Australian Journal of Earth Sciences (2005) **52**, (277–295)

Late Neogene strandlines of southern Victoria: a unique record of eustasy and tectonics in southeast Australia

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Digital elevation and magnetic data from the southern Victorian basins (Otway, Port Phillip, Gippsland Basins) have enabled the recognition of a vast Late Miocene–Pliocene strandplain succession that is a correlative of the Murray Basin Loxton–Parilla strandplain. A combination of ferricrete formation and erosional dissection has made the strandline geometries visible on geophysical images and allowed the mapping of strandlines across most of the onshore Otway (often under continuous basalt cover), Port Phillip and Gippsland Basins. Strontium isotope ages from well-preserved molluscan assemblages of the exposed strandplain successions indicates the earliest sediments were deposited above the Late Miocene unconformity at around 5.8 $\pm$ 0.2 Ma (latest Miocene, Beaumaris). The youngest exposed strandplain sediments (from the Jemmys Point Formation, Gippsland) are Late Pliocene (*ca* 3.0–2.5 Ma), although younger strandlines occur offshore. Elevation differences across the strandplain of the Victorian basins give a quantitative measure of cumulative Plio-Pleistocene uplift. A broad east–west axis of regional uplift is present along the Western Highlands–Dundas Tablelands, with maximum uplift in the range of 250 m being indicated. The western extension of this axis affects the Mt Gambier coastal plain (Gambier Axis). The Padthaway High forms another uplift trending northwest from the Dundas Tablelands into the Murray Basin. The unconformable relationship between the Pliocene and Quaternary strandline systems across Victoria may be caused by intensified latest Pliocene Quaternary uplift and/or eustatic changes associated with the development of the Quaternary glacial episode. The strandplain successions of southern Victoria have probably developed during the latest Miocene and Pliocene in response to a period of relatively stable base-level (little uplift or eustatic fluctuation). Recognition of the southern Victorian strandline successions may provide potential new targets for heavy-mineral exploration.

KEY WORDS: ferricrete, Gippsland, Neogene, neotectonics, Otway, Pliocene, Port Phillip, Quaternary, strandlines

INTRODUCTION

The Late Miocene–Pliocene strandlines of the Murray Basin are well known and form one of the largest strandplains in the world (Blackburn 1962; Brown & Stephenson 1991; Kotsonis 1995). The Murray Basin strandplain is an important water resource and also contains economically significant heavy-mineral deposits (Roy *et al.* 2000; Roy & Whitehouse 2003). As well as being economically significant, it has also been suggested that the strandlines represent an unbroken record of glacioeustasy during the Late Miocene to Holocene. Furthermore, since the strandlines were deposited at sea-level, they can be used as a gauge to assess the amount of Plio-Pleistocene tectonism that has occurred in southeast Australia.

It is not well known that age-equivalent strandlines are present across large areas of southern Victoria (Paine *et al.* 2004). In this paper, we describe the distribution, stratigraphy, age, palaeogeography and neotectonic implications of strandplain sediments from the Otway, Port Phillip and Gippsland Basins. Marine Pliocene and latest Miocene shallow marine sediments have been extensively documented in the southern Victorian basins (Singleton 1941; Bowler 1963; Wilkins 1963; Mallett 1977; Carter 1979; Abele *et al.* 1988; Holdgate *et al.* 2003), but have largely been viewed as isolated occurrences because of their poor exposure. Detailed age determination of these Pliocene sequences has also been hindered by a paucity of planktic foraminifera, although Mallett (1977) made major advances in this respect.

In a paper that was largely ignored, Jenkin (1981) postulated the existence of extensive Pliocene strandlines in the Otway and Port Phillip Basins, based on geomorphological evidence. Recent high-resolution airborne geophysical data (largely total magnetic intensity and digital elevation) allow recognition and detailed mapping of strandline systems over large areas of southern Victoria (Dickinson *et al.* 2001; Sandiford,

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ISSN 0812-0099 print/ISSN 1400-0952 online © Geological Society of Australia
Taylor & Francis Group Ltd
DOI: 10.1080/08120090500139455

2003; Holdgate *et al.* 2003) confirming the earlier work of Jenkin (1981) (Figure 1). Here, we present the combined results of geophysical strandline mapping, field work and new geochronological results (Sr isotope dating) and attempt to produce an integrated picture of Late Miocene–Pliocene strandlines in southern Victoria.

Recognition of this vast strandplain system in southern Victoria has implications for mineral-sands exploration, and for an understanding of the relative roles of eustasy and tectonics in the southern basins.

GEOLOGICAL SETTING

The Late Cenozoic marine shelves of southern Australia are dominated by Late Eocene to Holocene cool-water carbonates. A major break in sedimentation occurred in the Late Miocene and this unconformity separates the Oligo-Miocene pure cool-water carbonates from the latest Miocene–Pliocene mixed clastic–carbonate successions discussed in this paper (Dickinson *et al.* 2002) (Figure 2). The Miocene–Pliocene unconformity is present in all of the southeast Australian basins, including the Murray, Otway, Port Phillip, Bass and Gippsland Basins (Figure 1). The unconformity has variously been considered to be of eustatic (Carter 1978a; Roy *et al.* 2000) or tectonic (Jones & Veevers 1982) origin.

Supporters of a eustatic origin for the unconformity generally correlate it with a period of globally low sea-levels in the Late Miocene on the sea-level curve of Haq *et al.* (1988). However, recent work by Dickinson *et al.* (2001, 2002) has demonstrated that the Miocene–Pliocene boundary is an angular unconformity in most

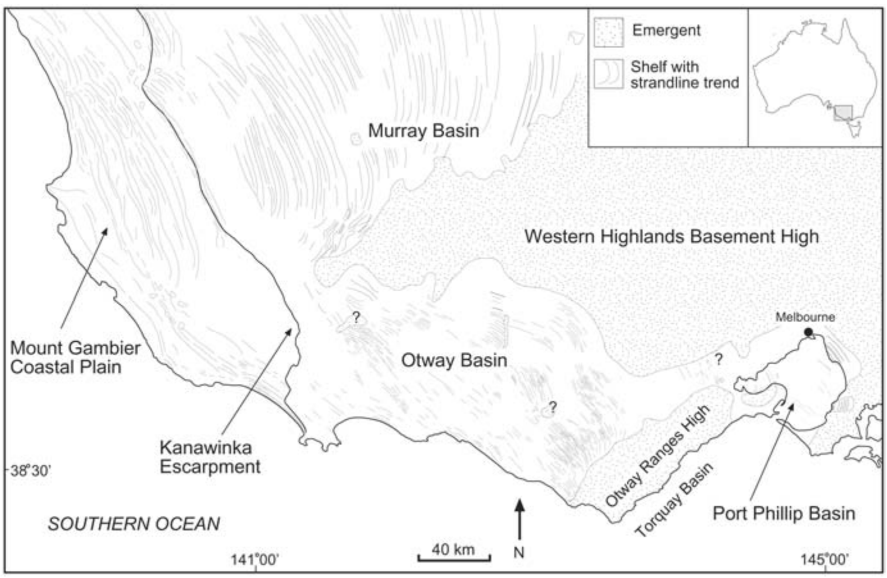

Figure 1 Pliocene palaeogeography and strandline morphology interpreted from geophysical data in the Murray, Otway and Port Phillip Basins. The Quaternary strandlines of on the western side of the Kanawinka Escarpment (in grey) are derived from Sprigg (1952).

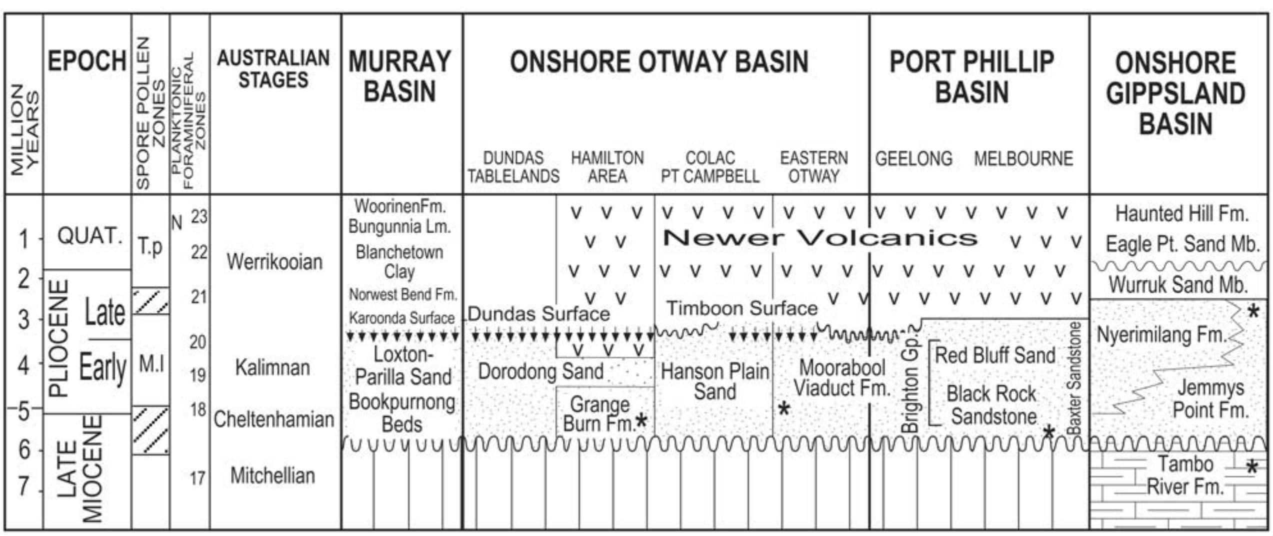

Figure 2 Chronostratigraphic chart for the Late Neogene strandplain successions of the southeastern Australian basins. Strontium isotope ages derived from this study are marked by asterisks. T.p., *Tubuliforidites pleistocenicus*; M.l., *Meyeripollis lipsis*; C.b., *Cingulolatisporites bifurcates*; T.b., *Triporollenites bellus*; P.t., *Proteacidites tuberculatus*.

southeast Australian basins, there having been significant deformation and exhumation prior to deposition of the Late Miocene Pliocene successions.

The Late Miocene unconformity is typically characterised by marine erosion and the widespread presence of phosphatic nodules and remanié vertebrate fossils (Coulson 1932; Carter 1978b; Singleton 1941; Dickinson *et al.* 2002). Dickinson *et al.* (2002) documented a consistent Late Miocene age gap at 10 to 6 Ma in all of the southeast Australian basins (except perhaps the Gippsland Basin). They concluded that the Late Miocene unconformity represents a significant tectonic event in the southeast Australian basins that heralded the onset of Neogene tectonism in southern Australia.

The latest Miocene – Pliocene transgression that followed the Late Miocene unconformity is responsible for deposition of the strandline successions discussed in this paper. The origin of this transgression is also controversial, with both eustatic (Kotsonis 1999) and tectonic (Jones & Veevers 1982) origins having been suggested. The deep-sea stable-isotope record indicates warm (and possibly ice-free) Early Pliocene conditions (Shackleton *et al.* 1995), perhaps supporting a eustatic origin for the transgression.

The latest Miocene – Pliocene strandplain successions consist of offshore marine marls, nearshore calcareous quartz sands and silts and alluvial sands or gravels. The strandline successions of southeast Australia are known by a variety of stratigraphic names (Figure 2). Ferricretes generally cap the strandplains and these are interpreted to be the product of prolonged ferruginisation during the Pliocene (Gill 1964; Lawrence 1966; Firman 1973; Kotsonis 1995, 1999).

Various units overlie the strandplain successions in each of the basins of southeast Australia. In the Murray Basin, the strandplain sediments are well exposed, but are, in places covered by the Plio-Pleistocene lacustrine Blanchetown Clay and by younger longitudinal-dune sediments of the Woorinen Formation. In the Otway and Port Phillip Basins, the strandplain sediments (known by a variety of local stratigraphic names) are almost entirely covered by the Plio-Pleistocene Newer Volcanics and other Quaternary alluvial sediments. In the Gippsland Basin, Late Miocene and Pliocene strandplain sediments (Tambo River and Jemmys Point Formations) are generally overlain by a relatively thick cover (several tens of metres) of Pliocene and Quaternary sediments (Holdgate *et al.* 2003). Because Plio-Pleistocene sediments and volcanics largely cover the Late Miocene – Pliocene nearshore sediments in the southern Victorian basins (Otway, Port Phillip, Gippsland Basins), the contiguous nature of these sediments and their strandplain geometry has largely gone unrecognised.

Considerable tectonic activity has taken place since deposition of the strandplain sediments. The margins of the Murray Basin bordering the Western Highlands of Victoria (Figure 1) and the Flinders Ranges – Mt Lofty Ranges of South Australia have been uplifted by more than 100 m. There is also considerable faulting and regional uplift of the strandplain sediments in the Otway, Port Phillip and Gippsland Basins (Dickinson *et al.* 2001). In the Otway and Port Phillip Basins, the Plio-Pleistocene Newer Volcanics commonly fill palaeodrainage systems developed on the strandplains, suggesting considerable erosion took place during the Late Pliocene and Pleistocene.

METHODS

Stratigraphic data was obtained through detailed sections taken at locations in the Otway, Port Phillip and Gippsland Basins. Digital elevation, radiometric and magnetic images used in this study were derived from data gridded at 200 m and sourced from GeoScience Victoria. The relevant acquisition and processing methods for this data are also available from GeoScience Victoria (Department of Natural Resources and Environment 2000). Grid references are given relative to the AMG 84 datum. NASA shuttle radar topography mission data was also used to construct elevation models.

All $^{87}Sr/^{86}Sr$ measurements (Table 1) were made on calcitic and unaltered aragonitic molluscs. All molluscan samples were first cleaned of any detrital material and then cleaned with conc. HCl to remove any potential surface overgrowths and rinsed with distilled water. Dissolution of powdered samples was carried out in 10% acetic acid (50 mg of sample in 3 ml of acid for 1 hour). Chemical separations were performed using 1 N HCl and 2.5 N HCl as eluents through AG 50W-X8 ion exchange resin in 15 mL quartz columns for Sr separation. The Sr isotopic composition of the separate was measured at the University of Adelaide with mass fractionation normalised to an $^{86}Sr/^{88}Sr$ ratio of 0.1194 and to an SRM 987 = 0.710248. Analytical reproducibility of samples is typically 12×10^{-6} (2σ of the mean). Ages were calculated using Howarth and McArthur's (1997) Sr isotope Look-Up Table Version 3:10/99. Age errors quoted incorporate the analytical 2σ error and the uncertainty in the Sr isotope curve (Howarth & McArthur 1997).

MURRAY BASIN STRANDPLAIN

The extensive Late Neogene strandplain of the Murray Basin has been the subject of much previous scientific and industrial literature and is therefore only briefly described here for comparison with the southern Victorian strandplains. In the Murray Basin, the major units are the Loxton – Parilla Sands (Brown & Stephenson 1991) and Bookpurnong beds (Ludbrook 1957). The Bookpurnong beds appear to be the shallow offshore marine facies equivalent of the Loxton – Parilla Sands which are a shoreface, beach and possibly alluvial succession of sands and some gravels (Firman 1966; Roy *et al.* 2000).

The Loxton – Parilla Sands and Bookpurnong beds are generally regarded as Upper Miocene to Pliocene units (Ludbrook 1961; Firman 1966; Macumber 1983; Kotsonis 1995; Roy *et al.* 2000). However, this age range is based on relatively sparse geological evidence. The oldest age suggested for the marine units is from the Late Miocene – Early Pliocene, or 6.6 – 5 Ma (Brown & Stephenson 1991; Kotsonis 1995; Roy *et al.* 2000). These

Table 1 Measured $^{87}Sr/^{86}Sr$ ratios and calculated ages of molluscan carbonate material from stratigraphic sections used in this study.

Location	Stratigraphic height in section (m)[a]	AMG 84 Grid Reference (m)	$87Sr/^{86}Sr$[b]	Std error[c]	Preferred Age (Ma)	Lower age (Ma)	Upper age (Ma)
Hamilton	2.9	54-582668E, 5822202N	0.709027	± 12	5.27	4.81	5.66
	2.9	54-582668E, 5822202N	0.709024	± 12	5.35	4.92	5.71
	2.9	54-582668E, 5822202N	0.709049	± 12	4.45	3.27	5.09
Batesford	6.1	55-262200E, 5779200N	0.709029	± 12	5.21	4.71	5.62
	5.7	55-262200E, 5779200N	0.709040	± 12	4.90	3.95	5.33
	5.1	55-262200E, 5779200N	0.709037	± 14	5.00	4.04	5.48
Beaumaris	4.3	55-328382E, 5793386N	0.709036	± 12	5.03	4.23	5.45
	2.8	55-328382E, 5793386N	0.709016	± 12	5.56	5.15	5.82
	2.5	55-328382E, 5793386N	0.708999	± 14	5.84	5.55	6.05
Trident Arm	-	55-600020E, 5813587N	0.709065	± 12	3.23	2.17	4.42
	-	55-600020E, 5813587N	0.709057	± 12	3.89	2.43	4.84
	-	55-600020E, 5813587N	0.709083	± 15	2.09	1.51	3.29
Swan Reach	-	55-575988E, 5813298N	0.709015	± 12	5.58	5.17	5.83
	-	55-575988E, 5813298N	0.708973	± 11	6.18	5.99	6.68
Red Bluff	-	55-593481E, 5808358N	0.709094	± 11	1.72	1.4	2.2

[a] Stratigraphic height from sections in Figure 3. The three Trident Arm samples came from the same locality and horizon; the two Swan Reach samples also came from the same locality and horizon.
[b] All results are normalised to the SRM-987 standard = 0.710248 and to $^{86}Sr/^{88}Sr = 0.1194$.
[c] Analytical uncertainty represents 2 standard errors of the mean of ~100 individual measurements and refers to the last two digits of the ratios.

ages appear to be largely based on correlation with various global eustatic curves (Haq *et al.* 1988). However, Ludbrook (1961) suggested a Cheltenhamian (latest Miocene) age for the Bookpurnong beds, while Beu and Darragh (2001) suggested a Bairnsdalian (mid to late Miocene) age for the unit, both studies being based on palaeontological data. The younger age limit for the Loxton – Parilla Sands (3.0 Ma) is constrained by palaeomagnetic dates from the base of the overlying Blanchetown Clay (An-Zhisheng *et al.* 1986).

The strandlines of the Murray Basin have strong topographic expressions, which are easily identified on digital elevation models. Hills (1939) was the first to recognise the strandline ridges topographically, but interpreted them as being due to folds in the underlying basement. Blackburn (1962) first suggested the ridges were beach ridges, and since then, the ridges have generally been accepted as being strandlines. The strandlines also have a radiometric and magnetic signature. On combined thorium – uranium – potassium images, the ridges have a low intensity dark signature, the result of the sands having an abundance of quartz and with relatively low concentrations of heavy minerals, feldspars and clays.

PORT PHILLIP BASIN STRANDPLAIN SEDIMENTS

Geelong – Corio Bay

The banks of the Moorabool River provide good exposures of the Moorabool Viaduct Formation (Bowler 1963), the most complete section being at the Old Batesford Quarry (Figure 3). Here, the Moorabool Viaduct Formation unconformably overlies the Fyansford Clay with slight angular discordance (Bowler 1963; Dickinson *et al.* 2002) (Figures 3, 4). The unit consists of basal marine calcareous sands (with burrows and marine molluscs) that are overlain by non-calcareous sands and silts of probable non-marine origin. The age of the unit has been the subject of some debate (Singleton 1941; Bowler 1963), but based on the molluscan fauna, Abele *et al.* (1988) suggested an age from the very late Miocene to Early Pliocene. Strontium isotope analyses from unaltered molluscs yield ages ranging from 5.3 to 4.9 Ma, consistent with the age suggested by Abele *et al.* (1988). Newer Volcanics overlie the sands of the Moorabool Viaduct Formation and have an estimated age (based on palaeomagnetic data) of 2.0 Ma (Whitelaw 1989).

Magnetic and topographic images of the Geelong area reveal few indications of the strandline trends. Immediately south of the township of Maude, a series of northwest-oriented parallel ridges and swales developed on strongly ferruginised Moorabool Viaduct Formation may represent strandlines. Other weak linear magnetic features in the area have this orientation, but are not strong enough to be definitely assigned as strandlines.

Magnetic images of Corio Bay display very distinct arcuate trends that are concave to the west (Figure 5). These arcuate magnetic trends increase in curvature to the south (along the Curlewis Monocline), suggesting a topographic high or coastline. This geometry indicates the Curlewis Monocline/Fault was probably active prior to and during the Pliocene. Carbon dioxide-rich springs discharge on the beach where the Curlewis Monocline/Fault crosses the coastline at Clifton Springs, indicating that the fault is presently a conduit for gas.

The basal phosphatic nodule bed of the Moorabool Viaduct Formation is exposed on the coast at Curlewis and along the western shore of Lake Conewarre (Coulson 1932). The Moorabool Viaduct Formation is also mapped as covering most of the central Bellarine Peninsula. The proximity of the arcuate magnetic

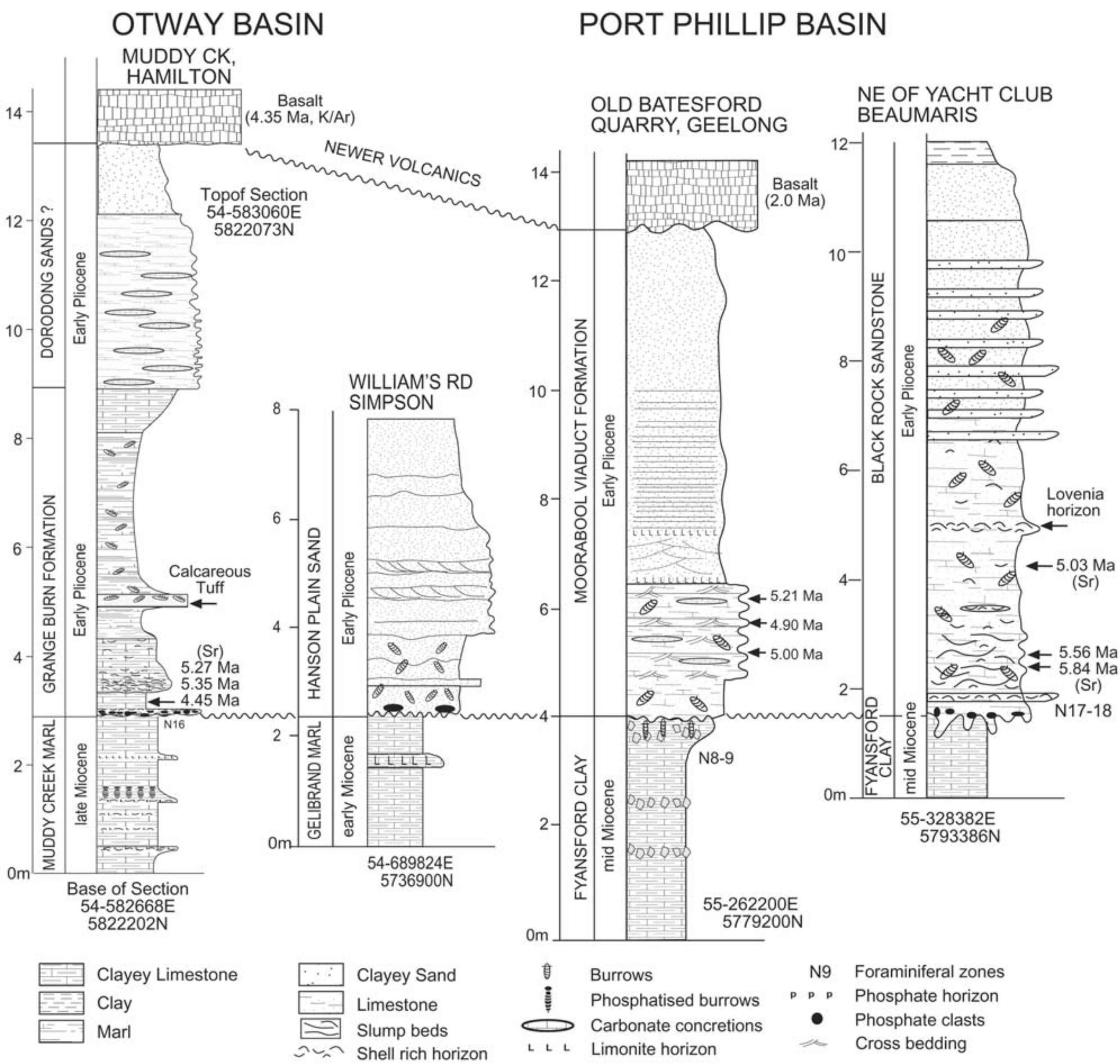

Figure 3 Stratigraphic sections measured through the strandplain succession of the Otway and Port Phillip Basins. Sr isotope ages are also shown on the sections.

trends in Corio Bay to marine Pliocene outcrops on the Bellarine Peninsula strongly suggests they are Pliocene strandlines.

Melbourne – Port Phillip Bay

The Melbourne area provides some of the most well exposed stratigraphic sections through the strandline sediments, including the type section of the Black Rock Sandstone and Red Bluff Sand (Kenley 1967). The section at Beaumaris (southeast of Melbourne: Figure 6) includes the basal phosphatic nodule bed which unconformably overlies the Fyansford Formation. The phosphatic nodule bed consists of phosphatic and limonitic intraclasts, and a rich fauna of teeth, bones, and shell material, with a quartz-rich sandy matrix.

The overlying Black Rock Sandstone (Figures 3, 4) consists of fine calcareous sands and silts which are extensively burrowed and contain molluscs and echinoids (*Lovenia woodsi* and *Monostychia incisa*). The unit becomes slightly coarser upwards with some gravel beds being present higher in the section. The upper portion of the section is ferruginised and contains no carbonate, but does contain burrows, probably indicating a marine environment to the top of the section. The section at Beaumaris resembles a sandy lower shoreface facies.

The Black Rock Sandstone at Beaumaris is also the type section of the Late Miocene Cheltenhamian stage (Singleton 1941). This Late Miocene age was supported by foraminiferal data from Mallett's (1977) study. Strontium isotope ages from the base of the section at Beaumaris (Table 1; Figure 3) range from 5.8 to 5.6 Ma,

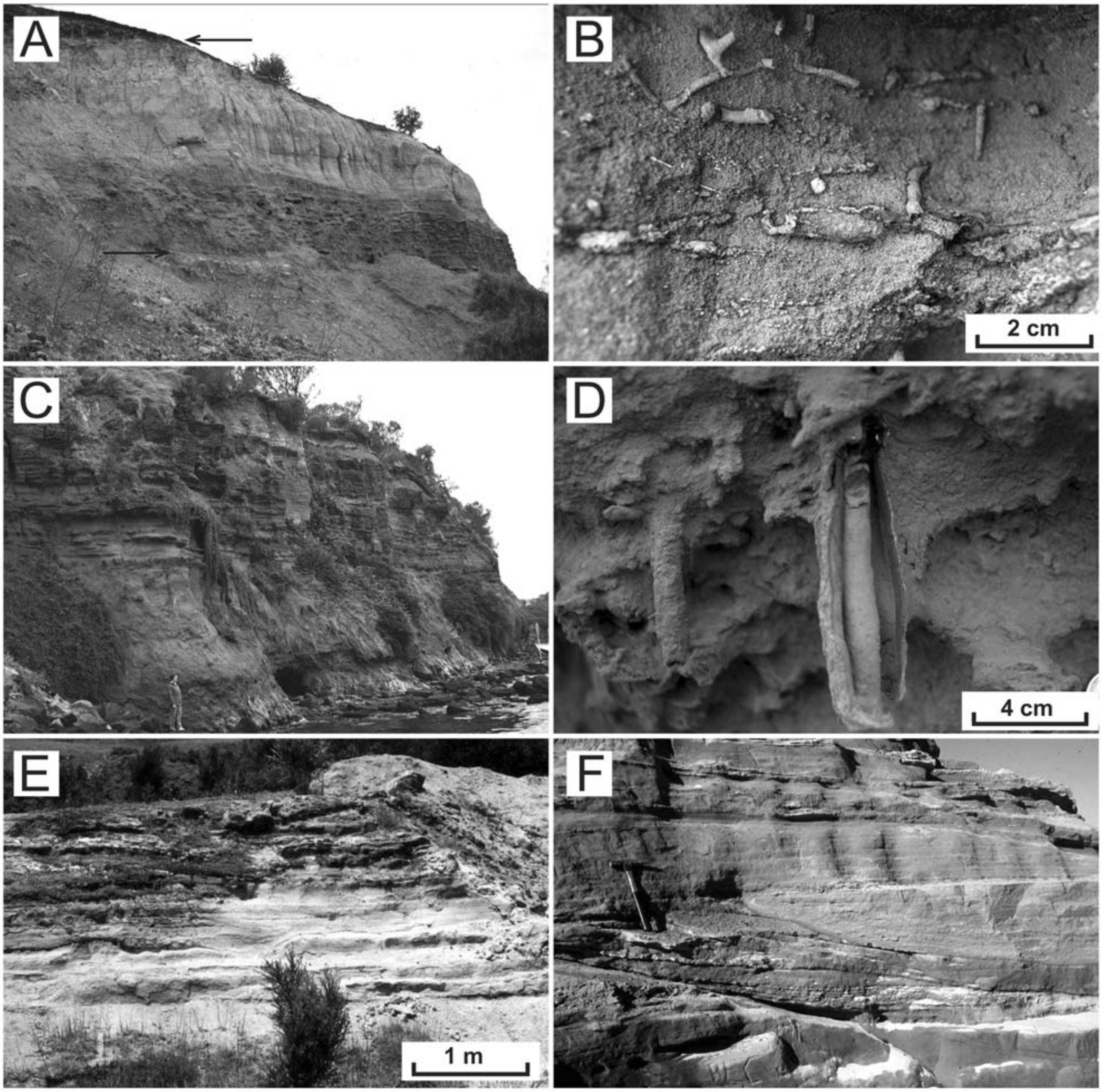

Figure 4 Outcrops of strandplain sediments from the southern Victorian basins. (a) Moorabool Viaduct Formation at Old Batesford Quarry, near Geelong. Fyansford Formation (lower portion of photograph below lower arrow) is overlain by Moorabool Viaduct Formation, which is overlain by Newer Volcanics basalt (above upper arrow). Thickness of section between arrows is 9 m. Grid Reference: 55-262200E, 5779200N. (b) Burrows preserved in the lower calcareous portion of the Moorabool Viaduct Formation, Old Batesford Quarry, near Geelong. Grid Reference: 55-262200E, 5779200N. (c) Outcrop of the Black Rock Sandstone at Beaumaris. Base of cliff section is the base of the unit, with the phosphatic nodule bed exposed within the tidal range. Figure for scale. Grid Reference: 55-328382E, 5793386N. (d) Large vertical burrows in the Black Rock Sandstone, Beaumaris. Grid Reference: 55-328382E, 5793386N. (e) Hanson Plain Sand at the type section near Simpson. Lower portion of the section is the underlying Gellibrand Marl. Height of section $\sim$3 m. Grid Reference: 54-689824E, 5736900N. (f) Lower portion of the Jemmys Point Formation at Red Bluff, near Lakes Entrance. Hammer for scale. Grid Reference: 55-593481E, 5808358N.

consistent with the previously derived Late Miocene molluscan and foraminiferal ages. A strontium analysis from higher in the section (Figure 3) yields an age of 5.0 Ma, perhaps suggesting the section straddles the Miocene–Pliocene boundary.

A series of low parallel ridges and swales are present inland from the coastal Black Rock Sandstone outcrops (Figures 6, 7). The ridges and swales are only present on the coastal strip mapped as Brighton Group (Vandenberg *et al.* 1969) and display a slightly arcuate geometry (Figure 6). These ridges and swales also control the shape of the coastline (Figure 6), with headlands being located around the crest of the ridges and the intervening beaches forming parallel to swales (Hart 1913). Hills

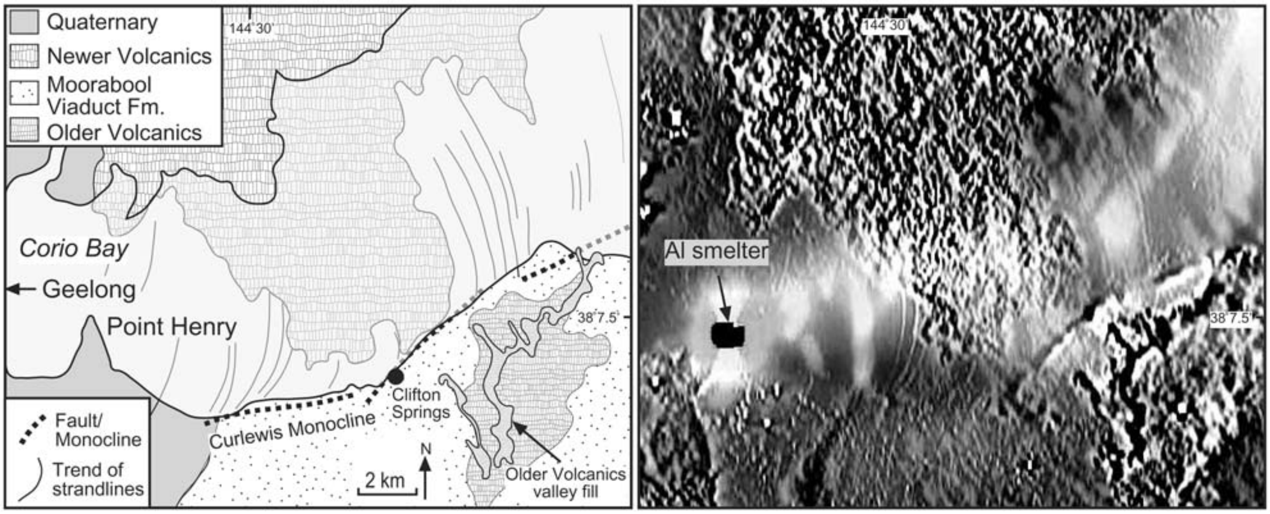

Figure 5 Total magnetic intensity image for the Corio Bay region and the interpreted strandline systems.

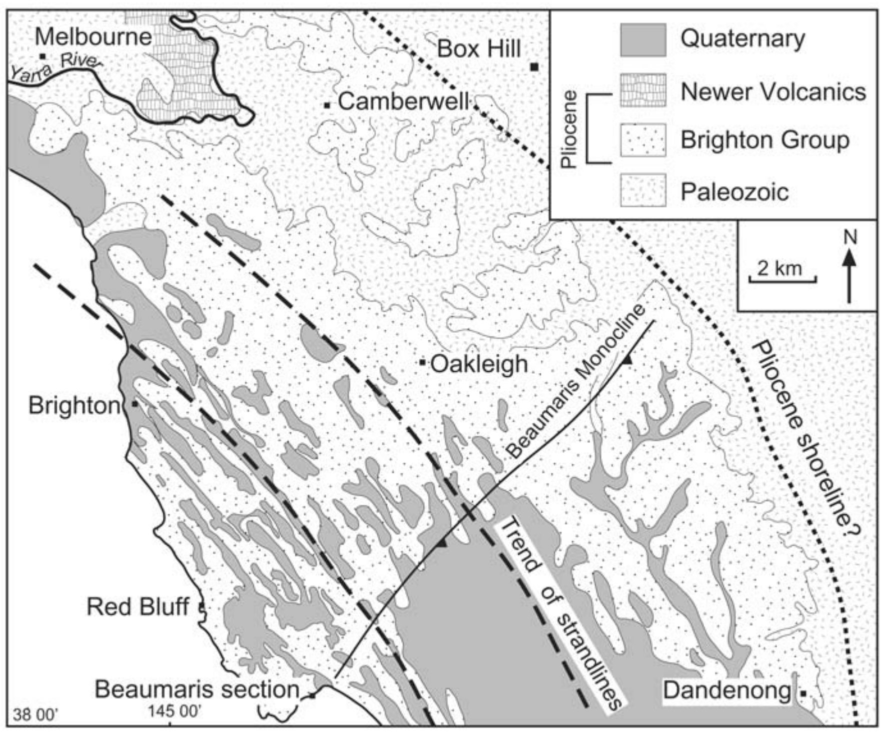

Figure 6 Geological map of the southeastern suburbs of Melbourne (from 1:63 360 Ringwood sheet: Vandenberg *et al.* 1969). Linear ridges and swales marking the strandline trends (dashed lines) are made visible by the Quaternary sediment-filled swales. The coastline in the region is also affected by the strandline trends, with much of it being parallel to the strandlines.

(1940), Whincup (1944) and Bird (1993) all suggested the linear ridges were Quaternary aeolian longitudinal sand dunes, while Kenley (1967) suggested they were of tectonic origin.

Whincup (1944) suggested the linear ridges were longitudinal desert dunes because of their straightness and similarity to the longitudinal desert dunes of central Australia. She ruled out a beach-ridge origin for the features because of an absence of marine molluscs or waterworn pebbles. However, Whincup (1944) was concentrating on the surficial sand in outcrop. In fact, the whole of the Brighton coastal plain is underlain by marine Brighton Group. Furthermore, the fact that the present erosional coastline has a similar geometry to the linear ridges strongly suggests that the topographic ridges are not controlled by the surficial deposits, but by the nature of underlying Brighton Group. It appears likely that the coastal geometry and the linear ridges are a result of more strongly (iron oxide?) cemented zones (corresponding to strandline geometries) within the Brighton Group. Finally, with the aid of new elevation data (NASA shuttle radar topography mission: Figure 7) it is shown that the topographic ridges are in fact slightly arcuate, rather than perfectly straight, as suggested by Whincup (1944). From the new elevation data, it is also clear that there is

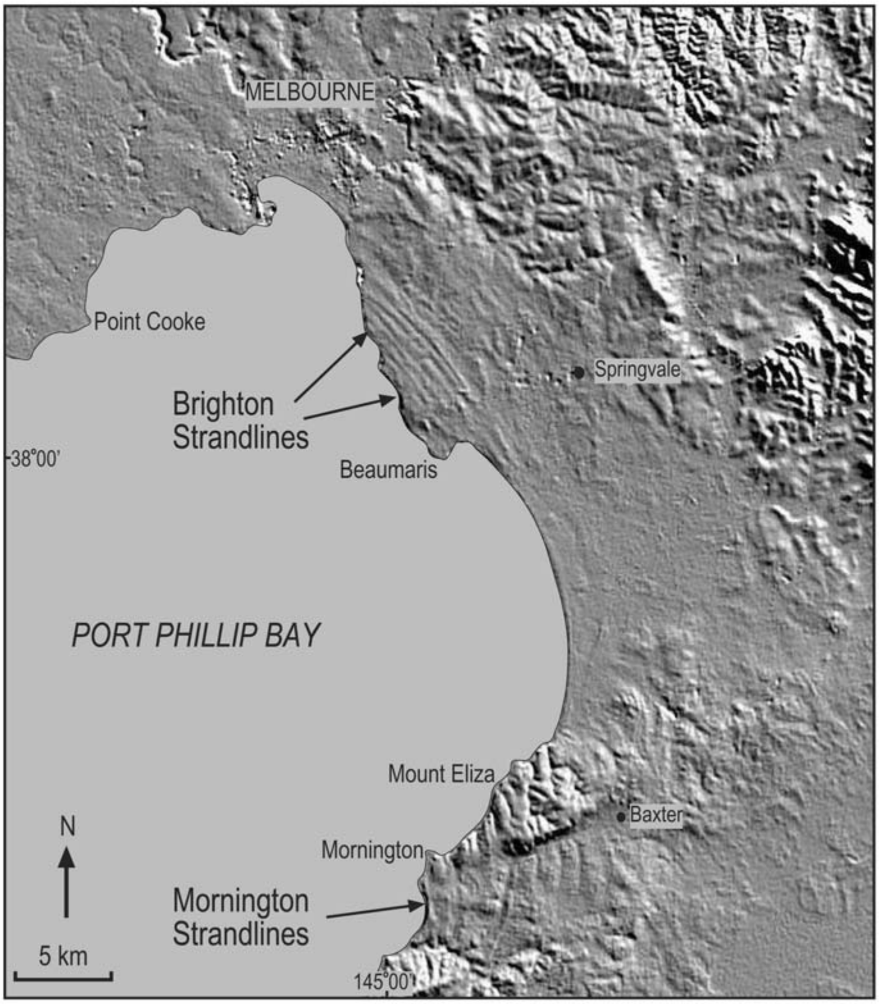

Figure 7 Digital elevation model of the Port Phillip Bay region (from NASA Shuttle radar topography mission). Two regions of strandlines are evident.

no bifurcation of the ridges, as would be expected in linear aeolian dunes.

We therefore suggest that the ridges and swales of the Brighton region are strandlines of the same nature as those described from the Otway Basin. Offshore from Beaumaris, in Port Phillip Bay, linear features with the same orientation as the onshore ridges and swales are visible on magnetic images. Similar arcuate magnetic features with the same orientation are visible further south towards Point Nepean.

Another less-distinctive set of strandlines near Mornington and Baxter is present on elevation models (Figure 7). These strandlines appear to correspond roughly to the position of the Baxter Sandstone, generally regarded as Late Miocene to Early Pliocene (Abele *et al.* 1988).

OTWAY BASIN STRANDPLAIN

The overall strandplain geometry of the Otway Basin has not been previously recognised as it is largely covered by Newer Volcanics. The isolated and poorly exposed nature of individual Pliocene outcrops has unfortunately led to a proliferation of local stratigraphic names (Figure 2). On the Dundas Tablelands, the strandline sands are known as the Dorodong Sand (Kenley 1971, Quinn 1997), whereas at nearby Hamilton, marls and sands underlying the Newer Volcanics are known as the Grange Burn Formation (Gill 1964). Further east in the Colac region, Tickell *et al.* (1992) defined Pliocene sands near Simpson as the Hanson Plain Sand, as distinct from the Pliocene Moorabool Viaduct Formation defined by Bowler (1963) from near Geelong. While not being as well exposed as the Murray Basin strandplain, the Otway Basin succession does have much better age constraints. In the following section, individual areas of the Otway Basin strandplain are described in terms of their age, stratigraphy and strandline characteristics.

Hamilton

The Hamilton area is largely covered by Newer Volcanics, with marine Pliocene sediments exposed where stream dissection has removed the basalts [as at Muddy Creek (Figure 3) and at Minhamite]. Arcuate trends indicative of strandlines are well expressed on magnetic intensity images and are also visible on digital terrain images (Figure 8). The strandline trends face southwest and are well developed between Hamilton and Branxholme (Paine *et al.* 2004). The trends show an onlapping

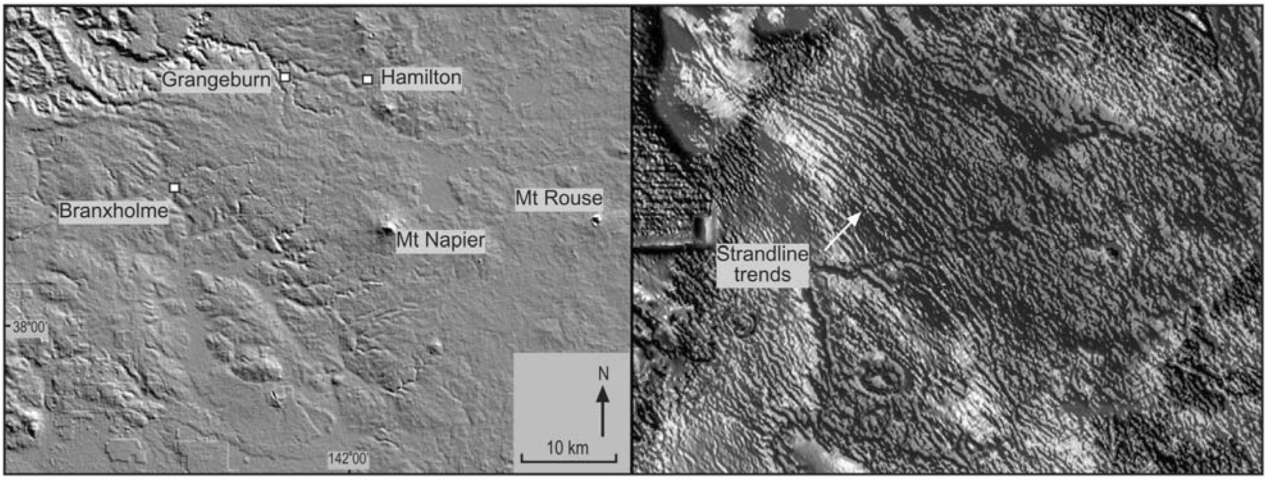

Figure 8 Digital elevation model (from NASA Shuttle radar topography mission) and magnetic intensity image of the Hamilton region. Strandlines trends are most conspicuous on the magnetic image.

geometry of strong curvature towards the Merino Block (with exposed Cretaceous sediments), which indicates the presence of a topographic high in the region during the Pliocene. Arcuate trends are also visible on magnetics images towards the Dunkeld region, immediately south of the Grampians.

The strandplain succession is well exposed on the banks of Muddy Creek and Grange Burn Creek (Figure 3). The Miocene – Pliocene unconformity is exposed in the region and is marked by the development of a phosphatic nodule bed (Dickinson *et al.* 2002). The Grange Burn Formation (Boutakoff & Sprigg 1953) is a molluscan-rich marl which is generally considered as Kalimnan in age (Abele *et al.* 1988). Three strontium isotope analyses taken from molluscs near the base of the unit yield ages ranging from 5.5 to 4.7 Ma (Table 1; Figure 3). The Grange Burn Formation is overlain by a Newer Volcanics basalt with a K – Ar age of 4.35 Ma (Turnbull *et al.* 1965).

In a measured section on Muddy Creek, the Grange Burn Formation consists of molluscan-rich marls that resemble shallow offshore marine facies. The unit also contains a tuffaceous horizon in its lower part and this may represent an early Newer Volcanics phase. Overlying the Grange Burn Formation are calcareous sands (?Dorodong Sands of Kenley 1971) that may represent a shallower shoreface facies.

Paine *et al.* (2004) have suggested that some of the strandline trends around Branxholme overlie the 4 Ma basalts and therefore are younger than the Grange Burn Formation and Dorodong Sands. This suggestion was largely based on the observation that the Dorodong Sands are not present beneath the basalts around Branxholme. However, it is possible that the magnetic strandline trends are related to a sub-basaltic erosional topography that reflects the former presence of pre-basaltic strandlines (discussed below). The Branxholme strandline trends are only visible on topographic and radiometric images (Paine *et al.* 2004) (Figure 8) where the basalt cover is thin or non-existent. This observation is more consistent with a sub-basaltic origin (equivalent to the Dorodong Sand) for the Branxholme strandlines.

Colac – Camperdown – Corangamite

The eastern onshore Otway Basin displays some remarkable strandplain features on digital elevation, magnetic and radiometric data (Figure 9). Around Simpson, west of the Otway Ranges, the arcuate strandline trends are prominent features of the topography. A dissected plateau, known as the Timboon Surface (Gill 1964) or Hanson Plain, is underlain by a thin cover of the Pliocene Hanson Plain Sand (Tickell *et al.*1992). The northwest-trending arcuate ridges and valleys were recognised by Jenkin (1981) as being strandline features. However, Sprigg (1986) suggested the arcuate trends were produced by incipient slumping, and Tickell *et al.* (1992) suggested some of the features were folds.

More recently, Dickinson *et al.* (2001) and Sandiford (2003) have interpreted the features as strandlines. The more pronounced curvature of the ridges as they approach the Otway Ranges indicates the presence of an adjacent topographic high. As suggested by Dickinson *et al.* (2001) this indicates that the Otway Ranges were in existence by the Pliocene.

On the Hanson Plain itself, the arcuate trends are visible on magnetic, radiometric and topographic images. However, where the Hanson Plain has been dissected by tributaries of the Curdies River, the topographic expression of the strandlines is very pronounced and the magnetic response also becomes more prominent. The most pronounced magnetic trends occur in association with intensely ferruginised Hanson Plain Sand. Along the Colac monocline, the magnetic strandline trends are most prominent on the crest of the uplifted block, with the downthrown block showing a much weaker magnetic response.

Further north, around Lake Corangamite, strandline trends are only visible on magnetic images. Further north towards Skipton, prominent arcuate strandline trends are visible in areas with extensive basalt cover. West of Camperdown, magnetic strandline trends are visible in areas with and without basalt cover. In areas with partial basalt cover, pre-basaltic drainage systems

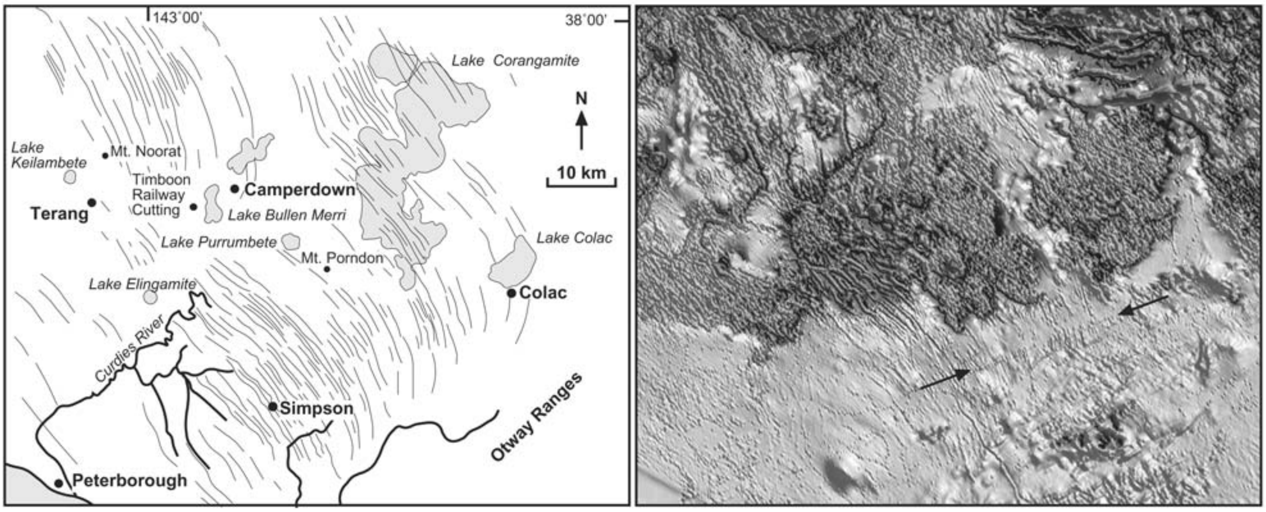

Figure 9 Total magnetic intensity image for the Camperdown – Colac region and the interpreted strandline trends. Areas of basalt cover have a darker and more irregular magnetic signature. Note that the strandline trends are visible in some areas with basalt cover. Black arrows on magnetic image indicate position of small fault.

are largely parallel to the strandline trends and these drainage systems have been filled by basalt flows, accentuating the arcuate trends.

The strandlines trends are spatially associated with the Pliocene Hanson Plain Sand. The type section of this unit near Simpson was defined by Tickell *et al.* (1992), who described the unit as being of non-marine origin. However, the abundant burrows in outcrop and clear strandline geometries displayed by the unit led Dickinson *et al.* (2001) to suggest a marginal marine origin for the unit. At the type section (Figure 3), the unit consists of fine-grained sand with burrows, cross-bedding and fragments of woody material. Rounded phosphatic clasts occur at the basal unconformity (Dickinson *et al.* 2002) and phosphatic concretions are present in the lower portion of the unit, consistent with a marine origin for the sands. The upper portion of the unit is intensely ferruginised.

Dundas Tablelands

Kenley (1971) described white and brown micaceous sands from the Dundas Tablelands and defined them as the Dorodong Sands. He also described rare plant remains in these sands as well as a ferruginised marine fauna that he considered to be Pliocene in age. However, T. Darragh (pers. comm. 2004) has examined the ferruginised molluscan fauna of Kenley (1971) and suggested that it is much older than Pliocene. Kenley (1971) associated low relief ridges and swales with the Dorodong Sands and went on to suggest that the ridges were probably related to strandlines of the Murray Basin. Quinn (1997) identified strandline ridges on the Dundas Tablelands between Harrow and Balmoral using radiometric images (mainly thorium). Quinn was able to correlate these strandlines with the Murray Basin Loxton – Parilla strandlines and estimated an age of between 4.2 and 3.6 Ma, based on the assumed strandline chronology of Kotsonis (1995).

Lake Bolac – Chatsworth

The Lake Bolac to Chatsworth area is one of the few areas in the northern Otway Basin not covered by Newer Volcanics. The area is characterised by a series of arcuate east-northeast-trending ridges and swales, with chains of lakes present in the swales. Ferruginised sands cover the area and these are interpreted to be Pliocene (VandenBerg 1997).

The arcuate ridges and swales are prominent on both digital terrain and magnetics images of the area. We interpret these as strandline trends (as did Jenkin 1981 and Paine *et al.* 2004). The trends are concave to the south and increase in curvature towards the east, suggesting that a topographic high was present, probably developed on a ridge of Grampians Group sediments at Egan Hill.

GIPPSLAND BASIN STRANDPLAIN SEDIMENTS

Holdgate *et al.* (2003) have recently documented an extensive Miocene – Pliocene strandline system from the Gippsland Basin using magnetic data. These magnetic strandlines trend south-southwest and have a different orientation from the modern barriers of Ninety Mile Beach (Figure 10). Holdgate *et al.* (2003) suggested that the magnetic strandlines correspond to the position of the Jemmys Point Formation onshore, with the older strandlines possibly correlating with part of the Tambo River Formation. These units are under a post-Pliocene cover of several tens of metres over most of the onshore basin.

In the Lakes Entrance area, the Jemmys Point and Tambo River Formations have been uplifted and exposed at several localities (Figure 11). The Jemmys Point Formation at its type section near Kalimna consists of basal, shelly offshore marine marls, overlain by a succession of sparsely fossiliferous shoreface sands. At Red Bluff, the unit displays a similar succes-

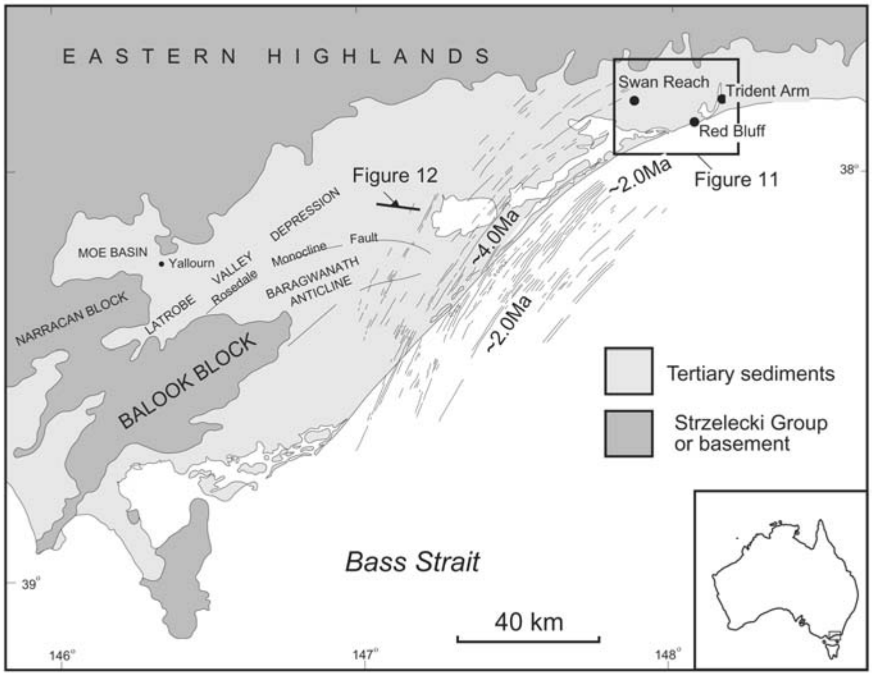

Figure 10 Onshore Gippsland Basin with magnetic strandline trends (modified from Holdgate *et al.* 2003 figure 12).

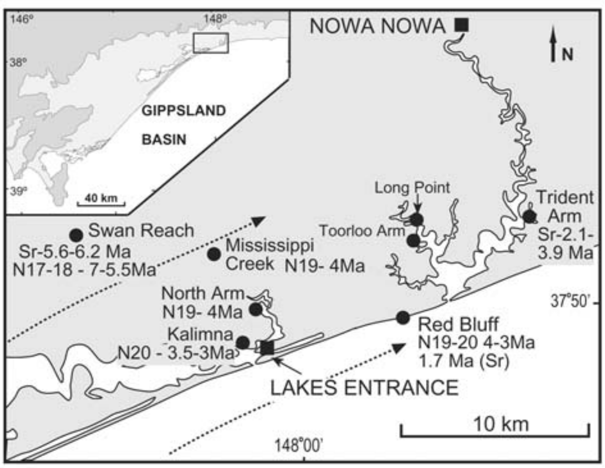

Figure 11 Outcrop localities for the Jemmys Point Formation around Lakes Entrance area in East Gippsland (see Figure 10 for location). Strontium isotopic (Table 1) and palaeontological ages (from Mallett 1977) are shown at each locality. Magnetic strandline trends shown as dashed lines.

sion, and is overlain by non-marine sands and gravels of the Nyerimilang Formation (Figures 3, 4). The base of the unit is not well exposed at any of the coastal sections but is exposed at Trident Arm (Carter 1978b) in Lake Tyers, where a basal phosphatic conglomerate is exposed at water level.

The Jemmys Point Formation forms the type section of the Kalimnan Stage (Hall & Pritchard 1902; Singleton 1941; Wilkins 1963) and is generally considered to be a Lower Pliocene unit. Foraminiferal data suggests the unit ranges in age from 4.5 to 3.1 Ma or younger (Kalimna, Red Bluff, Bunga Creek). Strontium isotope analyses from Trident Arm and Red Bluff are consistent with the palaeontological data and indicate an age of around 3.5 to 2.5 Ma. This suggests that the Jemmys Point Formation is likely to be Late Pliocene around Lakes Entrance, making this unit one of the youngest Pliocene strandline successions exposed in southern Victoria. Holdgate *et al.* (2003) suggested that the youngest visible magnetic barriers offshore (near the Barracouta field) are from the Early Pliocene (nannofossil subzone CN 13a).

The Tambo River Formation underlies the Jemmys Point Formation and consists of glauconitic and phosphatic marls that are poorly exposed. At Swan Reach, foraminiferal data indicate an age of N17–18 (Latest Miocene: Mallet 1977). Strontium isotope analyses suggest an age at this locality ranging from 6.6 to 5.3 Ma, or latest Miocene. These ages overlap with those of the Cheltenhamian Black Rock Sandstone at Beaumaris, perhaps suggesting that some of the older, more landward strandline trends may be a correlative of the Tambo River Formation (Holdgate *et al.* 2003).

A seismic profile (TR88-1) between Sale and Lake Wellington (Holdgate *et al.* 2003) displays very well developed prograding barrier systems which, from bore data, range in age from Early (N8a) to Late (N16–17) Miocene (Figure 12). The youngest barrier visible on the seismic line spatially correlates with the oldest visible strandlines on the onshore magnetic image, again suggesting that the oldest magnetic strandlines are correlatives of the Tambo River Formation (Holdgate *et al.* 2003). It therefore appears that the strandline system visible on magnetic images of the Gippsland Basin is only the youngest part of a virtually contiguous regressive barrier system that may be as old as the Early Miocene.

However, there are unconformities within the strandline system (e.g. Trident Arm phosphate bed: Carter 1978a, b; Dickinson *et al.* 2002). Dickinson *et al.*

(2002) correlated the phosphate bed at the base of the Jemmys Point Formation with a major Late Miocene tectonic event that occurs across southeast Australia. In the Lakes Entrance region, the Jemmys Point Formation dips gently seaward. At Trident Arm, the Jemmys Point Formation is unconformably overlain by the Haunted Hill Formation gravels (Figure 13). This indicates post-Pliocene uplift and erosion of the Jemmys Point Formation.

FERRICRETE DEVELOPMENT ON STRANDPLAIN SEDIMENTS

Ferricretes overlie many of the strandplain sediments of the Murray and Otway Basins. Ferricretes are also ubiquitously observed in association with the arcuate magnetic/topographic strandline trends on exposed Pliocene sediments (e.g. at Branxholme, Lake Bolac, Lake Corangamite, Hanson Plain and Geelong). The ferricretes are therefore important stratigraphic markers that overlie the strandplain sediments and probably play an important role in the development of the strandline trends visible on topographic and magnetic images.

In the Murray Basin, the ferricrete surface overlying the Loxton–Parilla Sands is known as the Karoonda Surface (Firman 1973) and can be up to 15 m thick. These ferricretes are overlain by the Blanchetown Clay and are therefore older than 3.2 Ma (An-Zhisheng *et al.* 1986). On the Dundas Tablelands, ferricretes form the Dundas Surface and are well developed on the Pliocene marine

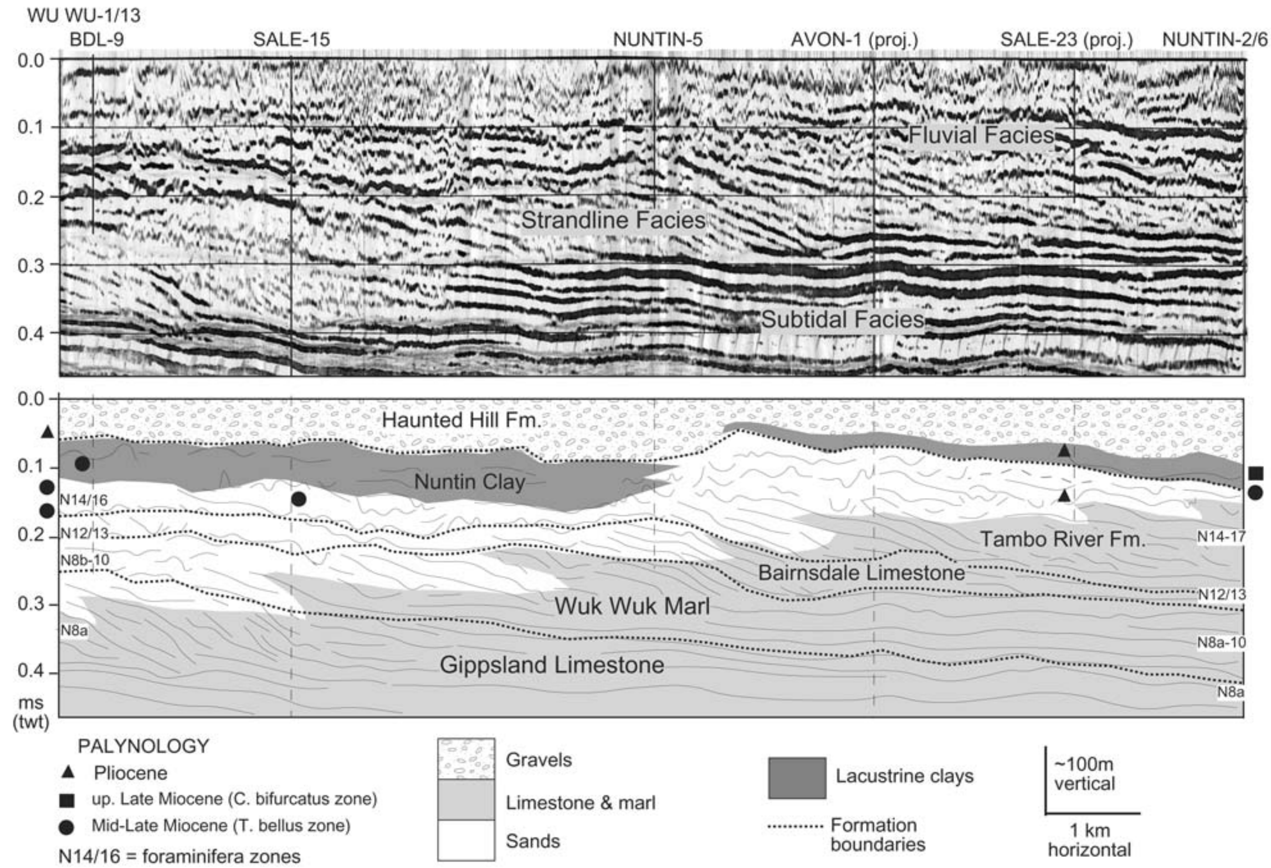

Figure 12 Seismic profile and interpretive section of prograding strandline system in the Gippsland Basin (modified from Holdgate *et al.* 2003 figure 16).

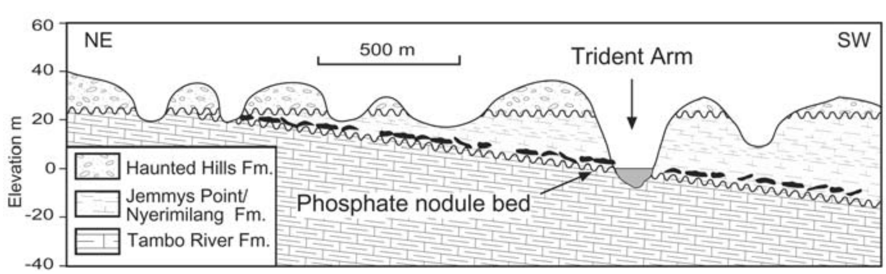

Figure 13 Geological cross-section through the Trident Arm area, on the eastern shore of Lake Tyers. The Jemmys Point and Nyerimilang Formations dip gently seaward and are overlain unconformably by quartz gravels of the Haunted Hills Formation.

sediments (Dorodong Sands) and older units, but are absent from the Quaternary sediments southwest of the Kanawinka Escarpment (Kenley 1971; Quinn 1997). Therefore, ferricretes of the Dundas Surface are younger than the Dorodong Sands (Early Pliocene) but older than the Quaternary.

In the Colac – Camperdown area, Gill (1964) described the Timboon Surface, and defined a type section west of Lake Bullen Merri (Figure 9). The ferricretes of the Timboon Surface cover large areas of the Hanson Plain, on the Hanson Plain Sand. The Timboon Surface must therefore be younger than the Hanson Plain Sand (Early Pliocene?), but older than the Newer Volcanics.

At the type locality of the Timboon Surface (on the old Timboon – Camperdown railway cutting, west of Lake Bullen Merri), the ferricrete is around 4 m thick and occurs beneath the Gnotuk Basalt (Figures 14, 15). A well preserved palaeosol is present immediately beneath the basalt and this contains abundant ferricrete pisoids (buckshot gravel). Beneath this palaeosol is a thick zone of platy ferricrete that consists largely of goethite – hematite-cemented silty clay.

Limonitic intraclasts are common in non-marine units directly overlying the marine strandline successions (e.g. Red Bluff Sand, Beaumaris, Nyerimilang Formation, East Gippsland), but are not common in younger units like the Haunted Hill Formation and various Quaternary gravels. This is again consistent with ferricrete development being a largely Pliocene phenomenon.

As suggested by Kenley (1971), ferricrete development probably did continue into the Late Pliocene. The more pronounced development of ferricretes on Late Miocene and Early Pliocene strandline sediments (as opposed to Late Pliocene sediments) may be partly explained by a more prolonged period of exposure and soil development, rather than more intense ferricrete development in the Early Pliocene.

Gibbons and Gill (1964) noted that the earlier basalts (particularly around Hamilton) of the Newer Volcanics were affected by some ferricrete development, again indicating ferricrete development into the mid-Pliocene.

Ferricrete development on Quaternary sediments in Victoria was noted by Boutakoff (1963) and Lawrence (1966), but these were minor occurrences. It therefore appears that the most intense ferricrete development occurred during the Pliocene, with the Quaternary being dominated by calcareous soil development.

Many authors have suggested that the transition from Pliocene ferricrete formation to Quaternary calcrete development is climate-controlled (Kotsonis 1999). It has been suggested that the Pliocene ferricretes are developed as a result of a warmer and wetter climate than that of the Quaternary.

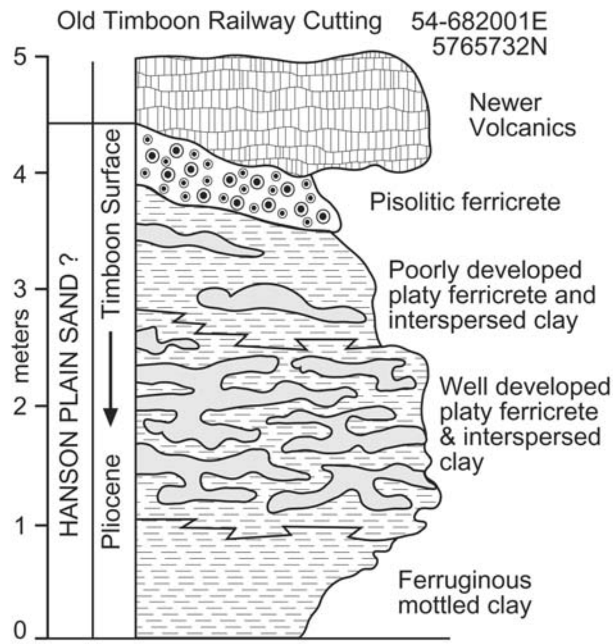

Figure 15 Stratigraphic section of the Timboon ferricrete, at the type section for the Timboon surface (Grid Reference: 54-682001E, 5765732N).

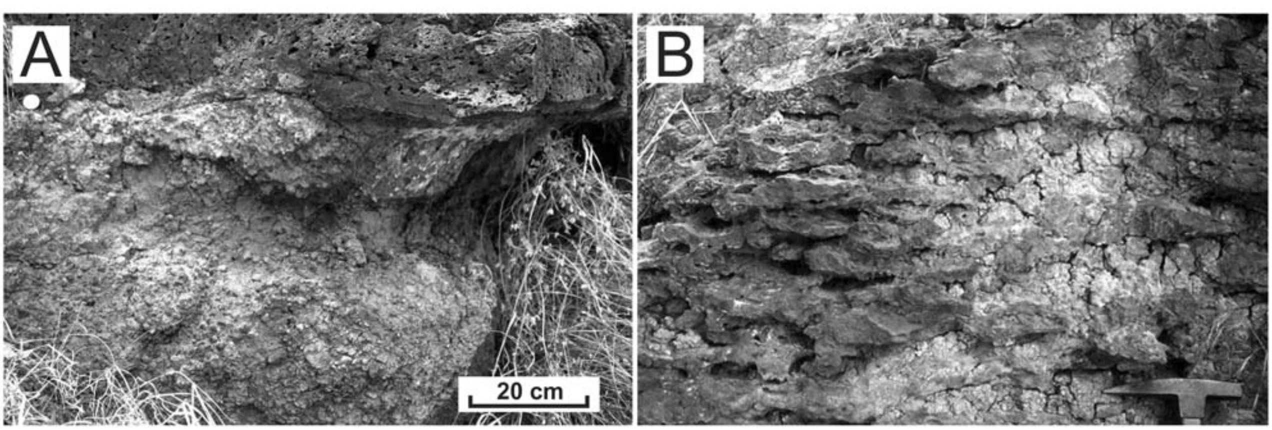

Figure 14 Type section of the Timboon Surface (Gill 1964) in the old Timboon railway cutting (Figure 8), west of Lake Bullen Merri (Grid Reference: 54-682001E, 5765732N). (a) Palaeosol with ferricrete pisoids (or buckshot gravel) overlain by Newer Volcanics basalt. (b) Well-developed platy ferricrete. Hammer head for scale.

ORIGIN OF GEOPHYSICAL AND TOPOGRAPHIC STRANDLINE TRENDS

The vast strandplain that extends across the southern Victorian basins was not recognised earlier because high-resolution geophysical data were not available to earlier researchers. The strandline trends are made visible by a combination of digital elevation, radiometric and magnetic data. The arcuate trends are generally most prominent on the magnetic imagery and the origin of this magnetic signature is therefore important.

There are several possible causes for the distinctive magnetic signature of the strandlines: (i) detrital magnetic minerals like magnetite and titanomagnetite are concentrated in zones along the strandlines; (ii) ferricrete is preferentially formed along particular lithologies or facies within the strandline system; and (iii) underlying structures like faults or folds have produced the magnetic lineaments and have controlled the distribution of the strandlines themselves.

The hypothesis that the strandlines are structural features of the underlying sediments has been suggested by some previous researchers (Hills 1939; Kenley 1967; Sprigg 1986; Tickell *et al.* 1992). However, the restriction to areas of Pliocene nearshore marine cover, the arcuate, closely spaced and repetitive nature of the lineaments and their relationship to topographic highs rules out a structural origin for the magnetic lineaments. In addition, the spatially well-defined character of the magnetic anomalies suggests they are shallow features at depths of around 10 – 30 m below the surface (FitzGerald & Brett 1999).

It appears possible that the magnetic signature for the strandlines is in some cases produced by heavy-mineral concentrations in the strandline succession. It is well established that strandline successions can contain economically significant concentrations of heavy minerals, as do the Loxton – Parilla Sands of the Murray Basin (Roy *et al.* 2000; Roy & Whitehouse 2003). However, the strandlines of the Otway Basin have much stronger magnetic signatures than those of the Murray Basin.

In the Otway Basin, the magnetic signature of the strandlines is generally more complex than in the Murray Basin strandlines. In many areas, few or no linear magnetic features are visible, while in other areas, very intense magnetic trends are visible. Furthermore, the intensity and character of magnetic trends is markedly affected by young structural features and local relief. For example, on the Hanson Plain, the Colac monocline has a major effect on the magnetic strandlines, with the crest of the monocline having the strongest magnetic trends. On the adjacent downthrown block, the magnetic trends are much weaker (Figure 9).

This structural control indicates that a post-depositional process is affecting the magnetic strandline trends. We suggest that the major post-depositional process affecting the magnetic and topographic properties of the strandlines is ferricrete formation. Furthermore, there is a clear spatial correlation between a strong magnetic strandline response and the presence of ferricrete in the Pliocene sediments. In the field, ferricrete can be up to 6 m thick (Figures 14, 15), and XRD analysis indicates that hematite, goethite and maghemite are present (Revie 2001).

Given the thickness and mineralogical composition of the ferricretes (particularly the maghemite content), we believe that the ferricretes are capable of producing the magnetic strandline trends in most areas. It appears likely that ferricrete formation has preferentially occurred on some lithologies and facies within the strandplain system and this has produced the strong magnetic trends in some areas. The evidence for a structural control on the magnetic trends may be explained if the ferricrete formed preferentially on units with higher relief (e.g. on the crest of monoclines and on dissected ridgelines) that might have better drainage.

We further suggest that the ferricretes play a critical role in the topographic expression of the strandlines where dissection and erosion have taken place. The iron oxide-cemented strandlines are much more resistant to erosion than non-cemented lithologies. Erosional dissection of a ferricreted strandplain would then lead to a series of erosional valleys along uncemented strandlines and ridges along ferricreted zones. Excellent examples of this style of topography are present around Simpson, west of the Otway Ranges (Dickinson *et al.* 2001).

Further south from Simpson, the topography strongly reflects the orientation of the Hanson Plain strandlines, but there appears to be little Hanson Plain Sand remaining on the ridges. This suggests that the original strandline geometry of a region can be preserved by inherited drainage, even after all of the Pliocene strandlines and ferricrete have been removed by erosion.

Magnetic strandline trends are also visible in many areas with extensive basalt cover (e.g. south of Skipton, Camperdown and Branxholme). In some cases, the strandline trends in basalt are a result of basalt flows that occupy strandline-parallel valleys eroded into the strandplain (e.g. around Camperdown). In other areas of continuous basalt cover, it is possible that the strandline trends are made visible by thickness variations in the basalt that reflect the pre-basalt dissected strandplain geometry. Therefore, it is possible that in some regions covered by basalt, there is no preserved Pliocene (the strandlines having been removed by pre-basalt erosion) and the strandline geometries are preserved because of the inherited drainage system beneath the basalt. Figure 16 illustrates an interpretation of the processes by which geophysical strandline geometries may be produced.

SEDIMENTOLOGY AND STRATIGRAPHIC ARCHITECTURE OF STRANDLINE SUCCESSIONS

The seismic line TR88-1 from Gippsland (Figure 12) provides an excellent subsurface analogue for the stratigraphic architecture of the Pliocene strandline successions (although most of the barrier sequence on the seismic profile is older than the magnetic strandline system). From bore data, the inclined prograding seismic facies of the barrier system consists of a lower carbonate facies and an upper calcareous sand facies, which probably equate to an offshore marine carbonate

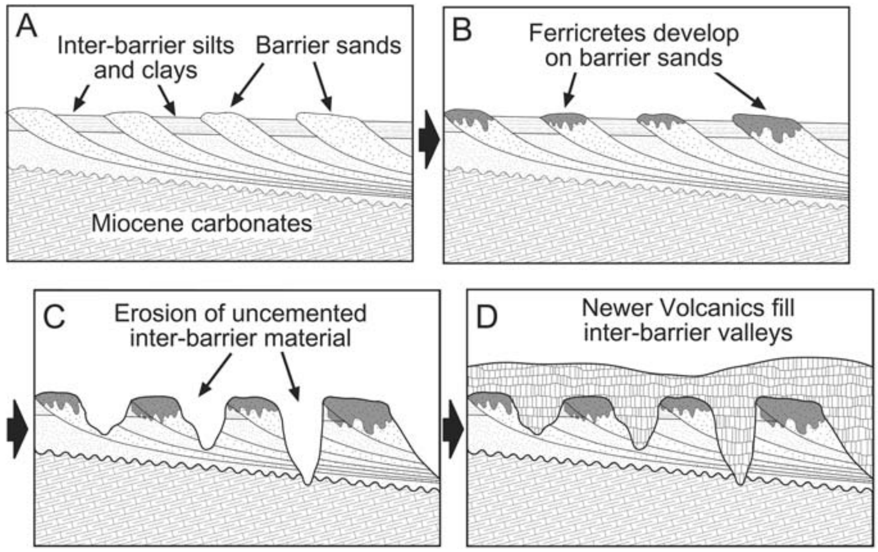

Figure 16 Diagrams of the interpreted processes that produce the strandline geometries observed on topographic, magnetic and radiometric maps showing the preferential development of ferricrete on the sands. However, it is possible that the ferricrete may develop preferentially on the fine-grained interbarrier sediments.

facies and a sandy shoreface facies respectively. Above the inclined prograding seismic facies, there is a seismic facies characterised by very irregular, but horizontal reflectors with abundant small channelised erosion structures. We interpret this seismic facies as the non-marine fluvial succession that commonly occurs above the strandline succession (represented by the Nyerimilang Formation and equivalent units).

This marine strandline to non-marine fluvial transition is characteristic of the Pliocene successions in the Gippsland Basin (Jemmys Point to Nyerimilang Formations), Port Phillip Basin (Black Rock Sandstone to Red Bluff Sand) and the Otway Basin (Moorabool Viaduct Formation with lower marine and upper non-marine facies). In some regions, the overlying non-marine facies is absent and the upper surface of the strandplain is preserved as a palaeosurface. The Hanson Plain is the best example of this situation, where the strandlines have very low relief (a few metres) and are intensely ferricreted.

Figure 17 illustrates a depositional and stratigraphic model for the strandlines of southern Victoria. In the most seaward position, the offshore marine environment is interpreted to produce marine marls. Examples of this lithofacies include the Bookpurnong beds, the Grange Burn Formation and the lower part of the Jemmys Point Formation. In a more shoreward position, the lower and upper shoreface consists of well-sorted sands, the lower shoreface being calcareous (with shelly fossils). These two lithofacies make up the bulk of the strandline sands and are represented by such units as the Loxton–Parilla Sands, the Hanson Plain Sand, and the Black Rock Sandstone. As illustrated in Figure 16, the entire strandplain succession overlies gently folded Miocene carbonates with angular discordance.

LATE NEOGENE – QUATERNARY TECTONICS, EUSTASY AND PALAEOCLIMATE

The present elevation of Pliocene strandlines can be used as a measure of total post-strandline Pliocene–Quaternary uplift (Figure 18). In western Victoria, the strandlines reach an elevation of greater than 240 m along the southern margin of the Western Highlands, indicating an axis of Pliocene–Quaternary uplift in this position. This uplift axis also continues into the Mt Gambier coastal plain, as indicated by broad doming in the vicinity of Mt Gambier (Gambier Axis or upwarp: Hossfeld 1950; Sprigg 1952; Kenley 1971). The Quaternary strandline geometries indicate a headland around this region (named the Mt Burr Peninsula: Sprigg 1952). Another region of broad uplift is present north of the Dundas Tableland and extends from Harrow to Kaniva and becomes the Padthaway High in South Australia.

Strontium isotope ages from well-preserved molluscan assemblages of the strandplain successions (Table 1) indicate the earliest sediments were deposited above the Late Miocene unconformity at around 5.8 ± 0.2 Ma (latest Miocene, Beaumaris). The youngest exposed strandplain sediments (from the most shoreward parts of the Jemmys Point Formation, Gippsland) were deposited during Late Pliocene–Quaternary time (*ca* 2.0 Ma), and younger strandlines occur offshore. Sites from the Otway Basin give ages between 5 and 3 Ma. Similar ages have been suggested for the Loxton–Parilla strandlines of the Murray Basin, Kotsonis (1999) assuming ages ranging from 6 to 3.5 Ma.

The internal geometry of the Pliocene strandlines across Victoria gives a measure of how much tectonism has occurred during strandline formation. The parallelism and conformable nature of most Pliocene strandlines is suggestive of little tectonism in the period of strandline formation from 6 to 3 Ma. The continuously regressive and conformable nature of the strandlines in each of the basins suggests that during the period 6 to 3 Ma, the basins were subject to either stable or falling relative sea-levels and this is in accord with the deep-sea oxygen isotopic record of Shackleton *et al.* (1995). The marine isotopic record indicates relatively warm and stable conditions throughout the Early and mid-Pliocene.

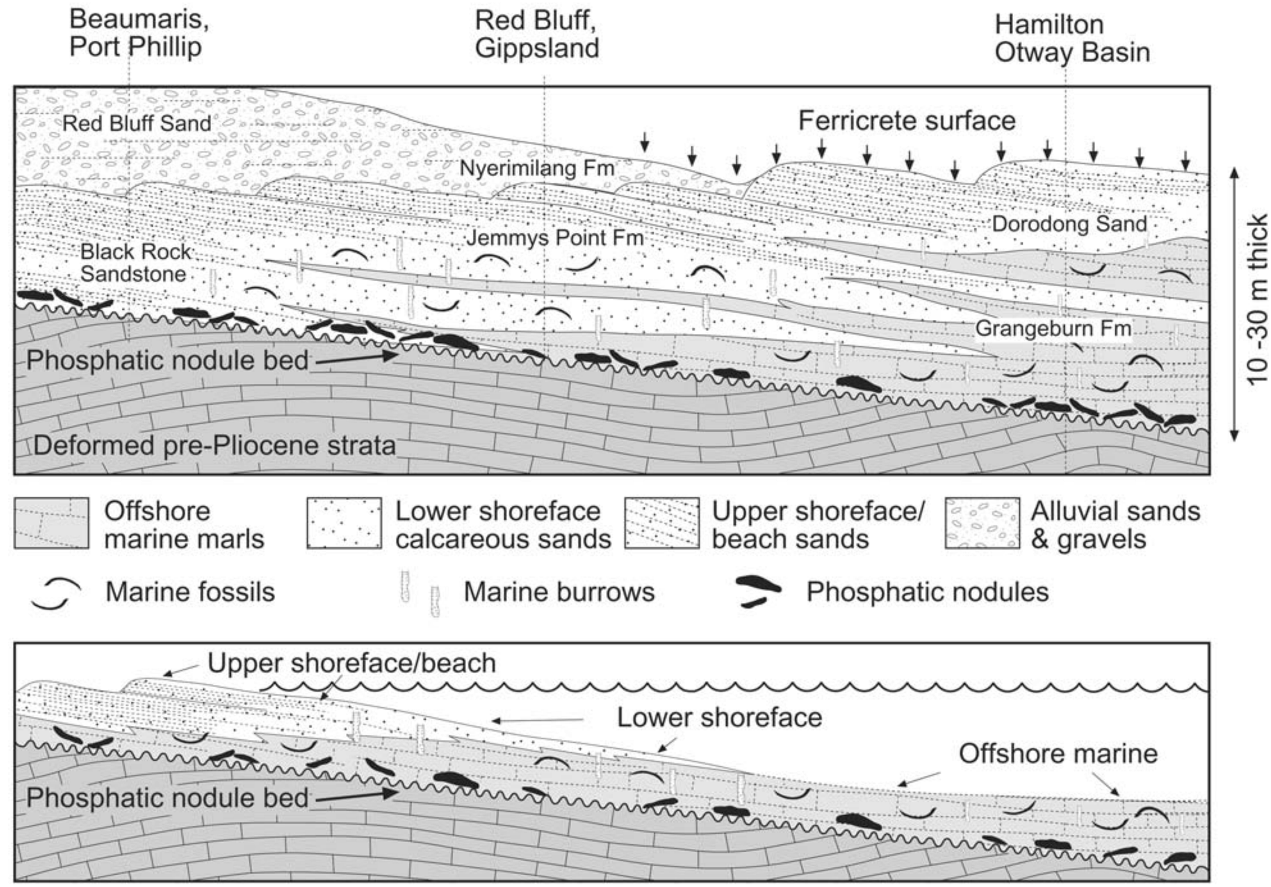

Figure 17 Sedimentologic and stratigraphic models for the strandlines of southern Victoria. Locality columns on the stratigraphic diagram illustrate the strandline stratigraphies and their interpreted facies at each location.

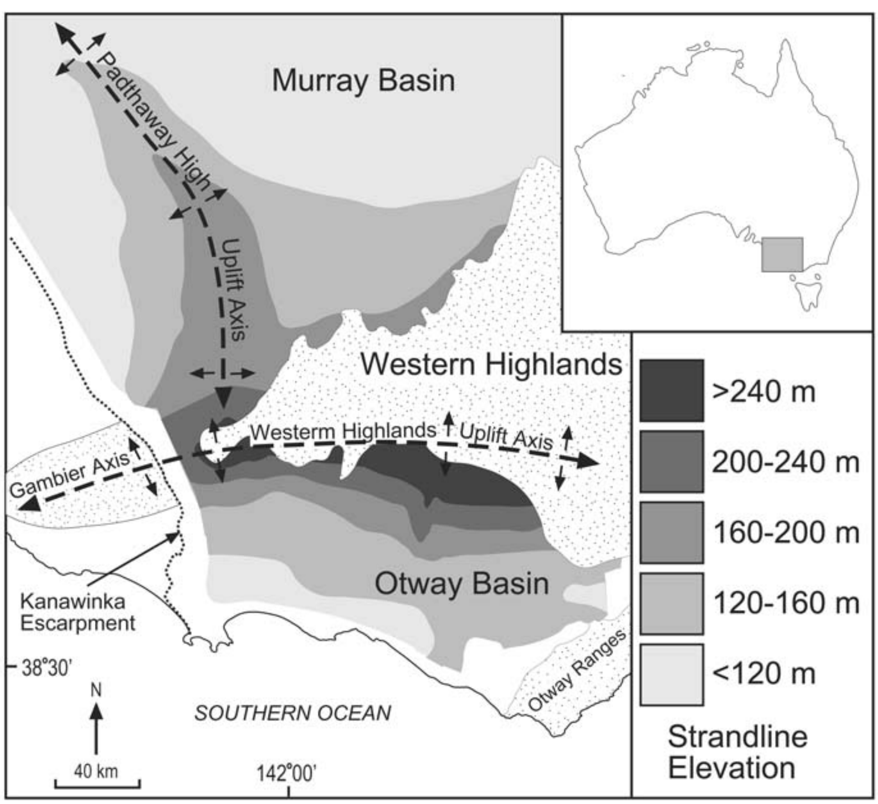

Figure 18 Present elevation of Pliocene strandlines of south-western Victoria, indicating the amount of Pliocene–Quaternary uplift. Two Pliocene or younger uplift axes are evident.

In each of the Victorian basins, there is discordance between the Pliocene strandlines and Quaternary–Holocene strandlines. In the Gippsland Basin, Quaternary strandlines overlie, and have a different orientation from Pliocene strandlines of the Pliocene Jemmys Point Formation (Holdgate *et al.* 2003). Furthermore, the contact between the Jemmys Point Formation and the overlying Haunted Hills Formation gravels at Lake Tyers (Figure 13) is an angular unconformity, indicating that some uplift and deformation has occurred post-3 Ma.

In the Otway and Port Phillip Basins, the Pliocene strandlines are not concordant with the Quaternary Bridgewater Formation strandlines. The Otway and Port Phillip strandlines have a dominantly northwest–southeast orientation, in contrast to the west-northwest–east-southeast orientation of the modern coastline. Much of the Otway coastline is erosional, with the Pliocene strandline successions (like the Hanson Plain Sand) being uplifted by several tens of metres at the coast. The Kanawinka Escarpment in western Victoria and southeastern South Australia separates the uplifted Pliocene strandlines of the Murray and Otway Basins from the Quaternary strandlines of the Mt Gambier coastal plain. The Kanawinka Escarpment has generally been interpreted as representing a connected series of faults (Fenner 1930; Kenley 1971), although some authors have suggested that the escarpment is a palaeoshoreline feature (Hossfeld 1950).

Several features of the Pliocene–Quaternary strandlines around the Kanawinka Escarpment support Hossfeld's (1950) hypothesis of a palaeoshoreline origin. Firstly, strandline geometries immediately northeast of the Kanawinka Escarpment in the Murray Basin indicate periods of erosion. These erosional shoreline features resemble the form of the Kanawinka Escarpment and are approximately parallel to it. Secondly, the Kanawinka Escarpment becomes an erosional shoreline feature (Figure 1) towards the northwest in South Australia. In contrast, Fryberger *et al.* (2001) extended the Kanawinka Fault across the entire Murray Basin to Tailem Bend, South Australia. Regardless of the faulted or palaeoshoreline origin of the Kanawinka Escarpment, there is clear evidence of an unconformable relationship between the Pliocene and Quaternary strandlines.

There are several possible reasons for this unconformable relationship between Pliocene and Quaternary strandlines. For much of the Early to mid-Pliocene, the marine oxygen isotopic record displays stable and warm conditions with high eustatic sea-levels. However, major changes in the climatic and eustatic record occur at *ca* 3–2 Ma (Figure 19). At around 2.5 Ma, the isotopic record first displays enhanced variability, suggesting greater climatic instability and the development of strong glacial–interglacial cycles. Furthermore, from *ca* 3 Ma, the average oxygen isotopic composition rises dramatically, suggesting much lower eustatic sea-levels and greater ice volumes. It is therefore possible that the change from a warm Early to mid-Pliocene climate with high eustatic sea-levels, to a cooler, drier Late Pliocene to Quaternary climate with low sea-levels and a greater amplitude of eustatic variation could produce the unconformable relationship between Pliocene and Quaternary strandlines in Victoria.

On the other hand, there is clear evidence of post-Pliocene strandline tectonism in all of the basins and this may suggest that Late Pliocene–Quaternary tectonism had a role in the discordance between Pliocene and Quaternary strandlines. In the Gippsland Basin, continued subsidence through the Late Pliocene may have allowed the continued progradation of strandlines into the Late Pliocene. The angular discordance between the Quaternary–Holocene strandlines and the Jemmys Point strandlines, together with the observed post-Jemmys Point angular unconformity at Lake Tyers provides evidence of renewed Quaternary tectonism and uplift. Similarly, the Pliocene strandlines of the Otway Basin show considerable uplift, indicating Late Pliocene or Quaternary tectonism.

The conformable nature of most Early to mid-Pliocene strandlines, and disconformable/uplifted nature of the Quaternary strandlines suggests a period of renewed tectonism occurred some time after 3 Ma (Figure 19). However, it is probable that climatic and

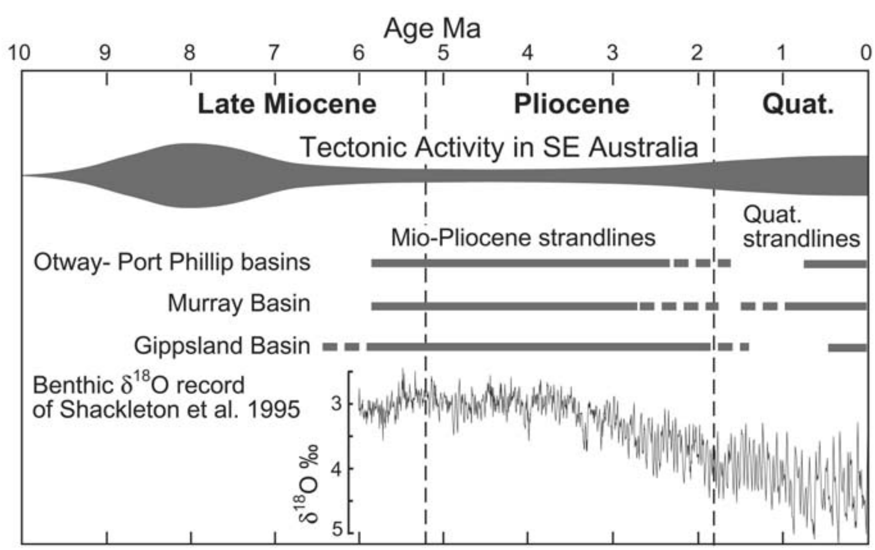

Figure 19 Diagram illustrating the estimated timing of the southern Victorian strandlines, together with the interpreted intensity of tectonism in southeastern Australia. The lower curve is the marine oxygen isotopic record of Shackleton *et al.* (1995). Timing of Murray Basin Pliocene strandlines is from the assumed ages of Kotsonis (1999).

particularly eustatic factors have also played a role in the Quaternary strandline discordance. The combined effect of renewed tectonic uplift and lower eustatic sea-levels in the Quaternary may be responsible for the mostly erosional nature of Victorian shorelines.

CONCLUSIONS

Late Miocene to Pliocene strandlines cover much of the onshore regions of the southern Victorian basins (Otway, Port Phillip and Gippsland Basins). Strontium isotope ages indicate the strandlines range from 5.8 to 2.5 Ma and may be even younger in the offshore Gippsland Basin. The combined areal extent of the Murray, Otway, Port Phillip and Gippsland Basin strandlines makes this one of the largest strandplains known.

The strandline geometries in the southern basins are most prominent on magnetic intensity images, but in some places are visible in radiometric and topographic images. The magnetic character of the strandlines appears to be a product of intense and preferential ferricrete development within the strandline succession (rather than a concentration of heavy minerals). The ferricrete surfaces (previously known as the Karoonda, Dundas or Timboon Surfaces) probably formed during the Early and mid-Pliocene, when warmer and wetter conditions prevailed.

The Otway Basin strandlines are largely covered by Pliocene – Quaternary Newer Volcanics basalts, while the Gippsland strandlines are covered by younger marine and non-marine sediments. Where the ferricreted strandline successions are exposed and dissected by erosion, the strandline geometry is accentuated because of the more resistant nature of iron oxide-cemented facies. This can lead to the strandline geometry being preserved by inherited drainage, even when the strandline succession has been completely removed by erosion. This erosional process may explain the magnetic visibility of strandline geometries beneath the Newer Volcanics basalts.

Since the strandlines were originally deposited at sea-level, the present elevation of the strandlines gives an estimate of post-depositional uplift. In western Victoria, there is an axis of strong uplift (up to 240 m) along the northern margin of the Otway Basin, and roughly parallel to the axis of the Western Highland. Another uplift axis is present along the Padthaway High, in the Murray Basin.

The unconformable nature of the Quaternary strandlines/coastal systems with those of the Pliocene in all of the basins may suggest a period of renewed Quaternary tectonism in southeastern Australia. The generally lowered and more variable eustatic sea-levels of the latest Pliocene and Quaternary may have also contributed to this Pliocene/Quaternary unconformity. The generally conformable and progradational nature of the Pliocene strandline successions in southeastern Australia may reflect the relatively stable sea-levels of the Early and mid-Pliocene.

Recognition of the extent of the southern Victorian strandlines that are equivalent in age to the Murray Basin strandlines may provide further targets for heavy-mineral exploration in previously unexplored regions.

ACKNOWLEDGEMENTS

The recognition of the southern Victorian strandlines would not have been possible without the world-class geophysical datasets produced by the VIMP Initiative and we would like to thank Geoscience Victoria for allowing open access to this invaluable resource. We would like to thank the reviewers Steve Hill and Tom Darragh whose reviews and comments greatly improved the manuscript. Thanks also to NASA for making their shuttle radar topography mission data available for use.

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Received 25 March 2004; accepted 10 February 2005

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Australian Journal of Earth Sciences
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