = 0.710250 and to $^{86}$Sr/$^{87}$Sr = 0.1194.
* $\delta$ Analytical uncertainty represents 2 standard errors of the mean of $\overline{1}$00 individual measurements and refers to the last two digits of the ratios.
amably overlie Eocene Knight Group and Miocene limestones of the Glenelg Group (Fig. 5). The youngest age of strata preserved beneath the unconformity is placed in the early Miocene (planktonic foraminiferal zone N5; Figs. 3, 5). The lower Werrikoo Limestone is here placed within the Werrikooan (upper Pliocene) on the basis of the molluscan fauna found towards the base of the unit, typical of Singleton’s (1941) Werrikooan stage, and the absence of planktic foraminifera Globorotalia truncatulinoides. G. truncatulinoides does not become apparent until higher in the section, placing the upper part in the Pleistocene (Fig. 5). In the vicinity of Jones Ridge basalt dated at 2.24 Ma by K–Ar (Singleton et al. 1976) overlies the lower Miocene sediments marking the unconformity, with deposition of the Werrikoo Limestone above this.

A regional cross section produced by Kenley (1971) based on outcrop and well stratigraphy in the western part of the Otway basin (Fig. 5) indicates that the Knight and Glenelg groups have undergone folding following their deposition. This folding occurred prior to the deposition of the Werrikoo Limestone, which overlies the angular unconformity. The folding is focused around the Merino High (as defined by Kenley 1971), an area of outcropping Otway Group (Lower Cretaceous) sediments (Fig. 4) that has been elevated and dissected.

**Portland**

In the coastal cliffs north of Portland (Fig. 4), Pliocene Whalers Bluff Formation and a younger subaerial basalt unconformably overlie Miocene Port Campbell Limestone (Fig. 5). The top of the limestone is dated as late Miocene by the presence of the planktonic foraminifera Globorotalia mio- tumida (planktonic foraminiferal zone N16; Fig. 3). The age of the initial deposition of the Whalers Bluff Formation is determined to be early Pliocene (Zone N19) by the presence of Globorotalia puniculata. Boutakoff (1963) noted that the Pliocene sediments infilled a karst topography developed on Miocene limestones. The basaltic rocks cap the top of the section are dated by K–Ar as 2.51 Ma (Singleton et al. 1976), giving an upper constraint on the age of the Whalers Bluff Formation.

**Hamilton**

To the west of Hamilton in the Muddy Creek–Grange Burn area, the Miocene–Pliocene sequence unconformably overlies mid-Paleozoic rhyolite and is capped by basalt. The Miocene Muddy Creek Marl contains a foraminiferal assemblage derived by Mallett (1977) that suggests that the unit spans the interval from foraminiferal zone N7 to N16. Directly beneath the Miocene–Pliocene boundary a distinctive limonitic and glauconitic green marl is present and contains abundant erosional lag beds yielding strontium isotope dates of 11.13 ± 0.5 and 10.86 ± 0.5 Ma (Table 1; Fig. 5).

The Miocene–Pliocene boundary is marked by a planar unconformity at the base of the Pliocene Grange Burn Formation, which overlies all older Miocene sediments (Fig. 5). The surface is characterized by the occurrence of a phosphatic nodule bed with abundant marine vertebrate remains. It also contains many fossils both reworked from the Muddy Creek Marl and autochthonous to the Grange Burn Formation, some attached to the phosphatic clasts. The Grange Burn coquinas contain typical Kalimnan (Fig. 3) shelly fossils and are considered to be early Pliocene in age (Ludbrook 1973). Strontium isotopes taken of the mollusc fauna derive ages of 5.0–4.0 Ma. The basalts have been dated by K–Ar at 4.35 Ma (Turnbull et al. 1965), placing deposition of the Grange Burn Formation during the early Pliocene.

**MIOCENE–PLIOCENE BOUNDARY IN THE CENTRAL COASTAL BASINS**

The Port Phillip and Torquay basins lie between the Otway and Gippsland basins and are bordered by uplifted areas of Lower Cretaceous sediment and Paleozoic basement (Fig. 6). The Miocene–Pliocene boundary is well exposed in coastal and river sections and is characterized by a planar unconformity. The unconformity is typically represented by a sharp lithological change from marl to quartz-rich carbonate sand (Figs. 7, 8A), with no evidence of karstification or oxidation. There is commonly a discontinuous horizon of coarse quartz gravel containing distinctive phosphatic clasts immediately overlying the unconformity. These phosphatic clasts commonly have borings (Fig. 8B). There has been much early work on the Miocene–Pliocene boundary in this region, largely because of the abundance of vertebrate remains (e.g., Coulson 1932; Keble 1932).

The strata underlying the Miocene–Pliocene unconformity range in age from early (e.g., Shelford) through to mid- (e.g., Geelong) and late Miocene (e.g., Beaumaris and Point Nepean; Fig. 7), which is detailed below. It is a succession of gray-buff calcareous clay-rich sediment with cemented ferruginous horizons and layers of carbonate nodules and sporadic phosphate concretions (Gellibrand Marl and Fyansford Formation). The overlying units are characterized by basalt marine quartz-rich calcareous sandstones and molluscan-rich sandy calcarenites that grade upwards into a nonmarine sand (Moorabool Viaduct Formation and Brighton Group). The abundance of quartz sand in these units contrasts with the quartz-poor clayey carbonates of the underlying Miocene.

**Shelford**

West of Geelong, on the Leigh River near Shelford (Fig. 6), the underlying Miocene sequence is attributed to the Gellibrand Marl (Fig. 7; Edwards et al. 1996), and the upper part of the unit is dated as early Miocene (planktonic foraminiferal zone N7) on the basis of the presence of planktic foraminifera Globigerinoides trilobus. Quartz sands of the overlying Pliocene Moorabool Viaduct Formation are poorly exposed.

**Geelong**

In the vicinity of Geelong, along the Moorabool River (old Batesford Quarry, Coghills section; Coulson 1932; Bowler 1963), the Miocene–Pliocene succession is represented by the Fyansford Formation, which is unconformably overlain by the Moorabool Viaduct Formation (Fig. 8C). The upper part of the Fyansford Formation, where exposed beneath the unconformity, varies in age from mid- to late Miocene (Fig. 3). A strontium isotope date from just below the unconformity at Coghills (Fig. 6) gives a date of 10.26 ± 0.5 Ma (Table 1).

Determination of the age of the overlying Moorabool Viaduct Formation has been based largely on molluscan fauna. It is consequently considered to be very late Miocene to early Pliocene (Abele et al. 1988), but there is the suggestion that the unit is as young as late Pliocene (Bowler 1963).
Strontium isotope analysis of marine molluscs at Batesford quarry places initial deposition at 4.5 ± 0.5 Ma. Basalts that overlie the sequence are dated at 2.0 Ma using K–Ar (Whitelaw 1989), constraining the upper age of deposition.

**Beaumaris**

At Beaumaris, on the coast southeast of Melbourne, the age of the underlying Fyansford Formation is poorly defined. However the upper part is dated as mid-Miocene where it outcrops at Mornington farther to the south (Mallett and Holdgate 1985). The phosphatic nodule bed, which marks the unconformity and consists of quartz pebbles, phosphatic clasts, and a rich fauna of teeth, bones, and shell material (Fig. 7; Singleton 1941), is located 0.5 m beneath beach level.

The exposure of the Pliocene (Black Rock Sandstone) at Beaumaris constitutes the type section of the Cheltenhamian Stage (Singleton 1941), placing the unit in the upper Miocene (planktonic foraminiferal zones N17–18). This is supported by the foraminiferal assemblage, which, although
Fig. 6.—Location map of the central coastal basins showing the sections studied and the position of offshore seismic profiles.

Fig. 7.—Measured stratigraphic sections across the Miocene–Pliocene unconformity in the Port Phillip basin.
poor, places deposition of the unit within the same time (Mallett 1977). However, strontium isotope analysis of molluscs within the unit (Fig. 7) suggests that the deposit formed during the early Pliocene (5.5–4.5 Ma). The Black Rock Sandstone grades upward into terrestrial sands and clays that are regarded as Pliocene (Abele et al. 1988).

**Sorrento**

The Nepean Peninsula extends northwest into the center of the Port Phillip basin from the southern end of the Mornington Peninsula. A number of bores are situated at Sorrento, where sediments of the Port Phillip basin are thickest. The Fyansford Formation is here present at its youngest, ranging up to upper Miocene. Elsewhere in the basin, the strata above the unconformity are Pliocene. At Sorrento, however, the overlying Brighton Group is considered to be upper Miocene (Mallett 1977). In contrast, the Wannaeue Formation (Fig. 7), as proposed by Mallet and Holdgate (1985), contains a rich faunal component that indicates an early to mid Pliocene age. Both the age and the lithology are comparable to the Whalers Bluff Formation at Portland (Mallett and Holdgate 1985). However, the unit is only apparent in the subsurface and has not been recorded in any other part of the Port Phillip area, reaching a thickness of 88 m in the center of the Sorrento Graben and becoming thinner towards the margins.

**TORQUAY SUB-BASIN**

The Torquay sub-basin, offshore from the Port Phillip basin (Fig. 6), contains an upper Tertiary succession similar to that exposed onshore. Carbonate-rich marls of the Torquay Group are offshore equivalents of the Oligocene–Miocene sequence. The sub-basin has been the subject of petroleum exploration, and although there is little sample material for study, much seismic and well log data are available (Trupp et al. 1994). Several shallow seismic lines have also been run across the sub-basin. Using palaeontological data from Nerita #1 (Fig. 6) and the nearby Nepean bores, it appears that the youngest Torquay Group (Trupp et al. 1994) ranges in age from early to late Miocene. Well-log data from Wild Dog #1 (Fig. 6) also indicate that the succession becomes less clay-rich upwards, as does the section onshore.

On industry seismic sections, the Torquay Group and underlying successions are folded and faulted (Fig. 9). Reverse faults in the underlying Otway Group and Paleozoic basement generally grade into monoclinal structures in the Torquay Group sediments. Folding and faulting affects the entire section up to the upper Miocene. Furthermore, much erosion of section is evident at the sea floor. On the Nerita #1 structure 400 m of Miocene section has been eroded and outcropping sediments at the sea floor are lower Miocene (Fig. 9; Shell 1967).

Near the Otway coastline and the Mornington Peninsula, the entire Torquay Group and underlying successions (Angahook Formation and Boonah Formation) have been removed by erosion, indicating more than 600 m of erosion (Fig. 10). No thinning of the Torquay Group towards the Otway Ranges or the Mornington Peninsula is visible on seismic, and this suggests that large thicknesses of Torquay Group have been stripped from these highs. Deformation and erosion must postdate the upper Miocene Torquay
MIOCENE–PLIOcene UNCONFORMITY IN SOUTHEAST AUSTRALIA

Group sediments, because the entire Torquay Group appears conformable and is uniformly affected by deformation.

On shallow seismic sections (Fig. 11), a spectacular angular unconformity is visible (also just visible on industry seismic, Fig. 9). From correlation with the Nepean bores and Nerita #1, the unconformity postdates the upper Miocene Torquay Group sediments and appears to be the lateral equivalent of the Fyansford Formation–Brighton Group unconformity in the Nepean bores (i.e., the Miocene–Pliocene unconformity). This would indicate that the overlying undeformed sequence is the equivalent of the Brighton Group and Wannaeue Formation described by Mallett and Holdgate (1985) from the Nepean bores.

The Miocene–Pliocene unconformity on seismic (at Nerita #1 and on shallow seismic) indicates that most deformation and erosion of the underlying Torquay Group took place during the late Miocene. The Nerita #1 structure, for example, appears to be almost entirely due to late Miocene deformation. On shallow seismic near the Otway Ranges, however, some folding is evident within the overlying Pliocene sediments, indicating continued deformation into the Pliocene.

GIPPSLAND BASIN

The onshore Gippsland basin is characterized by an Eocene to Miocene coal-dominated sequence that is laterally equivalent to the Oligocene–Miocene cool-water carbonates of the Seaspray Group in marine sections of the basin. A number of coal seams—Traralgon, Morwell, and Yallourn—make up the Tertiary brown coal measures, which constitutes the bulk of the Latrobe Valley Group. This is unconformably overlain by a siliciclastic sand- and gravel-dominated unit (Pliocene Haunted Hills Formation) and laterally equivalent marine sandy calcarenites and coquinas (Jemmys Point Formation). In the Latrobe Valley, the Miocene–Pliocene unconformity is expressed as an angular difference accompanied by erosion and weathering (oxidation) of coal seams, together with pronounced burn holes in the top-of-coal surface. The unconformity has been well documented by Bolger (1984, 1991).

The major structures of the onshore Gippsland basin are illustrated in Figure 12. Faulting associated with the folding tends to be NE-trending and is both extensional and compressional, resulting in horsts or tilted horst blocks (Smith 1982; Hocking et al. 1988). Many of the blocks and monoclines are now bounded by and overlie reverse faults at depth, and appear to be inverted structures. Tertiary drape over these reverse faults defines monocline warping (Barton 1981), which formed largely after Miocene coal-measure deposition.

Latrobe Valley Depression

The Tertiary coal measures of the Latrobe Valley Depression occupy an elongated asymmetric east-pitching syncline known as the Latrobe and Traralgon synclines (Fig. 12). Within these synclines over 700 m of Oligocene–Miocene coal measures are present. Peripheral to the central synclines are a series of en echelon structures that separate the Latrobe Valley into a number of blocks where the dips on Tertiary coal measures can reach angles exceeding 45°. The coal seams exposed in open cuts on the Morwell–Yallourn and Loy Yang blocks (Fig. 12) are also strongly jointed because of this folding. Most joints trend NNW to NW, swinging more northerly at Morwell because of regional stress accompanied by shear on the Morwell Monocline/Fault (Fig. 13; Barton 1979). The structures post-date coal-seam deposition, inasmuch as they are unconformably overlain by flat-lying Haunted Hill Formation sediments, which are also seen to fill the joints.

Post-coal measure folding, uplift, and subaerial erosion of the Latrobe Valley Group and equivalents dominates the near-surface geology of the Latrobe Valley (Thomas and Baragwanath 1949, 1951; Gloe 1960, 1976; Bolger 1984, 1991). Evidence for this erosion can be seen in all the anticlinal structures adjacent to the Balook Block, and along the northern and...
Fig. 10.—Section of the seismic profile OS88A–1 projected up onto the Otway Ranges (Fig. 6) with reconstruction of the eroded pre-Pliocene succession.

Fig. 11.—Shallow seismic profile 82-K-1, Kimbla Cruise, February 1982, across the Torquay sub-basin (Fig. 6) illustrating the angular unconformity at the Miocene–Pliocene boundary.
southern basin margins (Figs. 14, 15). The Miocene–Pliocene boundary is well exposed in all the brown coal open-cut exposures, where the Pliocene Haunted Hill Formation rests unconformably on coal seams (Fig. 8D). Areas of maximum uplift have largely been stripped of their Tertiary cover, and this stripping may exceed 200 m in places (e.g., the Baragwanath Anticline and Loy Yang Dome; Fig. 12; Dickinson et al. 2001). In the adjacent synclinal areas, evidence for the unconformity is provided by subsurface data. Post-Yallourn Seam truncation on the major bounding monoclines is evident on cross sections (Fig. 14), but in the center of the synclines more continuous sedimentation appears to have occurred between coal measures, post-Yallourn Seam clays, and Haunted Hill Formation (Bolger 1991).

The timing of structural uplift for the Tertiary coal measures in Gippsland is closely related by their peripheral occurrence to the Balook Block and Eastern Highlands uplift:

1. The isopachs of the Oligocene to lower Miocene Morwell 2 coal
seam show thickening towards the Yallourn Monocline and later uplift to form the Yallourn North and Extension coal fields (Holdgate 1985). The original extent of the Morwell 2 Seam is conjectural, but the present extent is clearly seen to be controlled by later uplift and erosion. The Morwell 2 (Latrobe) Seam is also cut and offset by reverse faulting along the Yallourn Monocline at Yallourn Power Station (Fig. 15) and is present on the upthrown Haunted Hill Block.

(2) The earliest appearance in the Traralgon Syncline of the lower Cretaceous Strzelecki Group detritus (taken to indicate erosion from the Balook and Narracan blocks) is observed in upper Miocene clays above the Yallourn Seam (Bolger 1984).

In the Traralgon and Latrobe synclines, clayey sediments of the Hazelwood Formation, reaching over 100 m thickness, conformably overlie the Yallourn coal seam (Fig. 13). Both are folded and unconformably overlain by sands and gravels of the Haunted Hills Formation. Constraints from palynology dates suggest that the Hazelwood Formation extends through the Upper T. bellus and lower part of the C. bifurcatus zones (Fig. 3), whereas the basal units of the Haunted Hill Formation include the upper part of the M. lipsis Zone (Fig. 13; Dawson 1983). This effectively indicates a hiatus during which folding took place spanning the time interval recorded between the upper C. bifurcatus and lower M. lipsis zones, i.e., between 7 and 4 Ma (Fig. 3).

The correlation of stratigraphy across the onshore Gippsland basin (Fig. 13) is consistent with the other southeast Australian basins. Here the best constraint, by palynology dates, microfossil biorstratigraphy, and structural control, confines the timing of unconformity development to the latest Miocene.

**Alberton Depression**

The structural pattern of the pre-middle Miocene Alberton Coal Measures in the Alberton Depression of South Gippsland is broadly similar to that of the Latrobe Valley Depression. The coal measures are folded and unconformably overlain by flat-bedded Haunted Hill Formation clastic sediments and Pliocene coquinas of the Jemmys Point Formation (Hocking 1976; Greer and Smith 1982; Holdgate 1982; Thompson and Walker 1982).

**Lake Wellington Depression**

Down-basin towards the Sale area, the timing of folding is further constrained. Here the latest age for the underlying folded Miocene (Tambo River and Boisdaile formations; Fig. 13) is dated as planktonic foraminifera zone N17 (Fig. 3), whereas the oldest part of the overlying Jemmys Point Formation is confined to planktonic foraminifera zone N20. Therefore the age of folding, given the constraints on the dating, must have taken place at the end of the Miocene (an interval of 8–4 Ma). Farther east towards the Bairnsdale–Lakes entrance area, the same relationship and ages are observed between the Tambo River Formation and the Jemmys Point Formation (Carter 1964, 1978a, 1978b; Mallett 1978), where horizons of phosphatic clasts are widespread along the unconformity.

**DISCUSSION**

The stratigraphic relationship summarized above points to a major change having taken place in the sedimentological regimes of the southeast Australian basins during the late Miocene to early Pliocene:

1. An unconformity of approximately late Miocene–early Pliocene age is present in every onshore succession from the Otway, Port Phillip, and Gippsland basins. Indeed, very few sections onshore from any of these basins have uppermost Miocene sediments preserved, and in many cases subsequent deposition did not occur until much later in the Pliocene.

2. Where the Miocene–Pliocene boundary is preserved in marine successions, the unconformity is typically sharp and planar, with no evidence of oxidation or karstification of the underlying strata (the only exception being Portland). Furthermore, the earliest sediments overlying the unconformity are of marine origin. This indicates that the unconformity was produced by marine erosion, or that any evidence of subaerial erosion has been removed by subsequent marine erosion.

3. The Miocene–Pliocene break is generally an angular unconformity, with differences in dip ranging from 0.5° to nearly 90° (most commonly in the range 0.5° to 5°). The underlying Miocene and older successions are folded, whereas the overlying Pliocene succession is generally not.

4. The Oligocene–Miocene carbonates of southeast Australia are characteristically clastic-poor successions. In contrast, the majority of onshore Pliocene to Recent marine sequences are characterized by mixed clastic-carbonate facies.

5. Accumulation of clastic-poor Oligocene–Miocene brown coal seams ceased during late Miocene–early Pliocene time. Nonmarine Pliocene to Recent sediments overlying the coals are characterized by high-energy siliciclastic fluvial successions.

The timing of the unconformity, which marks this change in sedimentation, is confined by the deposition of sediments above and below the unconformity. In many cases the youngest deposits beneath the boundary are lower to middle Miocene. Precise dating of the overlying units is made difficult owing to a lack of diagnostic fauna. The timing is best constrained by the hiatus that is apparent in the stratigraphy at Portland and Hamilton. At both locations upper Miocene sediments are preserved beneath the unconformity (~ 11 Ma from $^{87}Sr/^{86}Sr$ marine carbonate dating at Hamilton). Sequences above the unconformity are earliest Pliocene at Portland by
planktonic foraminifera (N19) and 5.5–4.0 Ma (early Pliocene) by $^{87}\text{Sr/}^{86}\text{Sr}$ dating at Hamilton. This places the commencement of the interval of unconformity development during the late Miocene (11–5 Ma), with cessation of the event by the Pliocene. Similar age relationships exist at Beaumaris (Mallett and Holdgate 1985), and in the Gippsland basin, a range of 8–4 Ma is determined for the unconformity.

**Uplift and Exhumation of the Southern Highlands**

Blocks of Lower Cretaceous sediments are present across the southeast Australian basins as structural highs. These blocks consist of sediments that are principally feldspathic sandstone, mudstone, and shale, with conglomerate in places prominent at the base. The relationship of Oligocene–Miocene sediments to these Cretaceous highs is important in determining their timing of uplift and exhumation and consequently the origin of the Miocene–Pliocene unconformity.

Where Oligocene–Miocene sediments flank the shoulders of these Mesozoic highs (e.g., Otway Ranges–Torquay basin, Strzelecki Ranges–La Trobe Valley) the stratigraphy is dominated by the deposition of carbonate-rich sediments (e.g., Port Campbell Limestone, Gellibrand Marl, Fyansford Formation) or nonmarine brown coal seams (e.g., Latrobe Valley Group). The siliciclastic component is everywhere low or nonexistent in these flanking Oligocene–Miocene sediments. This suggests that the Lower Cretaceous blocks had not been exhumed and exposed at this time, inasmuch as the erosion of the feldspathic beds would cause a significant clastic input to the surrounding depositional regimes and be evident in the resulting strata. Such a clastic component within the Tertiary succession is not apparent until the Pliocene, as reflect in the Brighton Group, the Haunted Hill Formation and the Jemmys Point Formation.

Further evidence for the Early Cretaceous highs not being as significant during the Oligocene–Miocene comes from seismic profiles in the Torquay sub-basin (Figs. 9–11). The Oligocene–Miocene Torquay Group overlying the Otway Group sediments in the subsurface shows no indication of thinning or onlap onto what would have been a topographic high had the Otway Ranges been present. Instead, the uniform thickness of strata indicates that deposition occurred on a relatively low-relief basin floor that has subsequently been uplifted. Furthermore, the Torquay Group sediments are removed by erosion at the sea floor as the Otway Ranges are approached (Fig. 10).

Very similar relationships exist around the Strzelecki Ranges in the La Trobe Valley. Near the margins of the ranges, Oligocene–Miocene brown coals are completely removed by erosion, with little or no evidence of stratigraphic thinning towards the ranges (Fig. 14). The significant emergence of the Balook Block above depositional base level and into an active denudation zone did not occur until post-Yallourn Seam times in the late Miocene. The stratigraphic and structural relationships around the Cretaceous highs indicate several hundred meters or more of erosion from the Cretaceous blocks during the late Miocene–Pliocene. The offshore seismic profiles and regional cross sections in the vicinity of the Early Cretaceous highs show that folding and faulting is most strongly developed in regions adjacent to these uplifted areas (Fig. 11; Skeats 1935).

The history and type of tectonism is illustrated best on shallow seismic sections from the Torquay sub-basin. Here, the bulk of folding, faulting, and erosion occurred during the late Miocene. This has largely taken the form of doming (e.g., line OS88A–1, Fig. 9) and reverse faulting in the Otway Group (producing monoclines in the Torquay Group) along the margins of the Otway Ranges and Mornington Peninsula. The Miocene–Pliocene unconformity overlies much of the eroded and folded Miocene section, indicating a pre-Pliocene origin for most deformation and erosion.

However, the Miocene–Pliocene unconformity in the Torquay sub-basin has a gentle synformal morphology with dips of less than $1^\circ$ on the limbs (Fig. 11). The initial surface is likely to have been a relatively planar feature (particularly because it is almost certainly of marine origin, discussed above) and the synformal geometry must be a result of Pliocene and younger deformation. Pliocene and younger sediments appear to have filled the syncline as it was formed. Most deformation and erosion therefore took place during the late Miocene, with significant, but less intense uplift occurring during the Pliocene–Quaternary. Similarly, in the Gippsland basin, tilting and faulting of the Haunted Hill Formation across the more active monoclines indicates that compressional uplift continues to the present day.

**Late Tertiary Uplift in Southeast Australia**

The evidence for a late Miocene tectonic uplift event is not confined to the southeastern margin. In the St. Vincent basin, which flanks the western
margin of the Mount Lofty Ranges (Fig. 1), the sedimentary succession shows siliciclastic Pliocene–Recent deposits lying upon an angular unconformity over a mid-Eocene to mid-Miocene dominantly cool-water carbonate sequence (Lindsay and Allen 1995; Tokarev et al. 1998). Evidence from morphological features and drainage systems in the Mount Lofty Ranges in conjunction with the neighboring stratigraphy suggests that two phases of tectonism took place (Tokarev et al. 1998), the first in the mid-Eocene and the second, of more relevance here, around 5 Ma. This second phase is associated with reverse faulting, as demonstrated by Bourman and Lindsay (1989).

Similarly, on the western side of the Flinders Ranges, there is evidence of young uplift. At Wilkatana North Creek, Pleistocene fanglomerates are affected by reverse faulting (Williams 1973). A series of uplifted and dissected ‘‘pediments’’ are also present on the western side of the Flinders Ranges, and these appear to be due to late Tertiary reverse faulting (Twidale and Bourne 1996).

In the Murray basin, a comparable stratigraphy is apparent. The clastic-rich upper Miocene to lower Pliocene Bookpurnong Beds unconformably overlie the carbonate-dominated mid-Miocene sediments of the Duddo Limestone, which changes laterally to the WINNAMBOOL Formation and Geera Clay to the east (Brown and Stephenson 1989). Although the general view is that this unconformity reflects eustatic cycles (e.g., Brown 1983; Brown and Stephenson 1989), there is evidence of late Miocene uplift events resulting in tilting of strata (Stephenson 1986).

Literature on the Eastern Highlands has been dominated by the concept of youthful uplift (e.g., Andrews 1910; Browne 1969; Hills 1975; Douglas and Ferguson 1988). The period is referred to as the ‘‘Kosciuszko Uplift’’ and culminated during the late Pliocene to Pleistocene. Our work shows that in the basins, there have been two successive pulses of tectonism initiated under the same stress regime. Of these two pulses late Pliocene to Pleistocene uplift is less significant than late Miocene uplift and exhumation. It is clear that the late Miocene uplift event we have documented is part of the same major episode of tectonism as the late Pliocene–Pleistocene Kosciuszko Uplift. However, the Kosciuszko Uplift has historically always been considered to be late Pliocene–Pleistocene in age, and to extend this terminology to a much older event may cause considerable confusion in the literature.

Correlation of the Miocene–Pliocene unconformity across the southeast margin indicates that the uplift event occurred over a regional area. Several datasets (in situ stress measurements, seismicity, and young faults) indicate that a compressional regime now characterizes the Australian continent (Coblentz et al. 1995), resulting in the reactivation of older structures as features of compression. In southeast Australia the regional stress field is oriented E–W to WNW–ESE (Fig. 16; Tokarev et al. 1998), which is consistent with the ENE–WSW orientation of the Early Cretaceous highs and the reverse faults that bound them. The stress field has been attributed to changes in the relative motion and forces at the boundary between the Australian and Pacific plates, with pressure along the New Zealand, Papua New Guinea, and Himalayan collisional boundaries (Coblentz et al. 1995). The onset and effect of the associated forces is related to the timing of plate boundary development.

The inception of the Australia–Pacific plate boundary through New Zealand is considered to have occurred during the Oligocene at about 25 Ma (Kamp 1986). At this time, strike-slip movement was dominant along the Alpine Fault section of the Australia–Pacific plate boundary. Between 12 and 5 Ma the plates became slightly compressive across the Alpine Fault, which initiated the uplift of the Southern Alps (Kamp et al. 1992; Sutherland 1996). To the north of the Alpine Fault, this change in stress is evident as the structural inversion of normal to reverse faults and resulted in late Miocene uplift across the Taranaki basin (Kamp and Green 1990). At around 6.4 to 5 Ma, the boundary underwent a marked increase in convergence, which resulted in very rapid uplift of the Southern Alps,
the inversion of Lower Cretaceous blocks and associated localized folding. of stress across the plate appears to have been focused around older struc-
and culminating at 6±5 Ma, is largely responsible for uplift and exhumation.

it appears likely that the change in plate dynamics, beginning at 12 Ma
tralian continent and the timing of compressional movement along them,

Paci®c plates resulted in kilometers of uplift throughout northern Papua

At 12±10 Ma a change to oblique convergence between the Australian and

Guinea collisional boundary a similar change in plate dynamics is observed.

ernland 1996; Walcott 1998).

which continued through to the Quaternary (Tippett and Kamp 1993; Suth-

At the northern margin of the Australian continent along the Papua New

Guinea collisional boundary a similar change in plate dynamics is observed.

At 12 Ma a change to oblique convergence between the Australian and

Pacific plates resulted in kilometers of uplift throughout northern Papua

New Guinea (Hill and Raza 1999).

Considering the relative proximity of these plate boundaries to the Aus-

tralian continent and the timing of compressional movement along them,

it appears likely that the change in plate dynamics, beginning at 12 Ma

and culminating at 6–5 Ma, is largely responsible for uplift and exhumation

in southeast Australia during the late Miocene (Fig. 17). The propagation

of stress across the plate appears to have been focused around older struc-

tures at depth, which have consequently become reactivated resulting in

the inversion of Lower Cretaceous blocks and associated localized folding.

Climate and Eustasy at the Miocene–Pliocene Boundary

In the past, the unconformity that is present between the Miocene and

Pliocene successions has been attributed to both eustatic and climatic

changes (e.g., Carter 1978a), with little importance placed on the role of

tectonics in producing the stratigraphy of the sedimentary basins. The role

tectonics has generally been invoked only when discussing the timing

of uplift of the Eastern Highlands, which is dominated by ideas of late

Pliocene to Pleistocene uplift (e.g., Douglas and Ferguson 1988). Although

some researchers have suggested a late Miocene inversion event along the

southeastern margin (e.g., Duddy 1994; Hill et al. 1995; Cooper and Hill

1997), most thermochronologic studies have constrained older events (e.g.,

Duddy 1994; Hegarty et al. 1988) showing substantial exhumation of the

Otway Group in the mid-Cretaceous. The preference for eustasy and cli-

mate change over tectonism as an explanation for the Miocene–Pliocene

unconformity reflects the influence of seismic and sequence stratigraphy in

the literature and a general belief that the Australian continent has been

tectonically stable through the Neogene–Recent.

The possibility of a climatic and/or eustatic event influencing the sedi-

mentation during the Miocene–Pliocene is plausible. The sea-level curve

of Haq et al. (1988) indicates a significant interval of regression occurring

through the late Miocene with subsequent transgression in the early Plio-

cene. More recent work (e.g., Miller et al. 1998) indicates, however, that

the magnitude of sea-level change presented by Haq et al. (1988) is grossly

exaggerated. It is also well established that the southeast Australian climate

experienced gradually increasing seasonality and aridity during the Tertia-

ry. The vegetation changed from a temperate, closed rain forest dominated

by Nothofagus sp. to open sclerophyll forest (e.g., Eucalyptus), as indicated

by plant microfossils and macrofossils (Bowler 1982). The change was a

reflection of pronounced global cooling at the end of the Miocene brought

about by the onset of glaciation and the formation of ice sheets in the

Northern Hemisphere (Kemp 1978). The humid conditions that prevailed

in the Oligocene–Miocene were replaced by the arid conditions experienced

during the Pliocene–Recent. The more seasonal climate is thought to have

contributed to an increase in runoff and with that a higher sediment yield

(Bolger 1991). This mechanism has been suggested as bringing more sil-

iclastic material into the marine basins and so could be used as an ex-

planation for increased siliciclastic sediment flux in early Pliocene succes-

sions overlying the Miocene–Pliocene unconformity.

However, the unconformity is typically angular, with Miocene strata hav-

ing been subjected to deformation (folding and faulting) and erosion prior
to deposition of Pliocene sediments. This is the case in all of the basins

that we have examined from southeast Australia (e.g., Figs. 9, 10, 11, 14

and 15). Therefore, a change in eustatic sea level or climate cannot be used

as a viable mechanism for the origin of the Miocene–Pliocene unconformity

in southeast Australia. Similarly, the increased siliciclastic content of Pli-

ocene sediments is best explained by tectonic uplift and consequent in-

creased erosion of older siliciclastic successions (like the Eocene clastic

successions, the Lower Cretaceous volcanoclastics, and the Paleozoic base-

ment rocks).

It does, however, seem likely that a period of eustatically driven trans-
gression is responsible for the marine erosion, deposition of earliest Plio-
cene sediments, and widespread phosphatization evident at the Miocene–

Pliocene unconformity. Evidence from deep-sea isotope records (Shackle-

ton et al. 1995) indicates that the early Pliocene was a warm (possibly ice-

free) period. This would explain the occurrence of a rapid and synchronous

flooding event across the southeast Australian margin made more invasive

by regional subsidence following the compressional uplift. From this it

would appear that the preservation of the late Miocene tectonic event is a

result of a eustatic cycle being superimposed on an extended period of

tectonism in southeast Australia.

CONCLUSIONS

An unconformity is observed close to the Miocene–Pliocene boundary

(between 10 and 5 Ma) in the onshore and nearshore parts of the Otway,

Port Phillip–Torquay, and Gippsland basins of southeast Australia. The

unconformity is generally angular, with the underlying Miocene units hav-

ing been deformed (gentle folding and reverse faulting) and eroded prior
to deposition of the Pliocene succession. It also marks the change from

Oligocene–Miocene cool-water carbonate and brown-coal-dominated suc-

cessions to more siliciclastic-rich Pliocene sediments.

The change to Pliocene siliciclastic-rich sediments and the angular nature

of the Miocene–Pliocene unconformity indicate that a significant regional

uplift event has occurred in all southeast Australian basins. The timing of

this uplift coincides with a change in the dynamics of the Australian plate

at around 12 to 5 Ma, most evident in New Zealand, where the Southern

Alps underwent an increase in the rate of uplift. The southeast Australian

margin is currently under a compressional stress regime, and this has prob-
ably persisted since the late Miocene, when the change in plate dynamics

occurred. The preservation of this tectonic event as an unconformity in the

stratigraphic record is probably due to the effects of a major early Pliocene

FIG. 17—Summary of the tectonic events and unconformity development across

the southeast Australian margin along with the tectonic history of the Indo–Austra-


eustatic transgression, which may also be responsible for widespread phos-
phatization.

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