Tasmanian Geological Survey
Record 2007/02

Some notes on the geology of King Island

Department of Infrastructure, Energy and Resources
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by C. R. Calver

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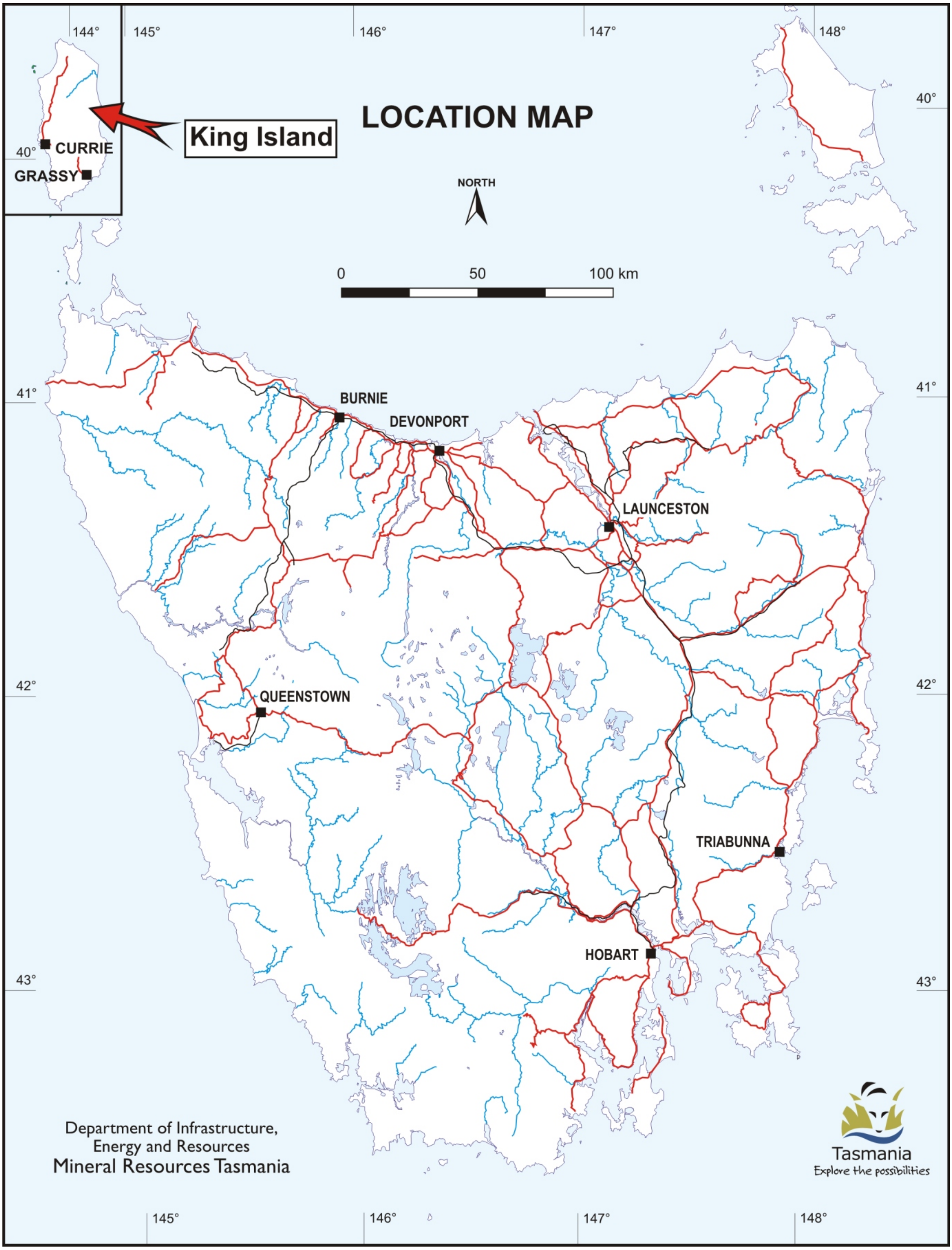

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Summary

King Island consists mainly of Proterozoic rocks and some Devonian granite, with an extensive inland cover of Pleistocene to Recent windblown sand (fig. 1). The Proterozoic geology of the western half of the island is different to that of the eastern half, and the relationship of the two areas is problematic. The geology is unusual in the Southeast Australian context, and is well-exposed around the coast.

The western half of the island consists of Mesoproterozoic (1300 Ma) amphibolite-grade metasediments, regionally deformed and metamorphosed at c. 1290 Ma and intruded by 760 Ma granite. The metasediments strike N–S and the granite is regionally concordant. The eastern half of the island mainly consists of a thick succession of relatively unmetamorphosed siltstone, probably a correlate of the lower Neoproterozoic (c. 1000–750 Ma) Cowrie Siltstone of northwest Tasmania. The contact between the metasediments and the siltstone is concealed by surficial sediments, and its nature (whether a fault or unconformity) is unknown. Along the southeast coast, the siltstone succession is overlain by an upper Cryogenian to Ediacaran, east-dipping succession of diamictite, cap dolostone, shale and mafic volcanic rocks (basalt and picrite). Along the east coast, three small, early Carboniferous granite stocks intrude the Neoproterozoic sedimentary rocks. Scheelite orebodies, which were mined up until 1990, occur in the contact aureoles of the two southern granite stocks. The world-class Grassy scheelite mine is planned to be re-opened in 2008. Most of the interior of the island is covered by Quaternary surficial deposits — mainly windblown sand and stabilised dunes. A number of small Tertiary basalt plugs are known, and Tertiary limestone crops out on the east coast.

Cover: Coastal outcrop, Quarantine Bay, west coast of King Island. [Photo: Brett Stewart]

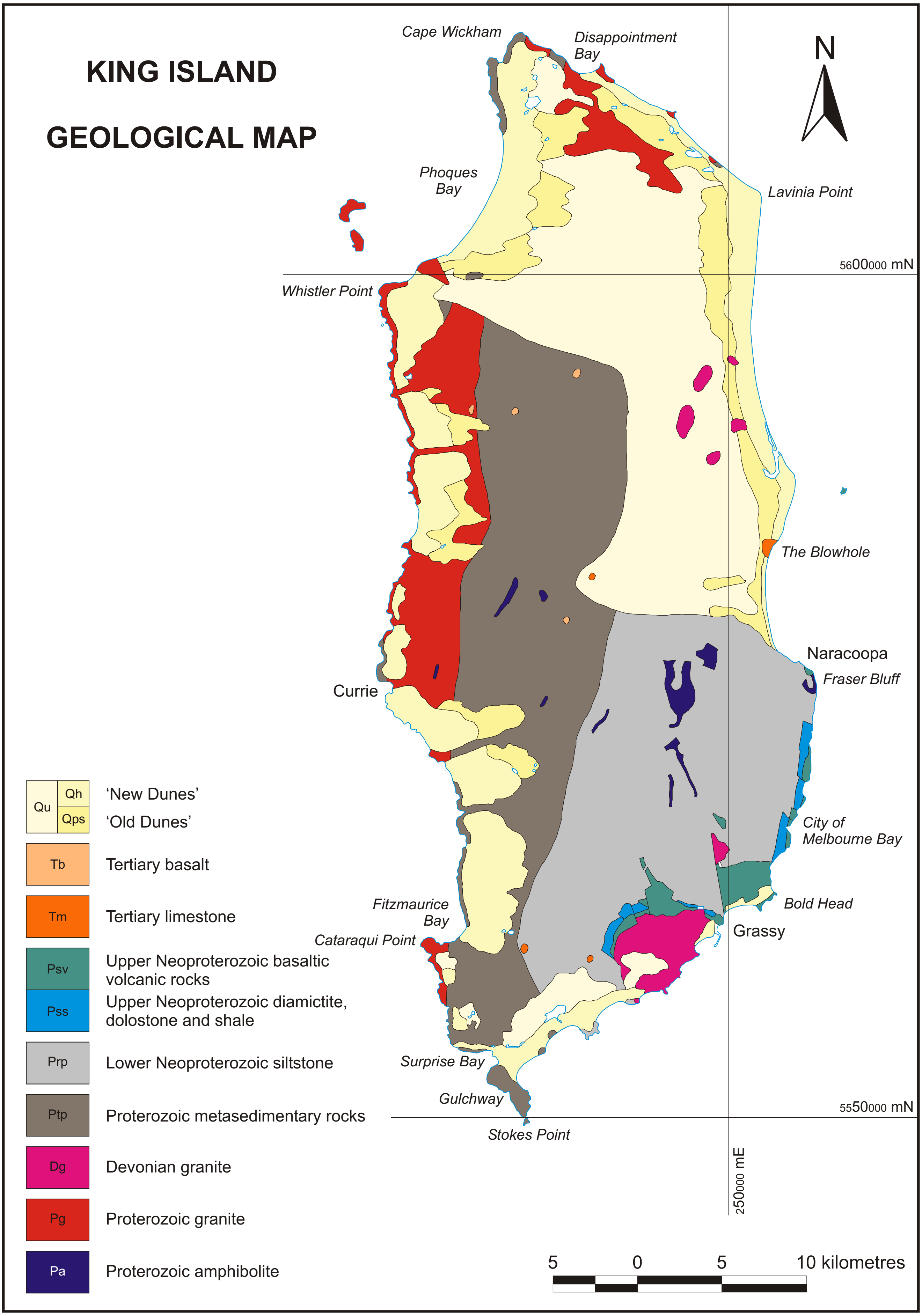


Figure 1

Geological map of King Island, from current Tasmanian Geological Survey 1:250 000 scale digital geological coverage.

Western King Island

Surprise Bay Formation: Metasediments c. 1300 Ma

The western half of King Island is dominated by metasediments (Surprise Bay Formation) and minor mafic intrusive rock, intruded by c. 760 Ma granitoids (Gresham, 1972; Cox, 1973; Blackney, 1982; Cox, 1989; Turner *et al.*, 1998; Holm, 2002). The Surprise Bay Formation consists of at least 1000 m of dominantly quartzofeldspathic schist with minor quartzite, pelitic schist and rare calcareous lenses. Schists typically consist of quartz + muscovite + biotite (+ plagioclase). Locally, pelite contains garnet and minor potash feldspar, and andalusite is present in alumina-rich rocks. Coastal outcrops between Ettrick River and Fitzmaurice Bay preserve graded bedding and appear to be fine-grained, quartz-rich sandy turbidites. The metasediments at Cape Wickham include relatively pure quartzite with rare cross bedding (Cox, 1973).

The mafic intrusive rocks are amphibolites and are chemically similar to tholeiitic basalt. Extrusive rocks were reported at Gulchway by Blackney (1982), but the 2004 Australian Geological Convention excursion visit to this locality failed to substantiate an extrusive origin.

A maximum constraint for the depositional age of the Surprise Bay Formation is given by the age of the youngest detrital zircons (c. 1350 Ma) in a sample of the turbidites north of Fitzmaurice Bay (Black *et al.*, 2004). The zircons in this sample show a predominance of ages at around 1450 Ma and 1600–1850 Ma (fig. 2).

Regional deformation and metamorphism, c. 1290 Ma

Electron microprobe dating of metamorphic monazite from metasediments at Fitzmaurice Bay and Surprise Bay (southwest coast of King Island), away from the granite aureoles, gives ages of around 1270 Ma, and this is interpreted as the age of the regional, amphibolite-grade metamorphism that affects these rocks (Berry *et al.*, 2005). The first major deformation phase (D_1) produced large, tight to isoclinal folds, associated minor folds, and a penetrative axial surface cleavage defined by muscovite. Prograde metamorphism appears to have commenced during D_1, and S_1 microfabrics are defined by amphibolite facies mineral assemblages.

This early Grenvillian-aged metamorphic event is unknown in northwest Tasmania, where the oldest succession (Rocky Cape Group) is thought to be significantly younger (<1000 Ma) (fig. 3). However, a 1300 Ma event is recorded in monazite in the cores of garnets in the Franklin Metamorphic Complex in central Tasmania, and this constitutes the only known occurrence of possible Mesoproterozoic basement on mainland Tasmania (R. F. Berry, pers. comm., *in* Seymour *et al.*, 2007).

The position of Tasmania in Rodinia reconstructions is highly uncertain. The presence of a Grenville-aged orogeny suggests it may have been close to the Musgrave Block, or alternatively near the recently identified Grenville-aged terrane in the Transantarctic Mountains (Berry *et al.*, 2005).

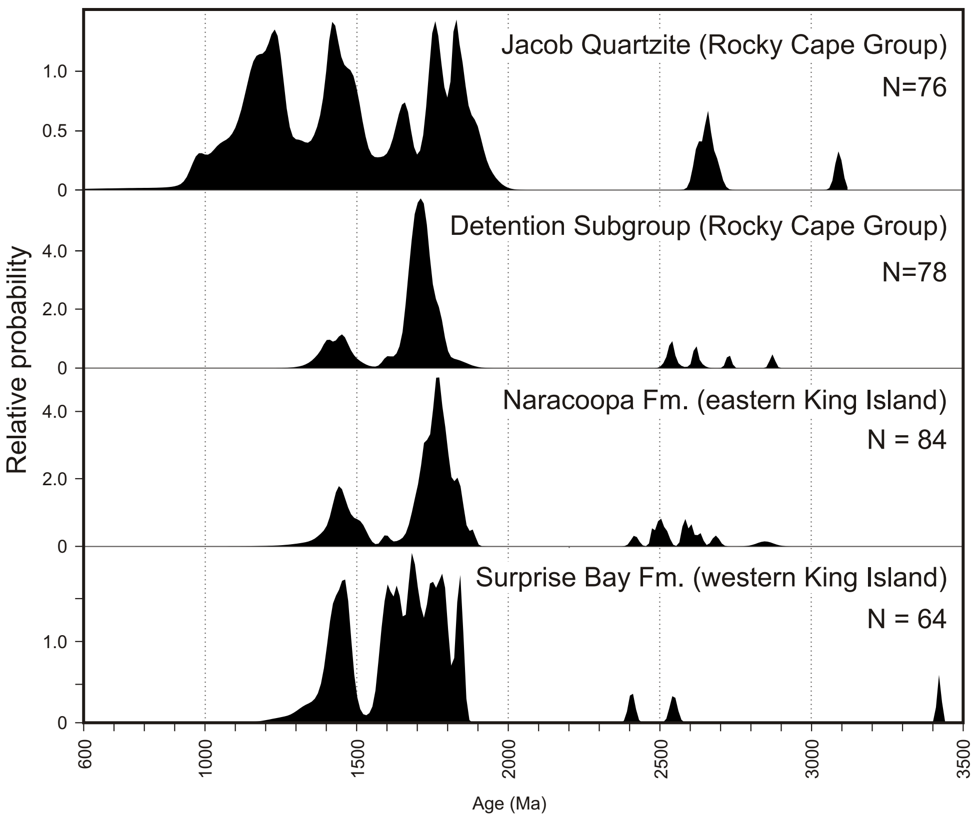


Figure 2

Detrital zircon age profiles: Jacob Quartzite and Detention Subgroup (both of the Rocky Cape Group of northwest Tasmania), and Naracoopa Formation and Surprise Bay Formation (eastern and western King Island respectively).

Granitoid intrusion and local deformation: Wickham Orogeny, c. 760 Ma

Turner *et al.* (1998), in defining the Wickham Orogeny, followed Cox (1989) in believing that the early regional phase of metamorphism and deformation was related to the c. 760 Ma granitoids, and included all these events in the Wickham Orogeny. Berry *et al.* (2005) dated the early regional phase at 1270 Ma (see above), so the Wickham Orogeny, as presently understood, only encompasses the granitoid intrusion, and localised deformation (D_2–D_4) in the aureoles of the granitoids. Consistent with this, there is no firm evidence for a 760 Ma orogeny in mainland Tasmania or southern Australia, although a regional low-angle unconformity in Tasmania could be about this age (fig. 3).

Cross-cutting relationships at the margin of the pluton east of Cape Wickham (northern tip of King Island) shows that major granitic intrusive activity post-dates the D_1 (1270 Ma) event. The dominant and earliest granitic intrusive phase is an S-type, K-feldspar porphyritic biotite adamellite. Later minor associated intrusive rocks include S-type biotite granodiorite, even-grained biotite adamellite, biotite-muscovite granite, aplite and pegmatite. Rb-Sr muscovite ages of 730 Ma and 726 Ma were obtained by I. McDougall (pers. comm. after McDougall and Leggo, 1965), from an even-grained biotite-muscovite granite which occurs near the western margin of the pluton. More recent dating using SHRIMP (Pb-Pb on zircon) has given 760 ± 12 Ma at Cape Wickham and 748 ± 2 Ma near Currie (Turner *et al.*, 1998; Black *et al.*, 1997). Minor dykes of epidote amphibolite, with a tholeiitic composition, post-date the metamorphic peak, but pre-date D_2 and minor granitic intrusive activity (Cox, 1989).

Garnet-biotite geothermometry in southwest King Island indicates that peak metamorphic conditions during granite emplacement had temperatures of 470–580°C, whilst the presence of andalusite and rare phengite suggests low pressures of 100–300 MPa (Blackney, 1982).

D_2 structures are weak away from the granites, but include tight folds within the contact aureoles (Cox, 1989). Within the granite at Cape Wickham, D_2 has deformed xenoliths, produced a foliation in some of the granitic rocks, and produced some mylonite zones. The granite here is interpreted as a syn-D_2 intrusion, although minor granitic intrusive activity and veining post-dates D_2 folding. Third generation folds, which are also cut by minor granitic sheets and veins, are moderately to gently inclined, open structures. Upright D_4 folds post-date all granitic intrusive activity, but are apparently cut by dykes of tholeiitic dolerite which form part of an extensive and dominantly north-trending dyke swarm in the Cape Wickham area. These extensively altered dolerites may be related to the Ediacaran mafic extrusive rocks on the east coast of King Island (Cox, 1989).

Eastern King Island

Naracoopa Formation (c. 1000–750 Ma)

The eastern half of King Island consists mainly of a thick (6–7 km?) succession of relatively unmetamorphosed shale, siltstone and fine-grained muscovitic quartz sandstone, which dips and faces east. This unit, the Naracoopa Formation, lithologically resembles the Cowrie Siltstone of northwest Tasmania, which is part of the Rocky Cape Group whose depositional age lies between 1000 Ma and 750 Ma (fig. 3). The unit has a detrital zircon age distribution similar to the Rocky Cape Group and Oonah Formation of western Tasmania (Black *et al.*, 2004; fig. 2). The contact between the Surprise Bay Formation of western King Island and the Naracoopa Formation is concealed by surficial sediments, and its nature (whether a fault, unconformity or metamorphic transition) is unknown.

Grassy Group

Along the southeast coast, the Naracoopa Formation is overlain by a late Neoproterozoic succession of diamictite, dolomite, limestone, shale and mafic volcanic rocks (basalt and picrite) — the Grassy Group (Knight and Nye, 1953; Calver and Walter, 2000). In the type area around Grassy, the succession is intruded by a Carboniferous granite stock, and the contact-metasomatised sedimentary rocks host large scheelite ore bodies (Knight and Nye, 1953; Large, 1971; Danielson, 1975; Danielson and Brown, 1976). These contact-metamorphosed and metasomatised sedimentary rocks are correlated with the well-preserved coastal sections around City of Melbourne Bay (e.g. Large, 1971; Danielson, 1975; Brown, 1990; Turner *et al.*, 1998), in which the following stratigraphy is recognised.

The contact between the Naracoopa Formation and the Grassy Group is poorly exposed and apparently regionally conformable (Waldron and Brown, 1993), although Danielson (1975) and Danielson and Brown (1976) suggested an unconformable relationship. If the shale-siltstone unit is a correlate of the Rocky Cape Group (older than 750 Ma), a significant lacuna must be present as the Grassy Group is probably <650 Ma. An unconformity at this level may correspond to the Wickham Orogeny of western King Island.

The Neoproterozoic successions of central and South Australia were deposited in intracratonic or non-volcanic rift settings (Centralian Superbasin and Adelaide Rift Complex, respectively: Preiss, 1987; Walter *et al.*, 1995). By contrast, in parts of southeastern Australia, including Tasmania, late Neoproterozoic sedimentation was interrupted at about 580 Ma by extrusion of mafic rift volcanic rocks accompanying the development of a volcanic passive margin (Crawford *et al.*, 1997; Calver and Walter, 2000; Direen and Crawford, 2003; Meffre *et al.*, 2004). The base of such a volcanic succession on King Island occurs within the Grassy Group, about 100 m above the top of a Marinoan glacial correlative (Calver and Walter, 2000; Calver *et al.*, 2004).

The Grassy Group is well exposed on the southeast coast around City of Melbourne Bay where it dips and faces east. The Grassy Group consists of (from the base):

1. **Cottons Breccia** (Jago, 1974): About 100 m of predominantly diamictite, of pebble to boulder grade, with clasts mostly of fine-grained quartzite, siltstone and shale similar to the underlying succession, but also including carbonate, chert, rare basalt and other lithologies unknown in the underlying succession. A tuffaceous sandstone up to 10 m thick, with a probably originally mafic composition now altered to carbonate and chlorite, occurs in the middle of the Cottons Breccia. Recent detrital zircon dating from the top of this unit shows an abundant 655–635 Ma population, but nothing younger (Evans, 2005).

2. **Cumberland Creek Dolostone** (Meffre *et al.*, 2004): Pale pinkish-grey, fine-grained, laminated dolostone passing up into thinly interbedded dolostone, limestone and shale, about 10 m thick in total. This unit has the distinctive lithology and carbon isotope signature (^{13}C-depleted, upward-decreasing) of the widespread 'cap dolostone' that overlies the Marinoan glacials on mainland Australia (the Nuccaleena Formation and correlates: Calver and Walter, 2000; Preiss, 2000) and correlative glacial horizons elsewhere.

3. **Yarra Creek Shale** (Calver *et al.*, 2004): Approximately 100–120 m thick, of planar-laminated shale with rare, thin, graded beds of volcaniclastic sandstone. Black shale beds in the middle part of this unit have the sedimentological characteristics of fossil benthic microbial mats, which are also locally seen low in the post-glacial succession on mainland Australia, further reinforcing the correlation (Logan *et al.*, 1999; Calver, 2000; Calver and Walter, 2000).

4. **Grimes Intrusive Suite** (Meffre *et al.*, 2004): Compositionally unusual, differentiated sills intrude the above-mentioned units. These are broadly andesitic in composition, with a basal cumulate zone of pyroxene-rich gabbro resulting from *in situ* fractional crystallisation following intrusion (Waldron and Brown, 1993; Meffre *et al.*, 2004). The upper and middle parts of the sills are 55–65% SiO_2, but have unusually high MgO, Cr and Ni contents indicating a mafic source component. Nd isotopes and trace element anomalies indicate marked crustal contamination (Meffre *et al.*, 2004). These rocks are characterised by acicular or skeletal feldspar phenocrysts in a groundmass of radially-arranged sheaves of feldspar. Locally, the sills are vesicular, suggesting shallow intrusion, but the Yarra Creek Shale appears to have been at least partially lithified at the time of intrusion. These intrusive rocks have been dated at 575 ± 3 Ma (SHRIMP U-Pb on zircon, Calver *et al.*, 2004).

5. **City of Melbourne Volcanics** (Meffre *et al.*, 2004): Up to 100 m of tholeiitic pillow lavas, peperites and volcaniclastic sandstone. Peperites, hyaloclastite breccias and lobate intrusions with a matrix of baked mudstone indicate extrusion and shallow intrusion into soft sediment at the top of the Yarra Creek Shale. The tholeiites have low Ti and Zr and variable LREE enrichment (Waldron and Brown, 1993). Nd isotopic composition indicates crustal contamination, but not to the same extent as the Grimes Intrusive Suite (Meffre *et al.*, 2004).

6. **Shower Droplet Volcanics** (Meffre *et al.*, 2004): 200–300 m of interbedded pillow lavas, thin flows and hyaloclastites. This unit is picritic in composition, and characterised by high MgO and very low incompatible element concentrations, particularly LREE (Waldron and Brown, 1993; Meffre *et al.*, 2004). Waldron and Brown (1993) state that this unit disconformably overlies the City of Melbourne Volcanics.

7. **Bold Head Volcanics** (Meffre *et al.*, 2004): At least 300 m of tholeiitic basalt flows, pillow lavas, and volcaniclastic sandstone and conglomerate. These tholeiites are compositionally similar to enriched mid ocean ridge basalts (Waldron and Brown, 1993; Meffre *et al.*, 2004). No stratigraphic contact has been observed with the older rocks, but dykes of similar composition to the Bold Head Volcanics cut both the earlier volcanic units. The Shower Droplet Volcanics and the Bold Head Volcanics have a Nd-Sm isochron age of 579 ± 16 Ma (Meffre *et al.*, 2004).

The latter three volcanic units, referred to as the 'lower tholeiites', 'picrites' and 'upper tholeiites' by Waldron and Brown (1993), comprise the Skipworth Subgroup of Meffre *et al.* (2004).

The top of the volcanic succession is not exposed and lies offshore. Modelling of aeromagnetic anomalies suggests that there may be a total thickness of 8500 m of mafic volcanic rocks (Direen and Crawford, 2003; Meffre *et al.*, 2004). The nature of the succession above the volcanic rocks is unknown, but in northwest Tasmania there is a broadly similar but much thinner mafic rift volcanic succession known as the Kanunnah Subgroup (part of the Togari Group: Everard *et al.*, 1996; 2007). The Kanunnah Subgroup contains a rhyodacite flow dated at 582 ± 4 Ma (Calver *et al.*, 2004), and is conformably succeeded by the Smithton Dolomite. The Smithton Dolomite is upper Ediacaran (c. 570–545 Ma), based on strontium isotope chemostratigraphy (Calver, 1998).

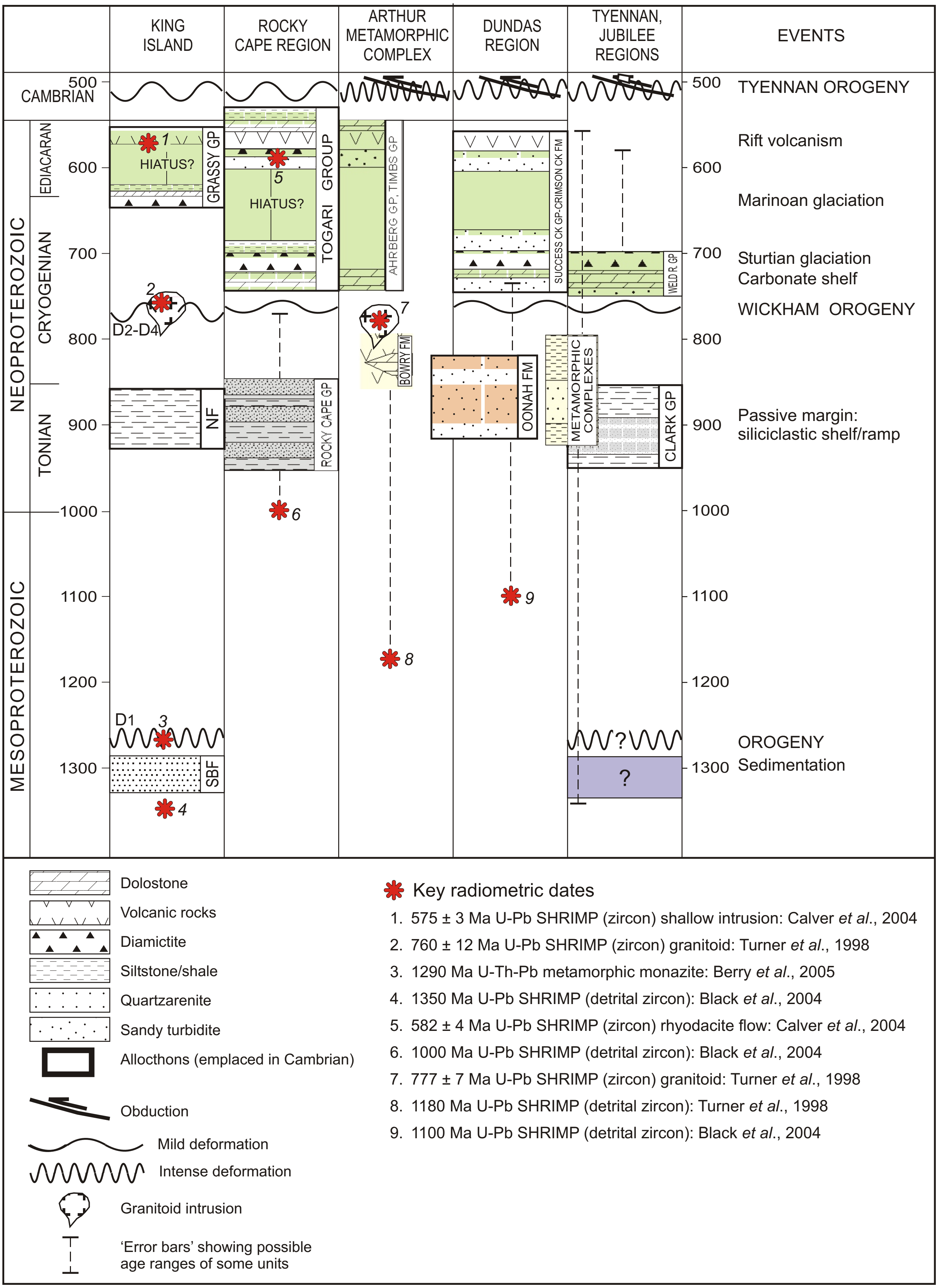


Figure 3

Time-space diagram for Proterozoic of King Island and other Tasmanian terranes. NF: Naracoopa Formation; SBF: Surprise Bay Formation.

The base of the Ediacaran: 580 Ma or 635 Ma?

The 582 Ma rhyodacite in the Kanunnah Subgroup directly underlies the Croles Hill Diamictite, which like the Cottons Breccia, is succeeded by a predominantly shale unit, then thick mafic lavas (but which unlike the Cottons Breccia, lacks a cap dolostone). The Croles Hill Diamictite is stratigraphically preceded by a convincing Sturtian glacial correlative (fig. 3; Calver, 1998). Calver and Walter (2000) and Calver *et al.* (2004) correlated the Croles Hill Diamictite and the Cottons Breccia with the Elatina Formation (Marinoan glacials) of South Australia, thereby deriving a date of c. 580 Ma for the hitherto chronometrically elusive base of the Ediacaran System. However several subsequent estimates from dating of purported correlates on other continents are all around 635 Ma (Hoffmann *et al.*, 2004; Condon *et al.*, 2005; Bowring *et al.*, in press), and this value is now generally accepted.

This discrepancy could be resolved by maintaining the Cottons Breccia–Elatina correlation at 635 Ma and inserting a major hiatus (c. 50 m.y.) in the Grassy Group somewhere between the cap dolostone and the picrite unit (fig. 3). The contact between the City of Melbourne Volcanics (lower tholeiites) and the Shower Droplet Volcanics (picrites) would be a likely horizon for this lacuna, as the picrites and upper tholeiites would have to be on the younger side (579 ± 16 Ma isochron age), and a disconformity was noted at this horizon by Waldron and Brown (1993).

Devonian granites and contact metamorphism and metasomatism

Three granite bodies — the Grassy, Bold Head and Sea Elephant plutons — intrude the Proterozoic sedimentary rocks of eastern King Island. Based on modal analyses, the intrusions are classified as monzogranite-granodiorite, and are I-type. The Bold Head intrusive may be a faulted sliver of the larger Grassy intrusive.

The Grassy and Bold Head granodiorites average 68.5% SiO_2, and are porphyritic, with large pink K-feldspar phenocrysts. The mineralogy consists of quartz, K-feldspar, plagioclase, biotite and amphibole with minor apatite, allanite, sphene, magnetite and zircon. The Sea Elephant Adamellite, in the northeast of the island, is the fractionated equivalent of the Grassy and Bold Head granodiorites. It is more felsic (70.15% SiO_2) and is texturally similar to the other bodies, differing only in that it contains minor amounts of amphibole and sphene (Williams *et al.*, 1989).

Scheelite deposits

Scheelite skarn mineralisation, formed by selective metasomatic replacement of carbonate horizons within the late Neoproterozoic Grassy Group, occurs in the contact metamorphic aureoles of the Grassy and Bold Head intrusions. The Bold Head and Dolphin ore bodies were mined intermittently from 1917 to 1990. The total pre-mining resource was 23.8 Mt at 0.66% WO_3 (Seymour *et al.*, 2007). King Island Scheelite Limited has signed a non-binding letter of intent with the Hunan Nonferrous Metals Corporation Limited under which Hunan would provide some equity funding in return for an off-take agreement to purchase 50% of the scheelite concentrate produced. Hunan is proceeding with due diligence in anticipation of an agreement being finalised by the end of July 2007.

The proposed project involves expansion of the Grassy open cut in an initial ten-year project to a depth of -180 metres RL and production of 6.8 million tonnes of ore grading 0.55% WO_3, necessitating construction of a sea wall (fig. 5). The open cut could later be further expanded to -248 metres RL, prior to resumption of underground mining. Earlier operations at Grassy focussed on the C lens skarns (see below) but the planned operation would involve extraction of ore from both the B and C lens horizons. Total resources in the Grassy deposit are 13.4 million tonnes of 0.64% WO_3.

Scheelite was first discovered at Grassy in 1911 and almost continuous mining since 1937 has produced over 60 000 tonnes WO_3 from the No. 1/Dolphin deposit at Grassy and the Bold Head deposit, three kilometres to the north.

The deposits formed within a 150–200 m thick sequence of contact metamorphosed and metasomatised pelitic and calcareous sedimentary rocks of the lower part of the Grassy Group (fig. 4; Knight and Nye, 1953; Danielson, 1975). The host rocks pass up into a thick (2500 m) metavolcanic sequence, presumably equivalent to the upper volcanic part of the Grassy Group in the City of Melbourne Bay area.

The ore bodies are within andradite garnet skarn horizons, mainly at two levels (B lens and C lens) in the host sequence (Danielson, 1975; fig. 4), given below in descending stratigraphic order (Brown, 1989):

- B lens hangingwall hornfels (10–20 m thick): actinolite-biotite and biotite hornfels.
- B lens (25–30 m): banded sequence of biotite pyroxene hornfels, marble, grossularite; variable scheelite.
- Hangingwall hornfels (5–50 m): actinolite-biotite and biotite hornfels.
- Pyroxene garnet hornfels (2–15 m): diopside and grossularite hornfels; calcite ovoids up to 150 mm diameter; variable scheelite.
- Upper C lens (0–20 m): andradite skarn, marble, minor pyroxene-grossularite hornfels; principal ore horizon.

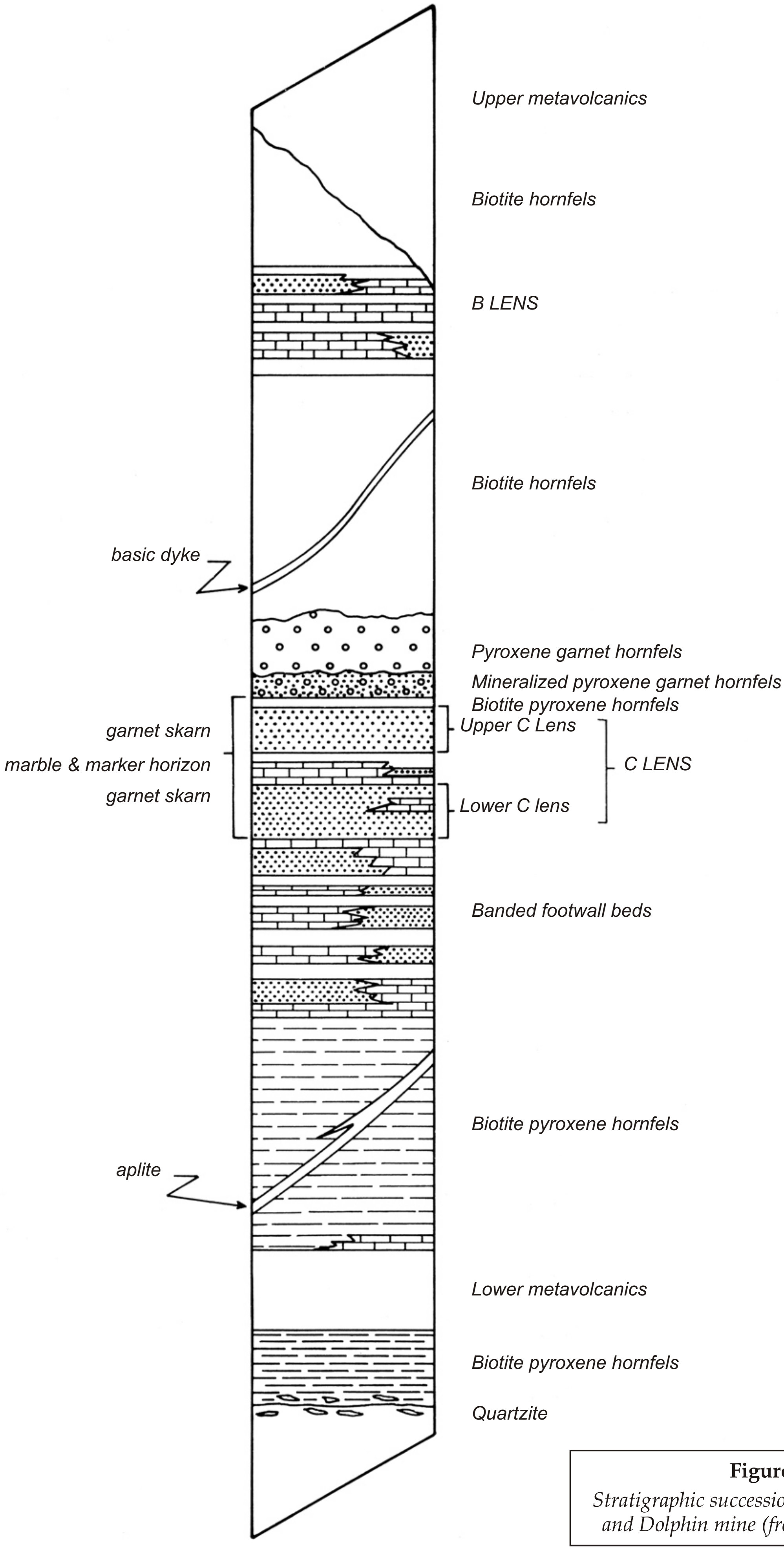


Figure 4

Stratigraphic succession, No. 1 Open Cut and Dolphin mine (from Brown, 1990).

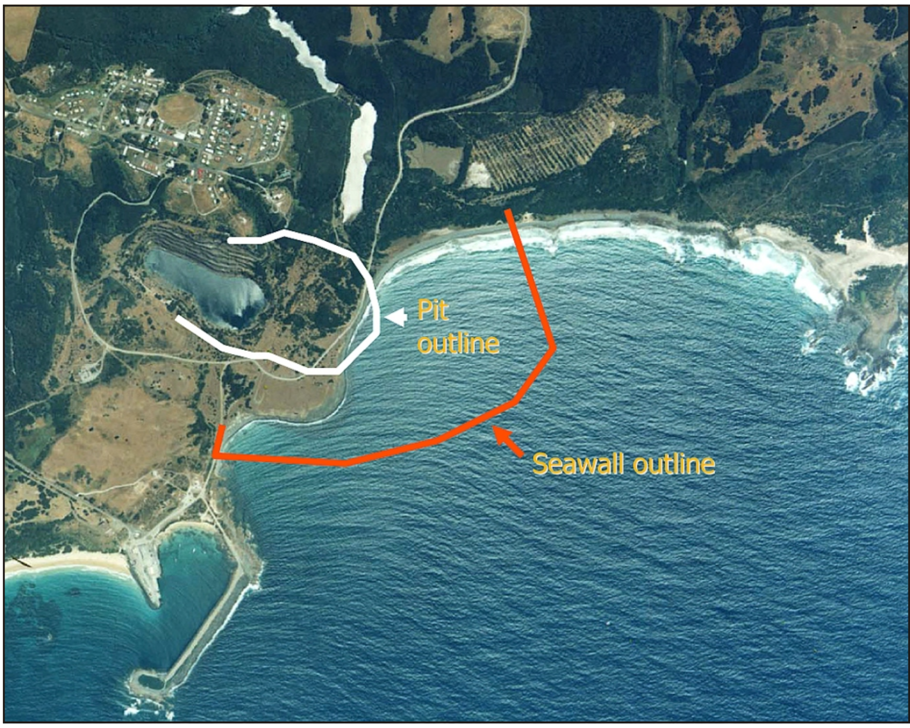


Figure 5
Aerial view of Grassy open cut showing extent of planned open cut and location of proposed sea wall.

- Marble marker (1–5 m): barren or weakly mineralised marble and pyroxene-grossularite biotite hornfels.
- Lower C lens (0–l m): banded andradite skarn and pyroxene hornfels.
- Banded footwall beds (7–30 m): interbedded (10–50 mm) marble and pyroxene-biotite-grossularite hornfels; variable scheelite.
- Biotite pyroxene hornfels (20–30 m): thinly banded (5–10 mm) biotite-pyroxene-actinolite hornfels.
- Lower metavolcanics (5–8 m): tremolite-phlogopite chlorite-magnetite rock.

Although the succession is highly altered, the stratigraphy appears to be somewhat different to the City of Melbourne Bay area, with more carbonate and possibly no diamictite (fig. 4).

The C lens primary skarn consists of andraditic garnet, pyroxene and scheelite; superimposed on this is a complex secondary skarn assemblage of ferrohastingsite, epidote, calcite, quartz, sulfides, scheelite and minor molybdenite and rarely, magnetite. Most scheelite is fine grained (0.02–0.5 mm) and formed within and adjacent to the margins of andradite garnets (Danielson, 1975; Kwak and Tan, 1981). Coarse-grained scheelite is found within pyroxene garnet hornfels above C lens, and in joint planes and quartz-filled tension gashes (Danielson, 1975). Primary scheelite is enriched in molybdenum, with the equivalent of about 30% powellite (Kwak and Tan, 1981), but there is also some secondary Mo-poor scheelite, usually associated with molybdenite. Other late-stage sulfide minerals within the ore include pyrite, pyrrhotite, arsenopyrite and chalcopyrite with minor sphalerite, galena, bournonite and bismuthinite near major faults. Wolframite has been found in trace amounts at Bold Head (Brown, 1989).

Mining of the No. 1 and Dolphin ore bodies was confined to the C lens horizons, with additional tonnages in the pyroxene-garnet hornfels, and in the lower grade B lens. The upper C lens contains most ore-grade mineralisation, generally greater than 1% WO_3. This horizon varies in width from about 12 m in the open cut area (No. 1 ore body) to 20 m in the underground area (Dolphin mine). The grade and thickness of C lens decreases down dip, where it terminates against granodiorite, whereas to the north and east, the mine sequence is cut by faults. The best ore development is within the hinge zones of two southeasterly-plunging anticlines, the western one being seen in the open cut, whereas within the intervening syncline, the ore horizons are narrow and weakly mineralised (Brown, 1989).

The Bold Head ore body is confined to the stratigraphic equivalents of the B lens and pyroxene-garnet hornfels/C lens units at the No. 1/Dolphin deposit, but on the opposite side of the Grassy River Fault. The Bold Head deposit lies within a down-faulted block, bounded by faults to the west, south and east, and in the north and west the host sequence terminates against biotite adamellite (Large, 1971).

The King Island scheelite deposits are considered by most workers to have formed by contact metasomatic replacement of limestone at the No. 1 and Dolphin deposits, and dolomitic limestone, limestone and dolomite at Bold Head, by magmatic hydrothermal fluids derived from an adjacent or underlying granitoid (Large, 1971; Kwak and Tan, 1981). Contact metamorphism of the original sedimentary and mafic volcanic sequence resulted in a variety of hornfels types, including marble, biotite hornfels and grossular-diopside hornfels derived from sedimentary rocks, while the mafic lavas and pyroclastic rocks were converted to actinolite-tremolite forsterite-spinel assemblages (Brown, 1989).

Subsequent diffusion and infiltration metasomatism of marble horizons formed skarns of andradite, diopside, quartz, epidote, actinolite, zoisite and scheelite (Large, 1971; Kwak and Tan, 1981). A general increase in grade towards major faults indicates that the faults served as conduits for ascending hydrothermal fluids which then permeated through the reactive marble. Replacement fronts of garnet skarn (with 1% WO_3) partially replacing barren marble are common at Bold Head. Where there was insufficient fluid to 'flood' the carbonate units, replacement has been confined to a transition zone between marble and overlying pelitic hornfels (Brown, 1989).

Tertiary–Quaternary

A number of small, eroded Tertiary basalt plugs are present on the island. Most of the small 'bullseye' magnetic anomalies can be attributed to these.

Outcrops of Miocene bryozoal limestone occur on the coast at the 'Blowhole', north of Naracoopa, and at scattered localities inland.

The present-day physiography of the island is essentially that of an inclined plateau (an early Tertiary erosion surface), with its highest point (159 m) in the southeast, and surrounded by a rim of stabilised, coastal sand dunes.

The belt of dunes extends almost continuously around the coast, with the exception of the steep coast between Grassy and Naracoopa. The belt is widest (up to 4 km) behind the west coast. Two sets of dunes were recognised by Jennings (1959); the 'Old Dunes' and the 'New Dunes'. The 'Old Dunes' are probably Pleistocene, are somewhat modified by erosion, and consist of leached, grey-white quartz sand. The 'New Dunes' are Holocene, little modified by erosion, and commonly parabolic in form. On the west coast, the dunes comprise calcareous shell sands; on the east coast, north of Naracoopa, they are mainly quartz sand and are prospective for heavy minerals (rutile and monazite).

In the central north of the island there are extensive flat plains underlain by estuarine/marine sediments (shelly sands), parts of which are covered by peaty soils and clay of former shallow lakes and swamps, such as Egg Lagoon (now drained). Skeletons of the extinct Pleistocene 'giant wombat' *Diprotodon* have been recovered from Egg Lagoon.

On the rocky coast from Grassy to Naracoopa, a narrow coastal terrace 10–20 m above present sea level is an emerged marine platform dating from a higher sea level stand, probably in the last interglacial (Jennings, 1959).

Detailed site descriptions

The following are detailed descriptions of the geology at selected sites on King Island. Most of the localities are coastal outcrop on exposed coasts, so please keep an eye on wave conditions.

Western King Island: Mesoproterozoic metasediments; Neoproterozoic granite; contact aureole

Locality 1: Cape Wickham: metasediments, granitoids, Wickham Orogeny

At the northern end of King Island, a coarsely porphyritic biotite adamellite dated at 760 Ma (Turner *et al.*, 1998) has intruded steep westerly-dipping metasediments of the Surprise Bay Formation. Metasediments lying to the west of this granitic mass may form a screen that continues south under Quaternary cover to separate this granite from the medium-grained biotite granodiorite/adamellite of the Whistler Point–Currie area, but this is not certain. A 700 m wide area of metasediments within the granite two kilometres east of Cape Wickham is interpreted as a roof pendant (Cox, 1973).

The country rock (metasediments) and contact aureole are best examined on the western side of the granite (to the west of the Cape Wickham lighthouse), with the granite examined just east of Cape Wickham. Most of the information below is from Cox (1973; 1989).

Metasediments and amphibolites, west of lighthouse

The best place to see the country rocks to the granitoids is on the coast immediately west of the lighthouse. The rocks here are quartzofeldspathic amphibolite facies metasediments: interlayered quartzite, micaceous quartzite, and quartzofeldspathic schist, striking NE-NNE dipping steeply NW or SE. There are less abundant pelitic schists and rare calcareous lenses, and numerous amphibolite sheets up to 30 m wide. Rare cross-lamination indicates facing to the southeast (in contrast to the Ettrick Beach–Fitzmaurice Bay area).

Beds of nearly pure quartzite are common, and indicate a compositionally mature sedimentary protolith. Cross bedding is locally seen. Slump folding and pelitic intraclasts have also been recorded. Isolated calcareous pods may be after calcareous concretions, or in some cases be derived from boudinage of calcareous beds (Cox, 1973).

Five deformation events have been recognised, with ages ranging from Mesoproterozoic to possibly mid-Devonian (Cox, 1973; 1989; Streit and Cox, 1998; Berry *et al.*, 2005). First generation folds are tight to isoclinal, with S_1 comprising a pervasive foliation sub-parallel to bedding in the area west of Cape Wickham. D_1 has been dated in southwestern King Island at 1270 Ma (Berry *et al.*, 2005) where it is associated with regional amphibolite-facies metamorphism. Peak metamorphic conditions at Cape Wickham were reached during granite emplacement and associated contact metamorphism. Younger folds (D_2 –D_4) do not have associated regionally penetrative cleavages. F_2 folds are isoclinal to open, NE-trending with steeply inclined axial surfaces. F_3 folds have gently to moderately SE-dipping axial surfaces in the coastal section south of Cape Wickham. F_4 folds are upright, open, NE-trending, with subhorizontal hinges (Cox, 1973).

Hornblende amphibolite bodies, with compositions similar to tholeiitic basalt, are found as discontinuous concordant to subconcordant lenses at several stratigraphic levels. The smaller lenses are clearly boudinaged, and it is probable that the large lenses are boudinaged fragments of originally continuous sheets. Some small-scale transgressive relationships suggest that the amphibolite bodies were probably emplaced as sills prior to regional deformation (Cox, 1989).

The amphibolites are dark, medium to coarse-grained rocks consisting of amphibole and plagioclase, with minor clinozoisite, quartz, and occasionally biotite and muscovite, and are metamorphosed tholeiitic dolerites (Cox, 1973). Cox recognised two groups of amphibolites in this area: an older, more extensively developed set that pre-dates the granitoids (being metamorphosed to hornblende/hornfels amphibolite facies and being cut by granitic dykes), and a syn- to post-granitic set of clinozoisite-amphibolites. Both were originally tholeiitic dolerites. There are also narrow dykes of still younger (undeformed) dolerite (possibly related to the late Neoproterozoic volcanic rocks of the Grassy Group), and lamprophyre.

Granitoids, north of lighthouse

Granitoids: If beginning from the lighthouse road, proceed north through a farm gate on the right, just before the gate down to the lighthouse. This track takes you to excellent outcrops of K-feldspar phyric adamellite about 300 metres east of the granite/metasediments contact.

The predominant rock type is a coarse-grained K-feldspar–porphyritic biotite adamellite. It is dated at 760 ± 12 Ma (Pb-Pb SHRIMP on zircon, sampled in the old quarry 1.1 km southeast of the lighthouse: Turner *et al.*, 1998). K-feldspar phenocrysts are usually around 20 mm, locally 40 mm, in length. A penetrative but weak foliation defined by phenocryst alignment formed early in the cooling history of the complex, enhanced by rotation during D_2. Within the main granitoid body there are minor internal intrusions ranging from biotite granodiorite to biotite-muscovite granite and pegmatite. These are mainly steeply dipping and north to northeast-trending. Just east of the contact with the metasediments, the porphyritic adamellite is in sharp contact with a medium-grained to sub-porphyritic biotite granite; a few metres further east is a 50 m wide wedge-shaped intrusion of biotite-muscovite granite (younger than the adamellite).

Granitoid intrusion occurred post-D_1, but pre-D_2. Microfabrics in the metasediments show that prograde metamorphism overprints the early penetrative foliation (S_1). Granitic intrusions, particularly in the 'roof pendant' east of Cape Wickham, cut across F_1 without themselves being folded.

D_2 occurred after emplacement of the main granitoid complex, late in its cooling history, but before the end of minor granitoid intrusion. Within the metamorphic aureole west of Cape Wickham, D_2 structures deform some minor granitic intrusions, but not others. Minor intrusive activity extended into D_3.

Shear zone: Just west of where the aforementioned track reaches the coast is a spectacular outcrop of a shear zone in the granitoid. This shear zone, and several others along the coast to the east, were studied by Streit and Cox (1998). The Cape Wickham Shear Zone is a moderately west-dipping mylonite zone with a sharply-defined, high-strain eastern border against porphyritic granite (phenocrysts <30 mm). Laminated mylonite and augen mylonite with porphyroclasts >2 mm long have an outcrop width of about one metre, and are followed to the west by a 10–20 m wide zone of intensely foliated granite, which grades progressively over several metres into weakly foliated granite. Mineral stretching lineations plunge moderately to steeply NNW, indicating oblique slip. Microfabrics indicate oblique normal slip with a dextral strike-slip component. The eastern laminated mylonites are K feldspar + plagioclase + biotite + muscovite + quartz + epidote + titanite, but the western gradational contact includes partly retrograded mylonites (sericitised feldspars, biotite to chlorite). Oxygen isotope data and the upper greenschist mineralogy indicates that the deformation took place at about 460°C and 300–600 MPa, and ^{18}O values (c. +9‰) are much lower than those of the enclosing granites. Whole-rock analyses indicate losses of Na, K, and possibly SiO_2, and gains of Ca during deformation, which was nearly isovolumetric. Substantial fluid infiltration, and up-temperature (i.e. downward) fluid flow is inferred. Other shear zones to the east (Disappointment Bay area) formed in similar mid-crustal conditions, but experienced up to 60% volume gain (chiefly SiO_2), and there, fluids are interpreted to have been upward flowing.

There are a few dykes between the shear zone and the granitoid contact, including altered dolerite, possibly related to the late Neoproterozoic volcanic rocks. West of the contact, there is a very fresh, plagioclase-phyric basaltic dyke — probably Tertiary — which contains titanaugite.

Locality 2 — Ettrick Beach: Metasediments (Surprise Bay Formation)

Along this stretch of coast there is good exposure of the Surprise Bay Formation, outside the contact aureoles of the granitoids, but intruded by dykes of granitoid and amphibolite. The metasediments here are fine-grained, quartz-rich sandy turbidites, dipping and facing west. Andalusite porphyroblasts are present in some pelite layers. Grading and possible sole marks are present. Cross lamination and climbing ripples are seen in the top parts of some thick sandstone beds.

Recent geochronology (discussed above) indicates a depositional age of 1350–1270 Ma for these metasediments, and these rocks are therefore the oldest known anywhere in Tasmania.

D_1 produced a pervasive S_1 cleavage and associated tight, shallowly southwest-plunging folds. The second deformation produced a crenulation cleavage and there is additional sporadic development of kink bands (D_3).

Mafic intrusive rocks are common, as sheets and dykes, commonly concordant, and typically 1–2 m wide. These are pale green, medium-grained equigranular, massive rocks, consisting of pale green actinolite, chlorite, epidote, albite, quartz, and opaque minerals, with relict igneous fabrics. Some of these rocks have trace element abundances implying tholeiitic affinities, while others have alkali basalt affinities (Blackney, 1982).

Quaternary tufa deposits occur about 500 m south of the Cataraqui Memorial. Here there are spectacular tufa terraces and rimstone dams, with tufa marsh above. These were deposited from lime-rich waters emerging from beneath Holocene dunes. They occur down to high water mark, and have been protected from wave action by offshore reefs.

Locality 3 — Seal Rocks State Reserve: 'Calcified Forest'

The 'Calcified Forest' consists of spectacular exposures of calcareous rhizoliths in a dune blowout with views over the Southern Ocean. The sand is part of enigmatic cliff-top dunes now perched 50 m above sea level, possibly developed during a lower early Holocene sea level (M. Pemberton, pers. comm.). Older aeolian calcarenite is also exposed.

City of Melbourne Bay area: upper Neoproterozoic Grassy Group

Exposures of the upper Cryogenian–Ediacaran Grassy Group occur along the coast north and south of City of Melbourne Bay. The geology and localities are shown on Figure 6 (from Waldron and Brown, 1993).

South of City of Melbourne Bay

Locality 1 — Car park at end of Skipworths Road: Diamictite (Cottons Breccia) crops out next to the car park, but much better exposures are seen elsewhere.

Locality 2 — Walk south around the foreshore on the southern side of City of Melbourne Bay: Intermittent outcrop of Yarra Creek Shale — red to green mudstone with occasional thin graded beds of volcaniclastic sandstone. There are thin intrusive sheets assigned to the picrites and 'upper tholeiites', some with undulose contacts suggesting intrusion into unconsolidated sediment.

Locality 3: At the base of the 'lower tholeiites' (City of Melbourne Volcanics), there is evidence for extrusion and shallow intrusion into hydroplastic sediment, with peperite, hyaloclastite breccia and lobate intrusions with a matrix of baked mudstone. Further east, a large lens of coarse volcanic breccia (agglomerate) is overlain by 30 m of finer-grained, graded breccia and volcanic sandstone, the latter with features suggestive of redeposition by turbidity currents (Waldron and Brown, 1993).

Locality 4: The above rocks are overlain, a little further southeast along the coast, by massive and pillowed basalt flows with only minor interbedded sediment. Massive and pillowed basalts occur as discrete flows, but in places pillows occur either at the top or base of massive flows.

Pillow shapes are varied. Smaller pillows (50 mm–1 m) occur individually or as interconnected sac and neck types, but there are also larger, stacked, mattress-shaped pillows up to four metres long. The pillows have a dark green devitrified glass rim passing into an amygdaloidal zone with radially arranged amygdales, and a variolitic core. Some pillows have quartz-filled interiors which may represent infilling of small lava tubes. The lower tholeiites consist in thin section of albitised plagioclase and fresh clinopyroxene with interstitial chlorite, titanomagnetite and epidote (Waldron and Brown, 1993).

Follow coast south: Good outcrop of the lower part of the picritic unit (thin flows, breccia and hyaloclastite) (Shower Droplet Volcanics). Look for pahoehoe surfaces observed by Waldron and Brown (1993) and Direen and Crawford (2003) (and interpreted by the latter as evidence for subaerial eruption); and evidence for disconformity at base of picrites (Waldron and Brown, 1993). The thin flows (20–50 mm thick) commonly occur as broken and contorted lenses and rafts in a hyaloclastite matrix. Picrite breccia fragments in hyaloclastite are generally 100–200 mm across. There are some thicker flows (up to 0.5 m) with sinuous outlines and hollow interiors, which are considered to be preserved lava tunnels. Hyaloclastite units consist of devitrified picritic glass shards and lava granules. They occur either as a matrix to the thin flows and breccia fragments or as individual graded or laminated units with soft-sediment deformation features (convolute bedding, slumps, rip-up clasts) suggestive of redeposition by turbidity currents (Waldron and Brown, 1993).

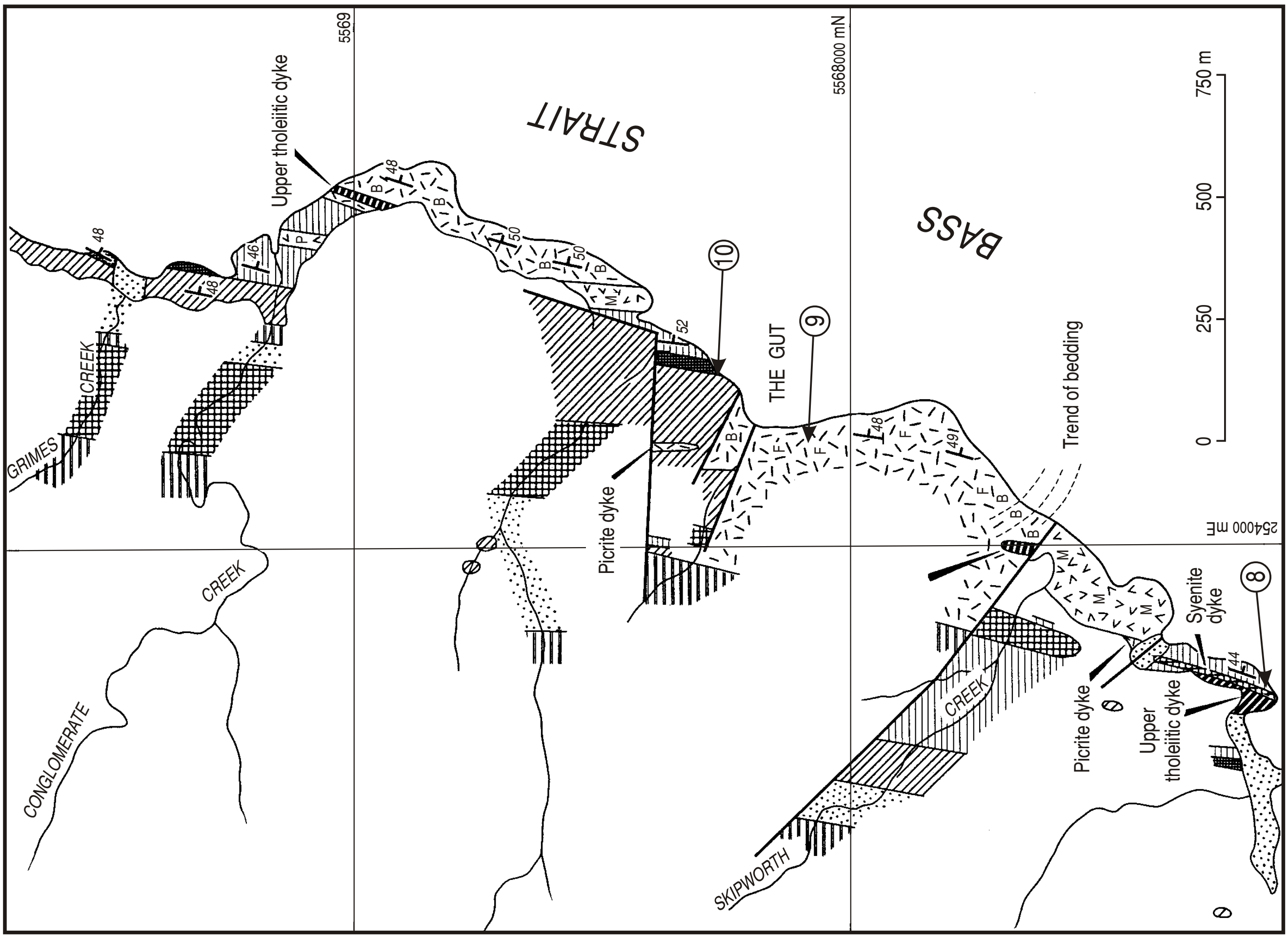
Locality 5: Picritic pillow lavas are common towards the top of the exposed picritic succession. The picrite pillows, unlike the tholeiites, are not zoned and occur as irregular subspherical bodies about 250 mm wide, or as elongate cylindrical tubes with smaller interconnected buds and branches. Flattened, internally-layered pillow structures are probably infilled lava tubes.

The picritic lavas are usually porphyritic and consist of pseudomorphed phenocrysts after olivine (0.1–3 mm across) and small (0.05–0.2 mm) chromite euhedra in a quenched clinopyroxene-rich groundmass. Phenocrysts are completely pseudomorphed by colourless chlorite. Spherulitic (2–20 mm) textures are common (Waldron and Brown, 1993).

Locality 6 — Cottons Creek: Good exposure of Cottons Breccia. The section can be divided into upper and lower diamictite units separated by a middle unit of green volcaniclastic sandstone. The lower diamictite unit, about 40 m thick, has a grey-green calcareous mudstone matrix and angular to subrounded clasts of carbonate, siltstone and fine-grained quartzite. Common, dark angular siltstone clasts resemble the underlying ?Cowrie Siltstone correlate. There is a variety of carbonate clasts, including a partly silicified oolite with large (3 mm) ooids. Thin-bedded sandstone and shale interbeds in the lower diamictite contain lonestones (dropstones?).

The middle unit of fine-grained, green volcaniclastic sandstone is about ten metres thick. In thin section it is seen to consist of glassy volcanic rock fragments and shards, probably of originally mafic composition, largely replaced by carbonate and chlorite. Minor pebbly layers with quartzite and carbonate clasts indicate that the unit is a redeposited volcanic sandstone.

The upper diamictite unit, about 25 m thick at Cottons Creek, has a brownish to reddish mudstone matrix, in contrast to the lower unit. A similar suite of clast lithologies is present. Fine-grained quartzite dominates the non-carbonate component. Also present are black chert, red mudstone, rare basalt, and rare red jasper. Dacitic lava clasts were reported by Waldron and Brown (1993).


5569
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STRAIT
BASS
Upper tholeiitic dyke
10
THE GUT
9
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Picrite dyke
254000 mE
Syenite dyke
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Picrite dyke
Upper tholeiitic dyke
GRIMES
CREEK
CONGLOMERATE
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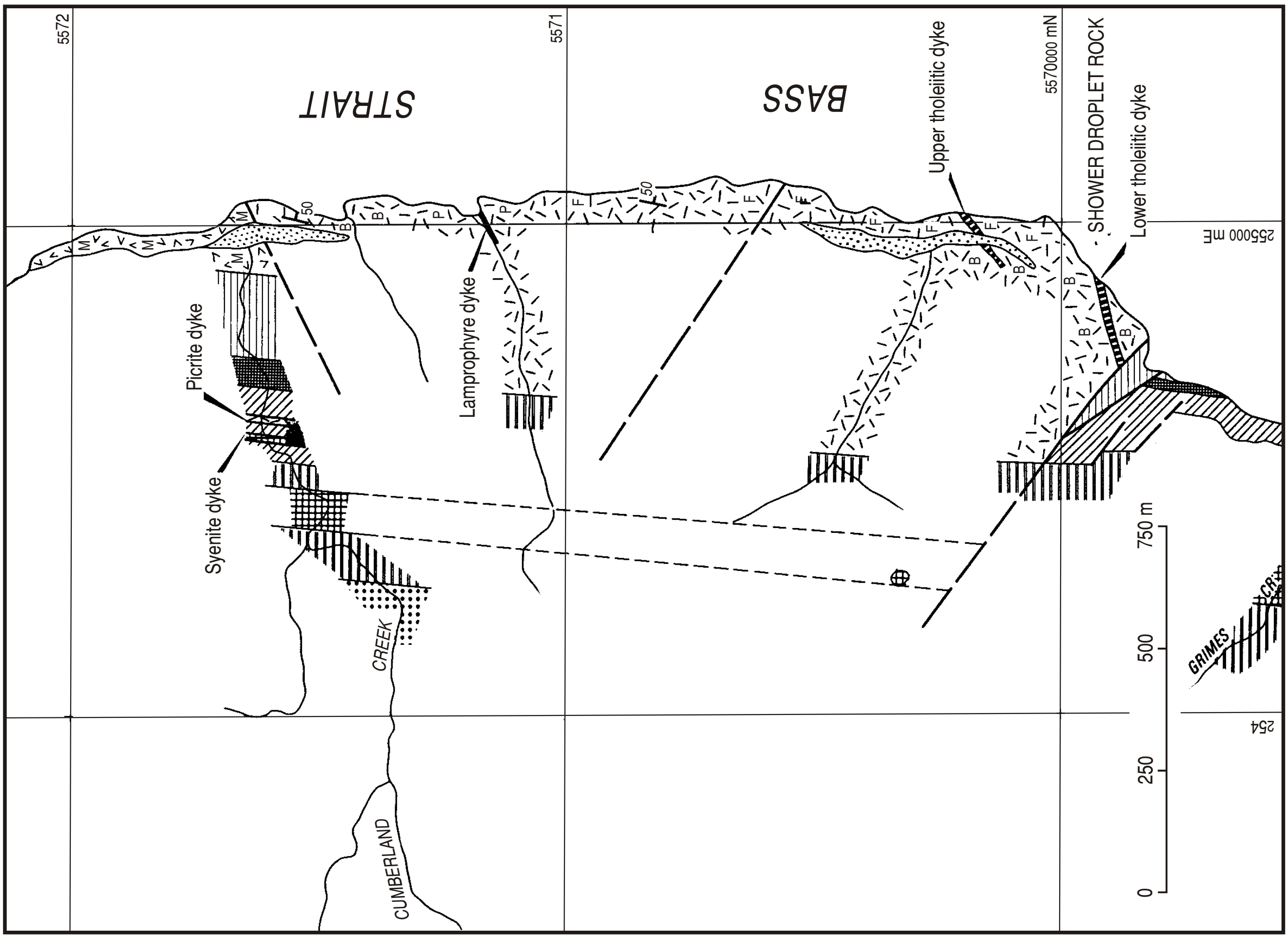
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Lower tholeiitic dyke
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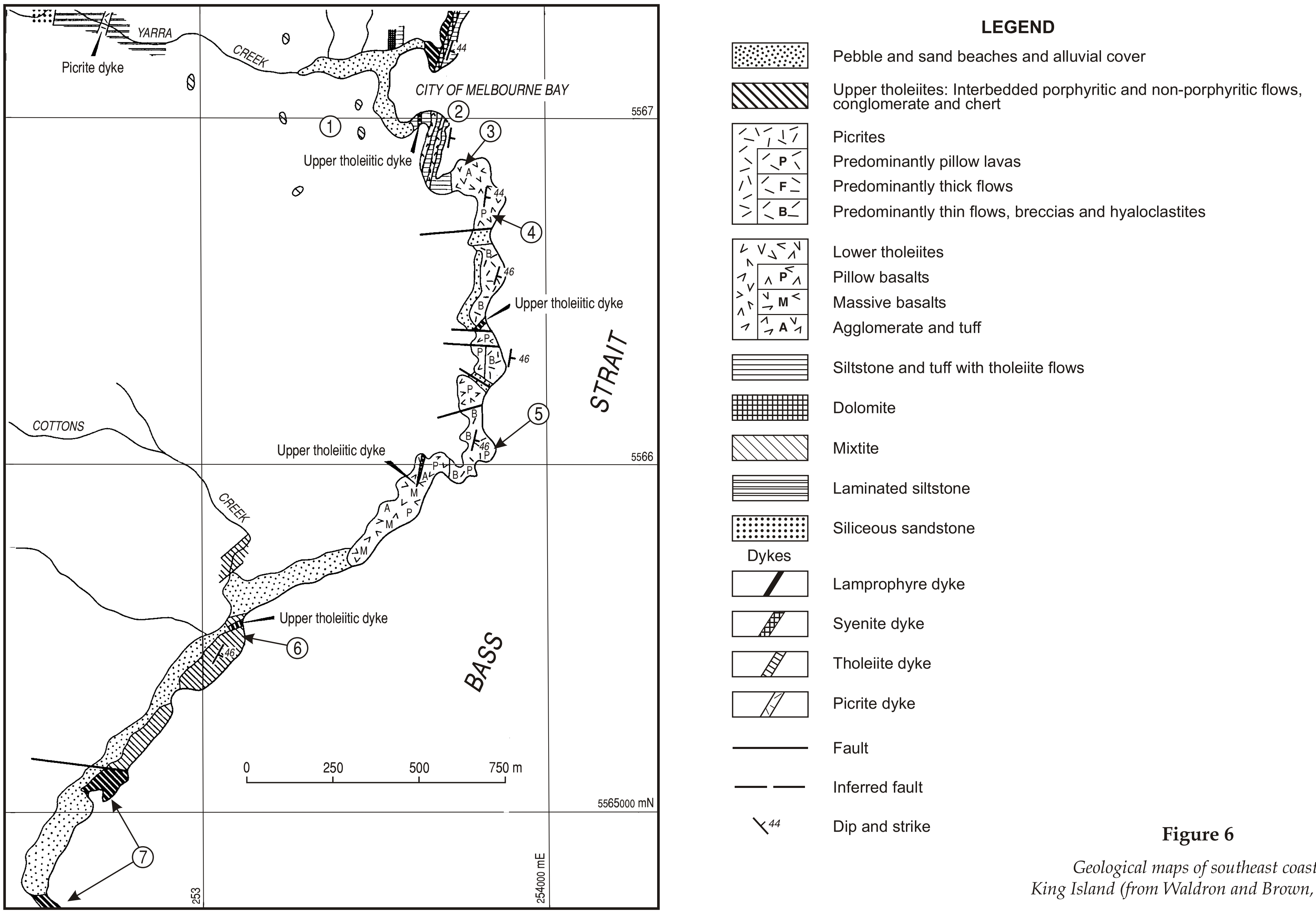

Figure 6

Geological maps of southeast coast, King Island (from Waldron and Brown, 1993).

The upper unit is crudely stratified due to variation in clast size and content (therefore not a mass flow). A sandstone bed near the base of the upper diamictite unit contains diffusely-bounded clumps of diamictite, 50–100 mm wide, that are probably till clasts. One to two metres thickness of closed-framework conglomerate occurs near the top of the Cottons Breccia, but the cap dolostone is not exposed here.

Of the clast lithologies in the Cottons Breccia, only the siltstone, shale and fine-grained quartzite can be linked to older rocks on King Island. The common carbonates and rarer chert, red mudstone and jasper appear to be foreign to the area. No felsic igneous rocks or high-grade metamorphic rocks are known in the clast assemblage (Jago, 1974). Slumping at one location indicates a west to east movement of sediment (Jago, 1974).

Evidence for glacial origin includes poor sorting, lonestones, till clasts, probably exotic clast lithologies, and the association with cap dolostone and implied correlation with the Elatina Formation of South Australia.

Locality 7 — walk one kilometre further south along the coast: Outcrops of the 'upper tholeiites' (Bold Head Volcanics); flows 2–5 m thick with vesicular tops and brecciated bases, and some pillow lavas, cyclically interbedded with 4–5 m thick beds of pebble-cobble grade volcaniclastic conglomerate grading up into granule conglomerate, hematitic mudstone and chert (Waldron and Brown, 1993; Meffre *et al.*, 2004). Altered felsic clasts, and coarse-grained felsic intrusive rocks were reported by Meffre *et al.* (2004).

Porphyritic and non-porphyritic flows are present in the upper tholeiites. The porphyritic flows contain large (6 mm) zoned, altered plagioclase, and smaller diopside phenocrysts.

North of City of Melbourne Bay

Locality 8 — north shore of City of Melbourne Bay: Sill (Grimes Intrusive Suite) within Yarra Creek Shale, about 30 m thick; this is amygdular in places, suggesting intrusion at shallow depth. These intrusions (575 ± 3 Ma; Calver *et al.*, 2004) are not found at stratigraphic levels higher than the Yarra Creek Shale, suggesting they pre-date the mafic volcanic rocks (Meffre *et al.*, 2004). Peperitic margins were reported by Meffre *et al.* (2004), but at this locality, parallel-sided, dyke-like apophyses at the upper contact suggest the Yarra Creek Shale was at least partially lithified at the time of intrusion. In thin section, the sill has acicular feldspar phenocrysts in a quenched quartzofeldspathic groundmass.

The Yarra Creek Shale here is planar-laminated and pale yellow-brown to red in colour, with rare, thin, graded beds of volcaniclastic sandstone. There is a middle interval, exposed on the northern side of City of Melbourne Bay, overlying the Grimes Intrusive Suite sill, of interbedded and interlaminated grey-green and pyritic black shale, at least 16 m thick. The grey-green and black shale layers are sharply delineated, and in places within the grey-green shale beds there are wispy intraclasts of black shale. In thin section the black shale displays a microstructure of anastomosing, organic-rich thin layers. The black shale layers thus display the sedimentological characteristics of fossil benthic microbial mats (Schieber, 1986). Impersistent but widespread and probably synchronous developments of similar black shale, comprised of remnant benthic microbial mats, occur in the lower parts of the post-glacial succession in many places on mainland Australia (Logan *et al.*, 1999; Calver, 2000). Carbon and sulfur isotopes, and biomarker data, suggest the mats were sulfide-oxidising bacteria (Logan *et al.*, 1999), so they may not have been limited to the photic zone.

Locality 9: Relatively thick, non-pillowed flows belonging to the picritic succession (Shower Droplet Volcanics) occur just south of The Gut. These flow units are 0.5–2 m thick; the boundaries between individual flows often have chilled bases, and in some cases have both chilled bases and tops. A few of the flows are amygdaloidal. In places the flow units grade along strike into predominantly pillow and breccia structures (Waldron and Brown, 1993).

Locality 10 — The Gut: Good exposure of the Cottons Breccia and cap dolostone (Cumberland Creek Dolostone). There is a middle unit of volcaniclastic sandstone separating two diamictite units, as at Cottons Creek. There is also a bed of coarse volcaniclastic sandstone in the lower diamictite unit. Large boulders of carbonate (up to three metres long) occur near the top of the lower unit.

The upper diamictite unit includes sandstone interbeds with lonestones. At the top of the upper unit there is one to two metres of closed-framework conglomerate, overlain by 0.8 m of plane-laminated red sandstone, pebbly at the base, which passes up conformably and gradationally into the cap dolostone. The sandstone has an abundant population of 655–635 Ma zircons (Evans, 2005).

The cap dolostone is a pale grey to pale pinkish-grey, fine-grained, laminated dolostone that weathers to a pale yellow-brown. About six metres thickness is present here, above which the section is interrupted by a poorly-outcropping mafic intrusion. Lamination is mostly planar-parallel, but a number of gentle, sharp-crested intrastratal anticlines, 100–200 mm in amplitude, are seen in the lower part of the unit. These resemble tepee structures, but lack cavity-filling cements. Identical structures are characteristic of the Nuccaleena Formation of the Adelaide Fold Belt and Marinoan cap dolostones elsewhere, and are of enigmatic origin (Kennedy, 1996; Plummer, 1979).

The cap dolostone displays most of the features of a 'classic' Marinoan cap dolostone (including depleted, upward-decreasing ^{13}C; fine grain size, pale pink to grey colour; lamination; petrographic character including peloids and microfenestrae; presence of tepee-like structures; and upward gradation into interlayered limestone and shale — seen at Cumberland Creek). Cap dolostones are globally distributed, and thought to represent a chemical oceanographic event associated with deglaciation, with deposition taking place mainly below storm wavebase under rising relative sea levels (Dyson, 1992; Kennedy, 1996; Hoffman and Schrag, 2002). Global synchroneity of cap dolostones is now widely accepted and provides the rationale for the definition of the base of the Ediacaran System/Period (formally defined as the base of the cap dolostone (Nuccaleena Formation) at Enorama Creek in the Flinders Ranges).

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