Cenozoic Willunga Embayment: from Australo-Antarctic Gulf to Sprigg Orogeny

Geological
field excursion guide

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Further Information

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Authors and acknowledgements

Between them, the four authors have accumulated almost two centuries' worth of geological activity in the field and the laboratory and the office, in research and publishing, in teaching and supervising and popularising, in minerals and fuels exploration and development. All of these facets of geological endeavour have applied to the Willunga Embayment. They thank the Director of the Geological Survey of South Australia, Steve Hill, for supporting the project, and they thank the GSSA editorial and production team for transforming a rambling manuscript into an attractive publication. The authors acknowledge Louise Christian for the initial foraminiferal micropalaeontology which confirmed the distinct tectonic entities in the upended limestones south of Sellicks Beach.

Front cover and title page images

Robert Hannaford's *Maslins cliffs in the afternoon* is used with his kind permission and interest in the project. Getting the rocks right is the most elusive accomplishment of landscape painters. Of the many perceptions of these cliffs, down the decades and through the schools and fashions in representation, Hannaford's are the most robust and compelling.

Dedicated to the vanished Adelaide Tribe (from *Imaginary Configurations* no. 8) Nikolaus Lang (Germany, 1941-), 1987, Maslin Beach, polyvinyl acetate on calico on framework of sticks, 202.0x356.0x20.0 cm.
South Australian Government Grant 1987, Art Gallery of South Australia, Adelaide. With kind permission; and thanks to Tracey Dall.
Nikolaus Lang took this polyvinyl acetate peel, about 3.5 m long, off a vertical quarry face in North Maslin Sand. Jeff Olliver was geological adviser to Lang's project on the richly coloured sands; the project was dedicated to the Kaurna people of the district.

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Geological Field Excursion Guide

Cenozoic Willunga Embayment: **from Australo-Antarctic Gulf to Sprigg Orogeny**

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April 2016

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Introduction

As superb exposures of fossiliferous strata, refreshed by coastal erosion and winter storms and backing popular beaches in what is now suburban Adelaide, the coastal cliff sections in the Willunga Embayment have attracted the attention of naturalists and painters since the mid-19th century. For the stratigraphy and micropalaeontology that solved Adelaide's problems of foundations and water supplies, they have been the key reference point (Lindsay, 1969, 1981, 1985; Cooper, 1979; Selby and Lindsay, 1982; Alley and Lindsay, 1995; McGowran, 2012). In the broader scene they offer something to two geohistorical enquiries, namely the birth of the Southern Ocean in the death of the Australo-Antarctic Gulf, and the impact of that development on the greenhouse-to-icehouse global transformation.

The St Vincent Basin is approximately 15 000 km^2 in area, about 60% of which lies beneath Gulf St Vincent. Together with the Mount Lofty Ranges, it originated in compressive reactivation of ancient structures in the Middle Eocene, just as Australian-Antarctic separation accelerated. A series of arcuate faults broadly following the grain of Delamerian (early Palaeozoic) structures define sub-basins or embayments — wedge-shaped asymmetrical tectonic valleys: the Willunga Embayment, Noarlunga Embayment, and Golden Grove Embayment (Figs 1a-c, 2).

The basin straddles the south end of the Torrens Hinge Zone, which lies between the Flinders-Mt Lofty Ranges and the Stuart-Spencer Shelf to the west. This zone is the 'Great Valley' of J.W. Gregory in 1906 and the 'South Australian Rift Valley' of Charles Fenner in 1927, with its sunklands, corridors and horsts (Lindsay, 1981). For essentially the same tectonic reasons, the Cenozoic basin has been denied full oceanic influence from the widening Southern Ocean owing to the position of Kangaroo Island (Cooper and Lindsay, 1978).

The modern account of the Cenozoic record begins with Glaessner's marine micropalaeontology and stratigraphy in the 1950s (Glaessner, 1951, 1953; Reynolds, 1953; Glaessner and Wade, 1958; Wade, 1964), and continues with Lindsay's (Lindsay, 1967; Ludbrook and Lindsay, 1969). The two decades 1950-1970 are outlined in McGowran (2012). Meanwhile Campana and Wilson (1953) and Sprigg and Wilson (1954) produced the Geological Survey one-mile sheets. Ward (1966; 1986) described and ambitiously synthesised the geology, geomorphology and soils of the district. Cooper

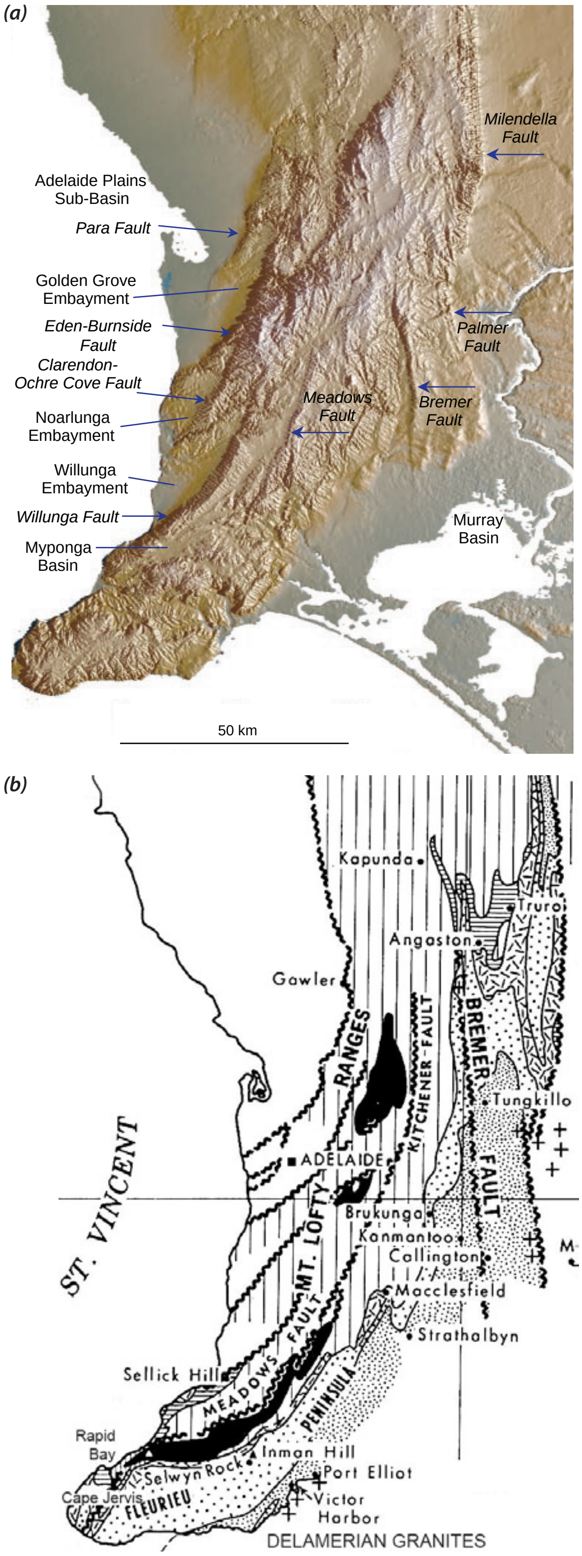


Figure 1 ***(a)*** *The eastern side of the Cenozoic St Vincent Basin and southern Mt Lofty Ranges. The basin and range topography is shaped strongly by neotectonics.*
(b) *B.P. Thomson's palaeogeological map (in Parkin, 1969, Fig. 44) with all post-lower-Palaeozoic rocks omitted. Black, Palaeoproterozoic; other fills, Neoproterozoic and Cambrian; crosses, Delamerian granites. The similarities are obvious and real. That is, Thomson was certain that these structures were authentically Delamerian, and not merely neotectonic with the cover removed; and that the Delamerian orogeny established a region of instability, prone to intermittent movement thereafter. Crosshairs are at 139°E, 35°S.*

(c)

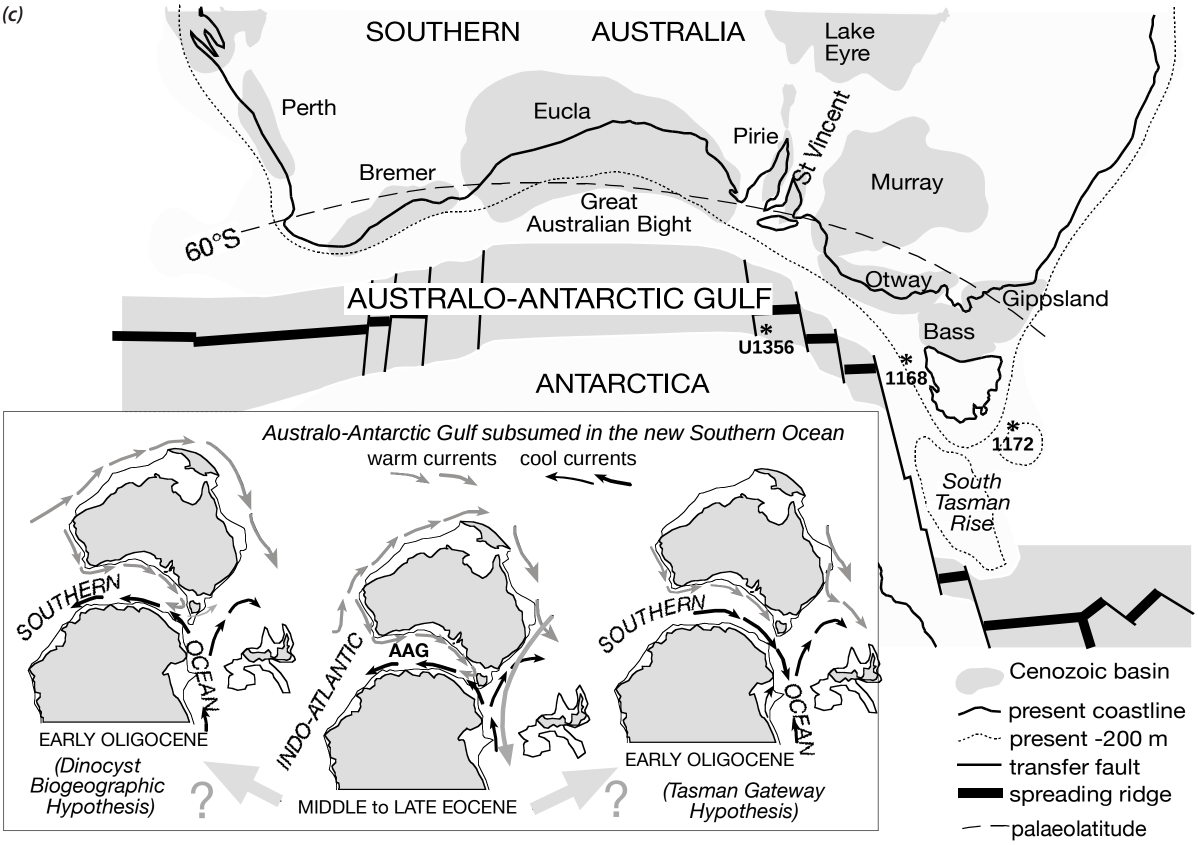


Figure 1 ***(c)*** *About 43 million years ago the Australo-Antarctic Gulf (AAG) at 60-65°S, flanked by new or rejuvenated basins, was about to widen and disappear into the new Southern Ocean. The AAG was already about 50 million years old (numbered asterisks are ocean-drilling sites critical to our present understanding of Palaeogene history.) The inset shows two scenarios for the death of the AAG and birth of the Southern Ocean in the roughly 15 million years before the early Oligocene ice sheet climaxed on Antarctica. The Tasman gateway hypothesis dating from 1970s ocean drilling emphasised the valve effect of plate tectonics and continental drift opening and closing major oceanic water bodies. The Dinocyst biogeographic hypothesis, now favoured, draws on recent drilling, modelling, CO_2-consciousness and dinocyst biogeography, in which cosmopolitan taxa accumulate in the eastern AAG, courtesy of the warm Proto-Leeuwin Current from the west, in stark contrast to southern-endemic assemblages on the other side of the South Tasman Rise barrier. (McGowran, 2009a; McGowran and Hill, 2015.)*

(1977, 1979) monographed the stratigraphy of the Willunga Embayment (Fig. 3). Modern lithostratigraphy and mapping are to be found in Fairburn (1998, 2000) and Fairburn, Preiss, Olliver and White (2010). Jones and Fitzgerald (1984, 1986, 1987) discussed the mineralogy and significance of the unusual Priabonian silicas; James and Bone (2000, 2008) described the Palaeogene carbonates and silicas.

A geological excursion to the Willunga Embayment is a flexible mixture of three components. The best-known is walking the coastal traverse up-section, north to south, from Maslin Bay to Blanche Point and from Perkana Point to Aldinga Bay. A second uses vehicles from outcrop to outcrop and winery to winery and neatly brackets the embayment with the great unconformity in the north and the best view of the Willunga Fault in the south. Third is a walk to the far south beyond Sellicks Beach, to coastal outcrops and gullies exposing the neotectonic record but requiring attention to tide times.

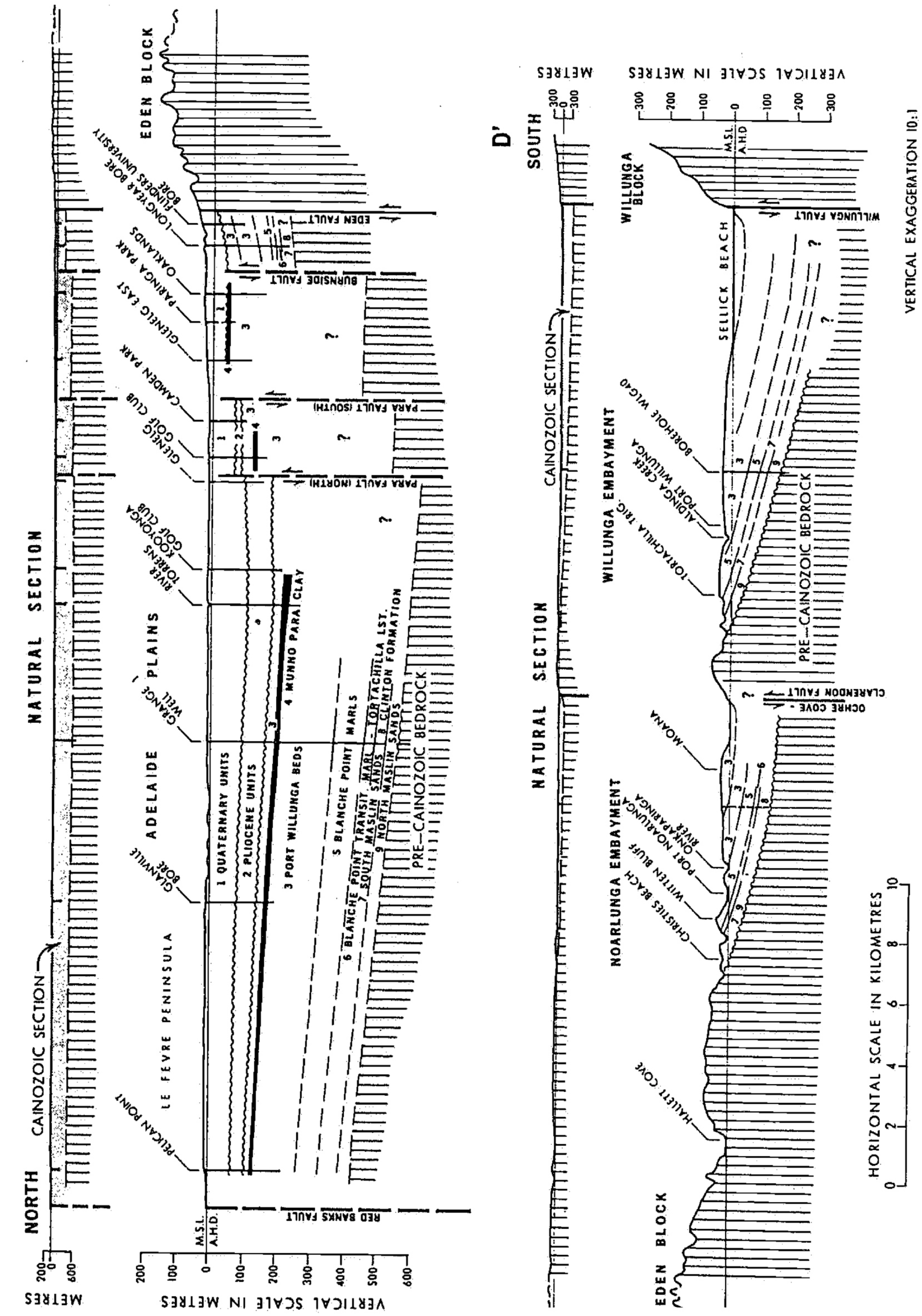
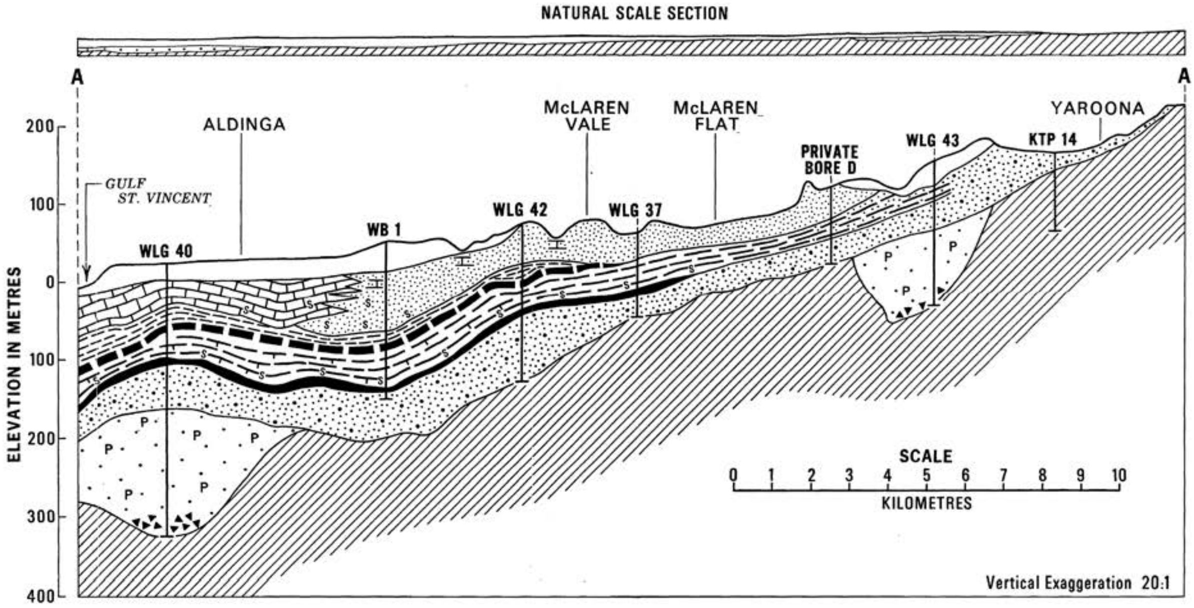
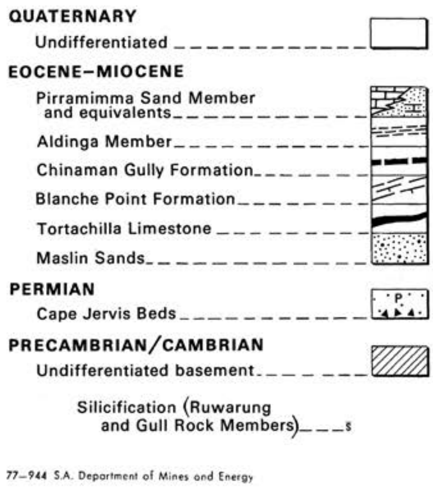


Figure 2 *Lindsay's north-south section in the eastern components of the St Vincent Basin: Adelaide Plains-Noarlunga-Willunga (Daily et al., 1976). Clearly displayed is the influence of neotectonic faults, but not whether their regimes are extensional or compressional.*





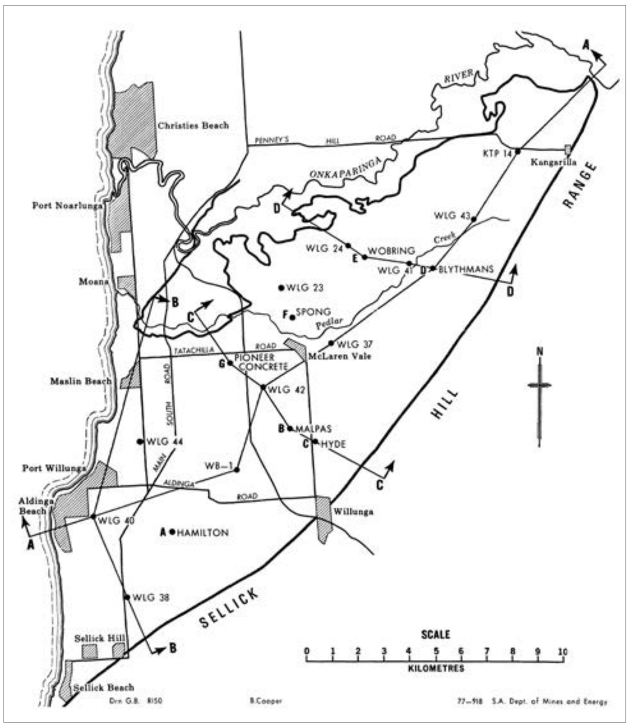


Figure 3 *Reconstructed section through the Willunga Embayment (Cooper, 1979). North Maslin Sand is confirmed on the great unconformity in the vicinity of KTP 14 near Yaroona, but lateral equivalence with the Blanche Point Formation is hypothetical. Likewise, it is contentious that the Pirramimma Sand is such an extensive lateral equivalent of the Oligo-Miocene neritic carbonates instead of being largely a Pleistocene channel, as in Fig. 4b. Sections B-B to E-E are not shown here.*

Stratigraphy

The exposed stratigraphic section (Table 1) falls naturally into two parts separated by a low-angle unconformity: late Palaeogene to early Neogene below the unconformity; late Neogene including Quaternary above it (Figs 3, 4a, 4b, 5). The break between the Port Willunga Formation and the Hallett Cove Sandstone was caused by a mild, continent-wide deformation in the Late Miocene.

Table 1 *Cenozoic stratigraphic succession outcropping at Maslin Bay and Aldinga Bay in the Willunga Embayment of the St Vincent Basin.*

Formation member	Characteristics	Age
Ngaltinga Formation	Grey-green or olive sandy clay. Includes Snapper Point Sand Member at Snapper Point.	Middle Pleistocene
Ochre Cove Formation	Sands and gravels, strongly mottled in reds.	Middle Pleistocene
Burnham Limestone	Limestone, fine-grained and poorly fossiliferous. Age uncertain: may be Late Pliocene.	Early Pleistocene
Hallett Cove Sandstone	Calcareous sandstone and sands, sometimes conglomeratic, with large bivalves and gastropods and other invertebrates, and the large foraminifer *Marginopora*. Often the main rocks on the beach.	Pliocene
Port Willunga Formation		
Janjukian Unit	Fossiliferous limestone, silt and sandstone	Chattian
Ruwarung Member	Fossiliferous limestone, marl and silt with bands of chert pods.	Rupelian
Aldinga Member	Sandstone and muddy limestone, clay, bryozoal.	Early Rupelian
Chinaman Gully Formation	Sands, silts, clays, brightly coloured in outcrop, darker and carbonaceous at depth.	Early Rupelian
Blanche Point Formation	Four members. Highly fossiliferous and with much aragonite preserved, and tending to show high dominances in contrast to the high diversities of the Tortachilla.	Late Eocene, Priabonian
Tuit Member	Similar to Gull Rock in diagenetically enhanced banding, silica as opal CT, and prominent *Spirocolpus*.	Late Priabonian
Perkana Member	Soft spongolitic mudstone, highly siliceous (opal A in pristine spicules). The fossil dominances of the Gull Rock are less apparent here. Banding is strong but less apparent than in the Gull Rock or Tuit.	Priabonian
Gull Rock Member	Strongly hard-soft banded and highly siliceous (opal CT) grey-black fossiliferous mudstone and marl. Faunas dominated by infauna (gastropod *Spirocolpus*, crustacean burrow *Thalassinoides*) as well as sponges.	Priabonian
Tuketja Member	Thin glauconitic and calcareous mudstone, penetrating and enhancing the colour of the unit below.	Early Priabonian
Tortachilla Limestone, "Upper Member" or "Glauconitic Limestone Member".	Fossiliferous, centimetres-thick glauconitic limestone, condensed and entangled in multiple hard grounds, and dominated in different patches by the bryozoan *Celleporaria* and the gastropd *Spirocolpus*, both strong indicators of a sudden nutrient shift in the eutrophic direction.	Early Priabonian
Tortachilla Limestone, "Lower Member" or "Polyzoal Limestone Member"	Bryozoan goethitic sands grade upward to richly fossiliferous limestone, highly diverse in molluscs and bryozoans. No aragonite is preserved. This unit is essentially the South Maslin facies enriched with a well-skeletonised biota in a stable, "normal", oligotrophic marine environment.	Late Bartonian
South Maslin Sand	Marginal marine ("estuarine") sands, cross-bedded and clay-draped, glauconitic and rich in goethite pellets. Sparse marine body fossils, common burrows. Being difficult to distinguish in cuttings, it is sometimes lumped with the North Maslin in the subsurface.	Late Bartonian
North Maslin Sand	Sands, cross-bedded and almost all quartz, gravels also, all ultramature, and carbonaceous clays usually bleached white. Environments include palaeochannels, braided streams and fluviolacustrine.	Lutetian-Bartonian

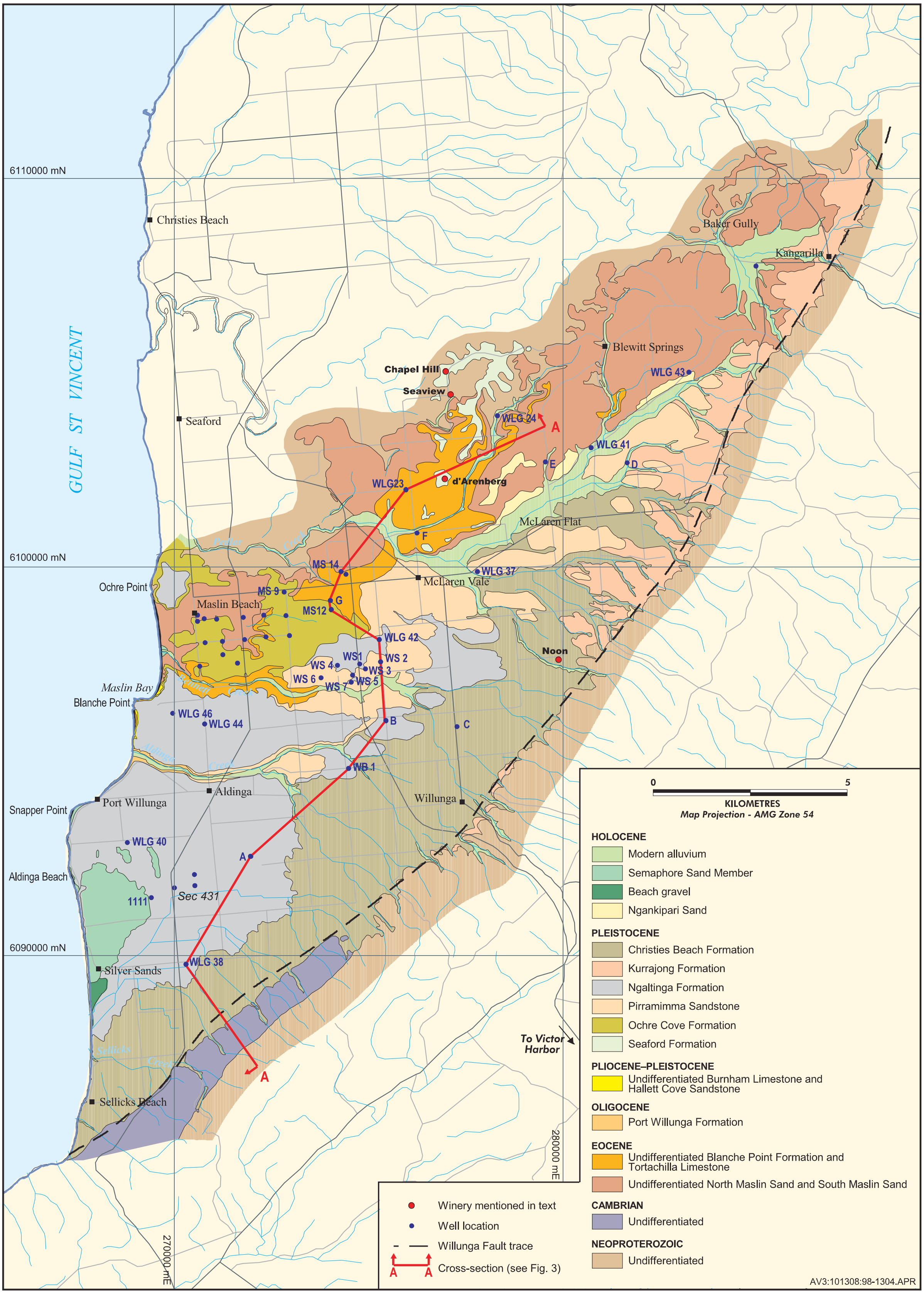


Figure 4 ***(a)*** *Fairburn's (1998) geological map of the Willunga Embayment. Aspects of Pliocene-Holocene (late Neogene) lithostratigraphy are contentious and some use of names is not resolved.*

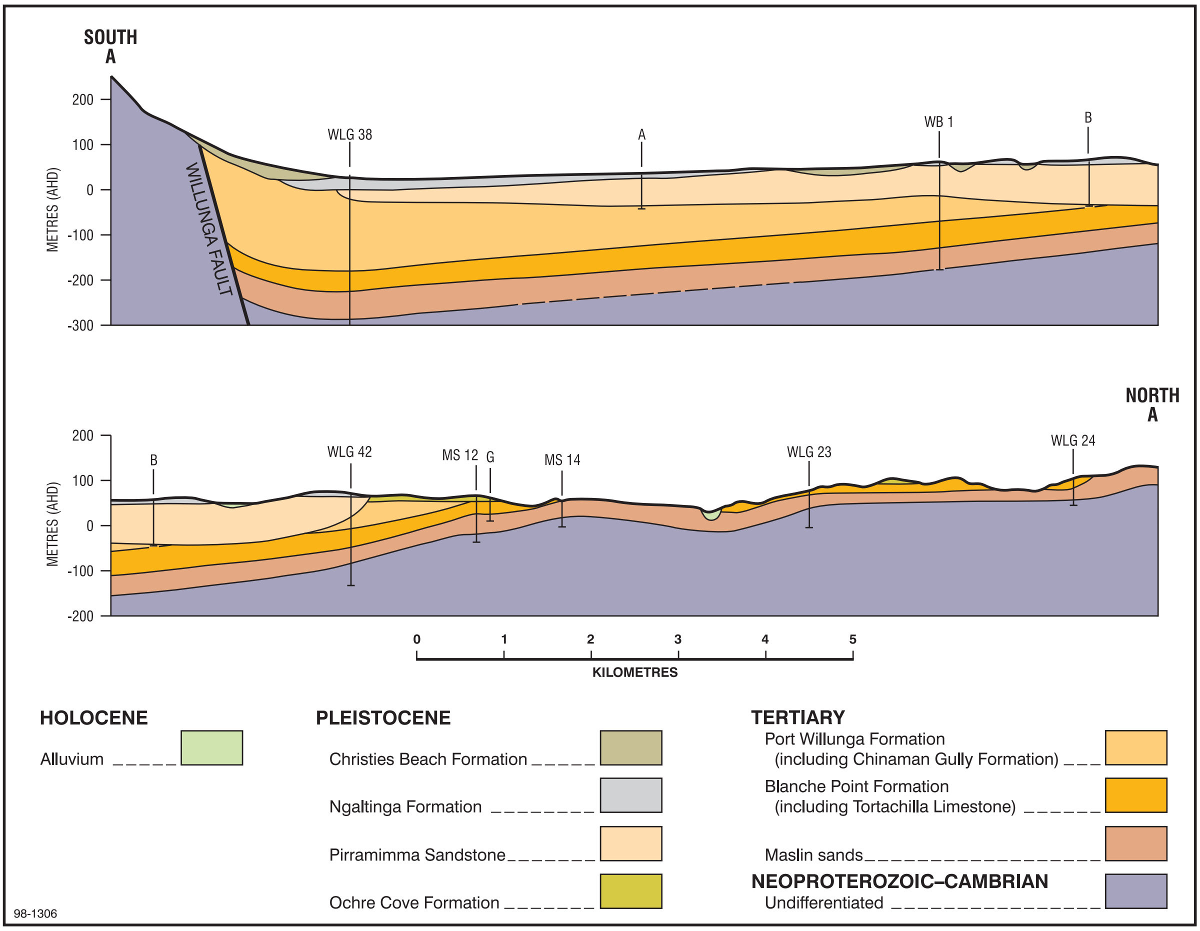


Figure 4 ***(b)*** *Fairburn's (1998) geological section of the Willunga Embayment.*

Late Palaeogene Stratigraphic Succession

Base of section

The Cenozoic succession unconformably overlies deeply weathered Neoproterozoic to early Cambrian, folded and cleaved, low-grade metasedimentary rocks of the Adelaide Geosyncline. In the Maslin sand quarries, Carboniferous-Permian sediments of the Cape Jervis Formation (diamictite and glaciolacustrine sediments with dropstones) underlie the Cenozoic. Similar to exposures at Hallett Cove to the north, they are more thoroughly weathered; for example, comprehensively kaolinised boulders are easily recognised as glacial erratics of Delamerian granite. On the margin there is an angular unconformity on deeply weathered Neoproterozoic bedrock (Fig. 6a). The weathered zone under the Cenozoic basin can be tens of metres thick, and Lindsay (1981) discussed difficulties in distinguishing the weathered zone from sedimentary clays in the subsurface. The bleached Cape Jervis Formation at Maslin Bay has Eocene borings, perhaps by insects or crustaceans (Glaessner and Pledge, 1985).

North Maslin Sand

In this district there is a reasonably clear succession of North Maslin Sand, of fluviatile and lacustrine facies, and marginal-marine South Maslin Sand. More regionally, the lower part of the succession in the St Vincent Basin is a mixture of siliciclastics and lignitic deposits, some clearly non-marine, others clearly marine. As a first approximation the fluviatile sands and gravels are North Maslin Sand, the clearly estuarine-marine sands are South Maslin Sand, and the lignitic strata are Clinton Formation. These facies are believed to recur up the section near the basin margins and in marginal pockets (e.g., Glaessner, 1953; Stuart, 1969; Daily et al., 1976; Cooper, 1979; Alley and Lindsay, 1995), but unambiguous identification is difficult.

The cross-bedded quartz sands and gravels of the North Maslin Sand are fluviatile and filling palaeochannels (Stuart, 1969; Pain, 1988; Alley and Lindsay, 1995). The sands are <30 m thick. Clays account for less than 10% of the deposit. The biggest clay lens, a 'billabong swamp deposit' (Lindsay, 1981), was perhaps 100x45x3 m. This and

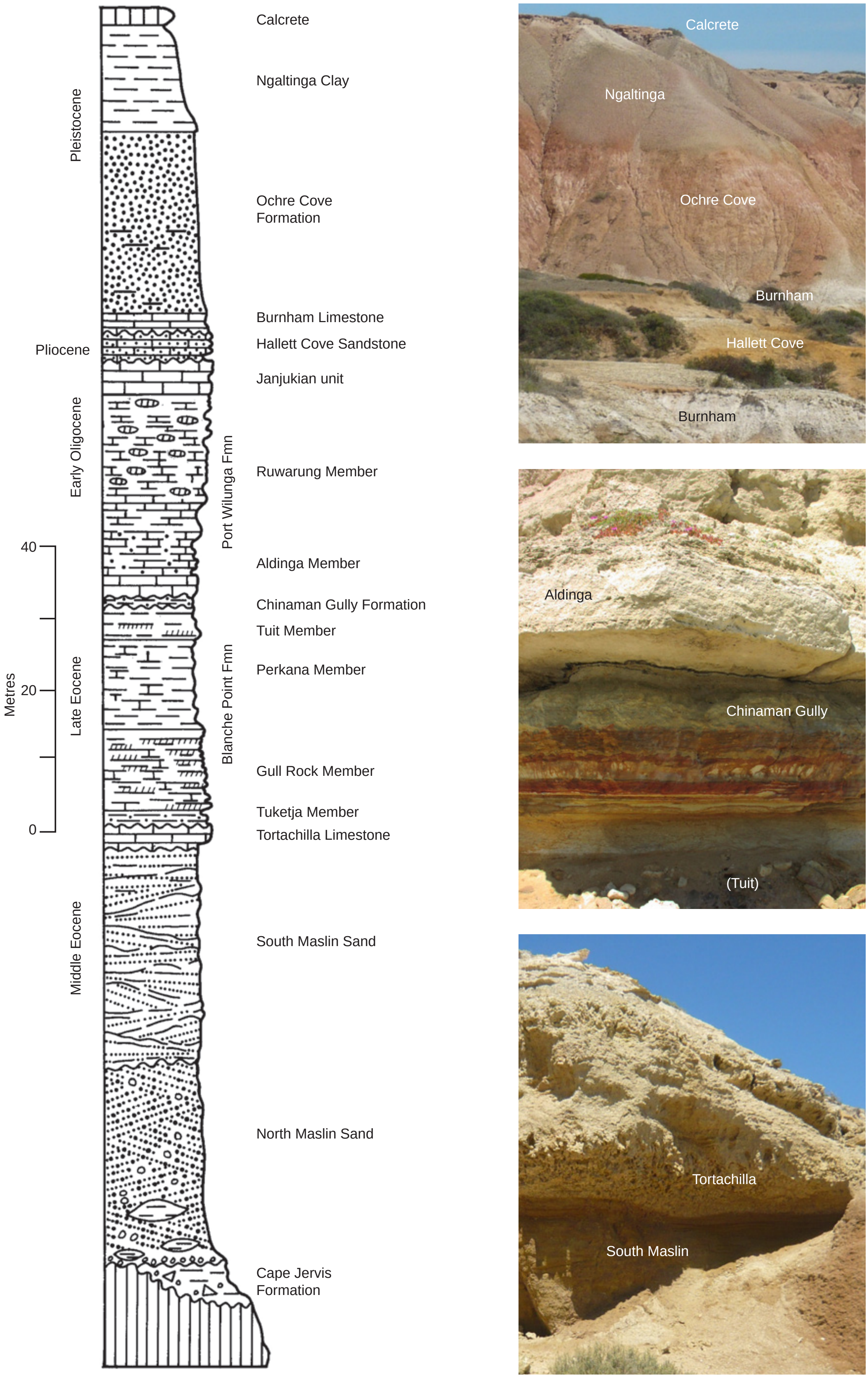


Figure 5 *Lithostratigraphic succession, from Maslin Bay to Port Willunga. The column is after Cooper (1983). (The unconformity frequently shown at the top of the South Maslin Sand is a strong solution effect.)*

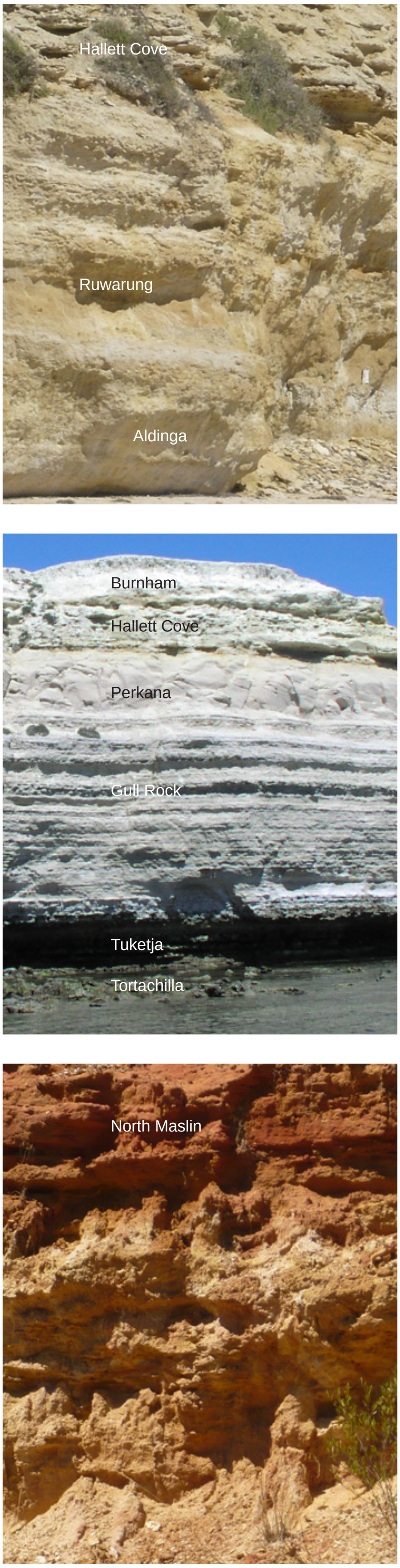


Figure 5 Cont.

a similar deposit at Golden Grove are the sources of well-preserved macrofloras and microfloras (Lange, 1970; McGowran et al., 1970; Christophel and Blackburn, 1978; Christophel and Greenwood, 1987; Scriven, 1993; Alley and Broadbridge, 1992; Alley and Lindsay, 1995). This was one of the several rainforests of southern Australia (McGowran and Hill, 2015).

The overlying South Maslin Sand is marine down to its base; in drilling, marine evidence tends to cut out at about the first downhole appearance of grey clays (Lindsay, 1981).

At the upper contact at Christies Beach, Glaessner and Wade (1958) noted a 'laterite', which was dismissed by Daily et al. (1976) as due to much younger ferruginisation. However, bleaching was well developed in outcrop at Maslin Beach under the South Maslin transgression, and a parallel profile was encountered during drilling which recalled to Lindsay (1981) the buried lateritic profile observed by Glaessner and Wade. Brown (1961) described scouring preceding deposition of the next unit, these cuts truncating the profile.

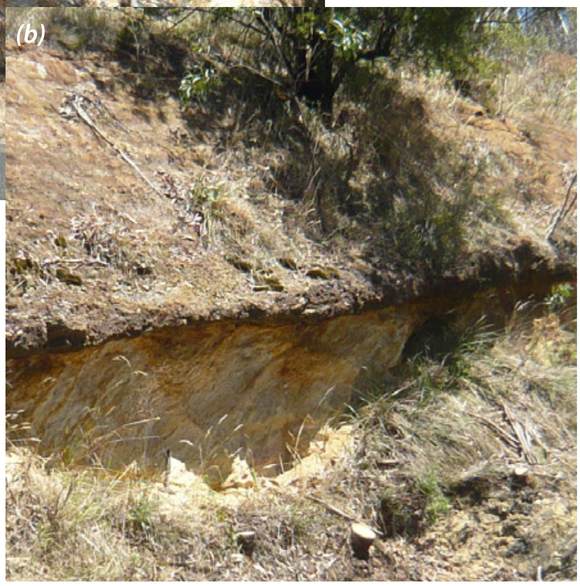
South Maslin Sand

The stratotype (Fig. 7) comprises cross-bedded sands, brown, purple and green in their exposed and oxidised state. In the subsurface they are dark grey-brown, carbonaceous, and pyritic (Lindsay, 1969). There are many ferruginous grains, probably mostly goethite, some presumably from the nearby land surface, others from the North Maslin Sand. Still others, and coatings on grains, seem to be oxidised glauconite, for there are numerous sand-sized faecal pellets and aggregates of glauconitic and goethitic clay (Lindsay and Alley, 1995). The unit exceeds 40 m in thickness in the Adelaide Sub-basin and Willunga Embayment.

Foraminifera, rare towards the base, are more common and diverse upwards and include planktonics (Lindsay, 1981), as well as echinoid spines, sponge spicules, bryozoans, and a small fauna of 'upper Eocene' molluscs (Ludbrook, 1963, 1969). Several kinds of trace fossil include *Gyrophyllites maslinensis* (Glaessner and Pledge, 1985). Shark teeth, sometimes common (Pledge, 1967), and *Thalassinoides* occur at the top.

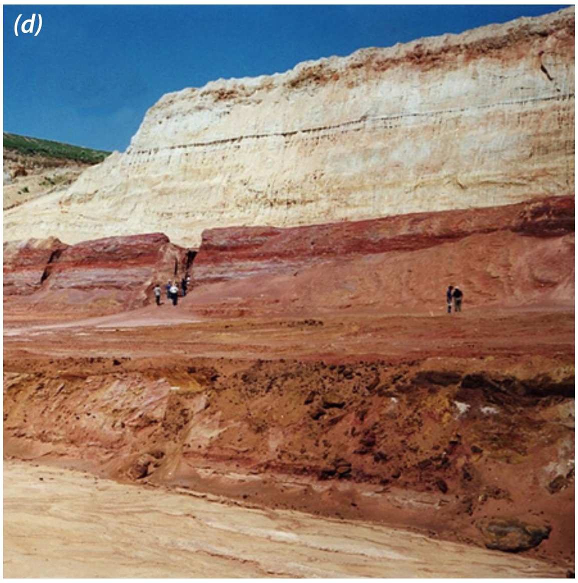
The quartzose and goethitic lithology show that the South Maslin and Tortachilla are parts of the same phase or cycle, shark tooth and *Thalassinoides* concentrations marking the flooding surface and the Tortachilla the highstand. The South Maslin environment was estuarine with oxygen and

(a) *The great unconformity at the base of the Cenozoic succession, south side of Chapel Hill road. North Maslin Sand is above Sturtian (Neoproterozoic) silts deeply weathered during the Early Eocene climatic optimum.*



(b) *A filled palaeochannel cut into the deeply weathered bedrock and feeding into the swampy North Maslin environment. The basal siliciclastics are the coarsest and the most heavily iron-cemented; and they would become the prominent ferricrete, a residual capping, in a future topographic inversion by differential erosion. The road cutting is on the Kangarilla Road above Clarendon, near the Bakers Gully turnoff.*

(c) *Boulders, commonly referred to as ferricretes or ironstones, have been assembled at the entrance to the Rocla (Maslin) Quarry near Maslin Bay. They are popular in the district as public and private ornaments. They are not residuals from a soil horizon but intraformational and diagenetic clots, as in 6(d).*



(d) *As photographed by Olliver in 1994, the North Maslin Sand in the Maslin Quarry displayed strongly contrasting colours. The Early Eocene deep weathering also concentrated the iron to be injected subsequently into the sands accumulating in the Middle Eocene. Note the large clot of strongly cemented (ferruginised) sand at right, and several hollows left by removed clots at the same horizon at the top of the dark red section.*

Figure 6 *North Maslin Sand.*

salinity stresses. The Tortachilla transgression begins at the base of the South Maslin Sand.

Tortachilla Limestone (*Figs 7, 8*)

A sandy (quartzose-goethitic), rubbly limestone has the first abundant body fossils in the section, dominated by epifaunal assemblages of foraminifera, bivalved molluscs and bryozoans; also brachiopods, infaunal echinoids, gastropods and burrows. Bryozoans are very diverse: perhaps 300 species in all with the Cheilostomata: Cyclostomata ratio at ~3:1 (Schmidt and Bone, 2003). Buonaiuto (1979) recognised three assemblages among the diverse, bivalve-dominated molluscs: *Chlamys-Hiatella, Dimya,* and *Dosina-Turritella-Chlamys*. Nautiloids include *Aturia clarkei* and *Cimomia felix* (Glaessner, 1955; McGowran, 1959).

The Tortachilla transgression is a widespread marine horizon in the Palaeogene of southern Australia. It is also an horizon of warming marked by an incursion of tropical-type neritic foraminifera (i. al. *Linderina glaessneri*, *Halkyardia bartrumi*) brought in on the Leeuwin Current (McGowran et al., 1997b).

Reynolds (1953) distinguished a Polyzoal Limestone Member and a Glauconitic Limestone Member. James and Bone (2000) identified three grainy, progressively bioturbated units separated by hardgrounds, the glauconite seeping down from the Tuketja member above (Fig. 8). The first and second units are part of the South Maslin-Tortachilla package. The third, muddier unit has a strongly recrystallised hardground with calcitic casts of the (originally aragonitic) turritellid gastropod *Spirocolpus* and the bryozoan *Celleporaria*.

Blanche Point Formation (*Figs 8, 9*)

There are four members (Jenkins et al., 1982). Jones and Fitzgerald (1984, 1986, 1987) studied the distribution of opal-A, opal-CT, smectite, calcite and aragonite, and other minerals. In strong contrast to the Middle Eocene and Early Oligocene carbonates,

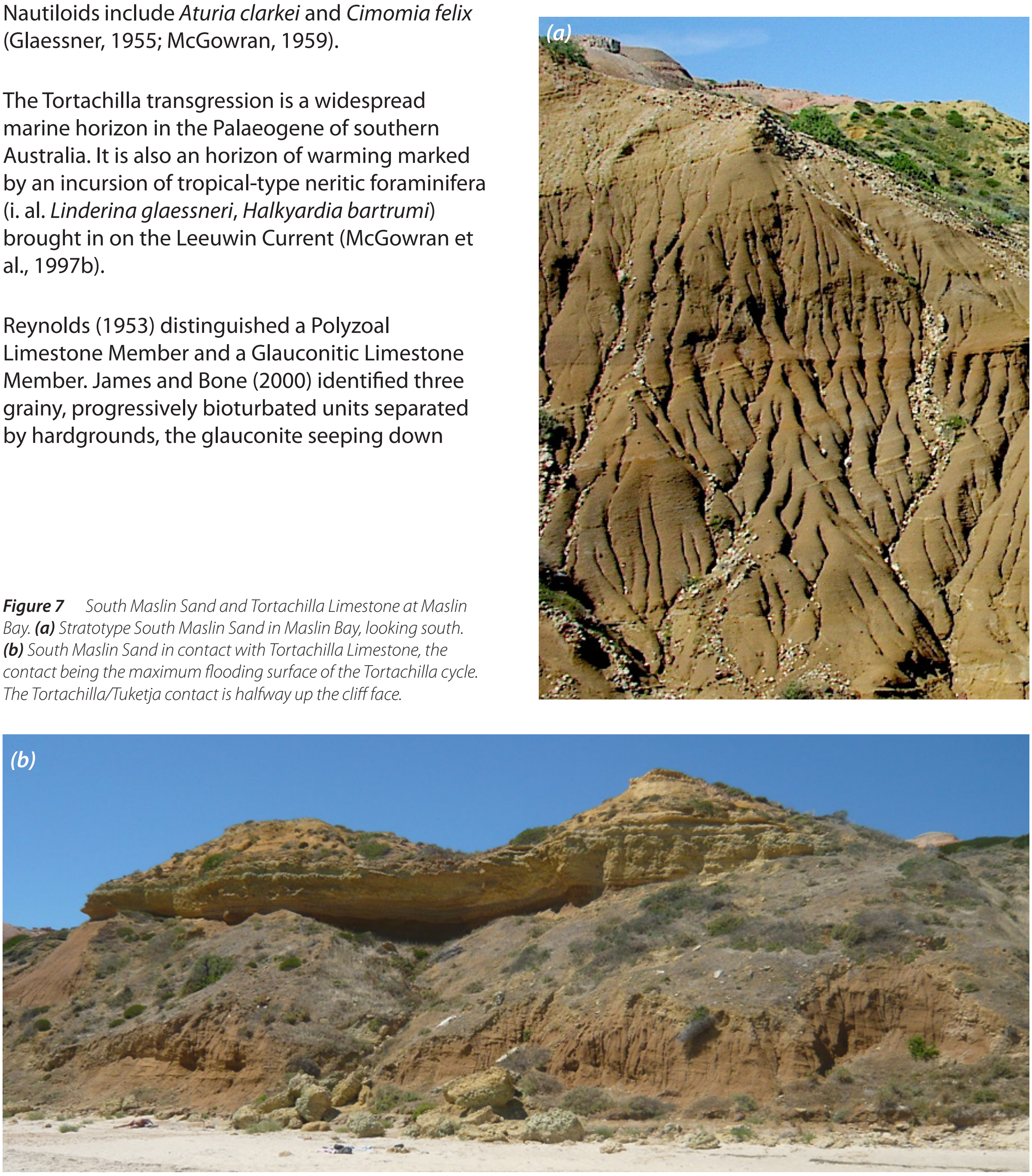
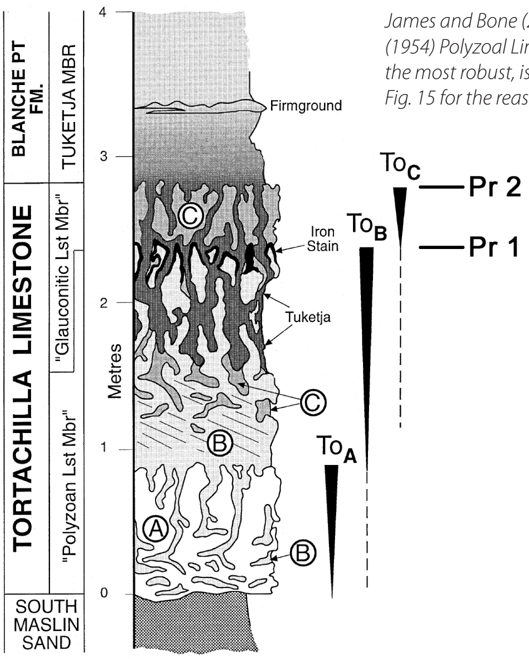
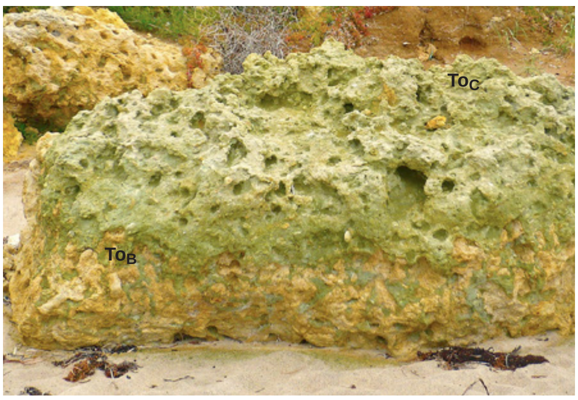


Figure 7 *South Maslin Sand and Tortachilla Limestone at Maslin Bay.* ***(a)*** *Stratotype South Maslin Sand in Maslin Bay, looking south.* ***(b)*** *South Maslin Sand in contact with Tortachilla Limestone, the contact being the maximum flooding surface of the Tortachilla cycle. The Tortachilla/Tuketja contact is halfway up the cliff face.*

Figure 8 Two views of the hardground on the 'upper member' of the Tortachilla Limestone at low tide. The early Late Eocene (Priabonian) hardground To_C is being exhumed, not created as a modern wavecut platform, as the very soft Tuketja Member is being undermined (deep shadow at the base of Gull Rock and the Point). Blanche Point owes its existence and location to the gently dipping hardground.



James and Bone (2000) distinguished three Tortachilla units each with a hardground. Reynolds' (1954) Polyzoal Limestone Member (at left) equals To_A plus To_B. The third unit, To_C, diagenetically the most robust, is actually the highly condensed remnant of the Browns Creek cycle or package (see Fig. 15 for the reasons).

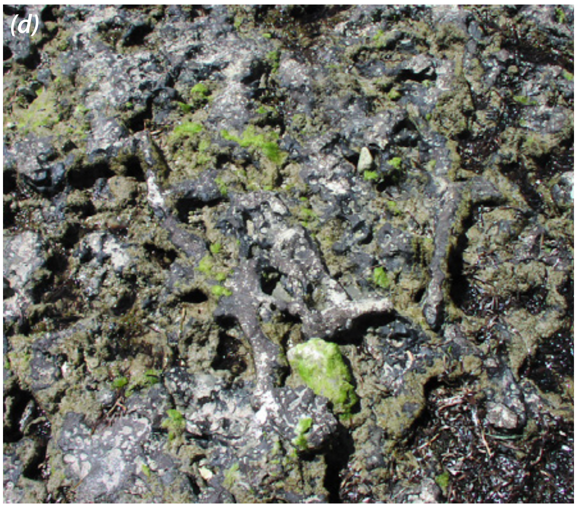


A boulder displays the two members of the Tortachilla Limestone named by Reynolds (1954), the field of view is about one metre across. The glauconite belongs mostly if not entirely to the overlying Tuketja Member, as sketched at lower left.

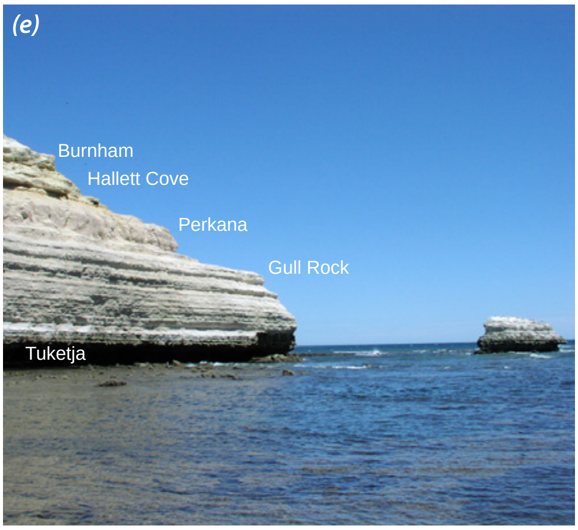
***(a)** Tuit Member, marking the return of opal-CT, and overlain by the Chinaman Gully Formation. The scale is Stephen Pekar, paleoceanographer at Queens College, New York.*

***(b)** Tuit Member, characterised by the gastropod* Spirocolpus *with the aragonitic shells preserved.*

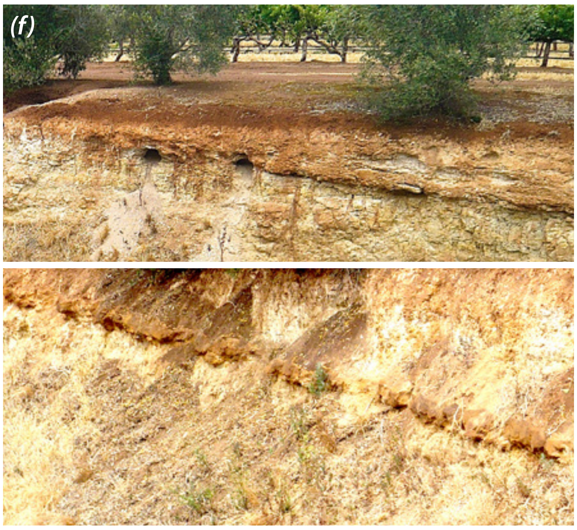
***(c)** The Gull Rock Member at Perkana Point, with hard-soft bands and the silica in the opal-CT state, is overlain by the Perkana Member, also with layering but with the opal remaining in the opal-A state in pristine spicules, and no diagenetic segregation.*



***(d)** Silicified burrows of* Thalassinoides *in the Gull Rock Member. Whether* Thalassinoides, Spirocolpus, *sponge gardens or the bryozoan* Celleporaria *are dominant is a function of balance between nutrient supply and oxygen stress.*



***(e)** Blanche Point and Gull Rock. The waves are breaking on the upper hardground of the Tortachilla.*



***(f)** Two ironstone bands in the Blanche Point Formation in a cutting on Field Street, McLaren Vale. Although detailed correlation with the coastal section is unavailable, these bands plausibly originated as layers of particularly rich organic muds with higher-than-usual levels of ferrous iron.*

Figure 9 Blanche Point Formation.

the Blanche Point Formation contains a variety of fossils with preserved aragonite.

Tuketja Member. This is a calcareous, glauconitic clay with bands of limestone including rafts of the relatively high-nutrient, opportunistic, biohermal bryozoan *Celleporaria* (which may belong to the upper Tortachilla), the nautiloids *Cimomia* and *Aturia*, and Buonaiuto's (1979) no less than five molluscan assemblages: *Turritella-Dosina, Spirocolpus-Dimya, Pycnodonte-Chlamys, Dimya-Chlamys, Spirocolpus-Trophon*. The clay minerals are mostly smectites with some interlayered illite. The glauconite is well-ordered with a few expandable layers. The sponge spicules are clear: pristine opal-A.

Gull Rock Member. This is made up of hard (silica-rich)-soft (more calcareous) couplets, mostly 10-50 cm thick and containing smectite, clinoptilolite and quartz. The silica is opal-CT, except for the clear and transparent spicules in the lowest metre which are pristine opal-A. The opaqueness (or sometimes translucence) of spicules is due to coatings of opal-CT lepispheres, which are also abundant in the matrix and as internal moulds of macrofossils. The couplets are enhanced by the rearrangement of silica to form a silica-enriched and silica-depleted layer. Quartz grains throughout the Blanche Point are angular and transparent, with sharp and uniform extinction under crossed polars, and no evidence of significant frosting or rounding (in contrast to South Maslin sand but resembling quartz from known volcanic ash). The colours are grey-green, darkening upward to almost black in some layers.

Although the overall macrofossil content is high, actual assemblages are rather low in diversity. Buonaiuto (1979) distinguished a *Phygraea* and a *Spirocolpus-Dimya-Ledella* molluscan assemblage. He also observed that the shift from Tortachilla to Blanche Point biofacies was a shift from high diversity to high dominance, from epifaunal-bivalve-dominated to low diversity, infaunal-gastropod-dominated assemblages. In the upper and darker part there tends to be still higher dominance and low diversity, with different layers bearing immense numbers of shallow-infaunal gastropods (*Spirocolpus*), dense burrowing networks (*Thalassinoides*) or sponges. Opal-CT concentrations are found associated with all three. Nautiloids and penguin bones (Jenkins, 1974) are found at various horizons (Fig. 10).

Perkana Member. This is the 'soft marls' of earlier literature. It is a succession of opal-A-rich calcareous clays with abundant, pristinely glassy sponge spicules. The banding seen in the Gull Rock clearly continues but is not enhanced by silica-enrichment and hardening. This member has less clinoptilolite but contains the only kaolinite in the Blanche Point Formation. The macrofossil content is much less, with a big drop in calcareous macrofauna even though aragonite is preserved.

Tuit Member. This member, usually poorly exposed, marks a return to the Gull Rock facies—opal-CT-rich banding with horizons of dominant *Spirocolpus*. The upper contact with the Chinaman Gully Formation is a downcut and backfill. In the Adelaide Sub-basin up to 50 m of section were cut out, removing the Perkana and Tuit Members.

Chinaman Gully Formation

This formation is characterised by bright ochre colours in lower outcropping sands and clays. Inland, in the subsurface, it is dark-coloured, carbonaceous and lignitic (its distinctiveness can be blurred by reworked silica) but identified confidently by identity of interval (Lindsay, 1981). Fossils include leaves and a poor fauna of brackish-type foraminifera. However, the greenish upper part has common dwelling burrows and foraging burrows and a new marine cycle begins here (Reynolds, 1953), not at the top of the formation.

In and around the city of Adelaide the Chinaman Gully includes the Tandanya Sand Member as an incised valley fill. The Perkana Member is missing there due to erosion and sometimes the Chinaman Gully rests on the lower Gull Rock or Tuketja. Lindsay (1981) demonstrated that up to 50 m section was cut out immediately preceding coarse siliciclastic infilling. Simultaneous downcutting in the western St Vincent Basin on Yorke Peninsula was followed by coarse siliciclastic fill (the Quartoo Sand). In the Willunga Embayment the unit is 7 m thick or less (Cooper, 1979).

The upper contact is with shoreface sands of the Aldinga Member and the marine transgression already was in progress. Belonging with the new cycle, not the old, the Chinaman Gully is transgressive, not regressive as frequently labelled.

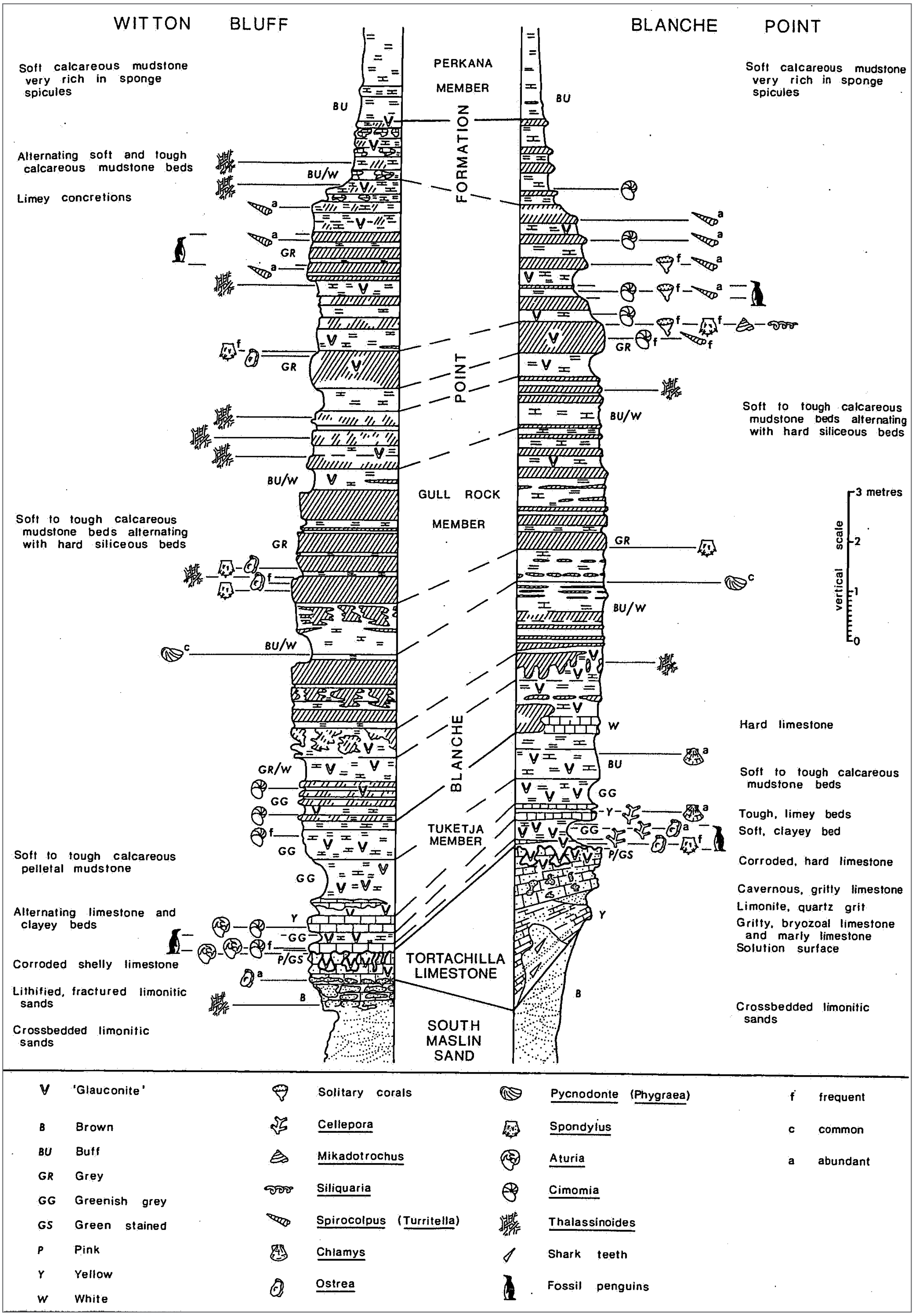


Figure 10 *Palaeontological log by R.J.F. Jenkins (Jenkins et al., 1982) of the lower members of the Blanche Point Formation at Blanche Point and Witton Bluff (Noarlunga Embayment).*

Port Willunga Formation (Fig. 11)

Tate's (1879) Lower Aldinga Series included the Port Willunga section. After the greys and greens, the macrofaunal dominances and the strange microfaunas of the poorly ventilated Blanche Point Formation, this formation marks a strong shift to the well-ventilated, yellow-brown, bryozoan-rich, neritic carbonate facies with some glauconitic horizons. The formation includes all the carbonates up to the regional unconformity in the middle Miocene. Its counterpart in the western part of the basin is the Port Vincent Limestone on Yorke Peninsula. Lindsay distilled many years' experience into the following succession of facies and ages, most remaining informal and given the regional stage names:

8. Port Willunga Formation above Munno Para (Balcombian-Bairnsdalian)
7. Munno Para Clay Member (Balcombian)
6. Port Willunga Formation below Munno Para (lower Balcombian and Batesfordian)
5. Longfordian Stage unit
4. Upper Janjukian unit (basal Miocene)
3. Lower Janjukian Stage unit (Oligocene)
2. Ruwarung Member; Janjukian and pre-Janjukian, post-Aldingan
1. Aldinga Member

These units mostly can be identified in Cooper's (1979) logs.

Aldinga Member. The stratotype is a fossiliferous sequence of bryozoal and foraminiferal sands and calcareous sandstones, muddy limestones, silts and clays (skeletal calcarenitic mudstones or 'marls'). The lower half is mostly quartzose and sandy; the upper half, more silty and clayey.

Notwithstanding very low numbers, planktonic foraminifera amount to ~20 taxa (Lindsay, 1981). However, Lindsay emphasised occasional specimens of *Praetenuitella insolita* and *Globigerinatheka* index which we believe to be reworked from the downcutting of soft Eocene sediments. Not reworked is an assemblage of *Cassigerinella winniana, Subbotina cf. linaperta, Praetenuitella aculeata, Turborotalia ampliapertura* and *Turborotalia increbescens*—the Aldinga transgression assemblage recognised in southern Australia (McGowran, 1989). Not reworked either is the assemblage of large benthics found consistently at the base of the Aldinga Member in all embayments and we agree that it is in place: *Linderina glaessneri*, *Halkyardia* cf. *minima*, *Crespinina kingscotensis* (Lindsay, 1967, 1981, 1985; Lindsay and McGowran, 1986). The assemblage marks a pulse of the Leeuwin Current.

Ruwarung Member. Soft, silty and clayey limestone, with fossiliferous cherts. Sponge spicules can be common elsewhere in the basin. The member continues almost to Port Wakefield where it grades to more quartzose and sandy chert-bearing Rogue Formation of Stuart (1969, 1970). It also becomes sandy on the eastern basinal margin (see below).

Figure 11 (a) *Port Willunga Formation, Lower Janjukian Member, on the footwall of the Willunga Fault at Sellicks Beach, overlain with low-angular unconformity by Burnham Limestone (white), possibly Kurrajong Formation, Ochre Cove Formation (partly mottled) and possibly Ngaltinga Formation (khaki knob).*

Figure 11 ***(b)*** *Port Willunga Formation, Lower Janjukian Member, looking east at low tide at Snapper Point, showing large cross-beds.*

Figure 11 ***(c)*** *Port Willunga Formation (Aldinga Member), Hallett Cove Sandstone, Burnham Limestone and Ngaltinga Formation at Port Willunga (the Ochre Cove Formation is absent). Offset on a normal fault is seen most clearly in the darkest of the brown layers (right side down). The overhanging Hallett Cove Sandstone (its base is close to the rail) is not displaced here but is tilted southwards. Sprigg (1942) spotted and quantified the contrast between more Miocene displacement and less post-Miocene; for Sandiford (2003) these pre-Pliocene movements were the compressional beginnings of the Sprigg orogeny.*

Its age is early Oligocene on the association of *Cassigerinella chipolensis, Guembelitria triseriata* and *Subbotina angiporoides*. The youngest planktonic foraminiferal event is top *Subbotina angiporoides*. Waghorn (1989) found a nannofossil assemblage at the top of the Ruwarung Member that indicated an age no older than the middle Oligocene zones upper NP23 and NP24 (Fig. 13), consistent with the foraminiferal evidence.

Lower Janjukian unit of Port Willunga Formation. At Snapper Point south of Port Willunga, cross-bedded bryozoal and sandy limestone make up this unit (Fig. 11b). In the Mile End bore west of Adelaide, there are bands of quartz gravel sands and calcareous sandstones above a 'conformable' contact with the topmost bar or nodule of spicular chert (Lindsay, 1981). Hard bands low in this unit are wholly or partly dolomitized in the northern Adelaide Plains; also in bore WLG-38 in the Willunga Basin. The top though is determined biostratigraphically by the top of one or the other of *Victoriella conoidea*, *Massilina torquayensis, Bolivinopsis cubensis*, or *Gyroidinoides* cf. G *alleni*.

Late Palaeogene correlation and age determination: biostratigraphy and chronostratigraphy

For a century or so, identifying the European Cenozoic series in southern Australia was very difficult because there were so few fossil links. Things improved when W.J. Parr found the Eocene planktonic foraminifer *Hantkenina* in western Victoria and at Maslin Bay (Glaessner, 1951; McGowran, 2012). Subsequent biostratigraphic advances came from using the microfossils, first the foraminifera and in due course the pollen grains, calcareous nannofossils, and marine dinocysts. But the traps and subtleties of biostratigraphy, biofacies and biogeography are still with us because the three main variables still pose the same old question: is the presence or absence of a species a signal of time, of facies or of geography? That problem recurs especially in the Blanche Point Formation.

Late Eocene and Early Oligocene chronologies are shown in Figures 12 and 13 and informative foraminiferal biofacies in Figures 14 and 15. Sweeping stratigraphic generalisations are displayed in Figure 16. Although regional bioevents are listed in Figure 12 alongside zones, oceanic planktonic zones do not function in these facies at these palaeolatitudes. Nor do Palaeogene regional stages work well without the necessary formal revision, which nobody working in the terrrestrial, neritic or pelagic domains has felt impelled to undertake. The informal regional packages, on the other hand, fit very well with putatively global sequence boundaries, and so they become the central stratigraphic entities.

Wilson Bluff transgression and package: base of the marine Eocene; age of the St Vincent Basin

The base of the marine later Eocene in southern Australia was firmly dated by correlation with the planktonic foraminiferal zone P12 or E11 (McGowran and Lindsay, 1969). The Wilson Bluff planktonic foraminiferal assemblage included *Globigerinatheka index* and others, *Acarinina primitiva, Acarinina bullbrooki, Subbotina frontosa, Planorotalites pseudoscitula, Turborotalia pomeroli, Dipsidripella danvillensis, Guembelitrioides nuttalli,* among others (McGowran and Lindsay, 1969; McGowran, 1989a, Fig. 3; Li et al., 2003). Since the Berggren-Pearson (2005) revision, the few specimens of *Guembelitrioides nuttalli* (previously '*Globigerinoides' higginsi*) become important, the top of this species defining the top of zone E10 and reported to fall within Chron C19r. In terms of the Antarctic zonation (Huber and Quillévéré, 2005) we are around the zone AE6/AE7 boundary, defined by first *Subbotina angiporoides.*

Calcareous nannofossil biostratigraphy is consistent with this dating (Shafik, in Davies et al., 1989). The lowest assemblage contains *Cyclicargolithus reticulatus, Chiasmolithus grandis, C. solitus, Discoaster barbadiensis* and *Neococcolithus dubius.* Relying on the absence of *Reticulofenestra scissura* (which then comes in) Shafik bracketed the assemblage by the two close events, base *C. reticulatus* and base *R. scissura*, and correlates this narrow interval with about the middle of the Martini zone NP16.

The age of the basin is the oldest biostratigraphic age of its oldest strata, the North Maslin Sand and Clinton Formation. The Wilson Bluff transgression did not reach the St Vincent Basin beyond some slight indications of estuarine facies, but the Lower *Nothofagidites asperus* pollen zone is found in the North Maslin Sand and this permits a direct correlation with the Wilson Bluff transgression. The North Maslin Sand may be Lutetian in part but is mostly Bartonian in age.

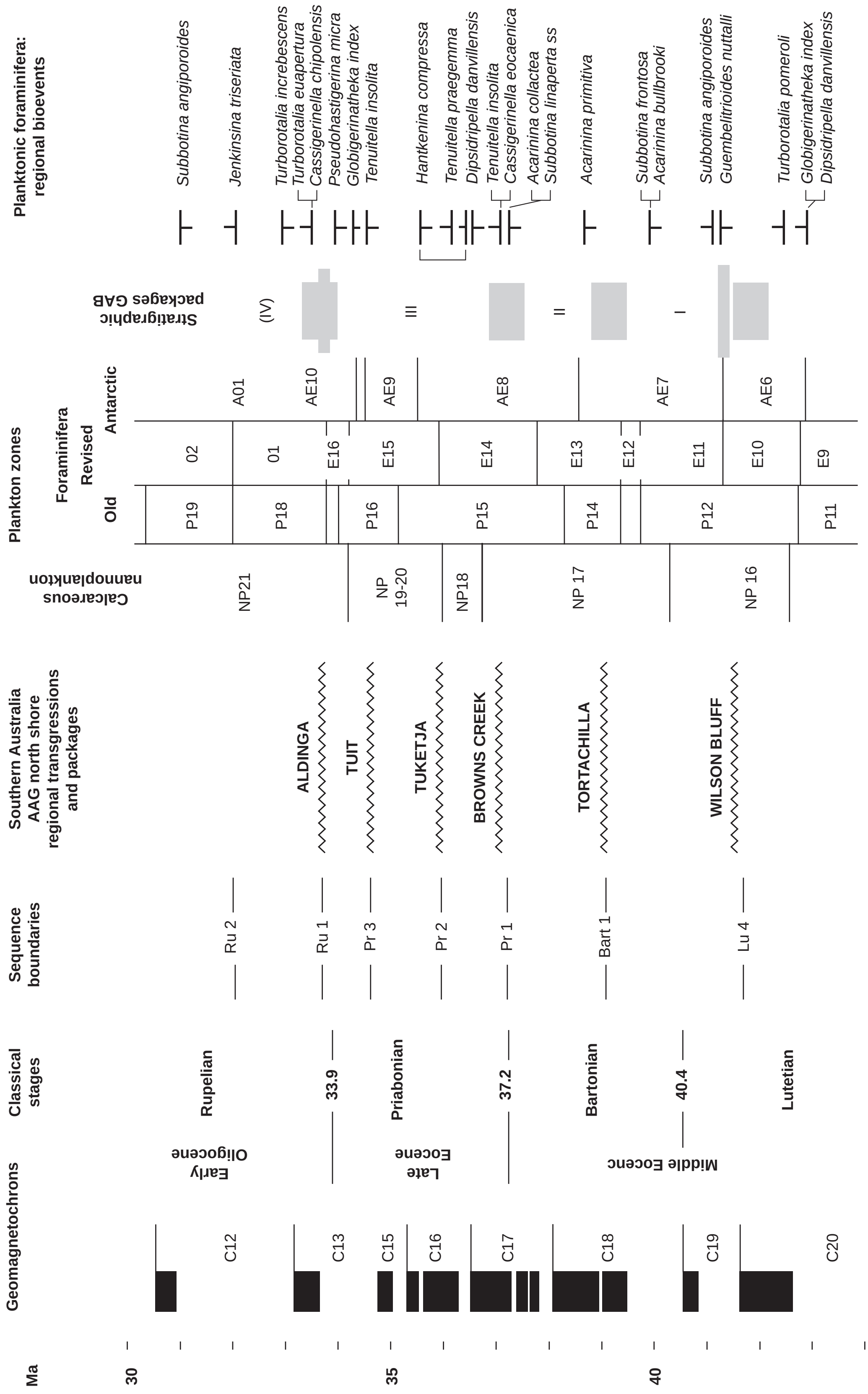


Figure 12 *Framework for chronology and correlation (McGowran, 2009a). Third-order sequences are from Hardenbol et al. (1998). The biostratigraphic framework for low-latitude and high-austral oceanic facies is from Berggren and Pearson (2005) and Huber and Quillévéré (2005) respectively. The regional bioevents in planktonic foraminifera, meaning lowest and highest occurrences of the respective species, are from numerous sources, including Li et al. (2003a, 2003b), McGowran et al. (2004), and Pearson et al. (2006). Stratigraphic packages in the Great Australian Bight Basin (GAB) are from Li et al. (2003a). Note that the numerical calibration here and in Figure 16 is slightly different from the calibration in Figure 13, which is more up-to-date; the differences do not matter here.*

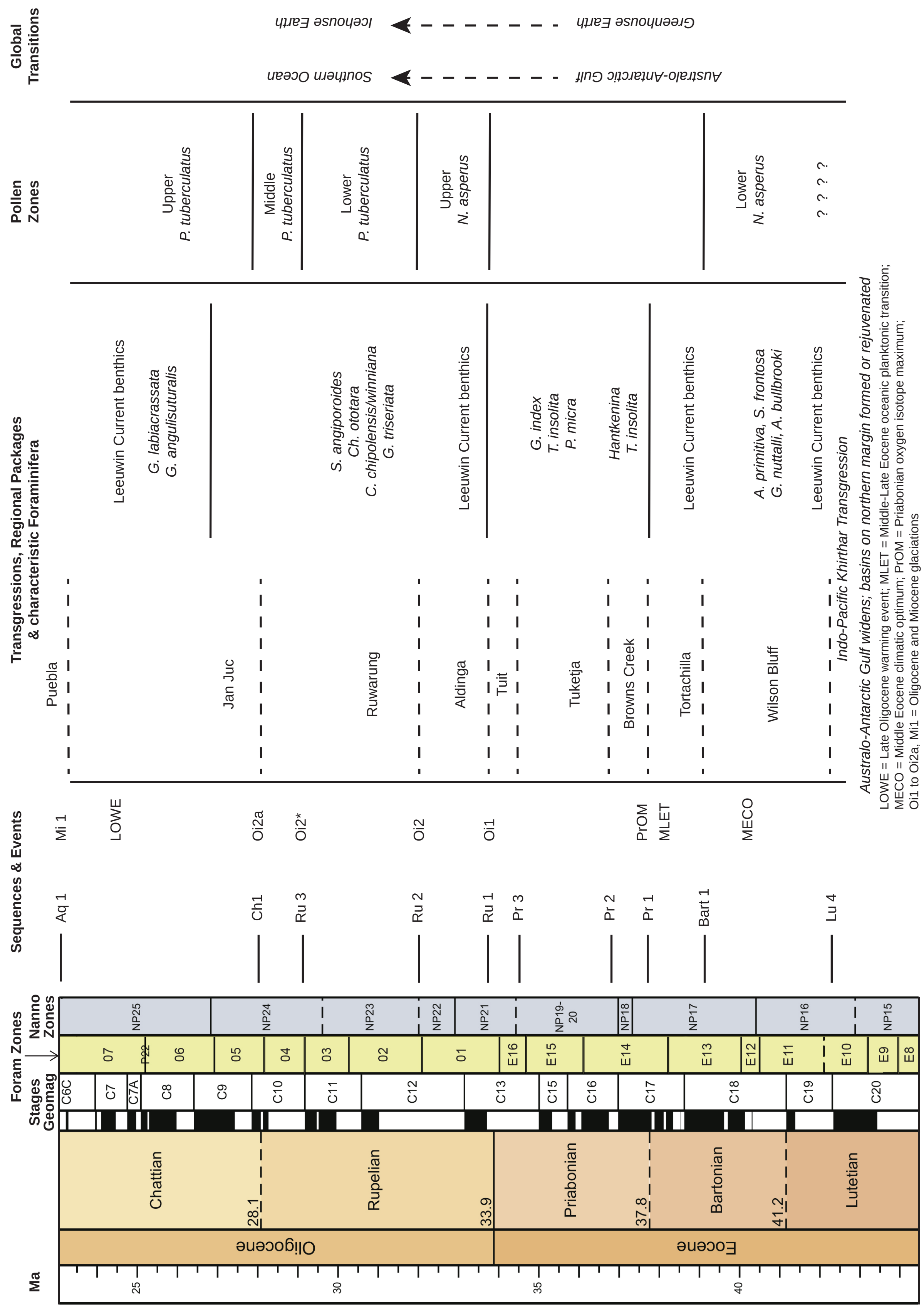


Figure 13 *Chronostratigraphic framework for the late Palaeogene (Lutetian to Chattian Stages). The time scale at left is from Geological Time Scale 2012 (Vandenberghe, Hilgen and Speijer, 2012). Putatively global sequences and events from Hardenbol et al. (1998), Vandenberghe et al. (2012), McGowran (2012), Kamikuri and Wade (2012) and Scher et al. (2014). The event labelled PrOM by Scher et al. is the strongest transient global cooling so far discovered prior to the buildup to Oi 1 at the close of the Eocene. 'Leeuwin Current benthics' mark episodic influxes of warmer-water benthic foraminifera. Similar biogeographic events recur through the Neogene as well (McGowran et al. (2004).*

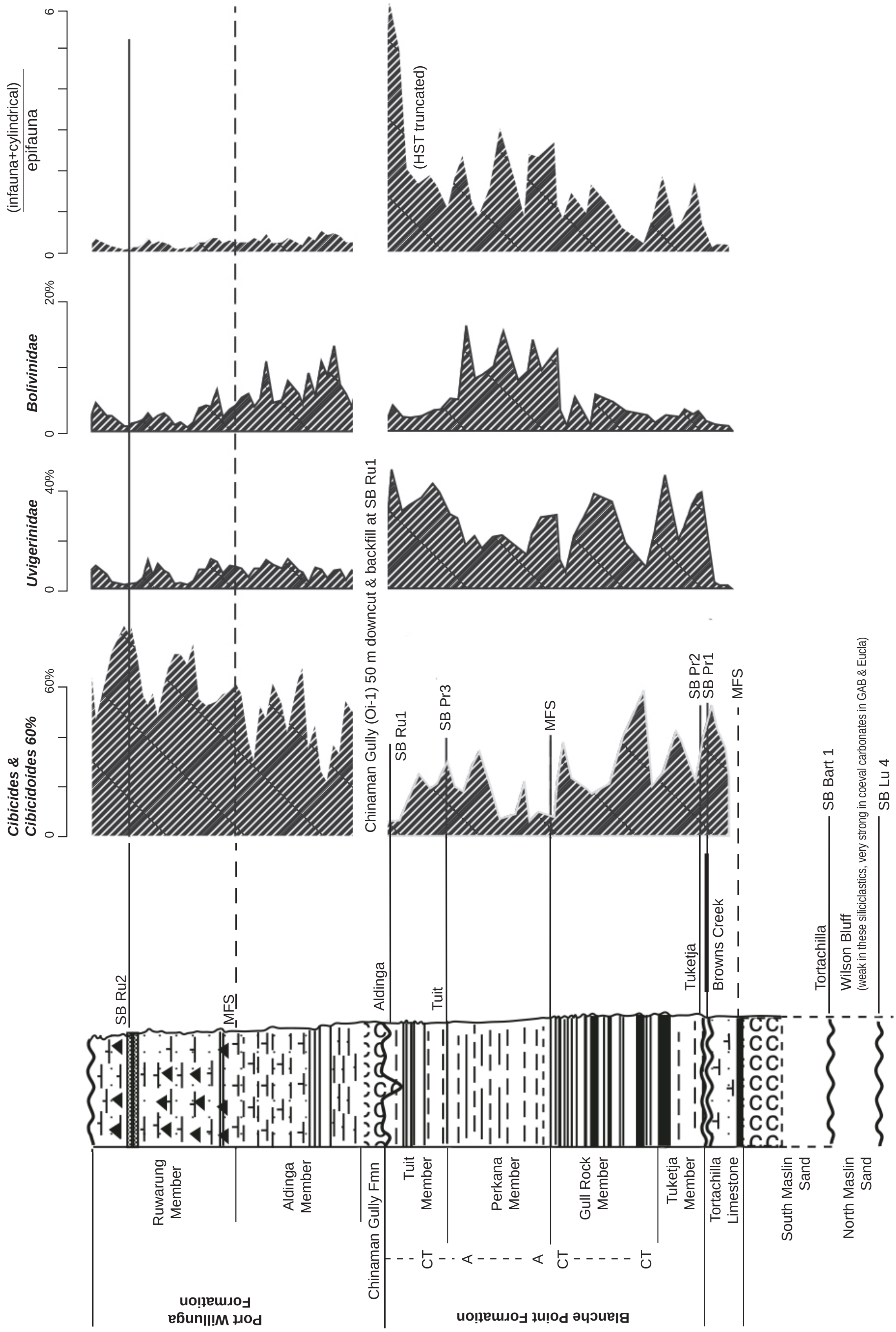


Figure 14 *Foraminiferal biofacies, Maslin-Aldinga Bays (McGowran, 2009a, Fig. 7). This figure contains much of the evidence for the stratigraphic generalisations in Figure 16. The two central points are (i) the great contrast between the Blanche Point and Port Willunga benthic foraminiferal assemblages and (ii) the fluctuations within the Blanche Point Formation. Both are to do with quantifying epifaunal and infaunal habitats, which in turn are to do with circulation and nutrients; and nutrients in sufficient amounts can be buried before they can be recycled, hence a sharp rise in infaunal numbers. SB, sequence boundary; MFS, maximum flooding surface; CT and A are states of opal, sharply segregated into transgressive and highstands, respectively; GAB, Bight Basin.*

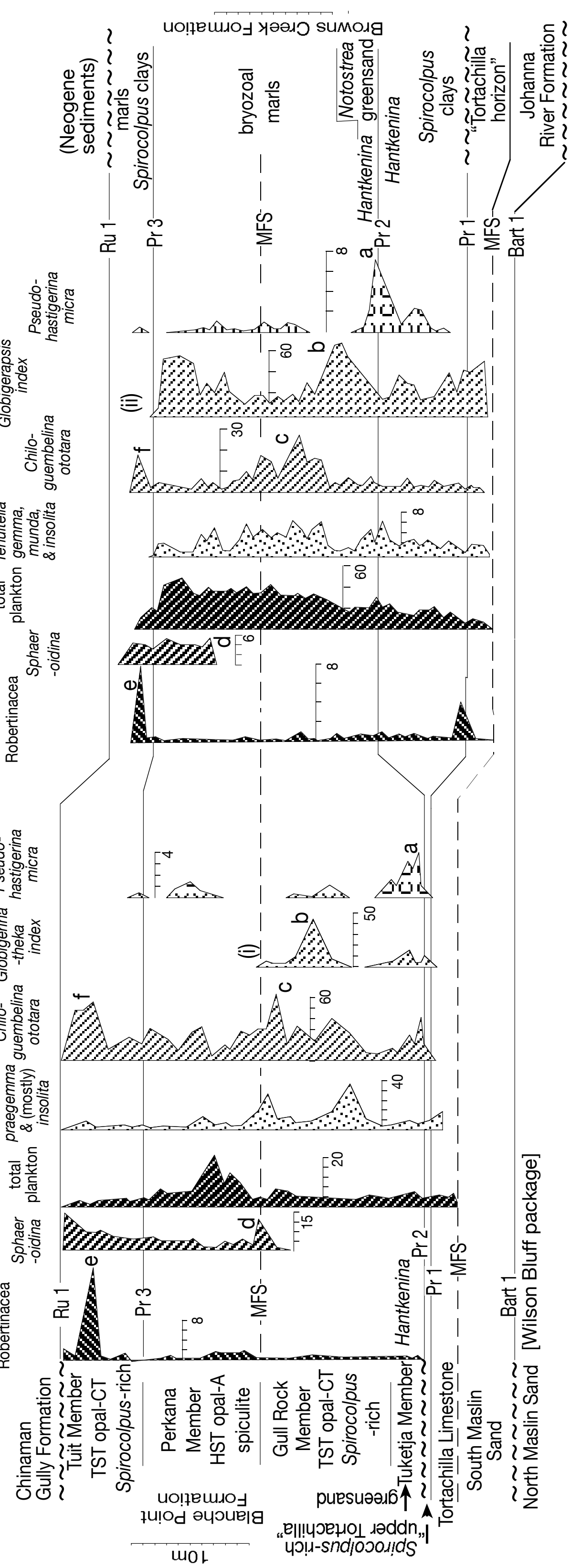


Figure 15 *Comparison of the biofacies succession at Maslin-Aldinga Bays and Browns Creek, sections 600 km apart on the north flank of the Australo-Antarctic Gulf. One section is in a basin of relatively restricted circulation and a poor planktonic microfossil record; the Victorian site was more open to pelagic influence (compare "total plankton"). This diagram emphasises strong parallels in biofacies or ecostratigraphy and in interruptions defining packages. Similarities and coeval shifts outweigh contrasts. Note the different scales in the relative abundances of foraminifera. Points* a *to* f *suggest coeval eco-shifts. Points* (i) *and* (ii) *indicate allochronous last occurrences in* Globigerinatheka index. *The main difference between the sections is the rich opal-A/opal-CT alternation at Maslin Bay and the absence of opal at Browns Creek. Although a strong tendency to dysaerobia under an estuarine circulatory tendency was very widespread in the AAG, silica fixation was a western tendency. After McGowran (2009a).*

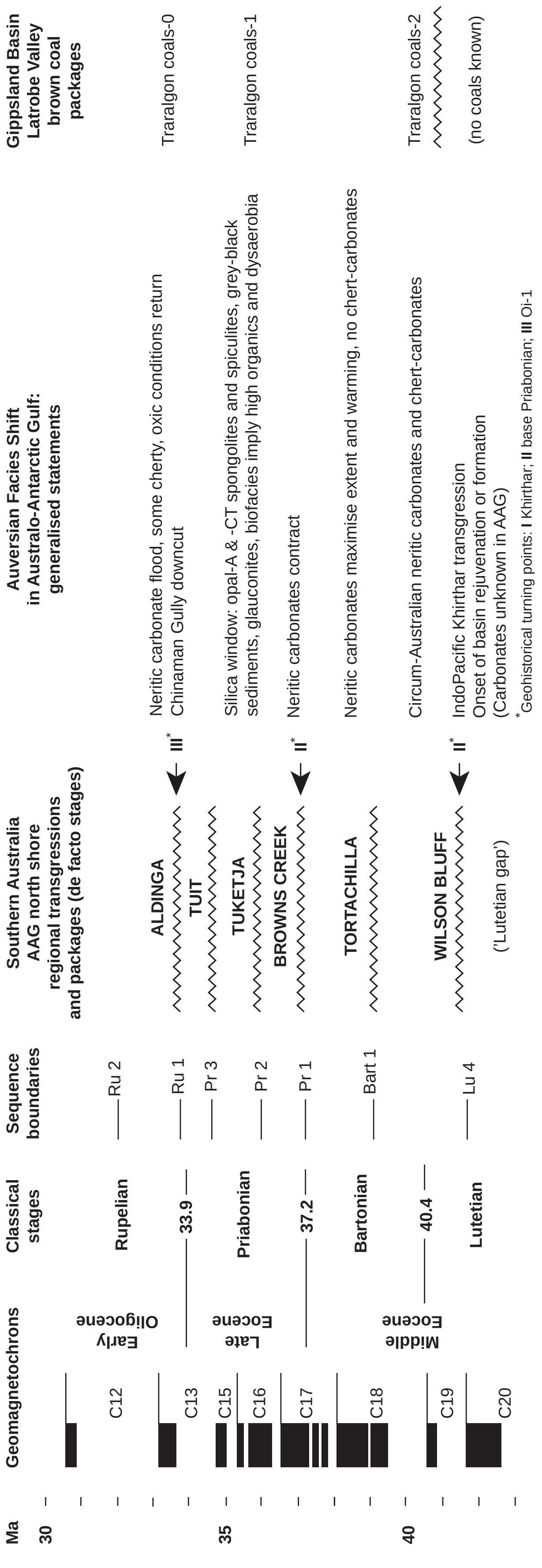


Figure 16 Bold summary statements capturing stratigraphic generalisations on the north flank of the Australo-Antarctic Gulf (McGowran, 2009a, b). In emphasising three turning points at or close to the Lutetian/Bartonian/Priabonian/Rupelian stage boundaries, the central claim is that the geohistory and biohistory recorded in the restricted and local Willunga Embayment has a very strong global component.

Tortachilla transgression and package

The planktonic foraminiferal assemblage includes *Globigerinatheka index, Acarinina collactea, A. primitiva* (rare), *Dipsidripella danvillensis, Subbotina linaperta, Turborotalia increbescens.* The warm-water, oligotrophic larger benthic foraminifer appear within the AAG for the first time on the inferred proto-Leeuwin Current. Although the phytosymbiotic orbitoid *Asterocyclina* reached the Bremer Basin but apparently no further into the AAG, a suite of warm-shallow-water forms spread from the Bremer Basin (Quilty, 1981) to the eastern Otway Basin—*Linderina glaessneri*, *Maslinella chapmani*, *Halkyardia bartrumi*, *Pseudopolymorphina carteri*, *Wadella rotaliformis*, *Sherbornina atkinsoni*, *Crespinina kingscotensis*. The neritic carbonate biotas attained peak diversities in echinoids, molluscs and bryozoans among others, especially as displayed in the Tortachilla Limestone in the St Vincent Basin.

Priabonian biofacies and correlations: recognising Browns Creek, Tuketja and Tuit packages

The biostratigraphic backbone for the Priabonian of the Australo-Antarctic Gulf is actually the comparison of the Maslin Bay foraminiferal biofacies (Fig. 14) with coeval patterns at Browns Creek in western Victoria (Fig. 15). Notice how the proportions of the higher taxa varying by tens of percent imply similar ecological swings in the availability of food and its burial, for the cibicidids are broadly epifaunal whilst the buliminids and bolivinids are broadly infaunal, and the infaunal/epifaunal ratio points to enormous environmental change from the Blanche Point to the Port Willunga. And at one step down, notice too the parallels between the biofacies shifts and (i) the switch from opal-CT to opal-A and back, and (ii) the switch from *Spirocolpus* facies to spiculites and back. The sequence-stratigraphic configuration in this restricted facies (note the very low plankton numbers) is reinforced when set against the open-marine profile from Browns Creek (note the much higher plankton numbers). These correlations show: (i) that several metres of *Spirocolpus* clays in Victoria are represented at Maslin Bay by the topmost few centimetres of the *Spirocolpus*-rich 'upper Tortachilla'; (ii) that the glauconite-rich Tuketja Member is coeval with the *Notostrea*-greensand at Browns Creek, the *Hantkenina* ingression appearing in both; (iii) that the *Spirocolpus*-rich Tuit Member also has its coeval equivalent at Browns Creek; and (iv) that fluctuations in foraminiferal numbers display matches that will be coeval (peaks labelled **a** to **f**).

The perils of allochrony

In the Willunga Embayment the planktonic foraminifer *Globigerinatheka index* disappears near the top of the Gull Rock Member below peak **b** and at level (i), whereas the same species at Browns Creek displays point **b** as the second of three peaks, disappearing at level (ii) (Fig. 15). *G. index* as an oligotrophic species reacted strongly in its numbers (tens of percent) to the variations in nutrient supply and circulation in the Gulf, and it left an allochronous record of highest occurrences. The extinction of the oligotrophic, planktonic coccolith *Discoaster saipanensis* defines the NP 19-20/21 boundary, at about the same level that *G. index* disappears globally at 34.3 Ma. Waghorn (1989) observed the very low numbers but he then naively drew the Eocene/Oligocene boundary at its local top, within the upper Gull Rock (and near the local top of *G. index*). At Browns Creek *D. saipanensis* occurs sporadically up into the Tuit package, again like *G. index*. Thus two oligotrophic species of quite different organisms disappear allochronously within the Gulf at about the same levels. Allochrony is well known in micropalaeontology for numerous species and specifically for *Discoaster saipanensis* (Aubry, 1995).

This digression into allochrony is necessitated by two recent miscorrelations. First, Opdyke et al. (2014), in their quest for the 'first detailed, high-latitude palaeotemperature record from a shallow-water site of the latest Eocene in the Southern Ocean', have taken Waghorn's correlation at face value. They have also trusted that no section of Tuit Member was cut out prior to the Chinaman Gully backfill (but the Tuit package has no highstand). Thus, their record of a cooling presaging Oi1 lacks the constraints essential to persuade that it is indeed that.

Second, Houben (2012) has recognised a greensand, a richly glauconitic horizon, from the Falkland Plateau to the Weddell Sea, the East Tasman Plateau, the Great Australian Bight and the *Notostrea* Greensand at Browns Creek in Victoria. We can add the Tuketja Member as being tightly correlated to Browns Creek. Such an oceanic chemostratigraphic event, stretching coevally around Antarctica, into the AAG and further still into the restricted-neritic St Vincent Basin and Willunga Embayment, is of immense global-environmental interest. However, Houben dated this event at Chron C16n.1n, about a million years too young, because of allochronous initial incomings of the key dinocyst species, *Schematophora speciosa,* in two sharply distinct biogeographic provinces.

Aldinga and Ruwarung packages

In the St Vincent Basin marine sedimentation soon resumed (the Aldinga transgression) in facies contrasting strongly with the latest Eocene. The contrast is seen most succinctly in the epifaunal/infaunal ratio of the neritic foraminifera (Fig. 14). Significant planktonic foraminifera (Lindsay, 1967, 1981, 1985; Lindsay and McGowran, 1986) include *Cassigerinalla eocaenica* (soon accompanied by *C. chipolensis), Dipsidripella danvillensis, Jenkinsina triseriata, Tenuitella praegemma, Turborotalia ampliapertura, T. increbescens, T. euapertura, Subbotina angiporoides, 'S. linaperta', Globoturborotalita labiacrassata.* (Sporadic records of *Globigerinatheka index,* given considerable weight by Lindsay, were reworked from the soft late Eocene strata during downcutting.) There is a brief but sharp warm interval, a Leeuwin pulse on the rebound after the Oi-1 chill, marked by the brief return of the warmer-water benthics of the Tortachilla assemblage: *Halkyardia, Linderina, Maslinella, Crespinina.*

Stratigraphic generalisations and global context

Australia-Antarctica separation produced the birth and widening of the AAG and then its death when subsumed in the new Southern Ocean. The stratigraphic record in the oceanic, terrestrial, but especially neritic environmental realms on the north flank of the AAG can be boiled down to six named marine transgressions, Wilson Bluff, Tortachilla, Browns Creek, Tuketja, Tuit and Aldinga. Each transgression characterises one of six stratal packages which are acting as informal regional stages. They comprise a natural three-part succession, Bartonian/Priabonian/Rupelian, with three punctuations, I, II and III.

The regional AAG record is a microcosm in chronostratigraphic and successional respects of the global geo- and biohistorical succession. The six packages match 'perfectly' (thereby strongly supporting) the putatively global third-order sequences Lu 4 to Ru 1 (Figs. 12, 13 and 16). The three-part configuration of punctuations likewise has a global feel, especially the Bartonian-Priabonian transition, hitherto somewhat under-emphasised.

Above the angular unconformity: Late Neogene including Quaternary

The following formations are exposed at Maslin Bay and Aldinga Bay.

Hallett Cove Sandstone

Successively younger strata, southwards to the Port Willunga Formation, are truncated by the low-angle unconformity. The Hallett Cove Sandstone transgressed that erosional surface, forming neptunian dikes in its progress. It is a calcareous sand, sandstone and limestone, and aragonite is preserved very rarely. Various facies are rich in oysters, large bivalves (especially *Anodontia*) and gastropods (especially *Campanile*) of warm-water aspect (Ludbrook, 1973), the large benthic foraminifer *Marginopora* (25 mm diameter) and nodular red algae. The fauna indicates a strong pulse of the Leeuwin Current and the last major warming event on the southern margin. The age of the Hallett Cove is not known with precision but is more likely to be later (~3 Ma) than earlier Pliocene. It is an eastern example of the richly fossiliferous Roe Calcarenite of Late Pliocene age in the Great Australian Bight (Ludbrook, 1978; James et al., 2006). These fossil assemblages, nourished by the Leeuwin Current, are a southern manifestation of the Piacenzian warm period, a cluster of super-interglacials around 3 Ma, just before the modern cooling set in (e.g., Raymo, 2011).

Burnham Limestone

This is a white, crumbly, micritic limestone, sitting on a karstic upper surface of the Hallett Cove Sandstone and containing clasts of the latter, and poor in marine fossils. It was correlated by Ludbrook (1973) with the richly fossiliferous Point Ellen Limestone on Kangaroo Island, of early Pleistocene age on the presence of the gastropod *Hartungia dennanti chavani* which, however, is now considered to be Late Pliocene not Early Pleistocene in age (see James et al., 2006). Alley and Lindsay (1995) placed it in the latest Pliocene. Fairburn (1998, 2000) lumped the Burnham with the Hallett Cove in the Late Pliocene, but Fairburn et al. (2010) left it in the Pleistocene, and so do we. This uncertainty around the Pliocene/Pleistocene boundary remains unsatisfactory so long as evidence for age and correlation go missing; however, it is likely that the Late Pliocene age will turn out to be correct.

Ochre Cove Formation

This is a red-orange iron-mottled gravelly, sandy and clayey sediment, prominent in the north-south coastal section from Ochre Cove to Maslin Bay but then disappearing, to reappear at Sellicks Beach. It is of middle Pleistocene age, being found to include the Brunhes/Matuyama geomagnetic reversal of 780 ka and the Jaramillo Subchron of 990 ka at Sellicks Creek (Pillans and Bourman, 1996). In Mount Terrible Gully (also known as "Cactus Canyon"), a thick section of clayey sands and gravels abuts the outcropping Cambrian bedrock of the Willunga Fault Scarp, and overlies weakly marine Burnham Limestone (Figs 11, 17). These alluvial fan sediments record the geomagnetic events.

Ngaltinga Formation

This is grey-green or olive in colour, a stiff sandy clay, inferred by various authors at various sections to be possibly fluvial, or aeolian, or weathered in situ.

Late Neogene stratigraphy

So far, so good: the coastal traverse is clear enough, matters of correlation and age determination notwithstanding. But coastal clarity does not hold inland in this district of poor and isolated exposures where even maintaining the separation across the divide of the deformational event is contentious. Lack of exposure is compounded by too much sand with too few biostratigraphic constraints and by the difficulty of distinguishing one sand from another even in limited exposures, let alone in rotary cuttings and cable-tool sludges. Hence, it is difficult to test and upgrade a reconstructed cross-section from plausible to compelling. Investigators from Ward (1966) and Firman (1967) to Fairburn (1998, 2000) and Bourman et al. (2010) described the complexities and uncertainties of late Neogene (Quaternary) lithostratigraphy. The present account includes three names: Pirramimma Sand, Kurrajong Formation and Christies Beach Formation.

Pirramimma Sand

Comparing Cooper's reconstruction (Fig. 3) with Fairburn's (Fig. 4a) clarifies the problem of sands and their correlations and ages. Cooper erected the Pirramimma Sand Member of the Port Willunga Formation in the orthodoxy of offshore, less sandy, onshore, more sandy; but Fairburn more or less reverted to the Sprigg and Wilson (1954) mapping of extensive sand as Pliocene by including swathes of surficial sand, overstepping the tilted Palaeogene-early Neogene, as sandstone of Pleistocene age. A late Neogene surficial sandstone in the McLaren Vale area is essentially flat-lying and overstepping dipping older Cenozoic units. Isopachs of sands including Cooper's stratotype section delineate a broad channel flowing NE-SW (Fairburn, 1998; see Fig. 4b). Unfortunately it is now likely that inshore, sandy facies of the Oligo-Miocene Port Willunga Formation and riverine Pleistocene sands are being identified under the same name, "Pirramimma", and it is unclear as to which the type section belongs. The Pleistocene unit should receive a new name with an outcropping type section.

Kurrajong Formation

The Kurrajong Formation is an assortment of clastics including a silicified breccia producing outstandingly strong outcrops, as in Sellicks Creek at Sellicks Hill. Fairburn (1998) regarded the Kurrajong as above the Ngaltinga, whereas Bourman et al. (2010) found it to merge with the base of the Ochre Cove Formation. We incline to the latter view.

Christies Beach Formation

Also known as the Pooraka Formation, these brown and red clayey sands and gravels sit directly on the Ochre Cove Formation close to the Willunga Fault (Figs 17, 18); elsewhere they may be separated by the intervening Ngaltinga Formation; south of Sellicks Beach they sit on a 125,000-year shore platform (Murray-Wallace and Bourman, 2002).

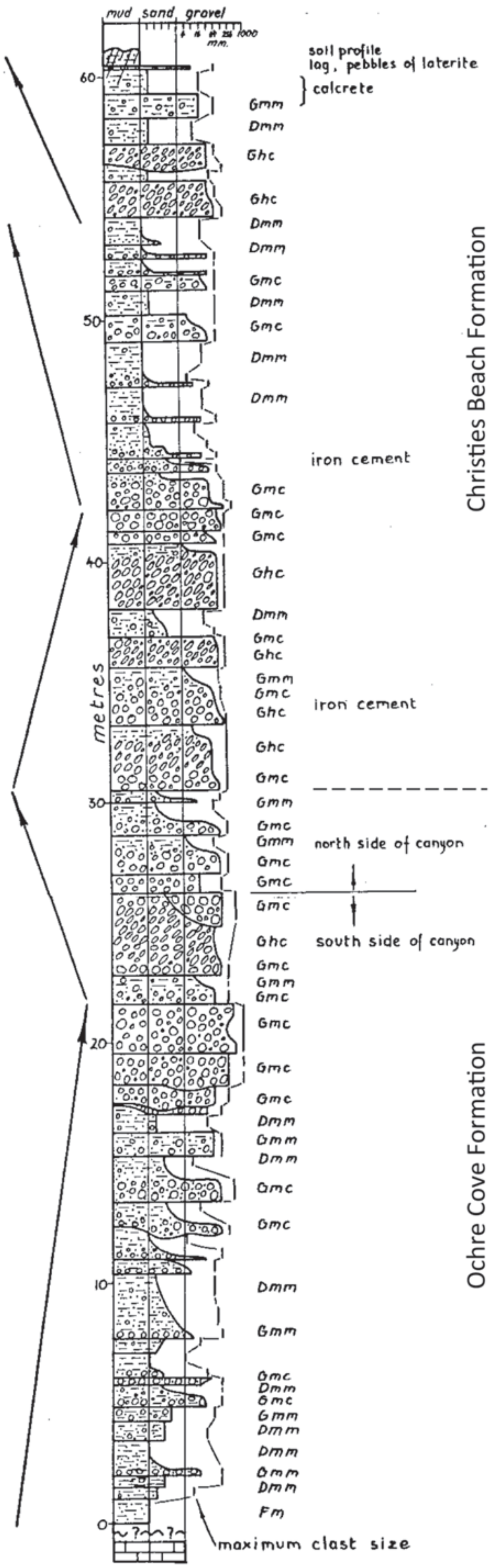
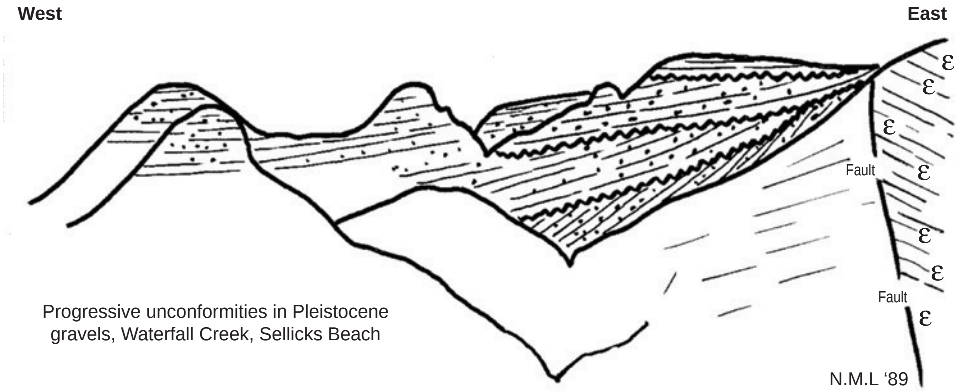


Figure 17 *Lemon's sedimentary log in Mt Terrible Gully (Cactus Canyon) (Lemon and McGowran, 1989). The recurring facies can be assigned lithostratigraphically to the Ochre Cove Formation and the Christies Beach Formation.*



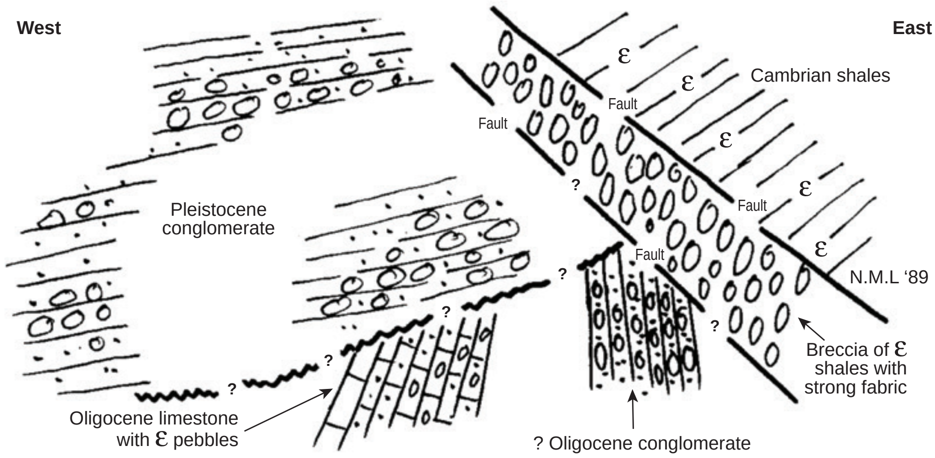


Figure 18 *Lemon's Pleistocene unconformities and rock relationships in Waterfall Creek, Sellicks Beach (Lemon and McGowran, 1989). The Willunga Fault crosses the coast and passes out to sea in the vicinity of Waterfall Creek. North, the footwall is on the coast; south, the hangingwall is on the coast. (Upper) Progressive unconformities can be seen in the fan from across the gully close to the beach. Both the Ochre Cove Formation and the Christies Beach Formation are involved and the mutual boundary is probably at the lowest of the three. (Lower) This rock-relationship diagram is not to scale but the ingredients are clustered within a few metres in the gully below the waterfall. The Pleistocene conglomerate is Ochre Cove Formation.*

Structural development of the Willunga Embayment

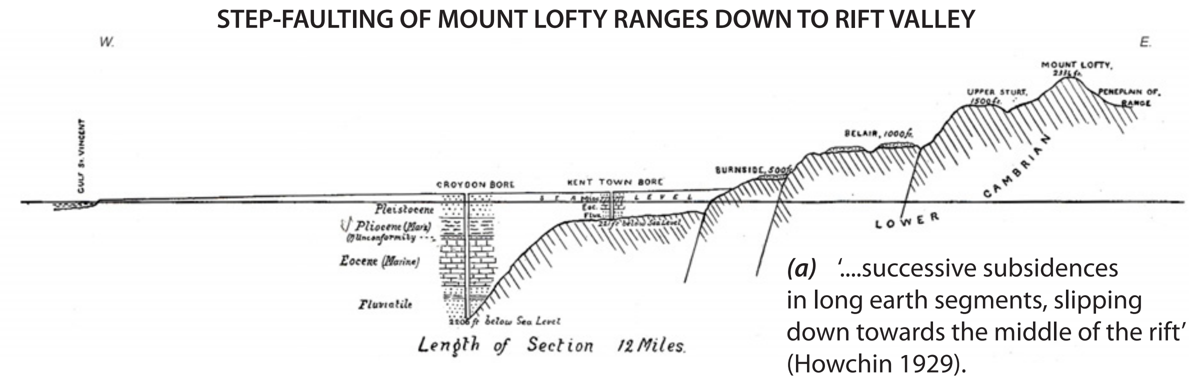
Table 2 *Geohistorical summary of the Willunga Embayment.*

Age, Date	Structural	Environmental	Lithostratigraphy
Holocene <10 ka	Most recent compressional uplift raises shore platform by several metres.		Various alluvial and coastal facies
Late Pleistocene ~125 ka	Alluvial fans accumulate on hangingwall. Shore platform is cut on near-vertical limestones. Progressive unconformities in alluvium. Willunga Fault cuts lower part of Christies Beach Formation, and is overstepped by upper part.	Proximal alluvial	~~~~~~~~~~~~~~~~~~~~~ Christies Beach Formation = Pooraka Formation
Mid-Pleistocene	Willunga Fault breaks through Port Willunga Formation. Limestones hoisted into near-vertical position on northwest limb of hangingwall anticline.		~~~~~~~~~~~~~~~~~~~~~
Early Pleistocene	Alluvial fans accumulating on footwall date major uplift.	Proximal alluvial	Ochre Cove Formation ~~~~~~~~~~~~~~~~~~~~~ Kurrajong Formation
	Hallett Cove Sandstone and Burnham Limestone are gently tilted on footwall.		~~~~~~~~~~~~~~~~~~~~~
Early Pleistocene	Deposition of Seaford Formation, "Pirramimma Sandstone" and Burnham Limestone in Willunga Embayment.	Fluvial to near-shore marine	Burnham Limestone Seaford Formation Pirramimma Sandstone ~~~~~~~~~~~~~~~~~~~~~
Late Pliocene ~3 Ma	Hallett Cove Sandstone is widespread but not seen on hangingwall.	Last strong Leeuwin pulse before serious cooling	Hallett Cove Sandstone ~~~~~~~~~~~~~~~~~~~~~
Late Miocene ~8± Ma	Angular unconformity is part of a platewide event. The event has been perceived as the onset of a new instability on the Australian continent. It includes tilting, jointing, minor normal faulting, and Pliocene neptunian dikes.		
Middle Miocene ~14 Ma	Continent-wide termination of neritic carbonates included the Port Willunga Formation.	Glaciation Mi 3 probably is sufficient to explain the disconformity glacio-eustatically and climatically	~~~~~~~~~~~~~~~~~~~~~
Middle Miocene 16-15 Ma		MICO, warmest Neogene time and strongest Leeuwin Current. Neritic carbonates accumulate in Myponga Basin.	Port Willunga Formation
Early Miocene 17± Ma	Chevron folding, intraformational conglomerates and slump rolls on hangingwall indicate compressional reactivation of the Willunga Fault during growth of hangingwall anticline. Third and main angular-unconformity-bounded unit forms at Sellicks Beach.		Port Willunga Formation Longfordian unit ~~~~~~~~~~~~~~~~~~~~~
Early Miocene 22± Ma	Second angular-unconformity-bounded limestone forms at Sellicks Beach.		Port Willunga Formation Upper Janjukian unit ~~~~~~~~~~~~~~~~~~~~~
Late Oligocene 24.5± Ma	First angular-unconformity-bounded unit forms at Sellicks Beach: neritic facies onlapping Cambrian on hangingwall of Willunga Fault. Early Neogene compressional deformation and formation of incipient hangingwall anticline begin.		Port Willunga Formation Lower Janjukian unit ~~~~~~~~~~~~~~~~~~~~~
Early Oligocene 35-32 Ma	Death of the Australo-Antarctic Gulf by its subsuming in the new Southern Ocean.	Reinvigorated circulation improves ventilation, permitting neritic communities to return to "normal" and to "modernise"	Port Willunga Formation: Ruwarung Member Aldinga Member
Early Oligocene 34 Ma	Chinaman Gully downcut and backfill; silciclastics supply resumes briefly.	This major sequence boundary is strongly inferred to be glacioeustatic, caused by Oi 1.	Chinaman Gully Formation ~~~~~~~~~~~~~~~~~~~~~

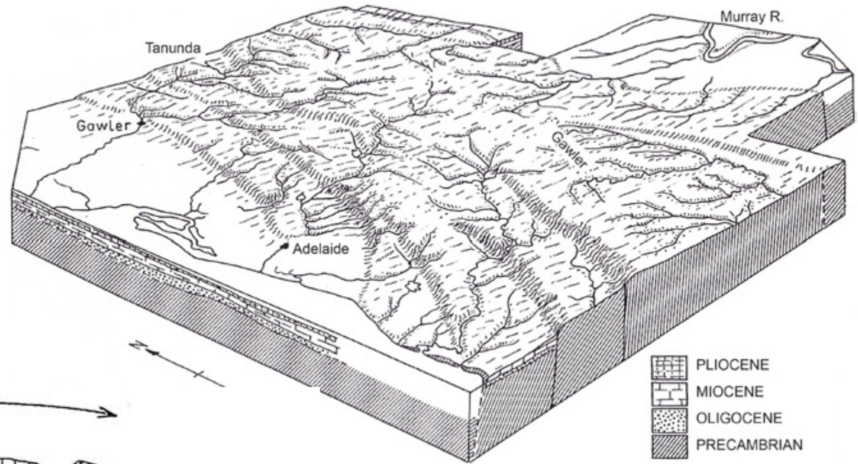
Late Eocene 38-34 Ma	Siliciclastics supply contracts sharply during Blanche Point accumulation.	Ecologically mesotrophic-eutrophic, neritic communities subjected to low-oxygen and high-nutrient stress.	Blanche Point Formation: Tuit Member Perkana Member Gull Rock Member Tuketja Member
Middle Eocene ~39 Ma		Ecologically oligotrophic-mesotrophic, neritic carbonate faunas. Tortachilla transgression begins with South Maslin Sand.	~~~~~~~~~~~~~~~~~~~~~~ Tortachilla Limestone South Maslin Sand
Middle Eocene 40± Ma	Compressional uplift and doming unclear in extent, but it supports endorheic drainage and extensive cutting of palaeochannels Sedimentary accumulation begins in fluvial, lacustrine, and coal swamp environments.	MECO Warm-temperate rainforest flora in North Maslin Sand at ~60°S. The Khirthar Transgression: IndoPacific neritic carbonates include massive limestones on three Australian margins	~~~~~~~~~~~~~~~~~~~~~~ North Maslin Sand ~~~~~~~~~~~~~~~~~~~~~~
Middle Eocene ~42 Ma	Sedimentary basins form compressionally on the Adelaide Geosyncline and Torrens Hinge Zone ("Sprigg Domain").		
Middle Eocene ~44 Ma	Oceanfloor spreading accelerates in the Australo-Antarctic Gulf, compressionally (and preferentially) reactivating Delamerian fractures.		
Early Eocene 55-49 Ma		EECO Tropical-type rainforests flourish all around the AAG at 60-65°S. Warm and very wet environments promote intensified deep chemical weathering.	
Carboniferous – Permian ~300 Ma	Glacial topography is carved into exhumed Delamerian orogen. Troubridge Basin is shaped by compressionally reactivated Delamerian fractures.	Gondwanaland-wide glaciation	~~~~~~~~~~~~~~~~~~~~~~ Cape Jervis Formation ~~~~~~~~~~~~~~~~~~~~~~
Mid- to late-Cambrian ~510-490 Ma	Delamerian Orogeny, northwest-directed tectonic transport.		
Neoproterozoic to early Cambrian ~800-510 Ma	Formation of bedrock of Mount Lofty Ranges.	Mostly marine shelf sediments	~~~~~~~~~~~~~~~~~~~~~~ Various formations of the Adelaide Geosyncline ~~~~~~~~~~~~~~~~~~~~~~

The first marker is the origin of the St Vincent Basin at about 43 Ma, late Lutetian. This is a profound turning point in being several things in hierarchy: globally, a new phase of seafloor spreading; regionally, the beginning of the end for the Australo-Antarctic Gulf, subsumed in the Southern Ocean, and the initiation or rejuvenation of sedimentary basins along its northern margin; and terrestrially, the initiation of endorheic drainage in southern-central Australia. The second turning point is the Neogene transcontinental deformation event, centred roughly on about 8 Ma (McGowran et al., 2004). The Willunga Embayment also has a prehistory with a problem, namely, if and how there was tectonic transfer from the Delamerian Orogen of the early Palaeozoic to basin formation in the early Cenozoic.

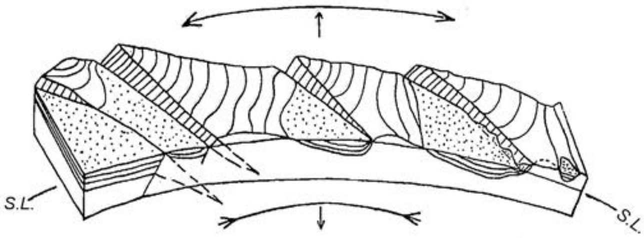
Extension was the ruling notion in early inferences of a rift valley, the Great Rift of Gregory, Benson, Fenner and Howchin (Fig. 19a) and it is seen in the horst and graben model of Sprigg's (1945) early geomorphology (Fig. 19b). Extension has sat comfortably with such plate-tectonic notions as the trailing or passive continental margin, which developed during the breakup of eastern Gondwanaland and the dispersal of its fragments including Australia. Less comfortable was the notion that Delamerian faults could be reactivated during the Cenozoic, for that transfer then entailed a shift from compressional mode to extensional and subsequently back to compressional. Thus Sprigg made no bones about Cambrian thrusting and imbricate faulting in the Adelaide region, even naming (unpublished) the 'Blackwood Overthrust' (McGowran, 2013, Fig. 10). But Sprigg was committed both to thrusting and imbrication in the Cambrian and to block faults being 'reopened' in the Mesozoic or Tertiary, even showing the symbols for both mechanisms together on the Willunga and Clarendon-Moana Faults (Sprigg, 1961; see also McGowran, 2013, Fig. 15), and referring to the St Vincent graben and the Mt Lofty horst.



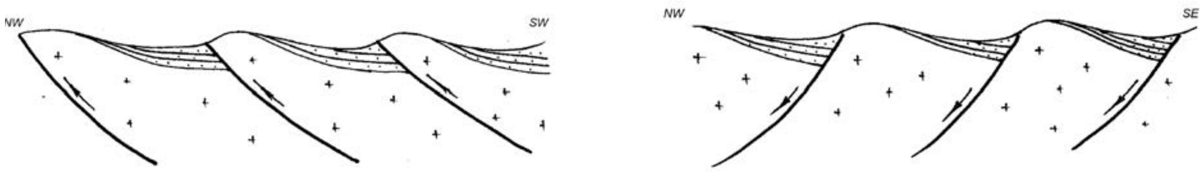
(a) '....successive subsidences in long earth segments, slipping down towards the middle of the rift' (Howchin 1929).



(b) Springg's (1945) horst and graben model of central Mt Lofty Ranges, modified by Twidale (1976).



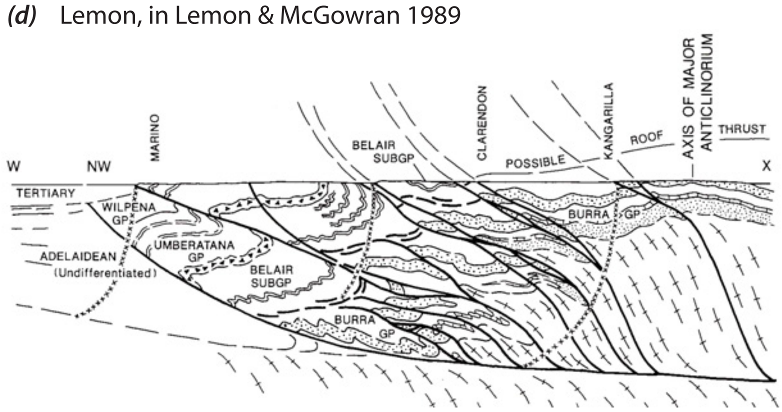
(c) Glaessner's (1953) scissors sketch of rotation in basin development: tension in basins, compression in hinterland.



Basin development: compressional

Basin development: extensional

(d) Lemon, in Lemon & McGowran 1989



(e) Locations of three Cenozoic, basin-forming faults, postulated as west-dipping extensional (xxxxxxx) and superimposed on Delamerian thrusting (Jenkins 1990).

Figure 19 *Development of notions of structure and tectonics, Part I.* ***(a)*** *Extensional structure is clear in the early 20thC perceptions of the great rift valley, such as in Howchin's, and* ***(b)*** *in Sprigg's widely known block diagram. Faults in the St Vincent Basin were drawn vertically, like Sprigg's and without discussion, by two of those most familiar with the reconstructed stratigraphy, namely Ludbrook (1969) and Lindsay (see Fig. 2).* ***(c)*** *Two others (Glaessner and Wade, 1958) clearly showed several west-dipping normal faults but were unclear about the Willunga Fault, for Glaessner had challenged the view of normal faulting under extension. Lemon* ***(d)*** *and Jenkins* ***(e)*** *put the stark alternatives of compressional and extensional structure.*

Campana and Wilson (1953) and Campana (1955; Fig. 20a) explained the uplift forming the Mt Lofty Ranges by compressional doming with faulting at the margins, namely 'cracking, block-faulting, or thrust phenomena, according to the degree of plasticity of the formations involved' (1953, p. 17). They interpreted the Myponga and Hindmarsh basins as inherited from Permian glacial topography.

The problem of tectonic transfer from Delamerian compression to Paleogene extension was illustrated succinctly by Jenkins and Lemon (Fig. 19d, 19e). It is difficult to see in Jenkins' sketch a Delamerian inheritance in extensional Cenozoic basin formation. Nevertheless Tokarev (2005; Tokarev et al., 1999; Tokarev and Gostin, 2003) distinguished three neotectonic stages and asserted the independence of neotectonic structure from basement (Delamerian) structure: (i) extensional stage (Middle Eocene to Middle Miocene; (ii) transitional stage (Late Miocene to Early Pleistocene); and (iii) compressional stage (Early Pleistocene to present). For example, Tokarev and Gostin presented a section across the Sellicks Hill Range with six vertical or near-vertical faults (without evidence and the motion not specified) (Fig. 20c). There are two Delamerian faults in the vicinity on the western slope (Fig. 20b) but these were ignored as being in the irrelevant basement structure.

Emphasis shifted to the more attractive notion of Cenozoic (Neogene including Quaternary) uplift by compression, under which Delamerian faults were, and are, being reactivated, thrusting eastwards in the east of the orogen, westwards in the west (Fig. 21). Cambrian is thrust over Pleistocene in the eastern Mt Lofty Ranges, and in two cases, on the Milendella Fault and the Bremer Fault (Fig. 1), Miocene neritic limestones are caught up in the faulting, indicating post-Middle-Miocene uplift of more than 100m (Lindsay, 1986; Bourman and Lindsay, 1989; Sandiford, 2003). (However, the Bremer Fault is western rather than eastern in being west side down). In the western Mt Lofty Ranges almost 200 m of elevation separate coeval Miocene strata in the Willunga Embayment and Myponga Basin (Fig. 20C, 20D).

The strongly tilted marine Miocene strata at Sellicks Beach attracted attention in attesting to young earth movements. Howchin (1929) contended that they 'have slipped down in the direction of the great rift'. More clearly than their forebears, Glaessner (1953; Fig. 19c) and Campana and Wilson (1953; Campana, 1955; Fig. 20a) observed that the Miocene limestones were unconformable on the Cambrian: no dragging, sliding, or distortion of fragile fossils, but with a basal transgressive breccia and neptunian dikes into the Cambrian. Indeed, almost all visible contacts of Oligocene-Miocene limestones over Cambrian are stratigraphic, i.e. unconformable not faulted (Fig. 22). Also, contra Sandiford (2003) and Sandiford et al. (2009), the limestones are tilted almost to the vertical on the hangingwall, not on the footwall.

Beneath the major unconformity on the Heatherdale Shale there are two other unconformities and two very small but distinct allostratigraphic units in neritic facies (Fig. 23). The first, the sample labelled M1, is inner-neritic with a spike in the benthic foraminifer *Pararotalia mackayi*, identifying the late Oligocene (Chattian Stage) warming event labelled LOWE on Figure 13, around 24.5 Ma. The second, sample 1, is a mid-neritic assemblage with the planktonic species *Globoturborotalita woodi* and the benthic *Sherbornina cuneimarginata* indicating early-early Miocene (Aquitanian Stage), around 22 Ma. The third, sample 2 just above the main unconformity, is inner-neritic like M1 but with abundant *Operculina victoriensis* and *Amphistegina lessonii*, indicating a warm spike in the later-early Miocene, (Burdigalian Stage), around 17 Ma. Thus we have progressive unconformities and allostratigraphic units which are tectonic, separately from a eustatic component. Large slump rolls in the carbonates were likely a response to tectonic instability and chevron folding to compression.

A new map by W.V. Preiss (Fig. 24) and a panoramic view of the rocky coast (Fig. 25) frame the neotectonic context of the Willunga Embayment.

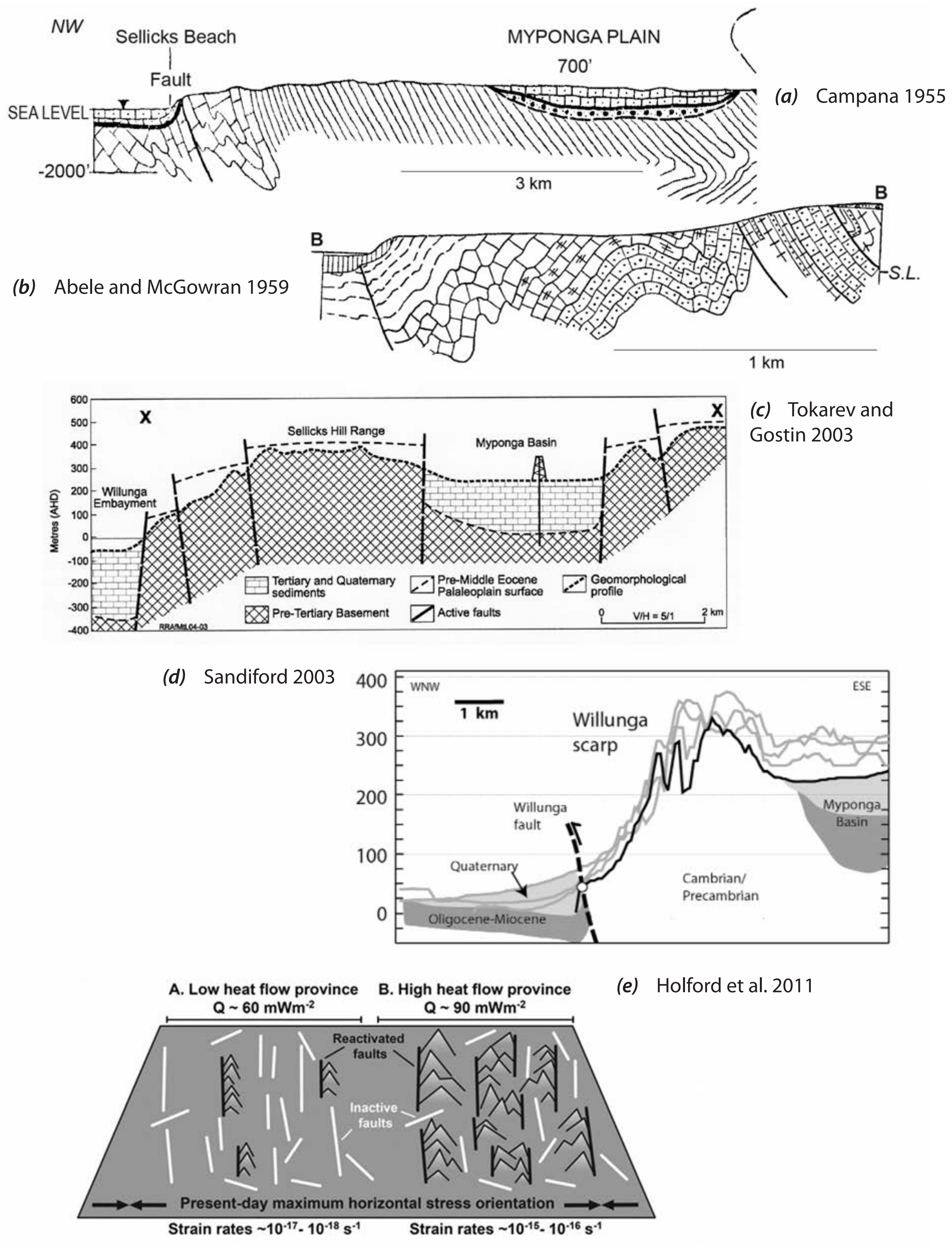
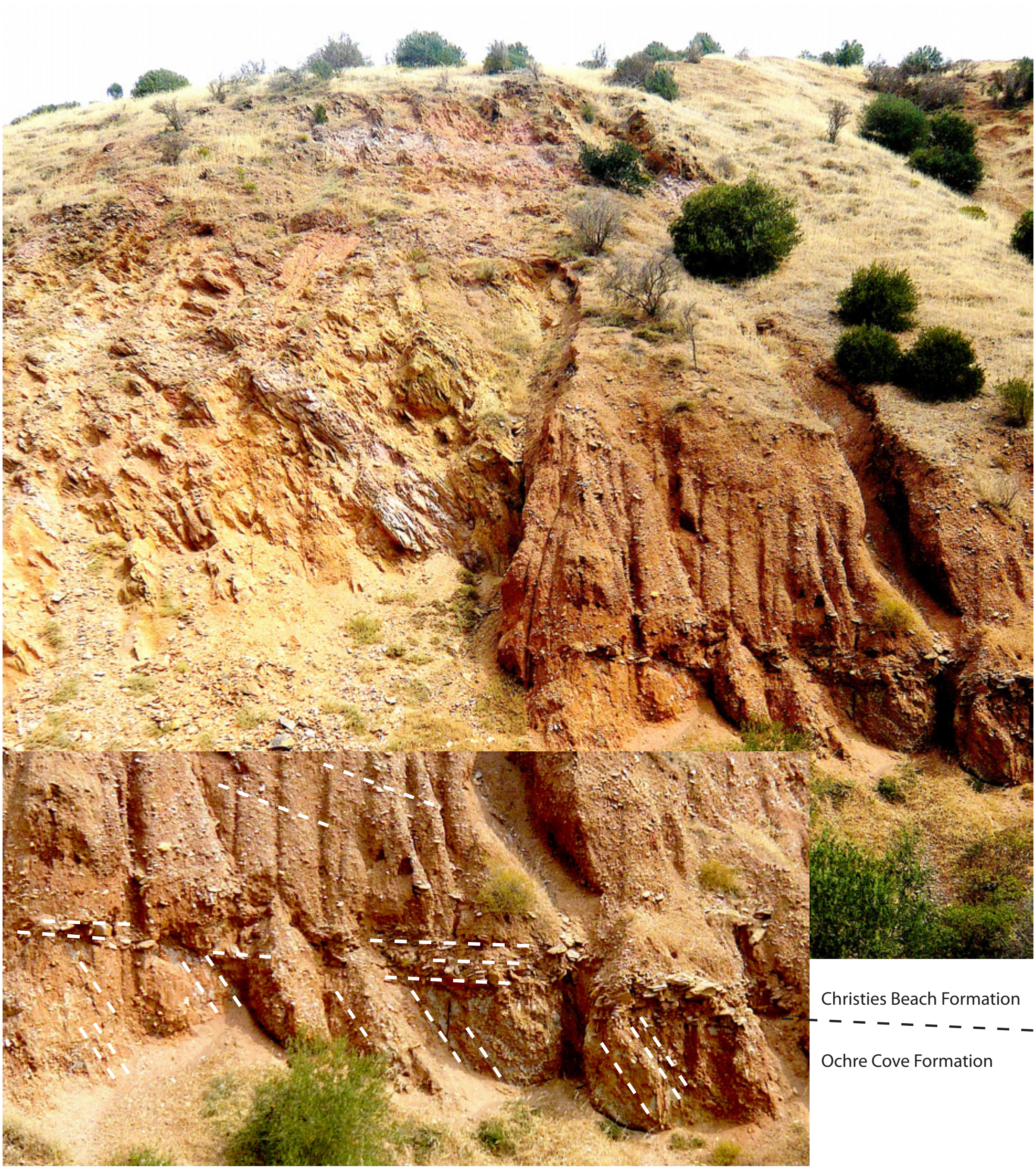
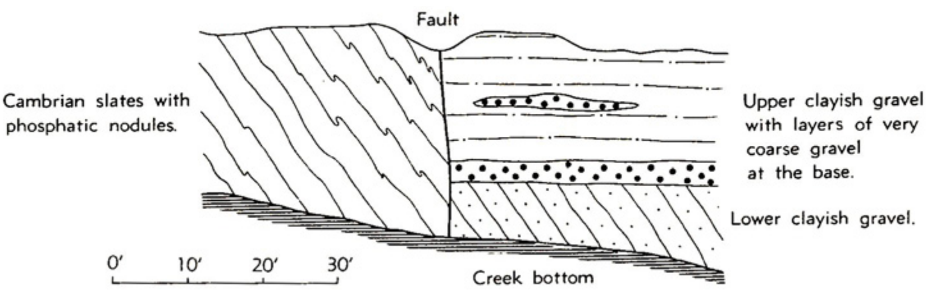


Figure 20 *Development of notions of structure and tectonics, Part II. For Campana* ***(a)*** *the Cambrian and the Pleistocene-Recent Willunga Fault with brecciated Heatherdale Shale were the same entity, a thrust fault activated and reactivated during doming and uplift. McGowran* ***(b)*** *discovered two more reverse faults between the Myponga basin and the coast, quite in the Campana mode (displaying the tilted Miocene limestones on the hangingwall was more by luck than insight.) Tokarev* ***(c)*** *followed the extensional alternatives of Lemon and Jenkins (19d and 19e) so that the three postulated, extensional, neotectonic faults west of the Sellicks Hill range in 20c have nothing at all to do with the three thrust faults discovered as in 20b. The weight of evidence supports compression and reactivation, with squeezing upward and outward on both sides of the orogen along ancient faults in what Sandiford* ***(d)*** *named the Sprigg orogeny. Some clusters of ancient faults are reactivated whereas others are not. To explain this difference, Holford et al.* ***(e)*** *contrasted a high heat flow province with a low; heat might not cause neotectonic uplift but it does influence by reactivation where the uplift happens, namely and variously, in the Flinders-Mt Lofty Ranges, in the Adelaide Geosyncline, and in the Neoproterozoic Sprigg domain.*





'Tilted Pleistocene lower gravel overlain unconformably by horizontal upper gravel, both in clearcut tectonic contact with Cambrian formations, Mount Terrible Gully' (Campana & Wilson, 1953, Figure 2)

Figure 21 *Mt Terrible Gully (Cactus Canyon) looking south at the Willunga Fault. Cambrian Heatherdale Shale is moving over the Pleistocene Christies Beach Formation. Campana and Wilson (1953) observed the tectonic activity recorded in tilting, planing and discordant contacts within Pleistocene gravels, the configuration perceived later to multiply as progressive unconformities (Fig. 18). Lines indicate the primary depositional dip on the surface of the top fan, slightly tilted. The dip below the lag conglomerate has been tilted twice. The lag surface itself is closer to the original horizontal at time of deposition but even this will show a slight tilt away from the active fault.*

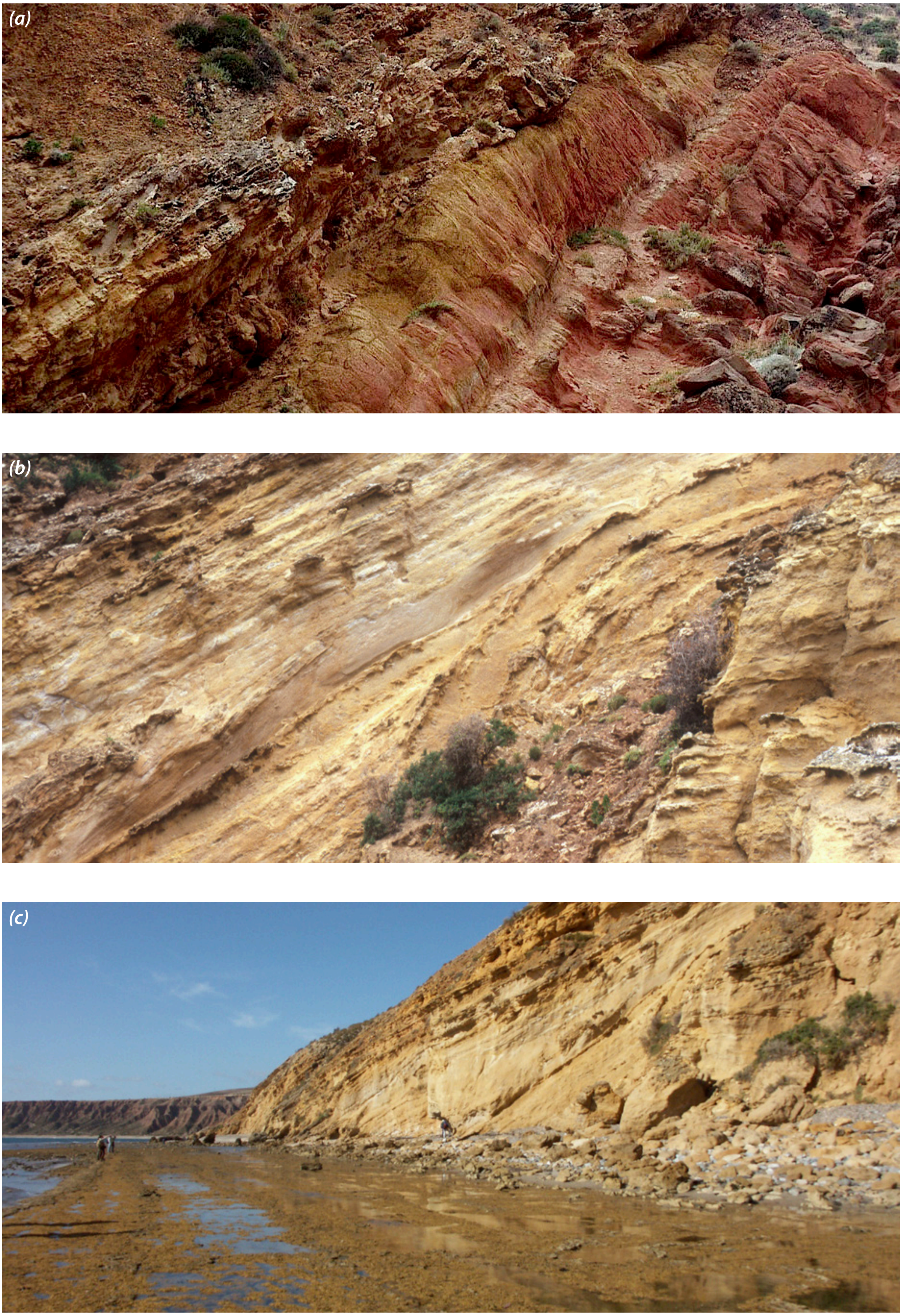


Figure 22 ***(a)*** *Miocene Port Willunga Formation in unconformable contact with Cambrian Heatherdale Shale south of Sellicks Beach. On the hangingwall of the Willunga Fault, both formations dip steeply westwards (left) towards the fault.*
(b,c) *Modern shore platform cut in Miocene limestones; looking north to Pleistocene clayey gravels. Changes in dip are due to large slump rolls, several metres across and caused by Miocene tectonic instability.*

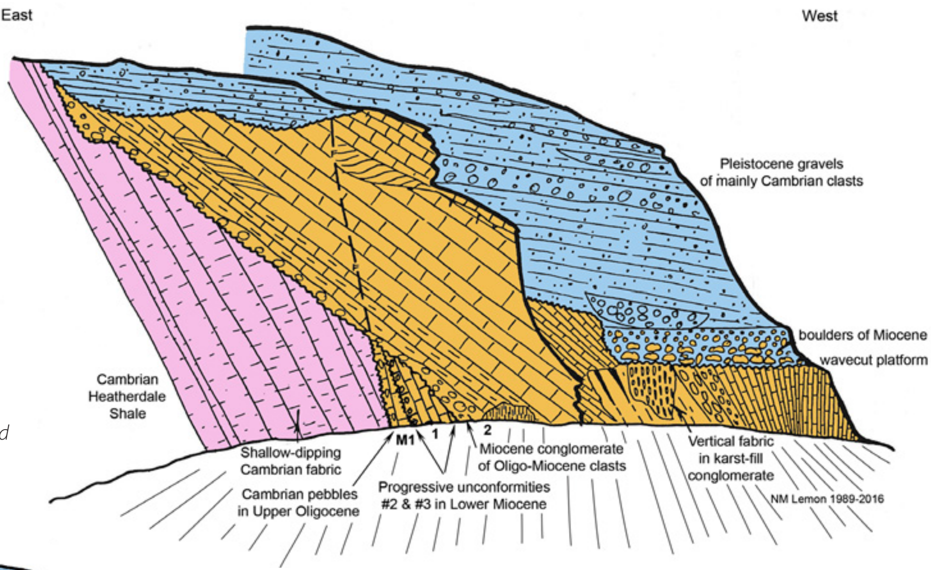
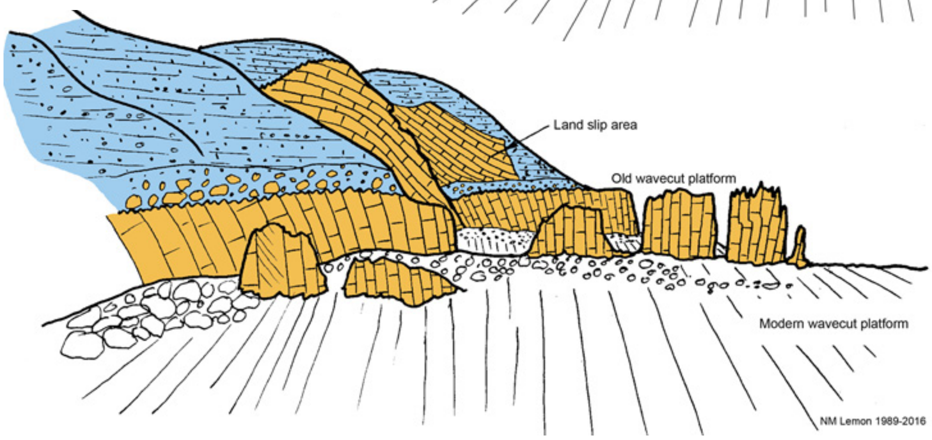


Figure 23 *Upended limestones, remnants of the northwest limb of the hangingwall anticline: this photo of 2015 shows almost the same view as Lemon's sketch of 1989 (Lemon and McGowran, 1989); the cliff of Pleistocene gravels (Christies Beach Formation on 125,000-year shore platform) is "behind" (south of) the Miocene slab, and there is a small cove between, hidden in this view. Lemon's lower sketch is further south showing the steepening dip, to the right and west, seawards, and towards the Willunga Fault.*



The progressive intra-Oligo-Miocene unconformities and allostratigraphic entities were confirmed by foraminiferal ages of samples M1, 1 and 2 as late Oligocene (Chattian), early-early Miocene (Aquitanian) and late-early Miocene (Burdigalian) respectively. Note the chevron folding in the Miocene, a sign of compression. Progressive unconformities, slump rolls and chevron folding collectively make a case for repeated compressional reactivation, punctuating the temporal stretch of seeming tectonic quiescence between late Palaeogene compressional basin formation and late Neogene (Pleistocene) compressional uplift.

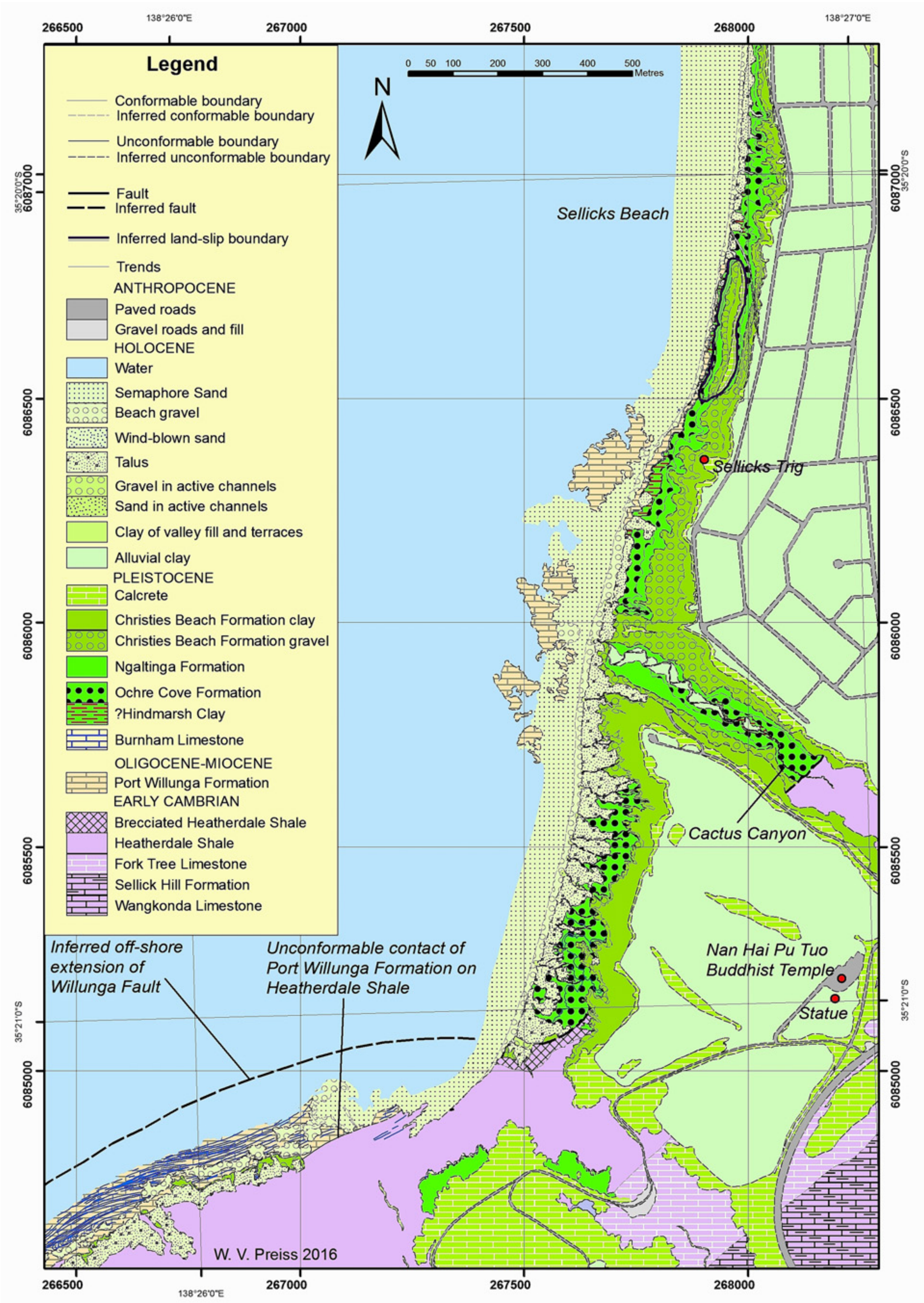


Figure 24 *Geological map by W.V. Preiss of the southwest corner of the Willunga Embayment. The street on the northeast rim of Cactus Canyon and parallel to it is the end-segment of the Esplanade. There is an excellent vantage-point at each end of the segment. One is of the Willunga Fault in the canyon (long known as Mt Terrible Gully) (Fig. 21). The other is of the rocky coast and shore platforms a kilometre and more to the southwest (Fig. 25). The belt of brecciated Heatherdale Shale, where the Willunga Fault crosses the coast, is in Waterfall Creek as sketched by Lemon (Fig. 18). Benignly overseeing the neotectonic restlessness is the goddess Guan Yin.*

Figure 25 *The rocky coast beyond Sellicks Beach, showing features in other figures and in the text.*

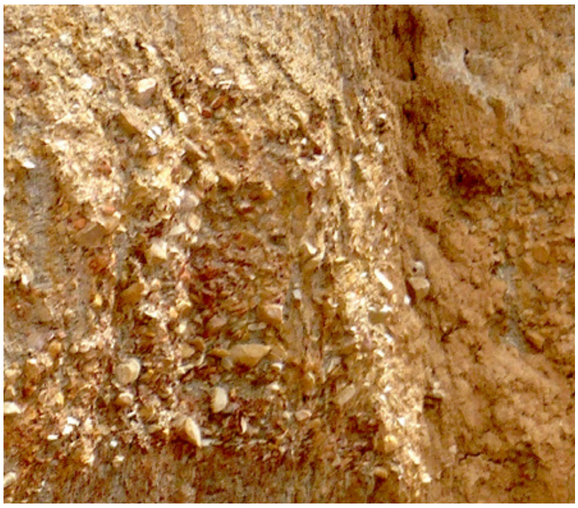
Conclusion

Willunga Embayment geohistory from the death of the Australo-Antarctic Gulf to the Sprigg Orogeny

The fundamental questions are: why is the basin with its embayments where it is when it is? As to the 'where?': There are persuasive reasons based in thermal weakening for accepting compressionally reactivated Delamerian structures in the Sprigg domain as the underlying control (Fig. 20e; Holford et al., 2011). Underlying the St Vincent Basin is the Permian Troubridge Basin with its abundant evidence of glaciation. The thickest sections of the glaciomarine Cape Jervis Formation are preserved in troughs or basins, partly tectonic, partly glacially excavated (Alley and Bourman, 1995). The abundant granites etc. that became erratics indicate several kilometres of prior unroofing. There is a sense in which the Mesozoic tectonic development of southern Australia, culminating in the birth of the Australo-Antarctic Gulf, began in Permian tectonism (Wopfner, 1969; McGowran, 1973).

As to the 'when?': With the exception of the Jurassic Wisanger Basalt on Kangaroo Island (Milnes, Cooper and Cooper, 1982), this part of the world seemingly slumbered through the Mesozoic Era. The separation of proto-Australia from proto-Antarctica was depicted (Krieg et al., 1995, Fig. 9.3) as beginning (Late Jurassic) in a crustal extensional field oriented NW-SE which swings to NNE-SSW, the direction maintained to become the direction of plate motion by the end of the era. There is no signal of Delamerian reactivation in central-southern Australia at that time. Indeed, the Australo-Antarctic Gulf had expended some fifty of its roughly sixty million years of life before our story really begins at its presaged death by oceanfloor spreading commencing at ~42 Ma. By that time the modern configuration of a predominantly E-W compression had developed in this part of the Indian-Australian Plate (e.g., Sandiford et al., 2009) after certain world-changing events, especially India-Asia collision.

Basin formation and perhaps some doming accompanied the surge in oceanfloor spreading in the Gulf, and the siliciclastics of the North Maslin Sand were the rapid sedimentary response (Fig. 26). The abundant pebbles are virtually all well-rounded quartz. The unconsolidated Permian sediment littering the landscape even today was a ready source for the ultramature Eocene sediment. There is little need to invoke compressional doming merely to generate source areas, but the cutting of



Christies Beach Formation, Late Pleistocene. Uplift well advanced.

Kurrajong Formation, Early Pleistocene. Early uplift of modern hills.

Pirramimma Sandstone, Early Pleistocene. Reworked Permian and North Maslin Sand.

North Maslin Sand, Middle Eocene. Reworked Permian.

Figure 26

channels indicates some doming. Deep chemical weathering climaxing during EECO concentrated much iron that was released episodically into the North Maslin Sands, and into probable equivalents on the uplands that were low swamps at the time. That iron clotted and cemented quartz clasts to form ferricretes, similar to the ferricrete crusts in abandoned paleochannels. Such ferricretes are not regolithic residuals in the usual sense but due to lateral transport (Bourman and Ollier, 2002). The siliciclastics flux waned in the Tortachilla episode but returned very briefly to form the Chinaman Gully Formation. The neritic and oceanic carbonate flood in the Early Oligocene, of which the Port Willunga Formation was a prominent part in this basin, marked the death of the Australo-Antarctic Gulf by its incorporation into the nascent Southern Ocean.

For Sandiford (2003) the end of the Miocene marked a new instability of the Australian landmass, the onset of episodes of faulting and uplift through the Pliocene and Pleistocene unto the present and the onset of the modern neotectonic regime. He called this happening the Sprigg orogeny, so the Flinders-Olary-Mt Lofty region became the Sprigg orogen or the Sprigg domain (Sandiford et al., 2009; Clark et al., 2011). Meanwhile, McGowran et al. (2004) pointed out that the angular unconformity at Maslin Bay and Aldinga Bay is part not only of a transcontinental event but a platewide tectonic event roughly at ~8 Ma.

Between basin formation in the late Palaeogene and the Sprigg orogeny in the late Neogene, there has been little evidence and little discussion of tectonic movement, an implication by default of a prolonged interregnum in the Willunga Embayment. The upended limestones at Sellicks Beach change this. Neritic facies onlapped the Cambrian in the Late Oligocene, the hangingwall of the Willunga Fault was moving, and progressive unconformities into the Early Miocene indicate an incipient hangingwall anticline. Chevron folding and slump rolls add evidence of steepening depositional slopes due to compressional deformation.

Meanwhile a late Oligocene to early-Middle Miocene seaway connected the Myponga and Hindmarsh Tiers basins to the Willunga Embayment or Murray Basin or more likely both (Glaessner and Wade, 1958; McGowran, 1959, Fig. 1, sketched by M.F. Glaessner). The notion was reactivated by Tokarev and Gostin (2003) for indirect reasons. The course would have been dictated by Troubridge Basin lineaments reactivated or glacial valleys exhumed before serious uplift began.

Instead of the Sprigg orogeny springing full-formed in the late Neogene, we have compressive activity as a significant early Neogene precursor. Beyond the minor normal faulting implying minor adjustments (Fig. 11) there is not a cogent case for extensional influence in the history of the Willunga Embayment. It is episodic compression, all the way down.

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Itinerary for one-day excursion to Willunga Embayment

Morning

Stop 1

Car park above Blanche Point, at the end of Bowering Hill Road, south end of Maslin Bay.

Below the angular unconformity: South Maslin Sand to Blanche Point Formation, Perkana Member.

Above the angular unconformity: Hallett Cove Sandstone to Ngaltinga Formation and calcrete.

Stop 2

Car park above Perkana Point, north end of Aldinga Bay.

Below the angular unconformity: Blanche Point Formation, Gull Rock and Perkana Members.

Above the angular unconformity: Hallett Cove Sandstone to Ngaltinga Formation and calcrete.

Stop3

Car park at Star of Greece Café, Port Willunga. North of Aldinga Creek.

Below the angular unconformity: Blanche Point Formation, Tuit Member to Port Willunga Formation, Aldinga Member.

Above the angular unconformity: Hallett Cove Sandstone to Ngaltinga Formation and calcrete.

Stop 4

Car park at Star of Greece Café, Port Willunga. South of Aldinga Creek.

Below the angular unconformity: Port Willunga Formation, Aldinga Member and Ruwarung Member.

Above the angular unconformity: Hallett Cove Sandstone to Ngaltinga Formation and calcrete.

Afternoon

Stop 5

McLaren Vale for lunch.

Stop 6

Chapel Hill Road. Cutting on south side of road.

The Great Unconformity: North Maslin Sand overlying deeply weathered Burra Group (Neoproterozoic).

Stop 7

Seaview Road, cutting on south side of road.

Pirramimma Sandstone (Pleistocene version).

Stop 8

Seaview Road, south side. Olivers Pit.

North Maslin Sand. Ironstone boulders.

Stop 9

Field Street, McLaren Vale. Cutting on western side.

Blanche Point Formation, inshore facies, with two ironstone horizons.

Stop 10

Battle of Bosworth Winery, Gaffney Road, Willunga.

Stop 11

Sellicks Creek, Victory Hotel, Main South Road, Sellicks Hill.

Strongly lithified (silicified) Kurrajong Formation.

Stop 12

End of the Esplanade, Sellicks Beach.

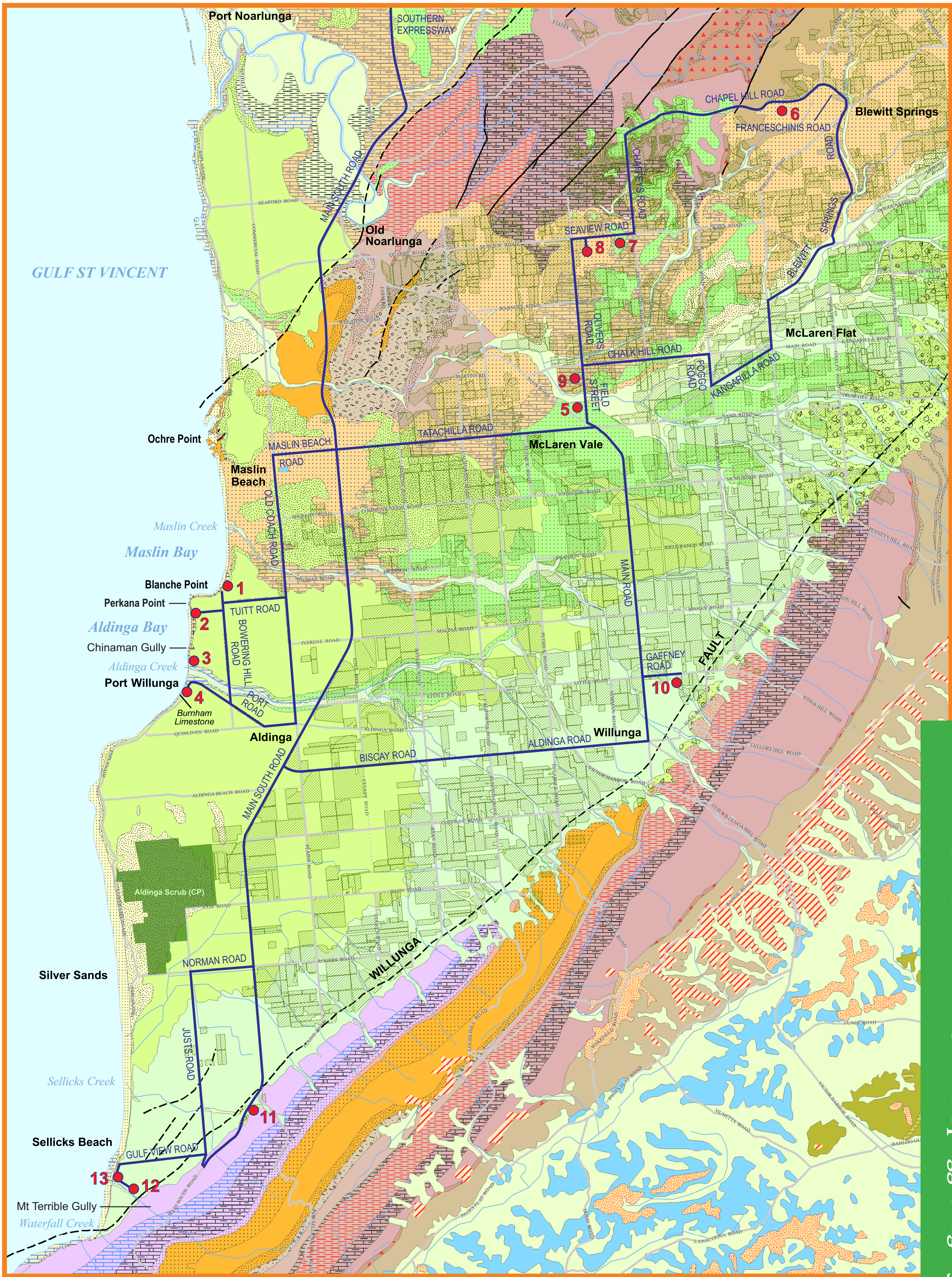
View across Mt Terrible Gully ("Cactus Canyon") of the Willunga Fault, with Early Cambrian Heatherdale Shale rising over Late Pleistocene Christies Beach Formation.

Stop 13

Lookout off the Esplanade near Palmerston Avenue, Sellicks Beach.

A panoramic view of cliffs and wavecut platforms in the hangingwall of the Willunga Fault: (i) the near-vertical Port Willunga Formation unconformably on the Cambrian Heatherdale Shale; and (ii) the late Pleistocene gravel fans (Christies Beach Formation) spilling on to the uplifted 125,000-year shore platform cut into the Port Willunga Formation.

The itinerary map is extracted from *Geology of the McLaren Vale Wine Region* by Fairburn, Olliver, Preiss and White (2010).


Port Noarlunga
SOUTHERN EXPRESSWAY
CHAPEL HILL ROAD
6
Blewitt Springs
FRANCESCHINIS ROAD
MAIN SOUTH ROAD
Old Noarlunga
SEAVIEW ROAD
8
7
GULF ST VINCENT
BLEWITT SPRINGS ROAD
McLaren Flat
OLIVERS ROAD
CHALK HILL ROAD
FOGGO ROAD
KANGARILLA ROAD
9
FIELD STREET
5
TATACHILLA ROAD
Ochre Point
MASLIN BEACH ROAD
McLaren Vale
Maslin Beach
OLD COACH ROAD
Maslin Creek
Maslin Bay
MAIN ROAD
Blanche Point
1
Perkana Point
TUITT ROAD
2
Aldinga Bay
BOWERING HILL ROAD
Chinaman Gully
3
Aldinga Creek
GAFFNEY ROAD
FAULT
Port Willunga
10
4
PORT ROAD
Burnham Limestone
Aldinga
Willunga
ALDINGA ROAD
BISCAY ROAD
MAIN SOUTH ROAD
Aldinga Scrub (CP)
NORMAN ROAD
Silver Sands
WILLUNGA
JUSTS ROAD
Sellicks Creek
11
Sellicks Beach
GULF VIEW ROAD
13
12
Mt Terrible Gully
Waterfall Creek