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DEPOSITIONAL FACIES AND EXTENT OF THE LATE NEOGENE SANDRINGHAM SANDSTONE IN SOUTHERN VICTORIA, AUSTRALIA

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ABSTRACT: The late Neogene sedimentary rocks in the Port Phillip region have in the past been subdivided into a lower shallow marine unit, Black Rock Sandstone, overlain by a fluvial unit, Red Bluff Sandstone. Re-examination of the type section of these units at Sandringham shows that it is entirely of paralic origin, with no evidence for fluvial deposition. Criteria for interpreting a shallow marine origin are sedimentary structures including a planar bedding style and swaley cross-stratification, and highly rounded clasts in conglomerates. Using these criteria it can be demonstrated that all named late Neogene sedimentary rock units in the Port Phillip region are paralic deposits, and that the same applies to the Hanson Plain Sand of the Port Campbell Embayment. Because these were deposited as a continuous sheet, the multiplicity of names used hitherto is not justified and should be unified under the single name Sandringham Sandstone. This formation was deposited on a strandplain that extends across western Victoria to the southern fringe of the Western Uplands. The same lateral continuity applies to the underlying Miocene marl formation, which is unified under the name Gellibrand Marl.

Keywords: Miocene–Pliocene strandplain, Sandringham Sandstone, sedimentology, stratigraphic nomenclature

Exposures of late Neogene sandstone in the Port Phillip region are widely scattered and of very variable quality. As a consequence, they have been studied outcrop by outcrop, often with little regard to adjacent outcrops. Their study was focused on their fossil content (or lack thereof) and their lithology, and a tradition grew of giving each outcrop its own rock unit name. Hitherto, not a single study has focused on their sedimentary structures. This paper focuses on the sedimentary structures of the rocks and gives a new interpretation of the depositional setting, and a revision of the stratigraphic nomenclature that is required by the re-interpretation. Figures 1 and 2 show the principal areas and sites of study.

PREVIOUS WORK

Selwyn (1861) noted that the surficial sandstone outcrops around Melbourne were called 'Flemington and Lower Brighton Beds' on the legend of the earliest 'Quarter Sheet' geological maps and were dated as Miocene. Gill (1950) proposed the name Sandringham Sands (formation) for these 'ferruginous sands and gravels'. He designated Red Bluff at Sandringham as the type locality (1 on Figure 2B) and subsequently subdivided the formation into the Black Rock Member overlain by the Red Bluff Member (Gill 1956). The Black Rock Member is undoubtedly marine, as it contains abundant marine fossils at Beaumaris (3 on Figure 2B), but Gill interpreted the upper Red Bluff Member to be fluvial.

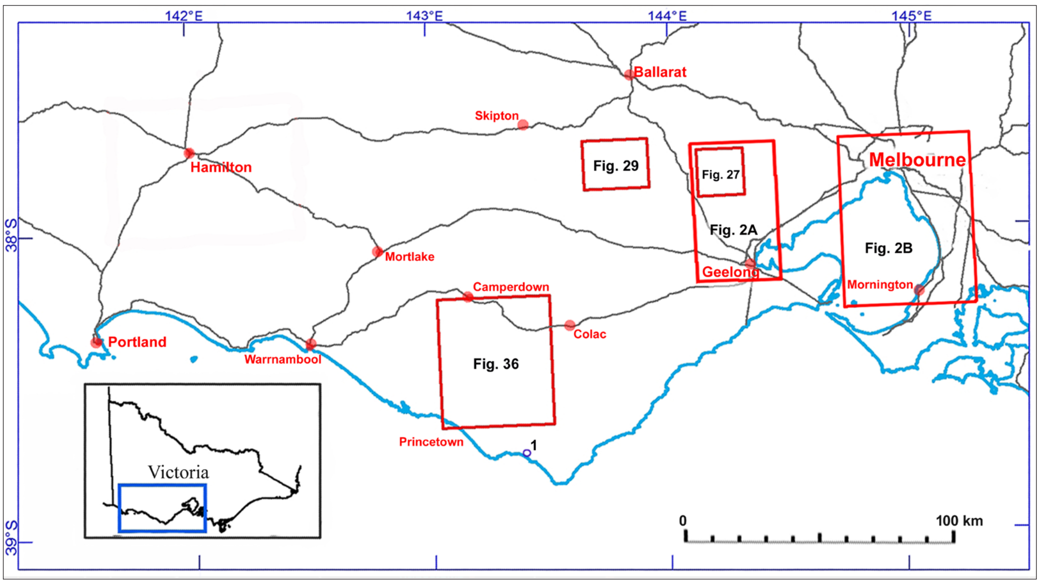


Figure 1: Map of south-western Victoria showing locations of more detailed maps.

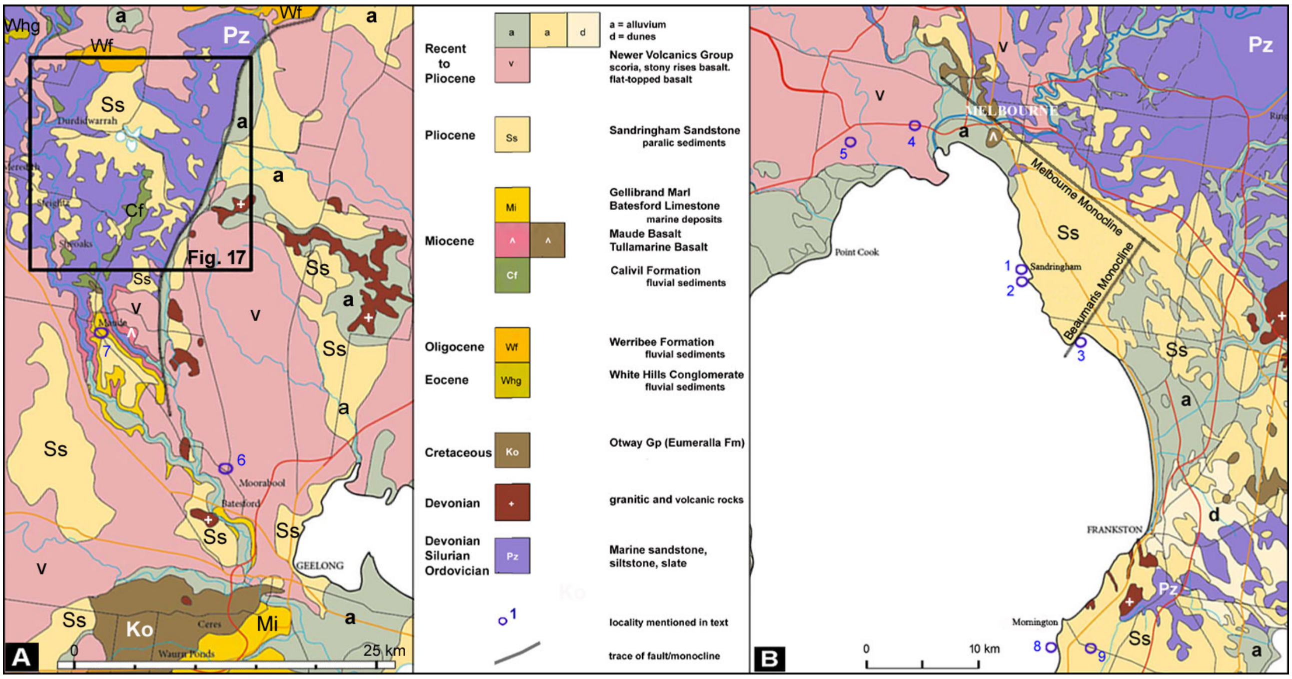


Figure 2: Geological map of the Port Phillip region showing location of Figure 19 and of localities mentioned in text. A = western outcrops, B = eastern outcrops. 1 = Red Bluff, Sandringham; 2 = Black Rock; 3 = Beaumaris; 4 = Newport; 5 = Altona; 6 = Moorabool Viaduct, type locality of the Moorabool Viaduct Sands; 7 = Maude; 8 = Marina Cove–Harmon Rocks; 9 = type locality of Baxter Sandstone.

Keble (1950) proposed a fluvial origin for the Pliocene sandstone on Mornington Peninsula, calling it Baxter Sandstone. He based his interpretation solely on the occurrence of two thin beds of 'grit with pebbles' in the type section, a road cutting near Mornington.

Kenley (1967) pointed out that Gill's concept of the Sandringham Sands was identical to that of the Brighton Beds of the Quarter Sheet maps and proposed that the name Brighton Group be used in place of the Sandringham Sands, with Black Rock Sandstone and Red Bluff Sands as the two constituent formations. Kenley's terminology has been used on Geological Survey of Victoria maps (e.g. VandenBerg 1970, 1974, 1997) and in other publications dealing with the Cainozoic sequence of the Port Phillip Basin (Dickinson et al. 2002; Holdgate et al. 2002, 2003; Wallace et al. 2005).

Wallace et al. (2005) used digital elevation data to reinterpret the arcuate ridges present in the Brighton region as strandlines. However, they still regarded the uppermost rock unit in this area, the Red Bluff Sandstone, as fluvial.

Ter & Buckeridge (2012) noted that the name Black Rock Sandstone was a junior homonym, having been first used in New South Wales for a Devonian sandstone, although they were erroneous about the details of the name's origin, which was not Voisey (1958) (which would have given Gill's name priority), but Stevens and Packham (1953). However, instead of considering other available, previously published names, they introduced the new name Beaumaris Sandstone to replace Gill's Black Rock Sandstone.

In the 1960s, the Pliocene sandstone of the Port Phillip region was described in two other papers. In the Geelong–Maude area, Bowler (1963) named it Moorabool Viaduct Sands, a widespread formation of marine sandstone with local calcareous sandstone (Figure 2A).

In his study of the Mornington Peninsula Cainozoic succession, Gostin (1966) described a Pliocene marine sandstone unit, which he named the Marina Cove Sand after a bay in Mornington. He noted the presence of marine bivalves and echinoids in the sandstone and this, in addition to the very good sorting of the sand, indicated shallow marine deposition. He observed that 'gentle cross-bedding may be present but is difficult to distinguish from limonite stains', the first time this type of cross-bedding was referred to in the Victorian literature. Gostin also thought that the Marina Cove Sand was overlain by the Baxter Sandstone of Keble (1950) which, like Keble, he interpreted to be a fluvial deposit. However, he considered Keble's 'type' locality (9 on Figure 2B) unsatisfactory because its limits here are undefined. Gostin gave as 'typical exposure' a section north of Fossil Beach and defined the base of the formation as the first entry of abundant coarse sand [above the Marina Cove Sandstone].

Bock and Glenie (1965) included the regressive Pliocene deposits of the Port Campbell Embayment in the Moorarbool [sic] Viaduct Formation but Tickell et al. (1992) gave them the new name Hanson Plain Sand, for the sole reason that it is 'largely fluviatile in origin', in contrast to the marine Moorabool Viaduct Sands.

THE TYPE SECTION OF THE SANDRINGHAM SANDSTONE

Gill's choice of Red Bluff as the type section of the Sandringham Sandstone has turned out to be appropriate as it is the best outcrop in the Port Phillip region, and one from which a great deal of information can be gleaned. Gill's (1956) sketch of the north face of Red Bluff, showing his subdivision, is here shown in Figure 3. Figure 4 shows the west face, essentially a mirror image of Figure 3. This west face is much more accessible, particularly the 'clayey gravel' interval shown on Figure 3. However, the swaley bedding is better seen on the north face where the cliff is less dissected.

The main reason given by Gill (1956) that the contact between the 'Black Rock' and 'Red Bluff' members is disconformable is the variation in bedding dip below the contact, and the 'practically horizontal' dip of the beds above them. Gill interpreted the upper Red Bluff Member to be fluvial, partly because of the presence of sand, gravel and conglomerate, and partly because of the presence of fossil leaves in clay balls in these sediments. At its base is a 'carbonaceous band' containing plant fossils, which Gill thought lay disconformably on the underlying marine sandstone (Figure 3) and, in the middle of the western cliff face, dipped into base of the cliff.

Because of its colour, the 'carbonaceous band' is most prominent on the small promontory that juts out from the main cliff (5 on Fig. 4; Figures 5 and 6). From there it can be traced into the main cliff but instead of dipping into the base of the cliff, it remains roughly horizontal. Its nature changes gradually, from sandy silt to fine sandstone, and it also thickens gradually. Ultimately, at about 40 m from the promontory, it has the same grain size as beds below and above, and its colour changes to the same orange–yellow of these beds — it becomes unrecognisable (Figure 6). Thus in the main cliff there is no perceptible change in lithology between the 'Black Rock' and 'Red Bluff' members. The thin conglomerate that overlies the 'carbonaceous band' on

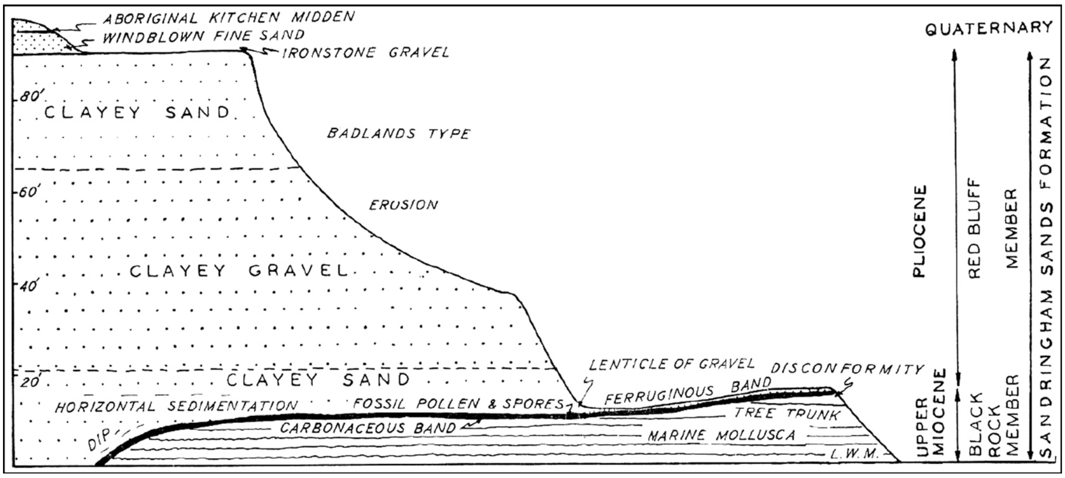


Figure 3: Sketch of the north face of Red Bluff, type section of the Sandringham Sandstone (from Gill 1956). The lithological descriptions are incorrect — the entire cliff consists of sandstone and conglomerate, with clay a very minor component. The 'clayey gravel' consists of interbedded sandstone, sandy conglomerate and pebbly sandstone. The 'ironstone gravel' is a ferricrete horizon — the Karoonda Surface — resulting from prolonged subaerial weathering. The windblown fine sand overlying it is a well-sorted quartz sand not derived from any of the material exposed in the bluff.

Figure 4: Photo of west side of Red Bluff, with mirror image of Gill's profile. Numbers indicate locations of Figures 5, 9 and 12.

Figure 5: View of north face of Red Bluff seen from the north-western tip of the small 'peninsula'(5) on Figure 4. Blue triangles point down to the top of Gill's 'carbonaceous band'; red arrows point to thin conglomerate about 30 cm above it. S marks positions of swaley lamination and the black rectangle outlines the area of Figure 9. Note that the predominant layering in the bluff is horizontal and reasonably continuous. Note also the planar nature and 'thin-ness' of the conglomerate, shown in closer view in B.

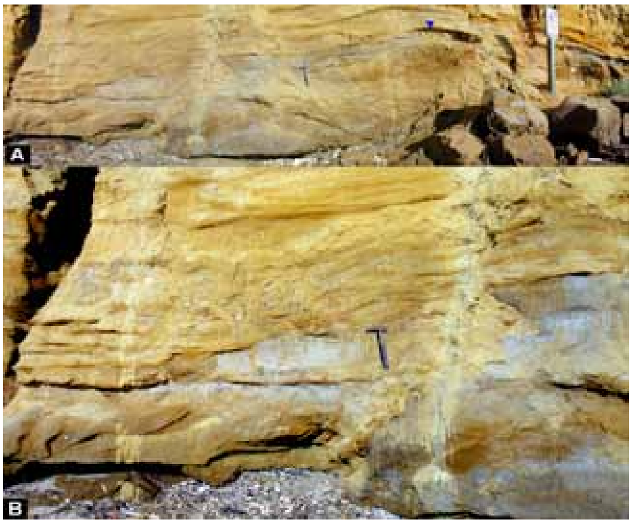


Figure 6: View of basal portion of the northern face of Red Bluff showing the disappearance of Gill's 'carbonaceous band'. The grey–green band is easily visible at the right in A, where it underlies a slightly more resistant sandstone (blue triangle), but becomes indistinct near the centre. B: Closer view of this disappearance; the area left of the hammer has been cleaned to show the true colour. Note the swaley cross-lamination at several levels above the hammer.

Figure 7: Horizontally laminated sandstone with lag deposits of gravel. The outcrop is at Black Rock, 5½ km south of Red Bluff, and at the same stratigraphic level as Figure 6. Note the single much larger, and more rounded, quartz pebble under the pencil.

the promontory does not occur in the main cliff but shows several characteristics that indicate it is not a fluvial deposit but a shallow marine one. These include its flatness, its 'thin-ness' (it is barely 3 cm thick across its entire extent), and the occurrence of highly rounded pebbles — rounding that indicates some residence in the surf zone. I interpret this conglomerate as a lag deposit. Similar beds occur at Black Rock, in fine-grained sandstone that shows burrowing and both horizontal and swaley cross-lamination (Figure 7).

Gill was mistaken about the bedding dip in the upper cliff section being 'practically horizontal'. This perception depends on sun angle, and only in mid-summer, when the sun is almost directly overhead, do the shadows show up the subtle swaley cross-lamination that occurs in many places (Figure 8). This cross-lamination is due to slight changes in grain size and sorting and is visible only at a small distance, because the rock is not stained or cemented. The base of the bluff, by contrast, is strongly ferruginised, so that differential erosion has emphasised the swaley cross-lamination (Figure 9).

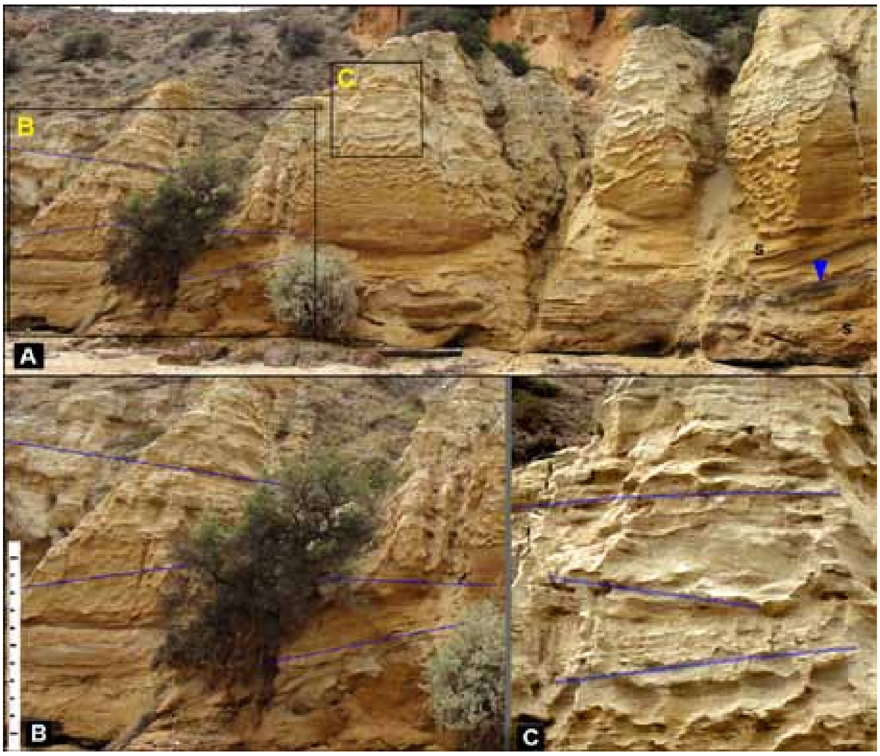


Figure 8: Section of north face of Red Bluff shown in the rectangle in Figure 5. In A, this square-on view shows swales (S) both below and above the 'carbonaceous band' (blue triangle points to its top). Blue lines at left are drawn along swaley cross-lamination, shown more clearly in B and C, which is picked out by slightly more erosion-resistant sandstone layers. Only portions of the swales are visible in the part of the cliff where the lamination is clearly visible. Scale is 1 m long.

Figure 9: Swaley cross-lamination is the dominant bed form in the type section of Gill's Black Rock Member (see Figure 4 for location). Burrows occur but are only obvious where they have been preferentially ferruginised. Notebook for scale is 18 cm long.

Gill (1956) implied that there is no conglomerate within the 'Black Rock Sandstone' (e.g. in his text figure 13) but that is incorrect. They occur on the shore platform at the Sandringham Yacht Club, just south of Red Bluff, in sandstones showing etched-out marine burrows, and are well exposed at Black Rock, again interbedded with burrowed sandstone (Figure 10).

Figure 10: Small erosional 'island' of conglomerate in sandstone with marine burrows at Black Rock. Most of the pebbles are highly rounded, indicating residence in a surf zone.

Conglomerates in the upper 'Red Bluff Sands' section at Red Bluff are all fine- to very fine-grained and have the same planar, horizontal bedding style and internal lamination as the sandstones (Figure 11). Bed bases of the conglomerate layers tend to be poorly defined (e.g. at the 45 cm level in Figure 11), showing that the deposition of larger clasts is the result of a change in the carrying capacity of the water column (i.e. a decrease in turbulence), not of the introduction of new coarse material (associated with an increase in turbulence) as might occur in a fluvial setting. The upper limit of clast size is quite sharp, with clasts rarely larger than 10 mm across — they are dominantly of fine-gravel grade. Rounding is very variable, with some showing high sphericity. Sorting is similarly variable but is generally poor, and many conglomerates have open framework with a matrix of sand. They show a complete range from sandy conglomerate to pebbly sandstone to sandstone with a few loosely scattered pebbles, similar to those in the 'Black Rock Sandstone' part of the section, as

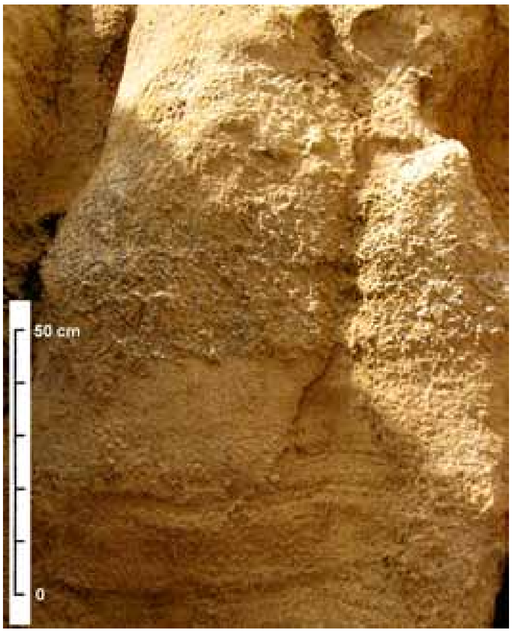


Figure 11: Conglomerate and pebbly sandstone showing planar lamination and considerable variation in the degree of sorting. The conglomerate is in the 'Red Bluff Sands' section of Gill (1956), close to the location of Figure 12. Some of the clasts show similar rounding to those in Figure 10, again indicating residence in a surf zone.

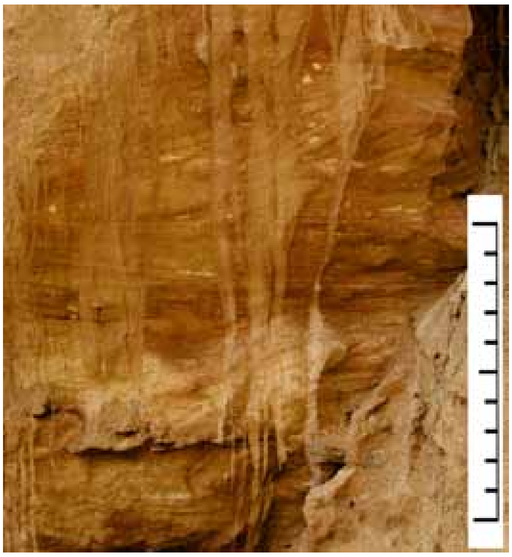


Figure 12: Red Bluff south face, upper section (see Figure 4 for location). Two beds of swaley cross-lamination dipping to the left are separated by one with lamination dipping (very gently) to the right, representing the edges of overlapping swales. Scale is 50 cm long.

in Figure 7. Sandstone interbedded with the conglomerates shows swaley cross-lamination (Figure 12).

The variable rounding indicates that only a proportion of the granules were captured in the surf zone, with the remainder bypassing it and deposited more distant from the shoreline, where it was not subjected to further abrasion. Thus while the pebbles (and indeed all the sediment in the sandstone) were originally of fluvial origin, their presence does not indicate a fluvial setting for the 'Red Bluff Sands'.

The poor sorting seen in many coarser layers can be explained by the dynamics in this paralic setting. The turbulent seawater during storms ensures that bottom sediments are continuously agitated, thus allowing the lateral distribution of coarse material. In the absence of currents that can carry the finest material out of the system, all the suspended material, from finest to coarsest, will eventually settle when the turbulence ceases. Fine-grained sandstones can therefore have a significant clay matrix, and conglomerates have a gritty sandstone matrix.

The land surface of the Brighton region is marked by a series of ridges at a spacing of ca 500–700 m, separated by swales. Early workers interpreted these as dunes (Hills 1940; Whincup 1944; VandenBerg 1971) but Wallace et al. (2005) considered them to be strandlines and interpreted their setting as a paralic strandplain. The sedimentary structures displayed in the Red Bluff section fit well with such a setting.

Fluvial or marine?

The observations at Red Bluff indicate that the entire Miocene–Pliocene sequence here was deposited in a paralic setting, interpreted as a storm-affected strandplain. Other coastal exposures in the Brighton–Beaumaris area are consistent with this — there is no evidence in any of the bluffs of the presence of fluvial sediments. This applies also to other rocks previously interpreted as fluvial such as the 'Baxter Sandstone' of the Mornington Peninsula, and 'Hanson Plain Sand' of the Port Campbell Embayment.

The identification of a paralic setting is based on a small suite of sedimentary features, chiefly planar and low-angle swaley cross-lamination in sandstone and fine conglomerate, and the presence of high-sphericity pebbles. Fossils are very rare, mainly because of leaching of the original carbonate. Leached fossils can still be found in cemented outcrops (e.g. at Royal Park, 5 km north of Melbourne) but are undetectable in uncemented rocks. Trace fossils similarly are only identifiable in cemented outcrops (e.g. Figure 13C). Unusual associations of marine and land-derived fossils (marine molluscs, shark's teeth, tree trunks, marsupial bones) occur in some places, notably at Beaumaris (3 on Figure 2B) (e.g. Ter & Buckeridge 2012).

The type area of the 'Baxter Sandstone' is in bluffs between Mornington and Fossil Beach, Dromana (Gostin 1966, Figure 2B). Sedimentary structures include both swaley cross-lamination and horizontal lamination (Figures 13B, 14) and vertical burrows (Figure 13C). Conglomerates include a mixture of poorly to very well rounded vein quartz pebbles (Figures 13B, 14C, 15B).

Figure 13: Uppermost portion of Sandringham Sandstone exposed at Fishermans (aka Linley) Point, Mornington. A: Bluff with dark ferricrete marking the conglomeratic portion of the sequence, traceable along the entire bluff. B: Close-up of sandstone in lower part of bluff showing swaley cross-lamination and horizontal conglomerate in a shallow swale (arrowed), which is discordant with the lamination below and above. C: Burrows, including vertical ones, at the base of ferruginised band.

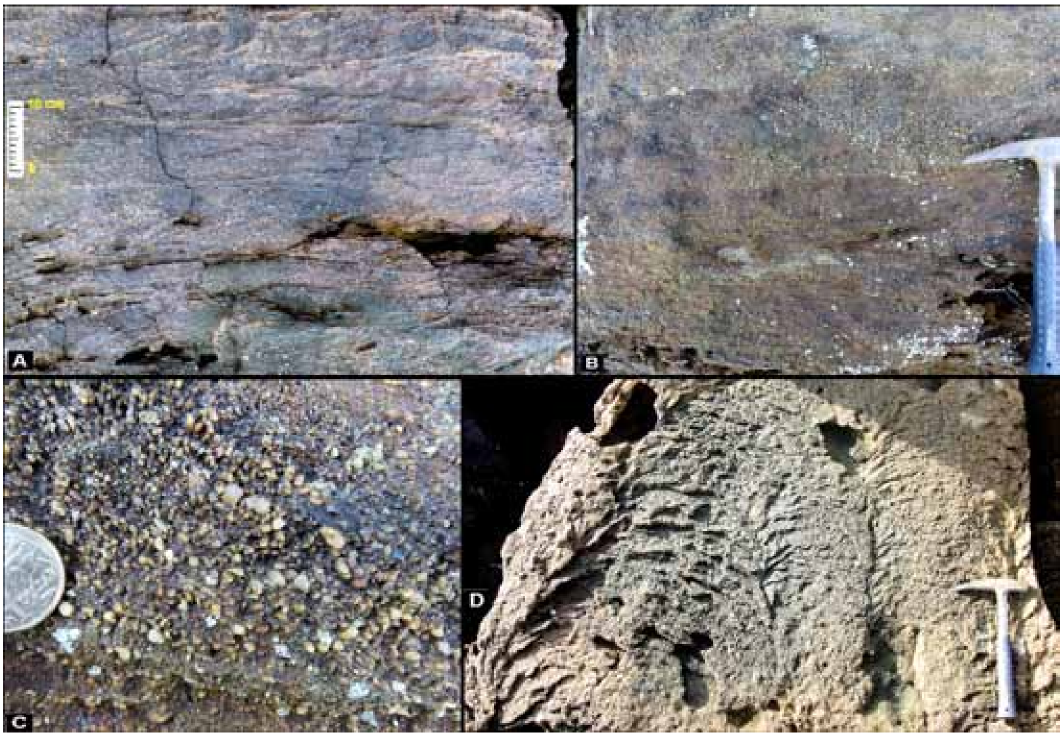


Figure 14: Photos of large, loose sandstone blocks from upper portion of north cliff, bay immediately south of Marina Cove, Mornington. A: Swaley cross-lamination in this block dips mostly to the left and is confined to relatively thin sets. The scale is 10 cm long. The rock is a gritty sandstone with generally <5% of pebbles mostly <2 mm across. B: Conglomerate/pebbly sandstone. Overlapping swale edges give rise to a herringbone-like pattern. Hammer for scale is 33 cm long. C: Close-up of a portion of B showing the variable fabric of the conglomerate, ranging from closed framework to sandy conglomerate to sandstone with dispersed clasts. All clasts are of granitic quartz (pale patches are lichen). Coin is 25 mm across. D: Base of a bed with swaley cross-lamination. Etching by storm waves has revealed a scaly fabric, with the cross-laminae dipping at a low angle into the rock ('upwards'—the depositing current would have flowed from the top of the slab to the bottom). The parallel swales give rise to a pattern of trough cross-lamination. Note that the base of the bed is flat, and that even in this small example, the width of the swales ranges from ca 40 cm to 80+ cm. Hammer is 33 cm long.

Figure 15: Trackside exposure of upper portion of Sandringham Sandstone 200 m south of Harmon Rocks, Mornington. A: The rock is weakly consolidated and consists of poorly sorted sandy conglomerate and pebbly sandstone. B: Close-up view of portion of the outcrop in A showing the poor sorting, which stands in contrast to the rounding of many of the grains. Although vein-quartz grains stand out, granitic quartz makes up more than 90% of the rock. Note also that there is a well-defined upper size limit to the grains (ca 5 mm).

High-sphericity vein-quartz pebbles occur interbedded with sandstone showing swaley cross-lamination in the type sections of the 'Moorabool Viaduct Sands' near Geelong (Figures 2A, 16) and of the 'Hanson Plain Sands' near Simpson (Figures 17A, 18).

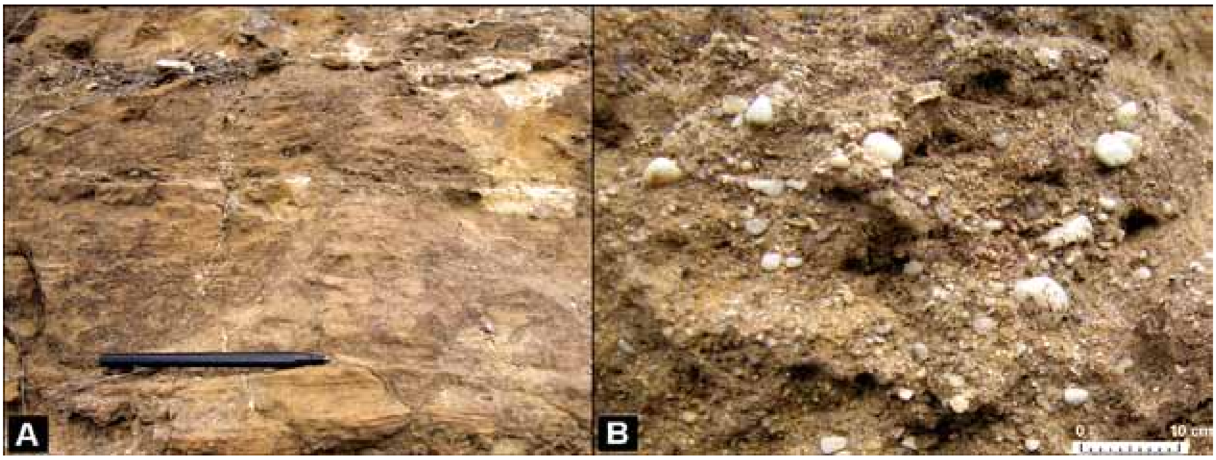


Figure 16: Sandringham Sandstone in the Moorabool Viaduct section near Geelong (6 on Figure 2A). A: well-sorted sandstone showing swaley cross-lamination. B: Close-up of pebbly sandstone. Note the apparent inconsistency between the poor sorting and the high sphericity of the pebbles that indicates prolonged abrasion under highly turbulent conditions.

High-sphericity quartz pebbles are associated with all the rocks previously regarded as fluvial and are strong evidence for a marine setting. The degree of rounding in such clasts is evidence for prolonged abrasion which is only available in a surf zone. The fact that most of the clasts in these deposits do not display such rounding is no evidence to the contrary — it merely shows that most material bypassed the surf zone.

Strandplain sediments are predominantly of distant derivation, transported by long-shore currents. In the case of the Sandringham Sandstone strandplain, sediment transport was from west to east. The predominant source would have been the Miocene Calivil Formation, a fluvial deposit derived from the Western Uplands that contains conglomerate consisting almost exclusively of vein quartz clasts (VandenBerg 2009).

The type locality of the 'Red Bluff Sands' and reference localities of the 'Baxter Sandstone' show dominant planar bedding in sandstone and conglomerate, with variable development of low-angle swaley lamination. There is at least one bed showing trough cross-lamination (Figures 6–9, 11–14).

Swaley cross-lamination is considered to have formed in water depths ranging from the surf zone to storm-wave base (around 2–50 m, Dumas & Arnott 2006). Planar-laminated sands are deposited within the surf zone where sheet-flow conditions prevail (Dumas & Arnott 2006).

In such a setting, most deposition occurs during storm events that can be highly destructive, causing extensive erosion of the adjacent shoreface. The highly turbulent water carries this material offshore where it will be deposited in storm-wave-dominated conditions. The turbulent water is capable of carrying considerable amounts of sediment in suspension, with a wide range of grain sizes. Deposition will occur when turbulence decreases, and can involve very rapid settling, resulting in poorly sorted deposits. Because of the limited grain size of the available sediment, there is little grain-size change at the base of swales.

The grain-size range in strandplain deposits is generally quite limited, from fine to very coarse sand, with very minor fine gravel (McCubbin 1982). Clay content of the sand can be considerable, probably because crashing waves inject water, including any very fine material it carries, into the porous sea bottom; once there, it remains trapped between the sand grains.

In addition to swaley, hummocky and planar lamination, tabular cross-lamination can occur under conditions of steady flow. The cross-laminae can be quite steep (30°) but the beds containing the cross-lamination are planar (McCubbin 1982).

Moore & Hocking (1983) found that swaley and trough cross-stratification occurred together in sediments interpreted to have been deposited above fair-weather wave base. Le Roux & Jones (1994) found a similar association together with planar-laminated sandstone and sandstone with tabular cross-lamination in their shallow marine 'facies 3', together with thin (1–3 cm) conglomerates with open framework along erosion surfaces.

The interpretation of the 'Red Bluff' and 'Baxter' sandstones as fluvial deposits is deeply entrenched in the literature, so it may be instructive to examine why. Gill's work was carried out at a time when studies of depositional facies, and particularly the interpretation of paralic sediments, were in their infancy. Tools to recognise paralic sediments, such as the characters of hummocky and swaley cross-lamination, were not developed until the 1980s (e.g. Dott & Bourgeois 1982; Leckie & Walker 1982). Neither Keble (1950) nor Gill (1956) gave any consideration to the sedimentary structures. Keble implied that the mere presence of pebbles made the sediments fluvial and that this was so self-evident that he did not discuss the matter. Gill gave as his main reason the supposedly disconformable contact between the 'Black Rock' and 'Red Bluff' members, here shown to be gradational. Gill gave as supporting evidence the presence of sand, gravel and conglomerate. However, conglomerate is a common component of paralic sediments (Dott & Bourgeois 1982; Le Roux & Jones 1994). Locally, it is interbedded with burrowed sandstone showing hummocky cross-lamination at Black Rock and with sandstone showing swaley cross-lamination in the bay immediately south of Marina Cove.

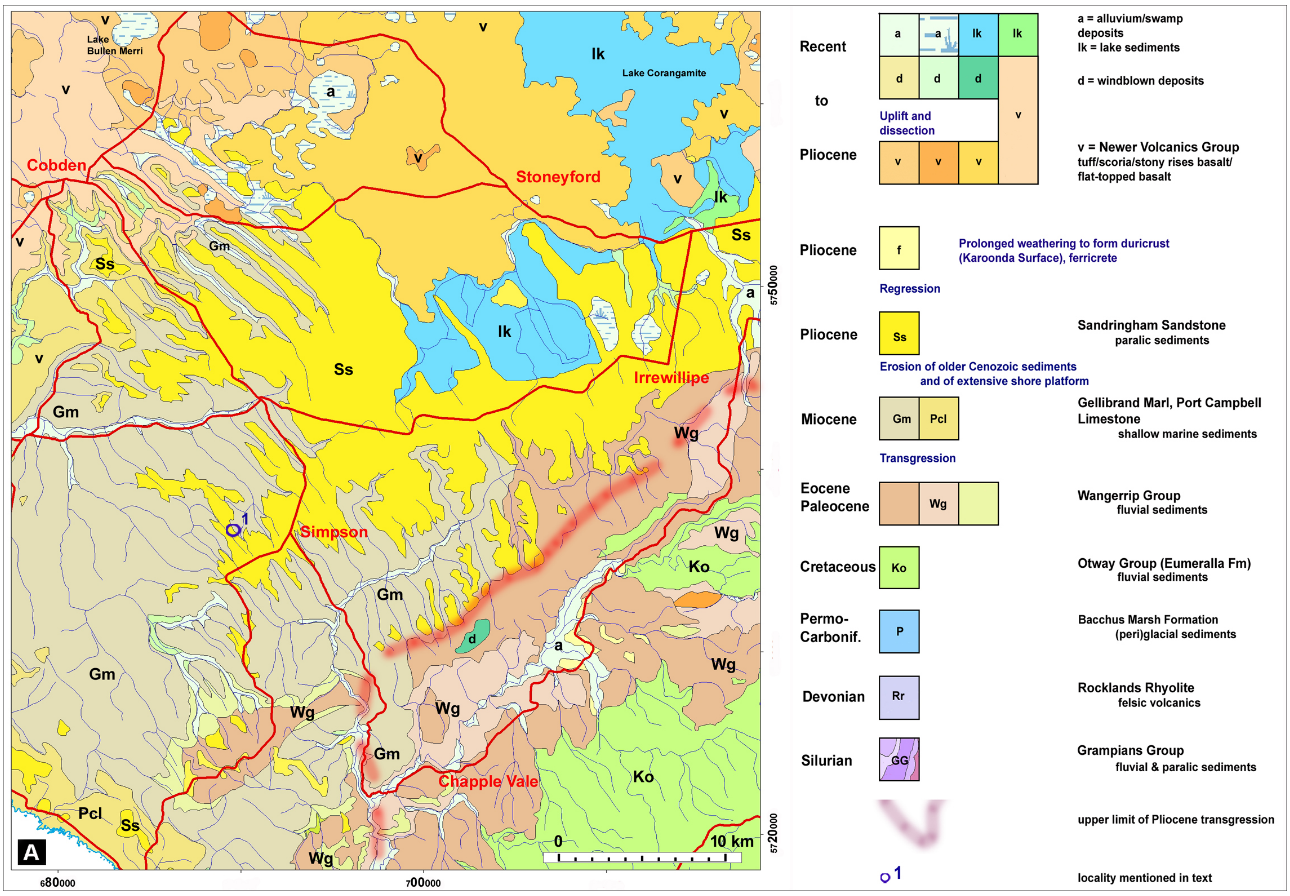
REGIONAL EXTENT

South-western Victoria

The most extensive Miocene–Pliocene strandplain deposit occurs in south-western Victoria, west of the Otway Ranges. Most of it is buried by a veneer of late Neogene Newer Volcanic basalts. However, magnetic mapping can be used to trace the extent of the strain plain because the differences in basalt thickness above the swales and sand ridges are sufficient to show up as a gently curved stripy pattern (e.g. Wallace et al. 2005, figure 9). This shows that the strandplain extends from the western edge of the Otway Ranges north to Lake Corangamite and west to at least as far as Hamilton (Paine et al. 2004; Wallace et al. 2005 figure 8; VandenBerg 2009 figures 5, 6). Immediately west of the Otway Ranges lies a large remnant of the strandplain that was uplifted and never covered by basalt. Erosion along the deeper swales has resulted in a remarkable trellis-like dissection pattern (Figure 17A; see Edwards et al. 1994). The bars and swales are well shown on the RGB image (Figure 17B) showing a series of arcuate pale and dark bands, a pattern also seen in the strandplain in the Murray Basin (Miranda et al. 2009, figure 6C). Dark bands correspond to siliceous ridges while pale bands reflect thorium in clay-rich swales. Tickell et al. (1992) interpreted the Pliocene cover unit in which the ridges occur as 'largely fluviatile' and gave it the new name 'Hanson Plain Sands'. However, the type section near Simpson (loc. 1 on Figure 17A) shows swaley cross-lamination and burrows, and conglomerate layers in which pebbles are highly rounded (Figures 18B–D). Thus both the surface features of the plain, and sedimentary structures in the type section, indicate the deposit is marine, part of the Sandringham Sandstone. The ridges and swales shown in the RGB have the same spacing, alignment and arcuate pattern as those in the basalt-covered plain to the north and northwest, indicating that the basalts are underlain by Sandringham Sandstone.

Brisbane Ranges plateau and Dereel surface

A large area extending west from the Rowsley Fault was never covered by Newer Volcanics lava flows and thus has Neogene sedimentary rocks exposed at the surface. Much of this plateau, known as the Brisbane Ranges, is covered by Sandringham Sandstone. Unlike the deposits to the west and east, the shallow marine nature of this deposit (mapped as 'Moorabool Viaduct Sand' — Bowler 1963; Bolger 1980; Bolger & Russell 1983; Taylor 1996) has long been



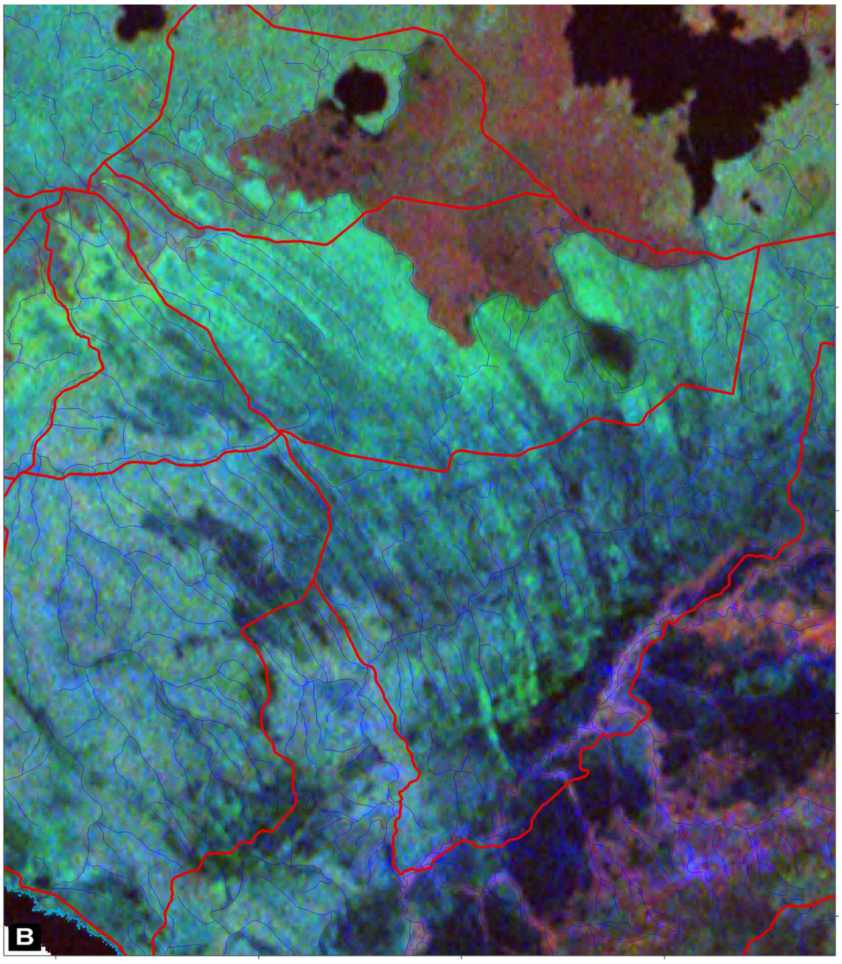


Figure 17: Geological map (A) and RGB radiometric image (B) of part of the Hanson Plain showing the distribution of the Sandringham Sandstone. Arcuate dark bands on B are siliceous strandplain bars while bright green arcs mark swales; both end abruptly at the Pliocene shoreline of the Otway Ranges, in which the blue–black colour comes from the siliceous Wangerrip Group sediments.

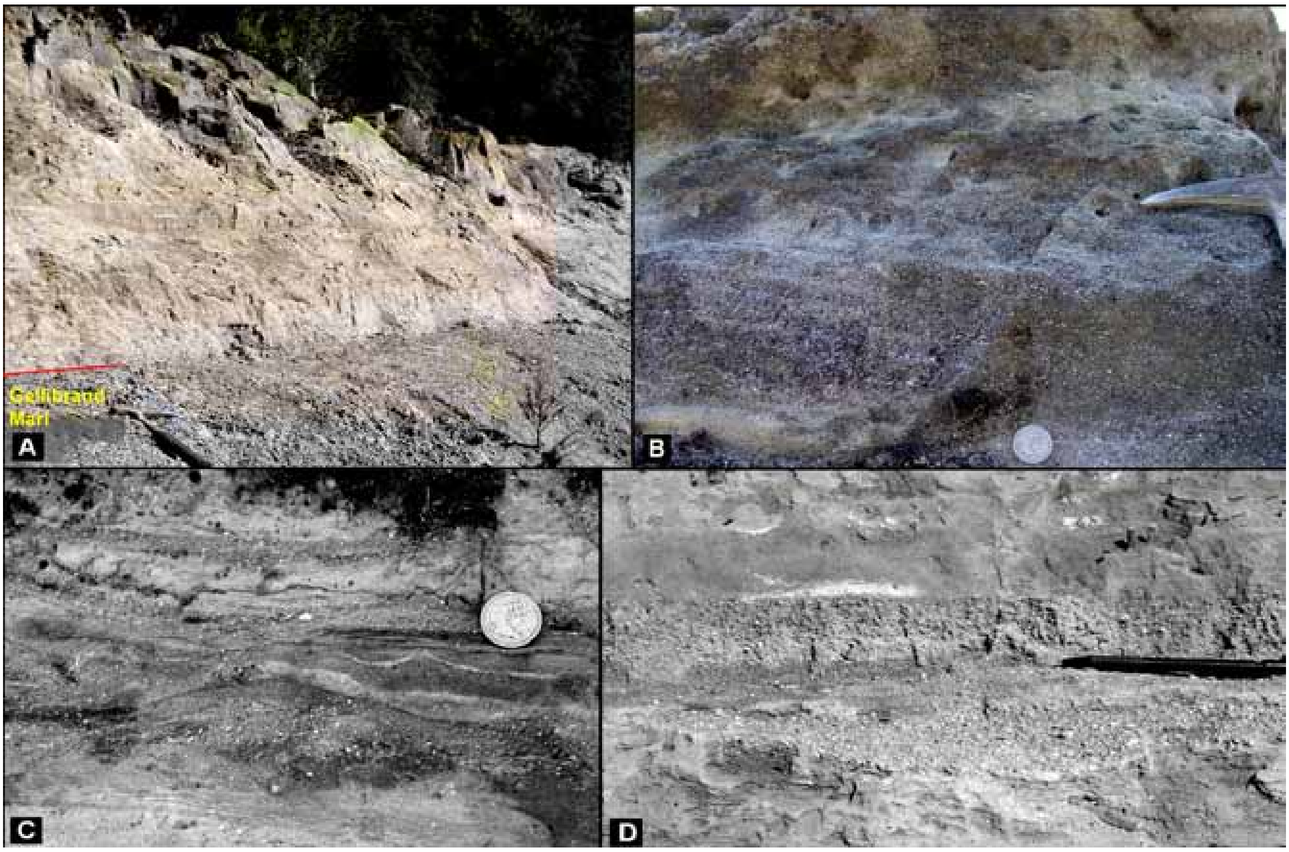


Figure 18: The type section of the Hanson Plain Sand. A: Northern side of cutting with Sandringham Sandstone overlying Gellibrand Marl. Little detail of the sedimentary structure is visible on this side. B–D are all from the opposite, southern side of the road. B: Swaley cross-lamination dipping in opposite directions in pebbly sandstone, akin to Figure 14B from Mornington. Coin is 28 mm across. C: Similar structures in alternating pebble-poor and pebble-rich beds laminated beds at base are bioturbated. D: Conglomerate-filled small swale below the pencil.

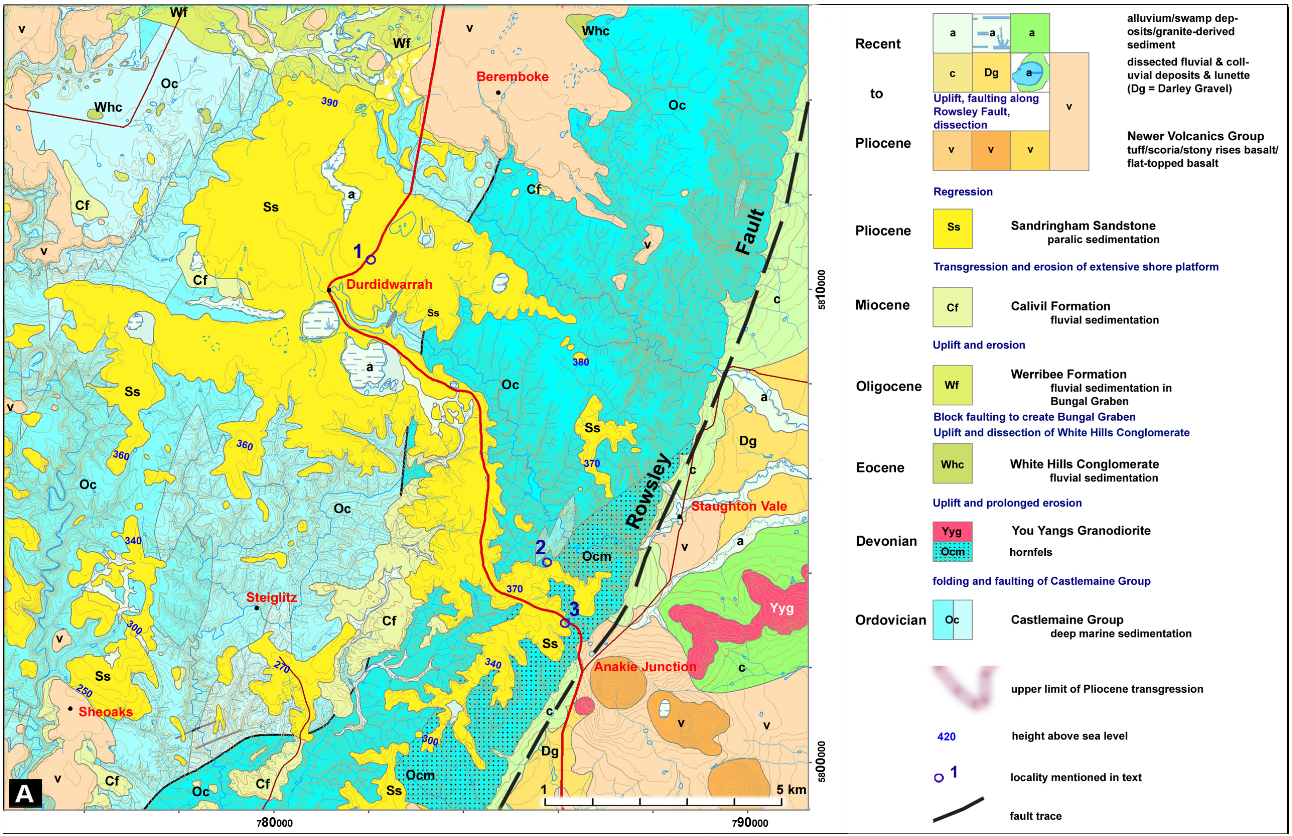
known, with marine shelly fossils found as far north as Durdidwarrh (Bolger & Russell 1983, loc. 1 on Figure 19A). This is again supported by sedimentary structures including swaley and rare hummocky cross-lamination and the presence of vein quartz clasts that show a high degree of rounding (Figures 16A, B).

The Sandringham Sandstone covers a dissected surface similar to the Brisbane Ranges plateau in the Dereel region, 25 km south of Ballarat, and was probably continuous with that plateau. At its northern edge, a Pliocene coastline is well preserved, forming an east–west sinuous escarpment that rises 50–70 m above the surface (Figure 20). Where conglomerates are present within the Sandringham Sandstone, pebbles are unusually well rounded (Figure 21B) indicating prolonged reworking in a surf zone. This is especially marked in a gravel pit 4 km east of Mt Mercer (loc. 2 in Figure 20), where the Sandringham Sandstone overlies Calivil Formation from which material was cannibalised and reworked to form a conglomerate several metres thick (Figure 22).

A major point of difference between the Sandringham Sandstone cover of the Dereel surface and Brisbane Ranges plateau is that whereas the Dereel surface shows remnants of the strandline topography seen elsewhere (Figure 20B), the Brisbane Ranges plateau seems much smoother (Figure 19B). The reason for the apparent absence of the strandlines here is uncertain. It may be due to the greater degree of dissection, but even on the flattest part of the plateau there seems to be no preferred alignment of features. Strandlines are generated during slow regression, so that their absence may be due to a more sudden retreat of the sea, perhaps due to tectonic uplift. The Rowsley Fault may have originated at this time. Ultimately, this tectonic uplift was considerable: the northern edge of the Sandringham Sandstone lies at elevations of 375–360 m on the Dereel surface (Figure 20), and above 390 m on the Brisbane Ranges plateau (Figure 19A).

AGE

The age of the Sandringham Sandstone is still not well known. Wallace et al. (2005) estimate the age of the base to be ca 5.8 ± 0.2 Ma at Beaumaris, which is the most fossiliferous exposure. They based this on $^{87}Sr/^{86}Sr$ ratios in molluscan carbonate from 2.5 m above the base of the formation. The youngest date obtained from Beaumaris is 5.03 Ma, but the upper part of the formation



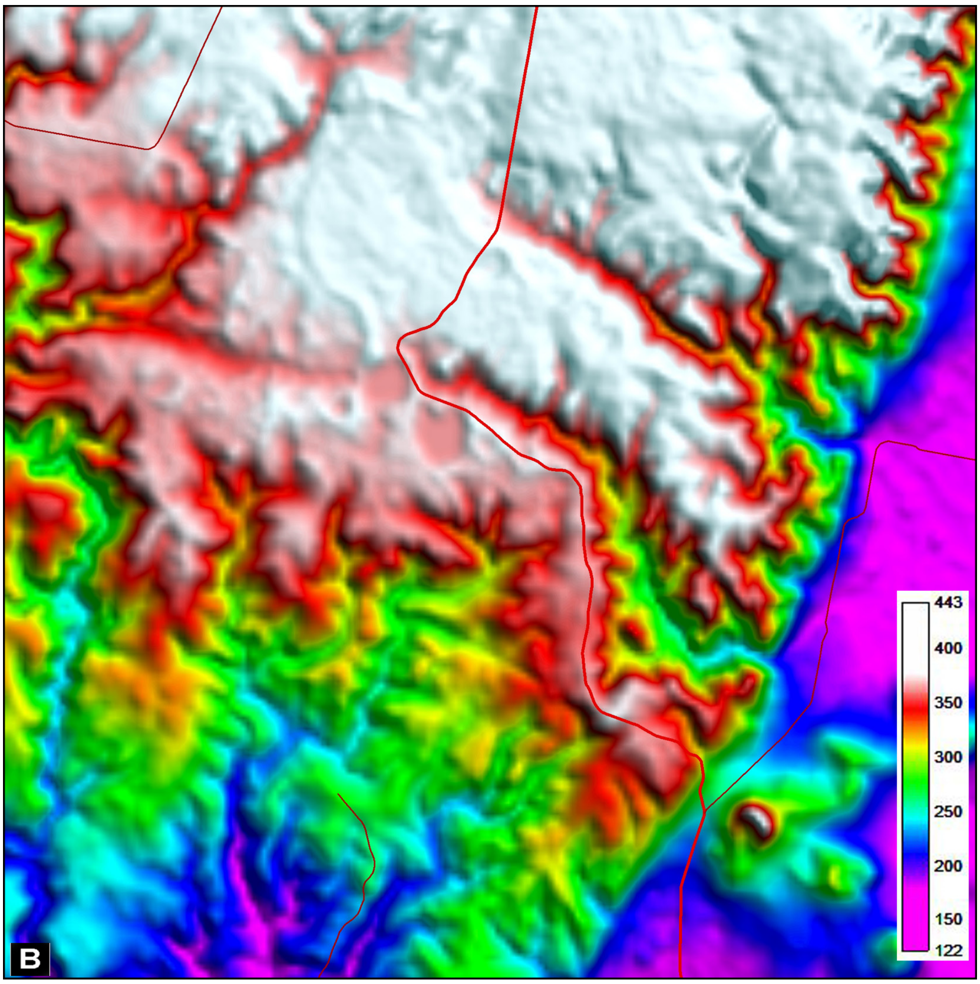


Figure 19: A: Geological map of the Durdidwarrh–Anakie area showing the extent of the Sandringham Sandstone on the Brisbane Ranges plateau (see Figure 2A for location). Geology by Bolger (1980) modified by VandenBerg (in Welch et al. 2011). B: Digital terrain model of the same area, showing the flatness of the Brisbane Ranges plateau.

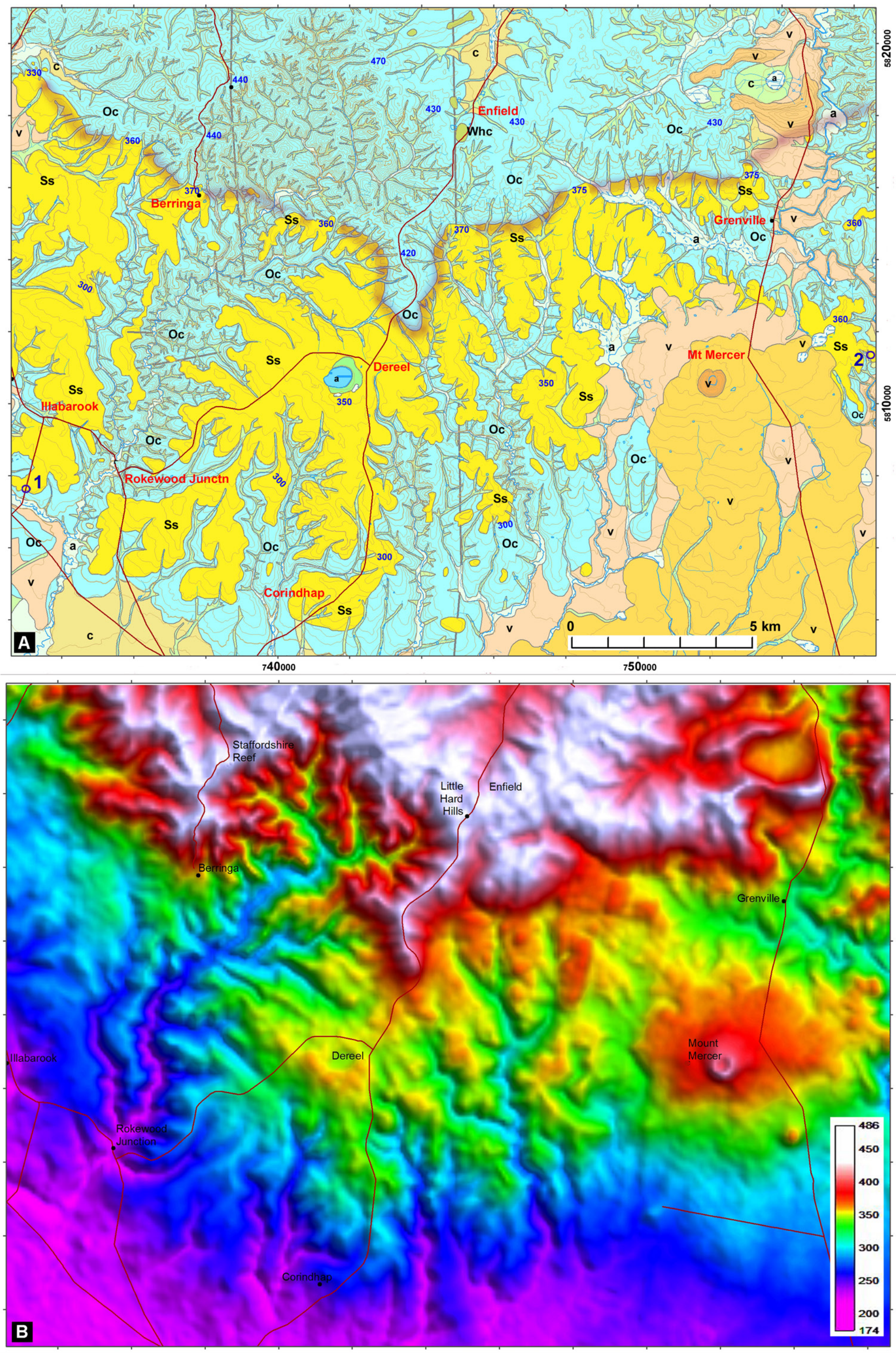


Figure 20: Geological map (A) and digital terrain model (B) of the Dereel surface south of Ballarat (see Figure 1 for location and Figure 19A for legend). The plateau covered by Sandringham Sandstone is much more dissected in this region but the Pliocene shoreline is easily traced along the northern edge of the sandstone. Geology in A from Welch et al. (2011) based on Taylor (1996) with minor remapping of the Sandringham Sandstone by the author.

is unfossiliferous. The $^{87}Sr/^{86}Sr$ method is not precise, as it reveals internal inconsistencies between the stratigraphic level and age, with higher levels giving older ages. Nevertheless, it is superior to other methods.

Much of the formation is devoid of dateable fossils in all its outcrops, so other evidence is needed to find its upper age limit. The best evidence has come from a study of drill cores of basalts in the Werribee Plains on the western side of Port Phillip Bay. Here, the basal flows in boreholes TAR12 and TRU50, in the lower, southern portion of the plains, contain hyaloclastite and are considered to have flowed into shallow water (Hare 2002; Hare & Cas 2005).

From this I infer that the onset of volcanism in the Werribee Plains coincided with the regression that ended Sandringham Sandstone deposition. Unfortunately the onset of volcanism is not precisely dated — Hare et al. (2005) give an estimate of ca 4.6 Ma, but the oldest flows have not been dated. The same applies to basalts in western Victoria, most of which have been dated from quarries dug into surficial flows.

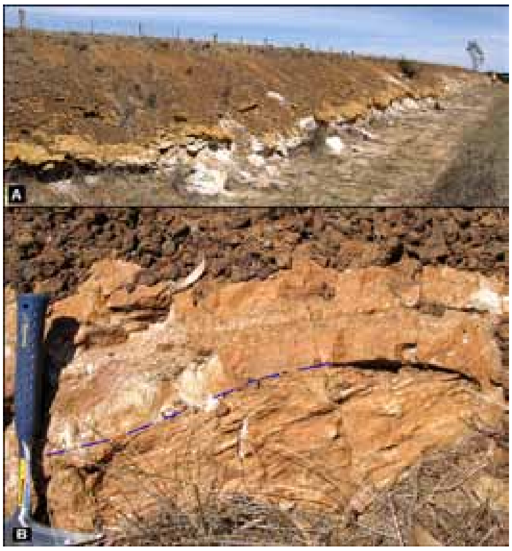


Figure 21: Sandringham Sandstone exposed in a road cutting at Illabarook, 35 km SW of Ballarat (4 on Figure 20). The pale-brown rock is well-sorted Sandringham Sandstone, overlying bleached St Arnaud Group bedrock. Most of the cutting consists of dark-brown ferricrete duricrust. B shows a close-up of the unconformity (blue line) with St Arnaud Group slate in which the cleavage dips gently to the left. Sandringham Sandstone above the unconformity mantles a low rise in the bedrock, and includes a pebbly sandstone with highly rounded and polished vein-quartz pebbles.

Thus the best age estimate for the duration of Sandringham Sandstone deposition is between 5.8 and ca 4.6 my, a period of a little over 1 million years straddling the Miocene–Pliocene boundary.

STRATIGRAPHIC NOMENCLATURE IMPLICATIONS

The character of the sediments and sedimentary structures in the Red Bluff section indicate that the entire section (excluding the capping of aeolian sand, Figures 3, 4) was deposited in a paralic setting. Moreover, there is no evidence for the existence of a disconformity — sedimentation was essentially continuous. Gill's original name for the entire Red Bluff section up to the top of the ferruginous cap, Sandringham Sands, is therefore appropriate, albeit slightly modified to Sandringham Sandstone. The names Black Rock Sandstone and Red Bluff Sand are therefore redundant.

One result of these findings is that inland outcrops of fluvial sediments that overlie the Silurian basement in the Melbourne region, which have traditionally been mapped as 'Brighton Group' or 'Red Bluff Sandstone' (e.g. Kenley 1967; VandenBerg 1970, 1971, 1973a,b, 1974, 1997; Anon. (undated); Holdgate et al. 2002, 2003; Welch et al. 2011), are without a name. Furthermore, before a new name is found, it needs to be established that they are

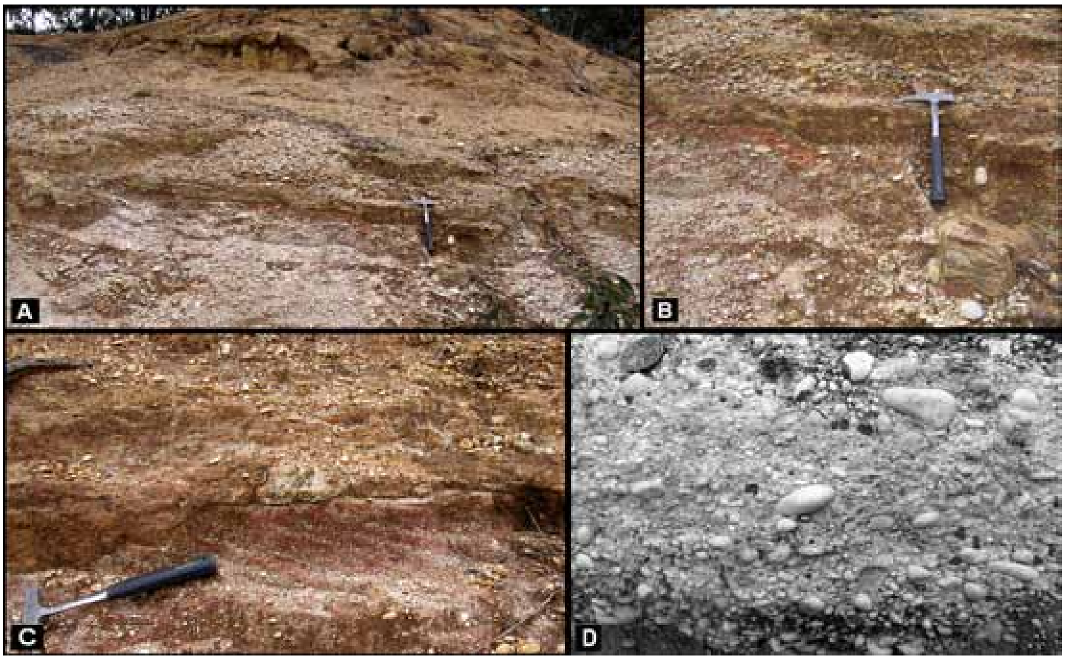


Figure 22: Sandringham Sandstone in Mt Mercer gravel pit (2 on Fig. 20A). A: Shows the tabular bedding style, dipping gently to the right (south). The main difference between adjacent beds is the variation in the ratio of larger pebbles to matrix. B: Close-up of the exposure in A showing an isolated cobble (below hammer) set in poorly sorted pebble conglomerate. Note the good rounding of pebbles and preferential alignment of flat clasts. C: Gravel showing planar cross-bedding contained within a fairly thin bed (ca 20 cm thick) that is concordant with the overall planar bedding style seen in the rest of the quarry (e.g. in A). D: The pebbles in this poorly sorted conglomerate show the unusually high degree of rounding typical of the entire deposit. Coin is 31 mm across.

indeed fluvial — a task that lies outside the scope of this paper. Gill (1956) remarked on the similarity between the sandstones along the Maribyrnong River and those of the Red Bluff section, suggesting these inland outcrops too may be marine and belong to the Sandringham Sandstone. The inland limit of the Sandringham Sandstone is currently not known.

The Sandringham Sandstone was deposited on a single, continuous strandplain that extended from the Mornington Peninsula to west of Hamilton. Drilling has shown that the Miocene marl formation underlying the sandstone is similarly continuous between Mornington and Hamilton, is of substantially the same age and depositional setting in this region, and has the same faunas. Using different names in different areas for these two formations requires the user to nominate where a particular name should change (e.g. where is the boundary between the Fyansford Clay and the Balcombe Clay?) and, more importantly, say why. Adjacent rock units should be based on geological, and usually lithological, differences. This applies just as much to laterally adjacent units as it does to vertically adjacent ones. Maintaining the practice of using different names for different outcrops confuses rather than clarifies, and therefore goes against the principles of stratigraphic nomenclature (e.g. Anon. 1956). This was most clearly restated by Brakel (2007) in reference to Australian usage.

Sandringham Sandstone

While I agree with Kenley (1967) that the name Brighton, as part of the name ‘Flemington and Lower Brighton Beds’ used on the early Quarter Sheet geological maps (Selwyn 1861), was used much earlier than the name ‘Sandringham Sands’ (Gill 1950), that name was never tied to any particular outcrop that might be regarded as typical nor were its limits given. I therefore prefer the name Sandringham Sandstone with its clearly defined type locality and limits. The concept of the Brighton Group includes the entire Sandringham Sandstone and therefore the name should no longer be used. The same applies to other names applied to the strandplain deposit. These include Moorabool Viaduct Sand, Baxter Sandstone, Marina Cove Sand, Hanson Plain Sand and Beaumaris Sandstone.

Gellibrand Marl

There is a similar confusing profusion of names for the Miocene marl that underlies the Sandringham Sandstone. In this case, early studies concentrated on the rich and diversified shelly fauna.

Muddy Creek

Woods (1865) described a ‘remarkable bed of fossils’ from Muddy Creek near Hamilton, gave a lithological log, and referred to them as the ‘Hamilton beds’. Etheridge (1878) used a variety of names for this outcrop, including Hamilton series, Hamilton beds, Muddy Creek (Hamilton) beds and Muddy Creek beds. In later publications, the name Muddy Creek beds was used (Tate 1879; Woods 1878, 1879; Dennant 1887, 1889). Singleton (1941) called it the Muddy Creek limestone. Boutakoff & Sprigg (1953) were the first to use the formal name Muddy Creek Formation and Gill (1956) provided a figure showing the Muddy Creek Marl lying between the Bochara Limestone (below) and the Grange Burn Coquina (above).

Port Phillip region

The outcrops of Balcombe Bay south of Mornington (Figure 2B) were variously called ‘blue clays of Mornington’ (Selwyn 1856), and ‘clays of the Lower Muddy Creek or Mornington type’ (Hall & Pritchard 1895). Balcombe Bay was first mentioned in Hall & Pritchard (1902), who named the ‘clays and limestones of Balcombe’s Bay’ and ‘Balcombe’s Bay Beds’ as the basis of their ‘Balcombian Series’, one of the new stage names they introduced when they subdivided the Cenozoic sequence into stages with local names. Keble (1950) referred to them as the ‘Balcombian marls of Balcombe Bay, Grice’s Creek and Tyabb’. Singleton (1935) called them the ‘Balcombian marls of Mornington’. Gostin (1966) formalised the name into Balcombe Clay.

From the opposite side of Port Phillip Bay, Tate & Dennant (1893) gave age determinations of outcrops along the Moorabool and Barwon Rivers. Under the heading ‘clays of the Lower Muddy Creek type’, Hall & Pritchard (1895) listed, in addition, Fyansford, the Altona Bay shafts (5) and the Newport bore (4), all from the western side of the bay (numbers refer to location on Figure 2B). The Altona Bay brown coal shafts, dug in the 1890s (Department of Mines, Victoria, 1895, 1903), and the Newport bore, drilled in the same decade (Figure 2B) showed the presence of marine Miocene clays with limestone bands to which Thomas & Baragwanath (1950) gave the name Newport Formation. Probably unaware of this, Bowler (1963) introduced the new name Fyansford Clay for the same rock unit outcropping farther west in the valleys of the Moorabool and Barwon rivers, and in the Batesford limestone quarry.

Port Campbell embayment

Miocene marl is well exposed in cliffs west of the Gellibrand River mouth near Princetown (Figure 1). Tate & Dennant (1893) referred to 'the deposits generally known as the "Gellibrand-beds"' which they described as 'Blue clay from 80 to 90 feet thick, highly fossiliferous; yellowish clay 20 to 30 feet' overlain by calcareous sandstone (now called Bridgewater Formation). Baker (1953) named the marl the Gellibrand Clay, a member of his new Heytesbury Formation. In the same year Gill (1953) gave the name Bullenmerri Calcareous Clay (or simply Bullenmerri Clay) to the marl outcropping in the craters of Lake Bullen Merri and Lake Gnotuk near Camperdown (Figure 1; in NW corner of Figure 17A). Gill's name seems not to have been used by subsequent authors. Glenie (1971) raised the rank of Baker's units, which are currently known as Gellibrand Marl (Formation) and Heytesbury Group.

The two most serious contenders for the name of the Miocene marl formation are Gellibrand and Muddy Creek. The other serious contender — Balcombe (Bay) (Hall & Pritchard 1902) — is clearly of later origin. The same argument holds for the Newport Formation (Thomas & Baragwanath 1950), Sherwood Marl (Jenkin 1962) and Fyansford Clay (Bowler 1963). VandenBerg (2009) selected Gellibrand as the name with the best claim to priority for the Miocene marl formation.

The name Gellibrand has a respectable heritage. Tate & Dennant (1893) described the section and it is the only early reference to the Miocene marl formation that is firmly tied to a particular cliff section, west of the mouth of the Gellibrand River near Princetown (Figure 1). It is the section that Baker (1953) designated as type section of the Gellibrand Marl. I therefore consider that the name Gellibrand Marl has priority over the other formal names of this marl formation.

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