SGTSG Conference Field Guide

King Island 2022

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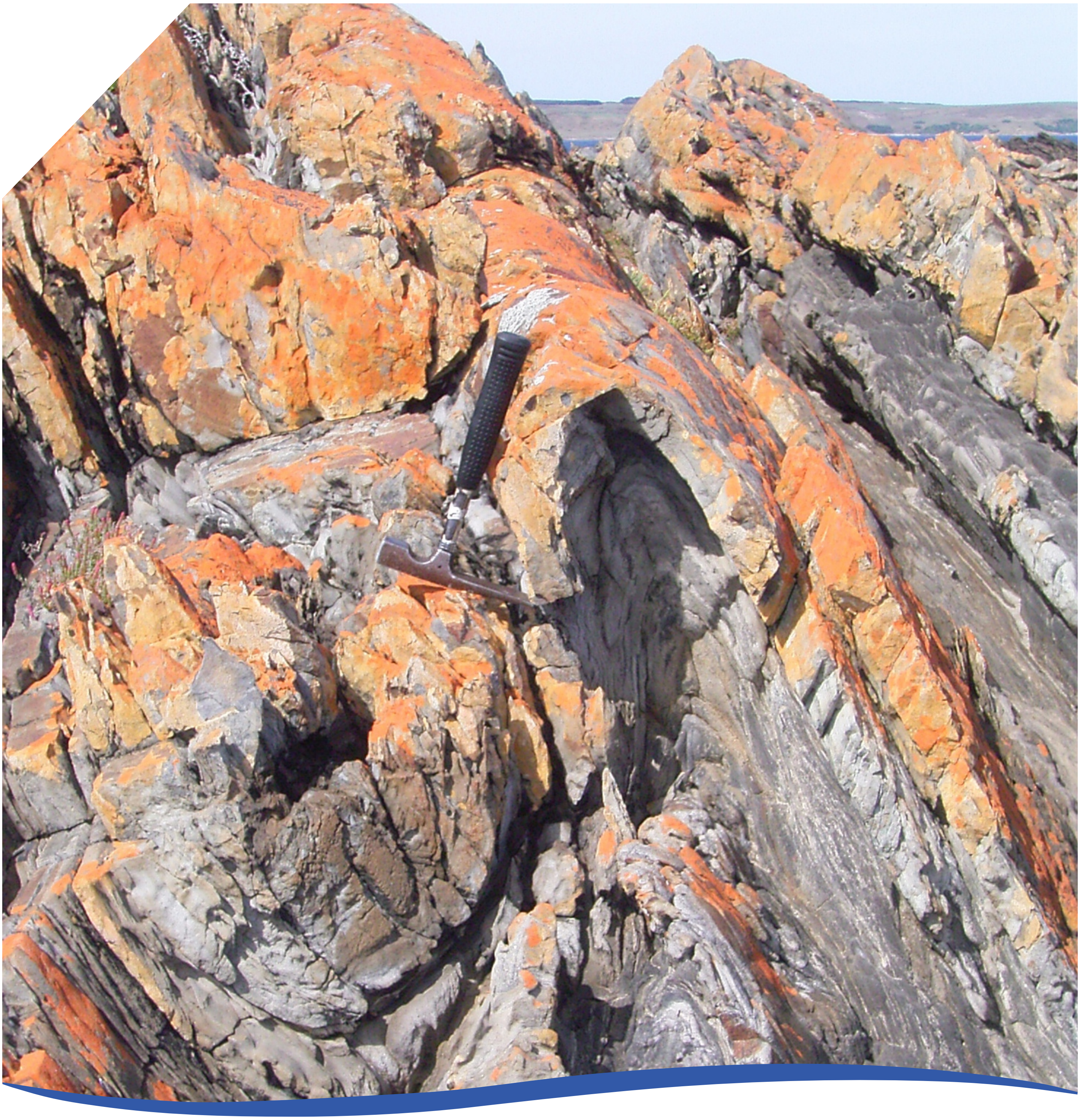

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King Island Field Excursion 2022:

Maps and Notes

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This excursion guide was prepared by MRT staff for the biennial conference of the Specialist Group in Tectonics and Structural Geology (SGTSG) of the Geological Society of Australia (GSA), held on King Island on 22-24 November 2022.

Cover: Tight west-vergent folds in the ~1400Ma Surprise Bay Formation, ~500m S of Cataraqui Memorial, west coast, King Island, (GDA94 Zone55 234200/5563660; Zone 54 746134/5564323).

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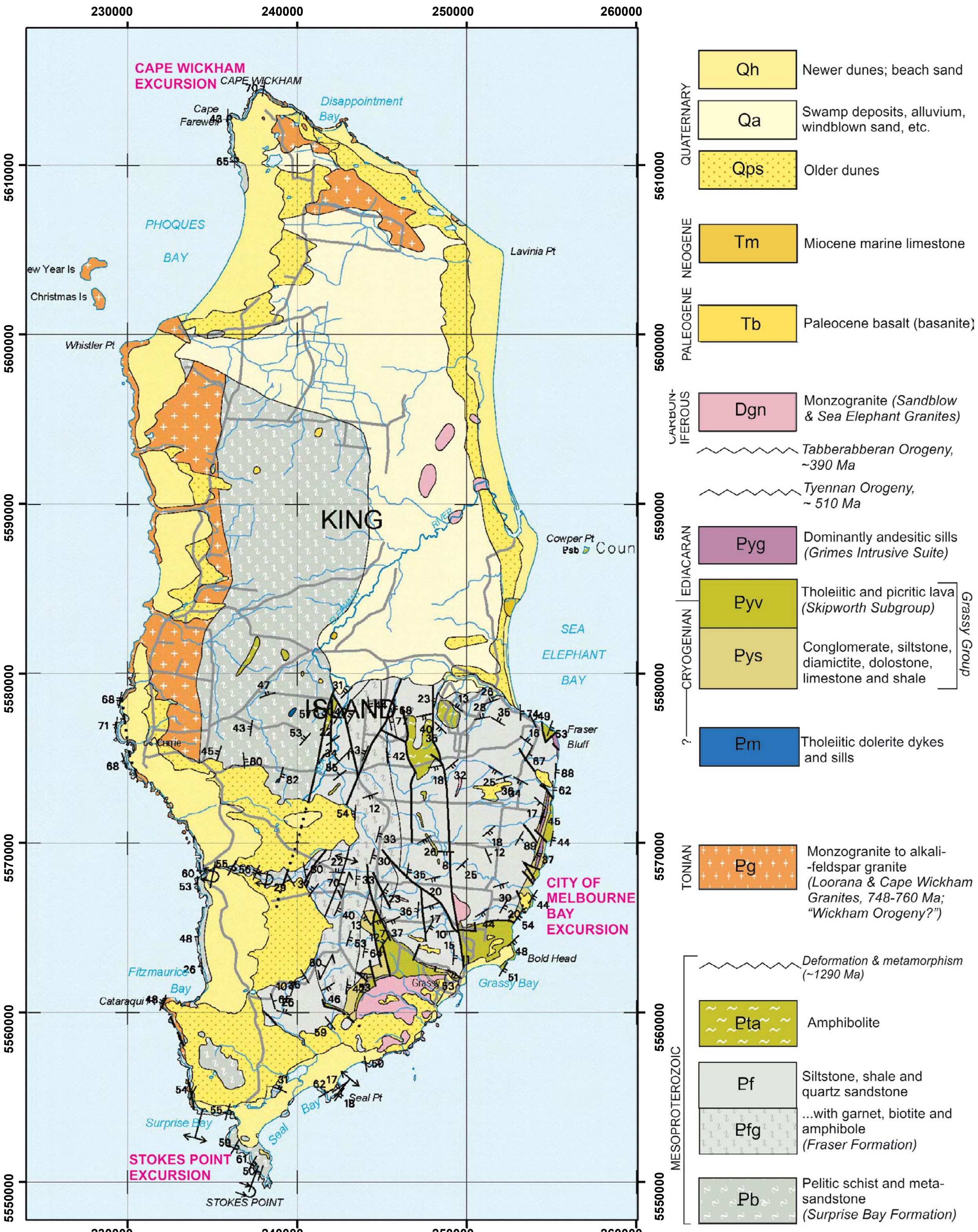

Figure 1. Geology of King Island, from MRT 1:250,000 coverage. Does not incorporate results of recent fieldwork in the central-north of the island.

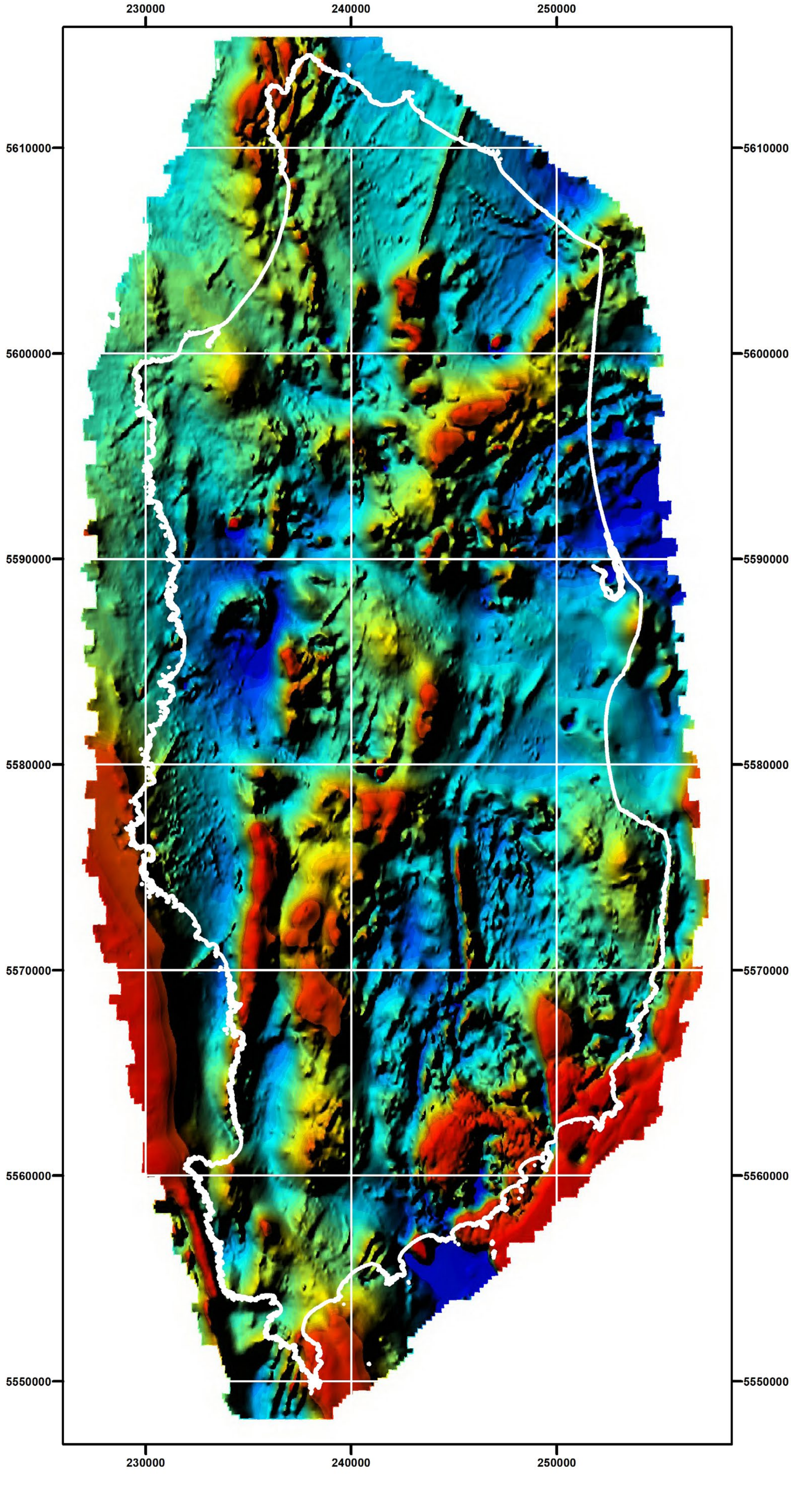

Figure 2. Total magnetic intensity (TMI) image of King Island, NW sun angle, 10 km grid shown. Based on MRT 2001 airborne survey, 200m line spacing.

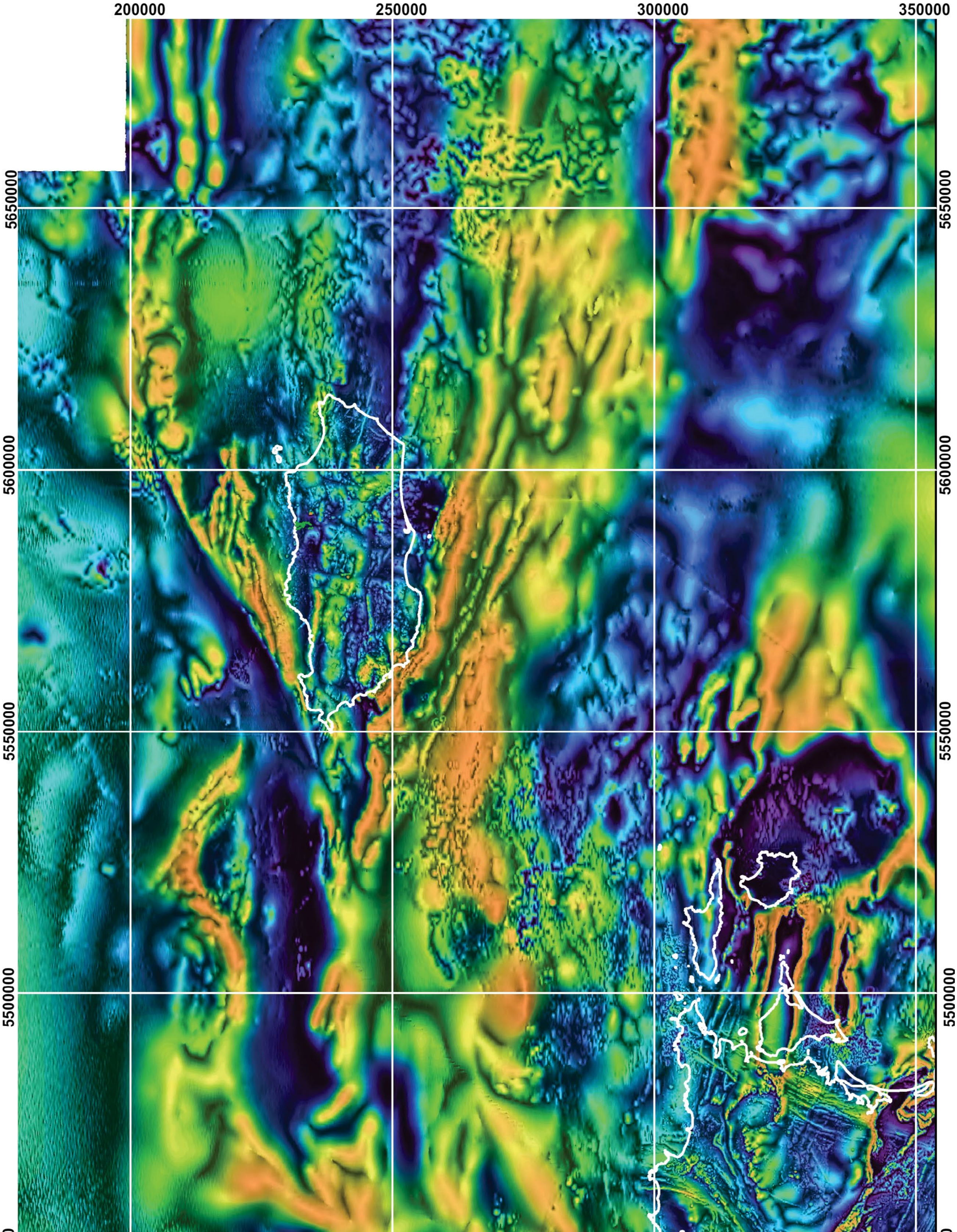

Figure 3. Total magnetic intensity (TMI) image of western Bass Strait region, 50 km grid shown. Composite based on Geoscience Australia and MRT surveys, line spacing 200-800m.

INTRODUCTION

King Island (~65 x 26 km, maximum elevation 162 m) forms the crest of a basement high, the King Island-Mornington Rise, which at times of low sea-level during the Cenozoic has formed a land bridge connecting northwest Tasmania and Victoria.

The geology of the island has been investigated by numerous university-based researchers, systematically explored by mining companies (notably Geopeko Limited, e.g. Gresham, 1972), and recently mapped at 1:25000 scale by the Tasmanian Geological Survey. It consists of mainly Proterozoic rocks and displays broad similarities to northwest Tasmania, with which it shares the oldest rocks in southeastern Australia. There are also intrusions of Carboniferous granite and very limited Cenozoic basaltic volcanics. About two-thirds of the coastline is virtually continuous outcrop, whereas inland Quaternary deposits largely obscure bedrock.

OUTLINE OF GEOLOGICAL HISTORY

Mesoproterozoic

Mesoproterozoic metasedimentary rocks, mainly turbidites, underlie about three quarters of King Island (Fig. 1). Two distinct formations have long been recognised (e.g. Gresham, 1972). The western sequence, the Surprise Bay Formation (Berry et al. 2005) generally has a higher metamorphic grade and is more deformed than the eastern sequence, the Fraser Formation (Direen & Jago, 2008). The contact between the two is nowhere exposed, but is most likely a west-dipping thrust (the inferred Pearshape Fault of Calver, 2012).

Recent sedimentological, structural and geochronological studies (Calver & Everard 2014; Black et al. 2004) suggest that the two sequences are derived from the same protolith. They are approximately coeval with, and may be deeper water equivalents of, the Rocky Cape Group of northwest Tasmania (e.g. Mulder et al., 2018).

Neither of the King Island Mesoproterozoic sequences, nor the Rocky Cape Group, have any known correlatives or plausible source rocks in mainland Australia. Detrital zircon studies (Black et al., 2004; Halpin et al., 2014), however, suggest correlation with Mesoproterozoic basins in western Laurentia, notably the ~1.45-1.37 Ga upper Belt-Purcell Supergroup of Montana and British Columbia, with implications for supercontinent reconstructions.

Surprise Bay Formation

The Surprise Bay Formation is a north-striking, tightly to isoclinally folded belt of mainly pelitic schist and metasandstone, up to 8 km wide, which extends the full length of King Island, from Stokes Point to Cape Wickham. Biotite, garnet and andalusite are locally abundant and staurolite has been recorded. A lower-grade, strongly sheared correlative is exposed on the coast near Currie. Its age is constrained between the youngest detrital zircons (3 grains at 1350 ± 90 Ma, or alternatively 14 grains at 1452 ± 12 Ma; Black et al., 2004) and a metamorphic monazite age of 1287 ±18 Ma (Berry et al., 2005).

We will examine key coastal exposures near Stokes Point and Cape Wickham.

Fraser Formation

The Fraser Formation (Direen & Jago, 2008) occupies most of southeast King Island, east of the Pearshape Fault, up to the unconformably overlying Grassy Group. Its northern extent is problematic due to sand cover. It largely consists of thick-bedded or laminated, micaceous, fine-grained quartz sandstone, siltstone and grey to black mudstone. Thin microbialite black shale beds at the top of turbidite beds may represent hemipelagic deposition. Although less deformed and mostly of lower metamorphic grade than the Surprise Bay Formation, garnet, biotite and amphibole are locally present, particularly in the core of the central "Lymwood Anticline" (Calver, 2008). The youngest detrital zircons in a sample from Naracoopa are 1444 ± 12 Ma (Black et al. 2004).

The Fraser Formation can be readily inspected at the type section on the foreshore at Naracoopa (Direen & Jago, 2008), where it consists of a monotonous succession of laminated pale grey fine-grained quartzose siltstone.

Amphibolites

Several large amphibolite bodies, derived from intrusions of tholeiitic basalt composition, occur within the Fraser Formation near Pegarah, and smaller intrusions are widespread in the Surprise Bay Formation. A body near Cape Wickham (below, Loc. 15) has been dated at ~1370 Ma (U-Pb, zircon) by J. Mulder (pers. comm.), providing another constraint on the age of the enclosing Surprise Bay Formation.

Deformation and metamorphism

D1 and amphibolite facies regional metamorphism of the Surprise Bay Formation, and by correlation the Fraser Formation, occurred at ~1290 Ma, based on U-Pb dating of authigenic monazites from southern King Island (Berry et al. 2005; see below).

Dolerite dykes (?)

A few undated, greenschist facies grade dolerite dykes in the Surprise Bay Formation appear to post-date the ~1290 Ma metamorphism, but are transected by presumably ~760 Ma granitic dykes.

Neoproterozoic

Tonian: granites

In the north of the island, the Cape Wickham Granite is dominantly a medium-grained K-feldspar-porphyritic, biotite monzogranite to alkali feldspar granite. Late minor intrusions of more mafic granodiorite, and more felsic leucogranite, aplite and pegmatite, are locally present.

The Loorana Granite, a north-south trending body extending along the west coast from Cataraqui Point to the New Year Islands, is very similar but more uniform and slightly less felsic.

The U-Pb SHRIMP ages of the Cape Wickham Granite (760 ± 12 Ma; Turner et al. 1998) and Loorana Granite (748 ± 2 Ma; Black et al. 1997) are just within error, so their relative timing remains unresolved. Both granites were assigned to the I-type, Sr-depleted, Y-undepleted group of Australian Proterozoic granites by Budd et al. (2001).

Two felsic porphyry sills intruding the Surprise Bay Formation near Currie were dated at 776 ± 6 and 772 ± 7 Ma (U-Pb, LA-ICPMS on zircon); their relationship to the nearby Loorana granite is equivocal (Calver et al., 2013b).

"Wickham Orogeny"

This term was introduced by Turner et al. (1998) to encompass D1, regional metamorphism and emplacement of the Cape Wickham Granite at 760 ±12 Ma; D2 (at least) was considered to represent a late stage of the Wickham Orogeny. Furthermore, the (usually low angle) basal unconformity of the Neoproterozoic Togari and Ahrberg Groups on the Mesoproterozoic Rocky Cape Group in northwest Tasmania was attributed to "the general period of mild deformation, magmatism and uplift associated with the Wickham Orogeny."

Berry et al. (2005), however, used monazite to date the regional metamorphism of the Surprise Bay Formation in southern King Island at ~1290 Ma. Monazite dates from schist near Cape Wickham (769 ± 25 Ma) are within error of the granite age and were interpreted as the age of D2 folding. The Wickham Orogeny is thus reduced to a minor event comprising the D2 - D4 "local folding in the aureoles of a few granite plutons." It remains possible that the Togari-Ahrberg/Rocky Cape Group unconformity is a distal manifestation of the Wickham Orogeny, either due to weak compressional deformation or extension, faulting, uplift and erosion.

Cryogenian-Ediacaran: Grassy Group

Along the southeast coast, the Fraser Formation is overlain by an east-dipping late Neoproterozoic succession of conglomerate, siltstone, diamictite, dolostone, limestone and shale, with uppermost mafic volcanic rocks (Scott 1951, Waldron & Brown 1993), known as the Grassy Group (Knight & Nye, 1953; Calver & Walter, 2000).

The Grassy Group consists of seven units, described later (see preamble to City of Melbourne Bay excursion), and is intruded by shallow ± syndepositional intrusions of unusual composition (Grimes Intrusive Suite; Meffre et al., 2004).

The age of the lower part of the Grassy Group is constrained by a U-Pb CA-TIMS date of 636.41 ± 0.45 Ma from the Cottons Breccia (Calver et al., 2013a), whereas the uppermost volcanic units are ~580 Ma (see later discussion).

Dolerite dykes

Numerous metadolerite sills and dykes, some up to 20 m thick, intrude the Surprise Bay Formation and the Tonian granites throughout King Island. They are of broadly tholeiitic basalt composition, and the more fractionated bodies are plagioclase-phyric. Attempts to date them have been unsuccessful, but they may be related to the Ediacaran (~ 575 Ma) volcanism in the upper Grassy Group on the east coast, although there is not an exact match in geochemistry.

Early Palaeozoic

Tyennan (Delamerian) and Tabberabberan Orogenies

The effects of the Cambrian Tyennan Orogeny (~514- 506 Ma; Berry, 2014 and references therein) and Middle Devonian Tabberabberan Orogeny (~389 Ma; Black et al., 2005) are difficult to identify or separate on King Island due to the lack of Early Palaeozoic rocks. The steep eastward dip of the Grassy Group on the east coast is probably due to the former. Recent dating of monazite from shearzones in the Tonian granites suggests some reactivation at both ~500 Ma and ~400 Ma (Berry et al., 2022).

Carboniferous

Sandblow and Sea Elephant Granites

In the southeast of the island, the Sandblow (formerly Grassy) Granite consists of unfoliated hornblende-biotite monzogranite, with common mafic enclaves and minor aplite dykes. At least three geophysically distinct phases are present (N. Direen, pers. comm., 2021). It is classified as an unfractionated, relatively oxidised (magnetite-bearing) I-type. At 350.8 ± 1.7 Ma (U-Pb SHRIMP on zircon, Black et al., 2005), it is the youngest dated granite in Tasmania. The genetically related Dolphin and Bold Head scheelite deposits near Grassy occur in its aureole (e.g. Kwak, 1978) and aplite dykes intrude the Grassy Group in the Grassy mine pit.

The poorly exposed Sea Elephant Granite in the northeast of the island is similar but less oxidised (non-magnetic) and slightly more felsic (with rare hornblende).

A granitic dyke within the Surprise Bay Formation south of Currie yielded an age of 350.5 ± 4.3 Ma (U-Pb SHRIMP on zircon; Black et al. 1997), and other small granitic bodies of probably similar age are locally present.

Microdiorite dykes

Numerous dykes of fine-grained dark hornblende-biotite microdiorite intrude the Sandblow Granite, and less commonly older units. Petrographic and geochemical similarities suggest a genetic relationship with the Sandblow and Sea Elephant Granites.

Cretaceous

Lamprophyre dykes

A narrow (0.5 m) dyke of biotite-olivine lamprophyre, bearing granulite xenoliths, intrudes the Shower Droplet Volcanics on the east coast, south of Cumberland Creek (Waldron & Brown, 1988). This dyke returned a K-Ar age of 143 ± 3 Ma (McDougall & Leggo, 1965; recalculated with decay constants of Steiger & Jager 1977).

An undated lamprophyre dyke intrudes the Loorana Granite at Netherby Bay south of Currie (Calver & Everard, 2013), and lamprophyre dykes were also reported near Cape Wickham by Cox (1973).

Cenozoic

Basaltic volcanism

Basalt (basanite) float, scattered over a low rise near Adams Road near the centre of the island, coincides with a positive magnetic anomaly and probably represents the remains of a small plug. A sample was dated at ~62 Ma (Sutherland et al. 2004). Drilling of a similar anomaly near Reekara by Geopeko also encountered basalt. Several similar "bulls-eye" magnetic anomalies, with both normal and reversed polarity, are scattered around the island and may indicate concealed Cenozoic plugs.

Several small islets between King Island and NW Tasmania, notably Black Pyramid (clearly visible from Grassy) and Reid Rocks, consist of Cenozoic basaltic volcanics (Everard et al. 1997).

Miocene limestone

Bryozoal limestone, probably only a few metres thick, crops out on the coast at "The Blowhole" north of Sea Elephant Bay. Small outcrops of similar limestone are scattered inland at elevations up to 75m asl. Thin section examination suggests that they formed in high energy coastal environments within the photic zone, probably in the Early Miocene. This suggests an episode of high sea-level at this time, consistent with similar evidence in northern Tasmania (Quilty in Calver, 2012).

Quaternary

Except for the coastal scarp between Grassy and Naracoopa, the island is surrounded by a belt of dunes, up to 4 km wide on the west coast.

Jennings (1959) recognised two sets of dunes. The "Old Dunes" are probably Pleistocene, somewhat modified by erosion, and consist of leached grey to white quartz sand. The "New Dunes" are Holocene, little-eroded and frequently parabolic. On the west coast they consist mainly of calcareous shell fragments, locally lithified to "aeolianite," and are worked for agricultural lime near Loorana. North of Naracoopa the "New Dunes" consist mainly of quartz sand and, together with modern beach sands, are worked for rutile and zircon.

In the north of the island, where relief is lower, the belt of dunes has impeded drainage and estuarine and lacustrine sediments were deposited. Skeletons of the Pleistocene "giant wombat" *Diprotodon* have been recovered from Egg Lagoon (now drained).

Local raised beach deposits and emerged marine platforms at 10-20m above sea-level may indicate a higher sea-level stand, probably in the last interglacial (Jennings, 1959), together with subsequent uplift (e.g. Colhoun et al., 2014).

NOTE ON GRID COORDINATES

Most published topographic and geological maps use the Zone 55 grid (the same as the rest of Tasmania), but a hand-held GPS will read out Zone 54 coordinates in the west of the island. Thus both Zone 54 and 55 coordinates (GDA94 datum) are given for two of the excursions. A further complication is that older topographic maps use the previous AGD66 datum; to convert Zone 55 GDA94 coordinates to Zone 55 AGD66, subtract 112m from the eastings and 183m from the northings.

SURPRISE BAY - STOKES POINT

Overview

The following is largely adapted from Calver & Everard (2014).

We will visit the type section and longest across-strike exposure of the Surprise Bay Formation, a coastal section between Surprise Point and Stokes Point in the southwest corner of King Island. Most of this section is a single overturned F1 fold limb about 3.8 km thick, between an anticline 175 m west of Dromedary Point and a syncline 1 km NW of Stokes Point (Loc. 6) (Figs 4, 5). The beds typically dip steeply (mostly at ~60°) WNW, whereas primary (S1) schistosity dips west more shallowly than bedding nearly everywhere in this section, and sedimentary structures confirm overturned (east-younging) bedding at many locations. Minor folds are rare. The total stratigraphic thickness is about 3800 m, but disruption of the section by undetected major faults cannot be ruled out.

The main regional folds are tight to isoclinal F1 folds with upright to WNW-dipping axial planes and subhorizontal NNE-trending hinges. The major anticlinal zone at Surprise Point and the synclinal zone 1 km northwest of Stokes Point bound an overturned common limb about 4 km wide (Fig. 5). The statistical F1 fold hinges plunge 15° SSW (Fig. 6) although in places minor F1 folds plunge more steeply (e.g. ~40°SSW near Denbys Bay). Later deformations have given rise to crenulation cleavages and minor folds in places without much affecting the regional D1 structure. Retrogressed andalusite porphyroblasts display dextral rotation on subhorizontal outcrop surfaces at Denbys Bay (Fig. 7).

Three members can be recognised (Fig. 5):

The lower sandy member, which we will not be visiting, is about 1400 m thick and exposed on the northern shore of Denbys Bay. Near its base, it consists of predominantly thick-bedded (>1m), fine-grained quartzose sandstone, interbedded with lesser grey pelitic siltstone. Its upper part tends to be more thinly bedded and finer-grained, with ripple cross-lamination and locally disorientated slump-folded rafts of siltstone within massive very fine-grained sandstone.

Localities 1 - 8

Locality 1 - Stokes Point Road reaches the coast south of Surprise Bay, just before a gate.

GDA94 Zone 55: 236160mE/5553000mN
Zone 54: 747371mE/5553556mN

We are within the lower part of the middle pelitic member of the Surprise Bay Formation, which consists of about 1400m of dominantly grey pelitic schist. The member is thin bedded or laminated (rarely thick bedded), with planar-parallel, continuous layering defined by paler, silty pelite alternating with darker, non-silty pelite layers. Minor thin beds and laminae of quartzose siltstone and fine-grained sandstone are common; these are mostly planar and continuous, in some cases graded, and commonly lensing and cross laminated (Fig. 8).

Here the beds dip steeply, mainly to the west, and young to the east. Cleavage is not strongly developed, but dips more shallowly west.

Subhedral to euhedral porphyroblasts of garnet (0.1 - 1 mm) and retrogressed andalusite (stubby columns up to 10 x 30 mm) are prominent on weathered surfaces here. Retrogressed andalusite porphyroblasts, now consisting of an undeformed fine-grained aggregate of quartz, sericite, muscovite and biotite, commonly preserve primary lamination (Fig. 7). The penetrative S1 foliation, defined by a strong preferred orientation of muscovite and minor biotite, wraps around both the garnet and andalusite porphyroblasts. Locally, chlorite occupies strain shadows adjacent to garnet porphyroblasts (Fig. 9) and the S1 foliation is locally overgrown by chlorite porphyroblasts (Fig. 10). Thus, garnet and andalusite pre-date D1, and porphyroblastic chlorite and retrogression of andalusite post-date D1, as seen in the Fraser Formation (Calver, 2012). Blackney (1982) used garnet-biotite geothermometry to estimate peak metamorphic conditions at 520° ± 20°C at 200-300 MPa, consistent with lower middle-crustal (~17 km) deformation.

On the northern side of the small cove, a minor tight sinistral fold plunges gently NNE. Near the northern headland of the cove, a narrow (0.8 m) subconcordant sill-like intrusion of fine-grained dolerite trends ~022W68 and terminates northward against a small fault.

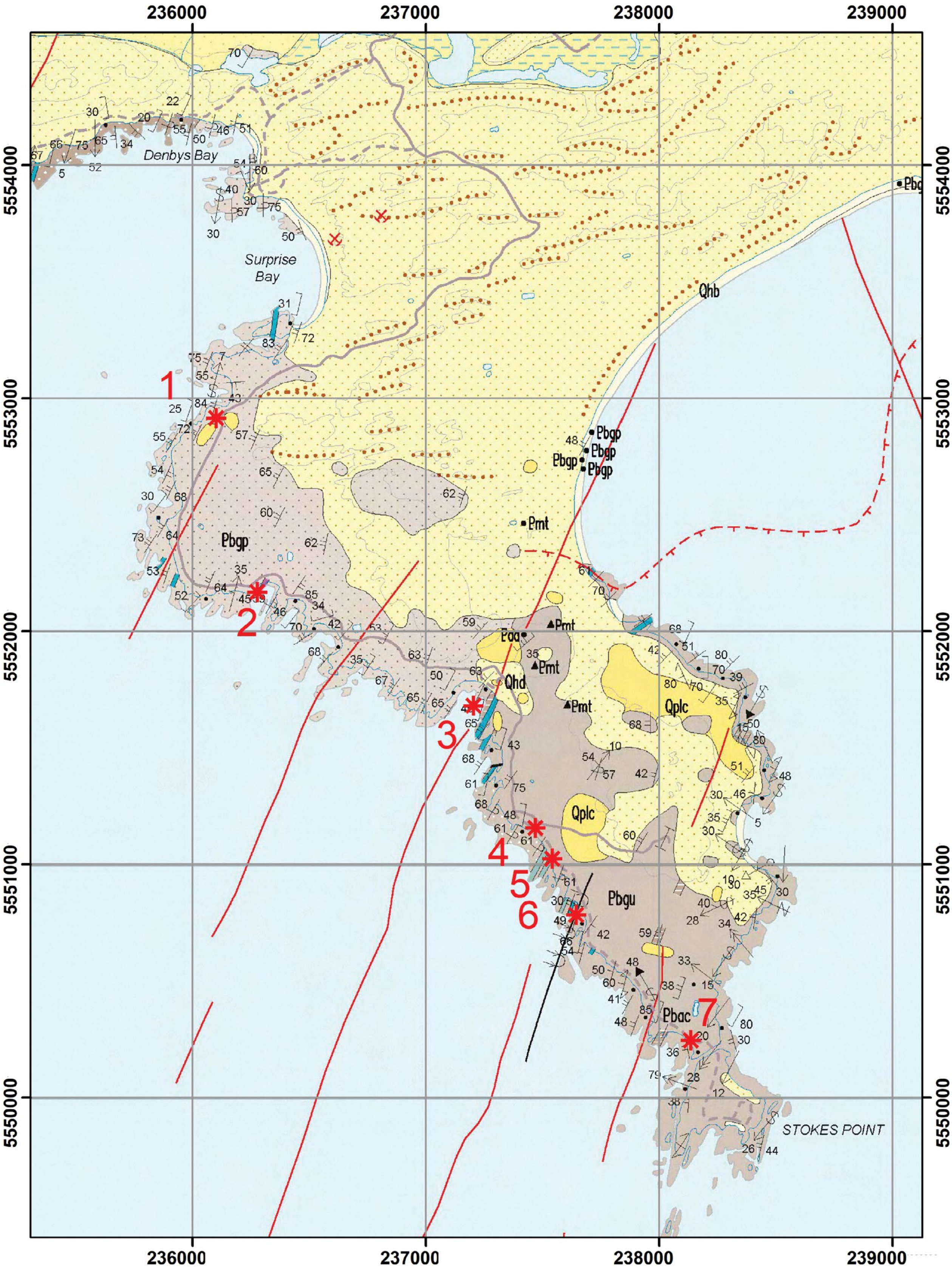

Figure 4. Map of Surprise Bay- Stokes Point area, with 1 km grid and excursion localities shown. From Everard (2011). Pbgp: Surprise Bay Fm, middle pelitic member; Pbgu: upper sandy member; Qplc- lithified calcareous dune sand, Qhd- dune sand; pale green- amphibolite, bright blue- tholeiitic dolerite, purple- plagioclase-phyric dolerite.

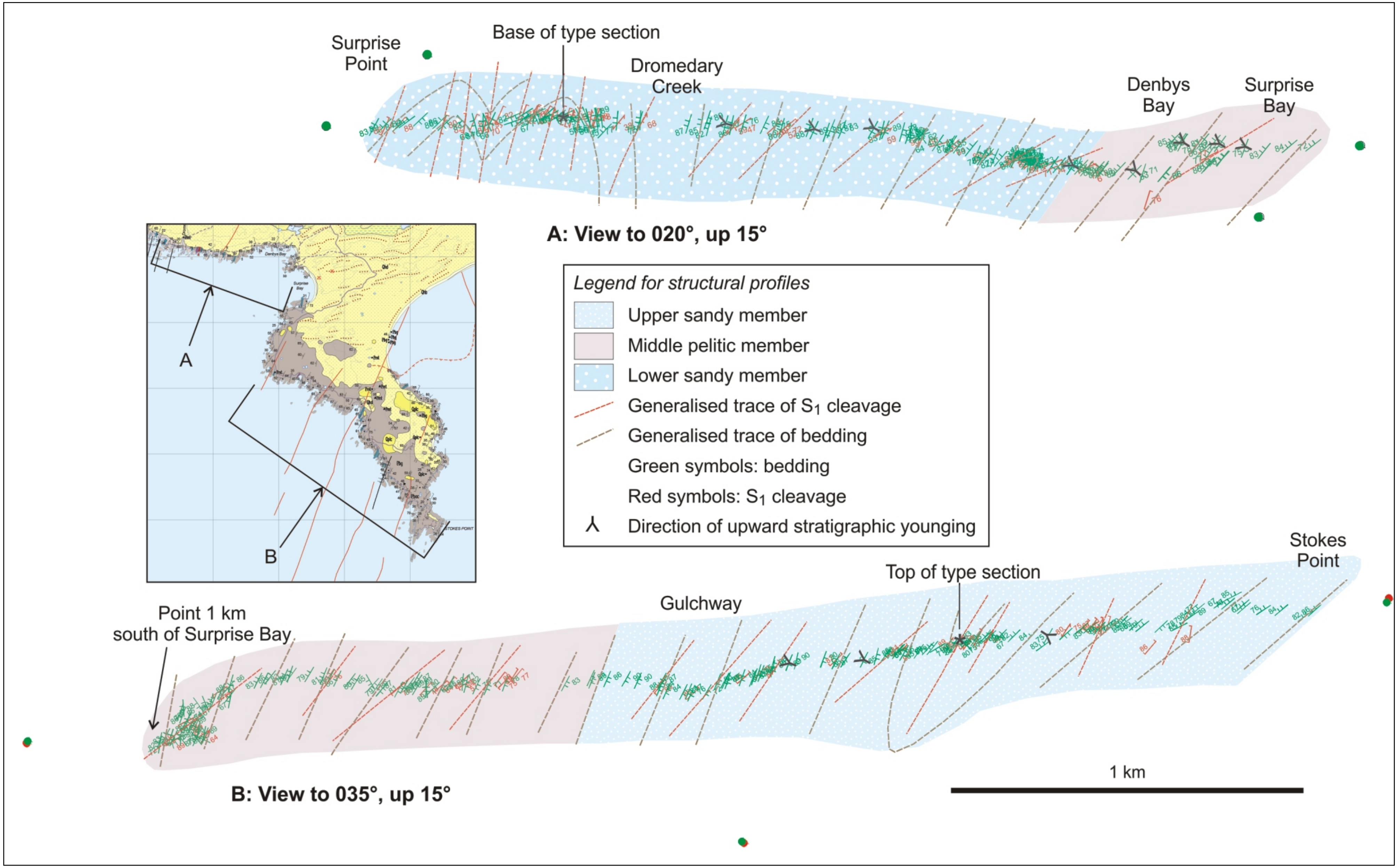

Figure 5. Structural profiles looking along F1 fold hinges, type section of the Surprise Bay Formation. From Calver & Everard 2014 (Figure 2, p. 9, UR 2014/1.)

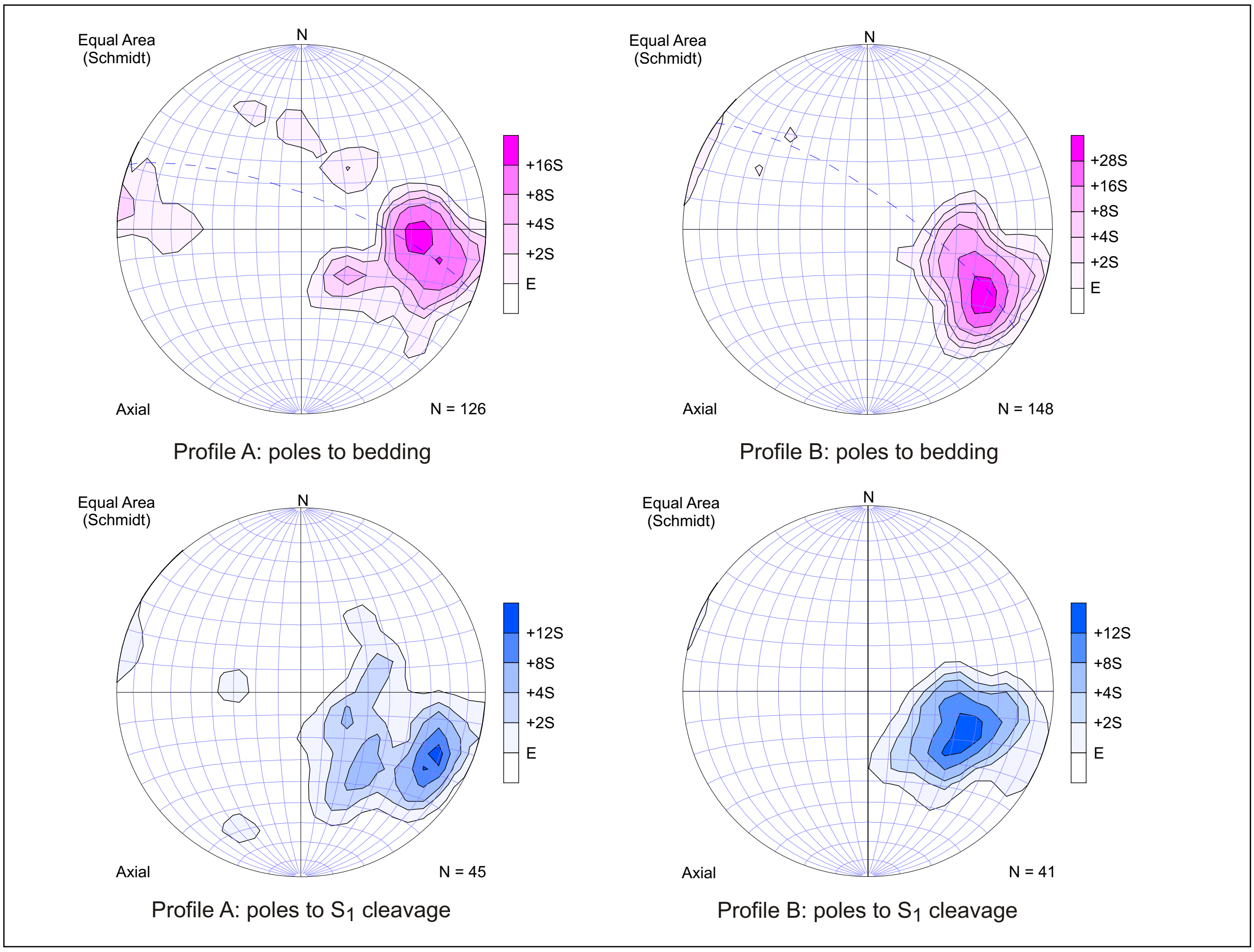

Figure 6. Equal-area stereoplots of poles to bedding and S1 cleavage used in structural profiles in Figure 5. From Calver & Everard 2014 (Figure 3, p. 10, UR 2014/1).

Figure 7. Laminated pelitic schist with garnet (1 mm prominent grains) and retrogressed ?andalusite, 'middle pelitic member'. The retrogressed andalusites preserve the lamination and show dextral rotation. Denbys Bay (236267/5554042). From Calver & Everard 2014 (Plate 6, p. 12, UR 2014/1).

Figure 8. Pelitic schist, with retrogressed andalusite (upper part of photo) and garnet, and plane-laminated to cross-laminated siltstone bed showing overturned facing; 'middle pelitic member'. Surprise Bay (236111/5553826). From Calver & Everard 2014 (Plate 5, p. 12, UR 2014/1).

Locality 2 - about 1.2 km by road from loc. 1. The road swings E then briefly NE near a small cove.

GDA94 Zone 55: 236318mE/5552213mN
Zone 54: 747476mE/5552761mN

Here, in the upper part of the middle pelitic member of the Surprise Bay Formation, andalusite porphyroblasts are absent, although biotite and locally garnet are present. Overturned bedding still dips WNW with shallower cleavage. The main point of interest here, on the western side of the small inlet, is a 2m sill thick of dolerite with abundant plagioclase phenocrysts 5 – 10 (-20) mm long, aligned parallel to the chilled margins. The body contains a 3 x 0.5 m raft of country rock.

The dolerite is a strongly fractionated tholeiite; similar plagioclase-phyric dykes and sills are widespread on King Island. Attempts to date them have been unsuccessful, but as they also intrude the Loorana Granite they are certainly younger than 750 Ma.

Locality 3 - about 1.5 km from loc 2. Pass larger cove (Gulchway) and turn into track on right, signposted "Sealers Wall." The track ends after 60m at a stone wall; climb southward on to the prominent outcrop.

GDA94 Zone 55: 237260mE/5551554mN
Zone 54: 748371mE/5552039mN

Here, near the base of the upper sandy member of the Surprise Bay Formation, overturned bedding dips consistently WNW (~035W60-70). At least five beds of actinolite hornfels, 1.5 – 8 m thick, are separated by mostly thinner (0.4 – 5m) beds of planar laminated grey metasiltstone, schist and fine-grained sandstone (Fig. 11). Most contacts are sharp, but a few appear gradational over up to 0.5 metres. Sparse, small (~50 mm) ellipsoidal siliceous concretions are locally present.

The actinolite hornfels beds contain abundant porphyroblasts (2 - 4 mm long) of actinolite and can easily be mistaken for sills of coarse-grained dolerite or basalt. Parts of the rock have incipient brown spheroidal weathering which led Blackney (1982) to (incorrectly) interpret the rocks as pillow lavas.

Thin sections (Fig. 12) show plumose, often bow-tie-shaped, aggregates of columnar to acicular pale green tremolite-actinolite, 2–4 mm long, in an abundant groundmass of fine-grained (50 um) granoblastic quartz, biotite ± garnet ± zoisite. In one sample, the tremolite-actinolite porphyroblasts appear to pre-date the main foliation. Similar units of "actinolite hornfels" are locally present as isolated beds elsewhere in the middle pelitic member, and also occur in the Fraser Formation in eastern King Island (Calver, 2012).

Whole-rock analyses resemble those of mafic–intermediate igneous rocks (e.g. with relatively elevated MgO, FeOt, CaO, Ni, V, Co and Cr) and the protolith may be a pelitic sediment modified by the addition of fine-grained mafic volcaniclastic material.

A further complication is that the sequence is enclosed by two sills of "real" dolerite, both aphyric. The western body is 1 - 1.5m thick, slightly transgressive and can be traced intermittently NNE parallel to the eastern side of Gulchway; the eastern body is 4m thick and is concealed inland beneath "calcarenite" (lithified calcareous dune sand).

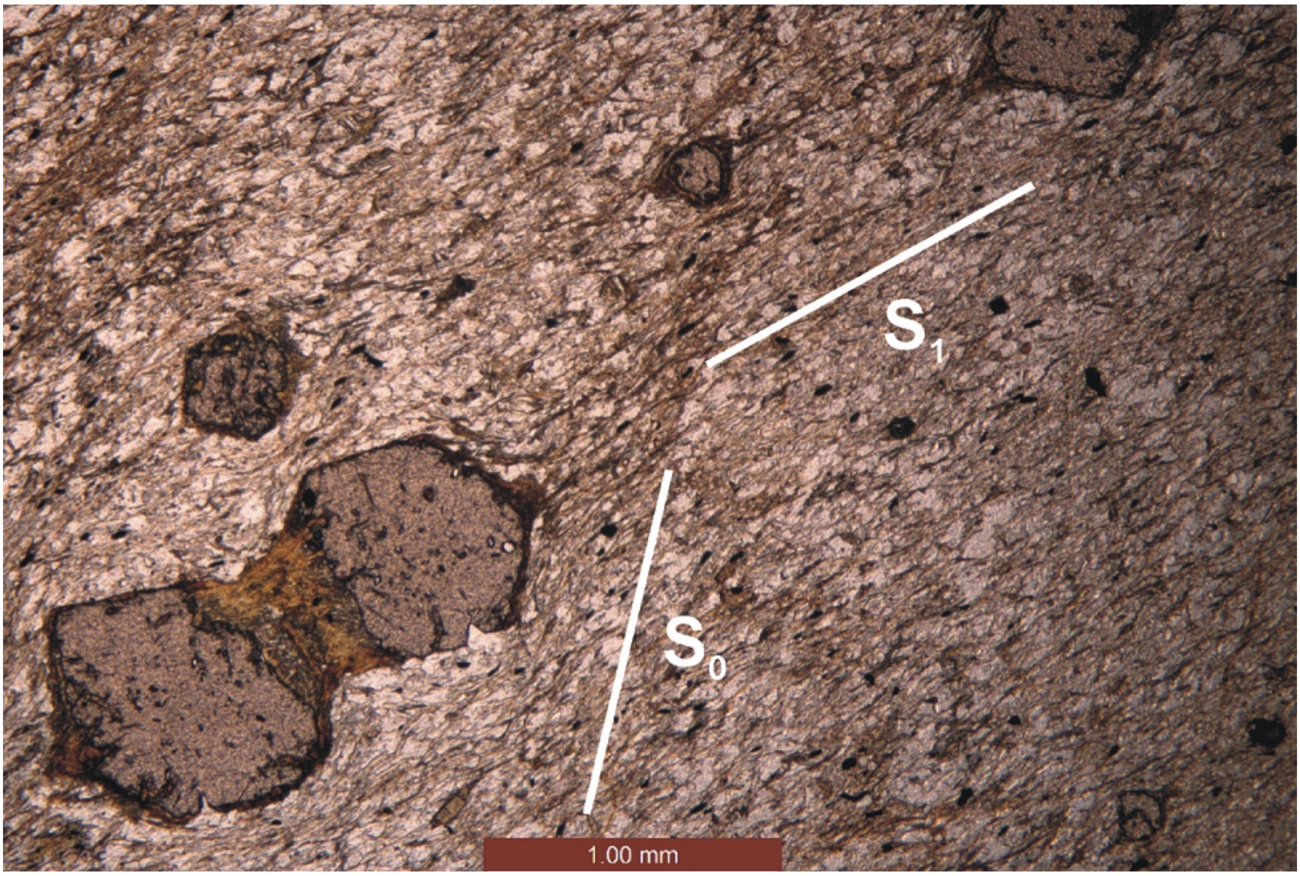

Figure 9. Photomicrograph of schist with foliation deflected about euhedral garnet porphyroblasts; strain shadows of fine-grained chlorite. Sample R014621 (KE607). From Calver & Everard 2014 (Plate 13, p. 15, UR 2014/1).

Figure 10. Schist, with chlorite porphyroblast overgrowing S1 foliation. Sample R013486 (KE429A). From Calver & Everard 2014 (Plate 14, p. 15, UR 2014/1).

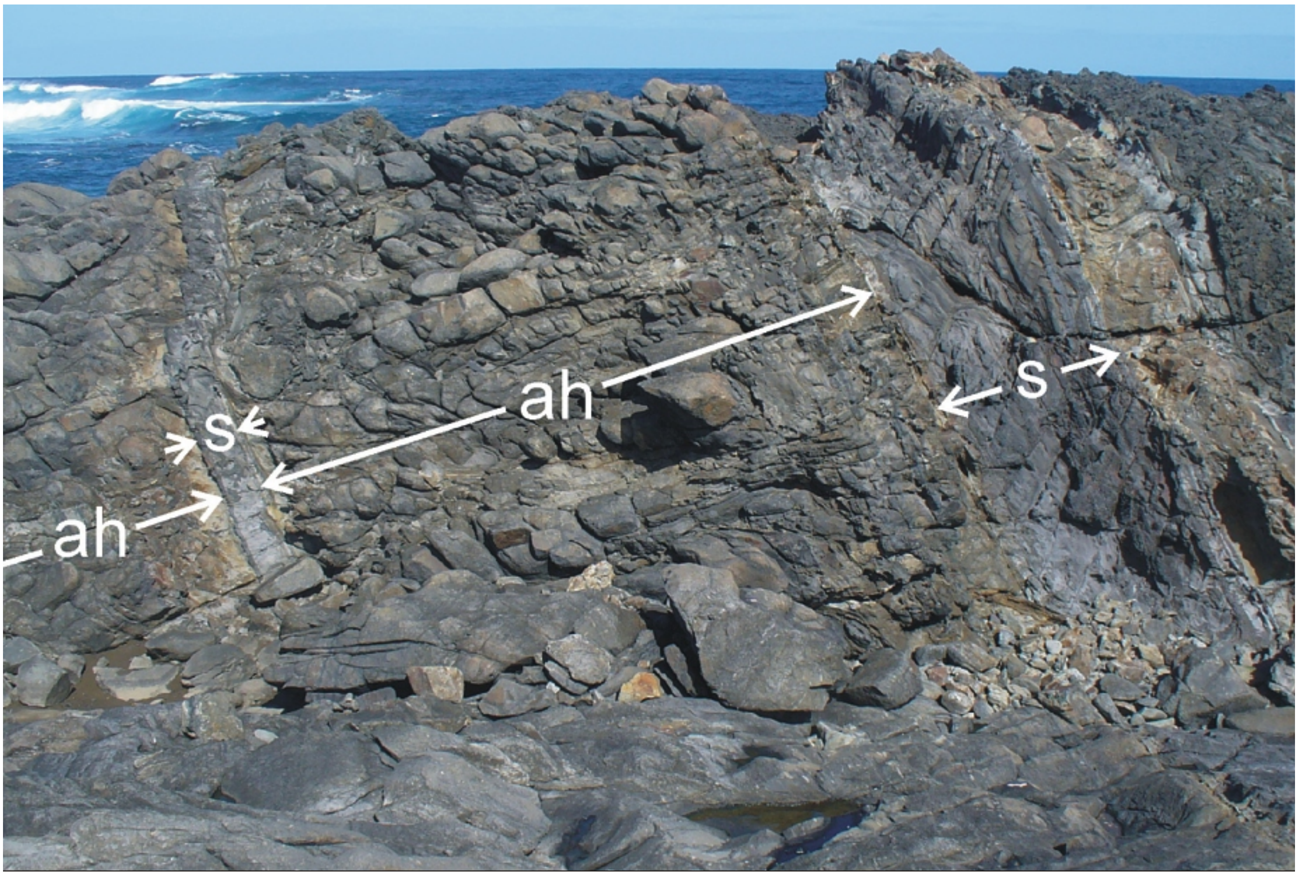

Figure 11. Alternating schist (s) and amphibole hornfels (ah) near Sealers Wall. The middle hornfels unit is about seven metres thick (237246/5551580). From Calver & Everard 2014 (Plate 11, p. 14, UR 2014/1).

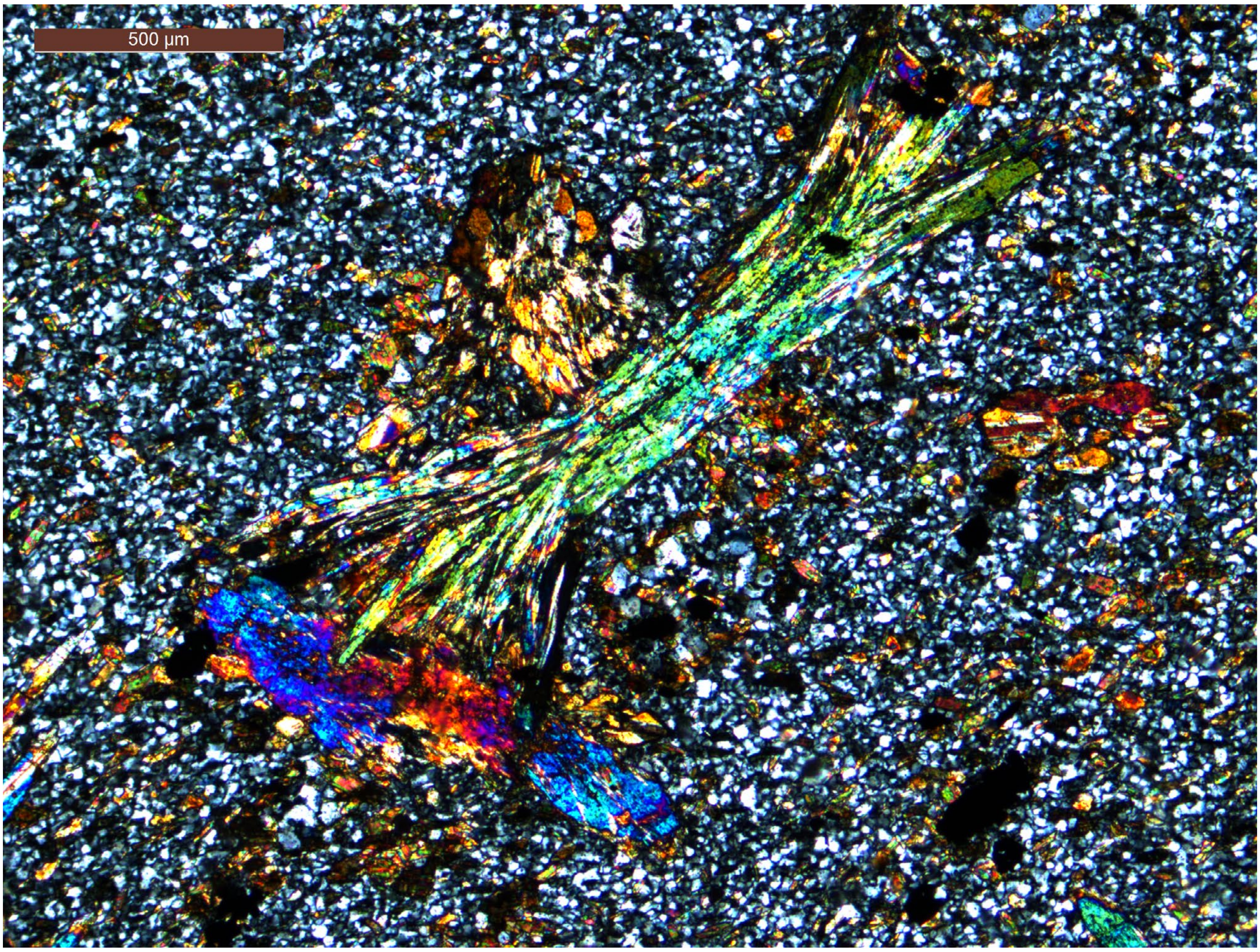

Figure 12. Photomicrograph of actinolite hornfels, crossed nicols. Sample R013467 (KE311A), Sealers Wall.

Locality 4 - proceed along the Stokes Point track for about 800 m past loc 3.

GDA94 Zone 55 237454mE/5551128mN
Zone 54: 748536mE/5551601mN

Time permitting, we will walk south along the foreshore for 400m, and rejoin the vehicles at Loc. 5.

Typical exposures of the upper sandy member of the Surprise Bay Formation consist of medium to thick beds of very fine-grained quartzose sandstone, interbedded with dark grey pelitic schist/phyllite. Lithologies and sedimentary structures are similar to the lower sandy member, although here sandstone is volumetrically subordinate (~30%). Sandstone beds are parallel, continuous, up to 1.5 m thick, and they tend to occur as groups or bundles totalling several metres to a few tens of metres thick. The sandstone beds tend to have sharp bases, and either sharp or gradational tops. They are generally internally structureless, in some cases with weak internal parallel lamination, and rarely partly cross laminated. Bouma CDE sequences are present.

Some sandstone beds contain elongate ovoid concretions (Fig. 13). These have calcitic cores, siliceous rims and amphibole-chlorite porphyroblasts that are absent from the surrounding rock. The interior of a concretion from near here was found (XRD) to consist of calcite, quartz, chlorite, plagioclase, amphibole and epidote.

Pelitic intervals, some many metres thick, display thin to medium, planar continuous bedding. In places thin, sharply bounded black shale beds are preserved that resemble the microbialite beds of the Fraser Formation (Calver, 2012).

Locality 5 - foreshore about 130m south of Loc. 4

GDA94 Zone 55: 237511mE/5551032mN
Zone 54: 748586mE/5551502mN

Still in the upper sandy member, interbedded quartz sandstone and thinly laminated phyllite consistently dip WNW at about 60°. Cross-lamination, flame structures and graded bedding confirm that they are still overturned.

Here, the beds are intruded by a subconcordant sill of amphibolite about 5m thick. It is separated from similar body about 15m to the southeast by a screen of massive quartz sandstone. The intrusions are massive with sharp margins. In thin section they largely consist of hornblende, with small amounts of plagioclase, biotite and titanite. Their grade suggests that they were emplaced prior to deformation and metamorphism of the metasediments (i.e. >1290 Ma, Berry et al. 2005).

Locality 6 - proceed along Stokes Point track for about 300 m past Loc 5.

GDA94 Zone 55: 237654mE/5550784mN
Zone 54: 748712mE/5551245mN

The top of the upper member (and of the type section) is a steeply overturned tight syncline, well exposed at 237653/5550815 (Zone 54: 748713/5551276) (Fig. 14). A 50 m wide zone to the south contains further, open to tight F1 folds, beyond which bedding predominantly dips to the west and is right-way-up. The folded zone thus corresponds to a regional, tight to isoclinal, F1 synclinal closure, plunging subhorizontally and with a west-dipping axial surface.

Locality 7 - proceed for 850 m to end of track at Stokes Point.

GDA94 Zone 55: 238170mE/5550200mN
Zone 54: 749187mE/5550627mN

We are now on the regional west-dipping and younging limb of the major fold. On the eastern side of the quasi-island at Stokes Point, common minor F1 folds plunge gently SSW. In pelites, cleavage is strong, close to and crenulates bedding, and locally wraps around garnet porphyroblasts. Berry et al. (2005) obtained monazite ages of 764 ± 52 Ma from a pelitic schist in this area, approximating the age of the Loorana and Cape Wickham Granites. Together with the crenulation, this was interpreted to indicate syn-D2 deformation and alteration by a concealed granite body.

Locality 8 (optional) - after leaving Surprise Bay, drive 4.5 km along Seal Rocks Road to the end.

Seal Rocks Lookout

GDA94 Zone 55: 233510mE/5557000mN
Zone 54: 744997mE/5557726mN

The highest cliffs on the island consist of breccia, cataclasite and locally mylonite derived from the Surprise Bay Formation. Easily accessible outcrop is poor, but near sea-level the dominant foliation (S0 and subparallel S1?) has local kink-folds and is cut by dolerite and granite dykes and quartz veins. We are close to the western contact of Proterozoic granite, much of it also strongly sheared, which crops out from just north of here to Cataraqui Point, about 4 km away. Here, a major NNW-trending magnetic lineament west of King Island passes only a few hundred metres offshore; its source is unknown but may be related to late Cretaceous break-up of Australia and Antarctica.

Figure 13 (Above). Part of an ovoid concretion in fine-grained sandstone. Pen is sitting on remnant weathered core of amphibole calc-hornfels; note siliceous dark grey and pale grey rim zones speckled with amphibole porphyroblasts. (237455/5551135). From Calver & Everard 2014 (Plate 9, p. 13, UR 2014/1).

Figure 14 (Left). Tight synclinal F1 closure at 237652/5550815, marking the top of the type section of the Surprise Bay Formation. From Calver & Everard 2014 (Plate 12, p. 14, UR 2014/1).

CAPE WICKHAM EXCURSION

The following is largely adapted from Calver & Everard (2014) and Cox (1973).

Surprise Bay Formation- lithologies

Schist and metasandstone, correlative of the Surprise Bay Formation, crop out along about 8 km of rocky coast, between intrusive contacts with the Loorana Granite at the northern end of Phoques Bay (Fig. 1) and the Cape Wickham Granite just east of Cape Wickham (Figs. 1, 15). Sills and dykes, of mafic and granitic composition, are very common. Contact metamorphism and locally anatexis has resulted in recrystallisation that overprints and partly obscures the primary foliation (S1) and the regional amphibolite facies metamorphism throughout.

Bedding for the most part dips steeply west (Fig. 16), and is overturned. Alternating units dominated by thin-bedded grey schist and fine-grained metasandstone have been differentiated along this coast, although no stratigraphic succession can be worked out because of faulting and deformation.

The pelitic units are mostly thin-bedded to laminated (banded), light grey to dark grey schist. Thin to medium beds of pale grey quartzose metasandstone are commonly a minor component. Packages of medium to thick beds of fine-grained quartzose sandstone are present in places. Boudinage of the sandstone beds is common. The schist is coarse-grained (micas 1–2 mm), probably a result of aggradational recrystallisation accompanying contact metamorphism, as they are distinctly coarser than schists in the Surprise Bay Formation distant from granite contacts (e.g. Surprise Bay area). There is a rough primary foliation sub-parallel to bedding. Facing evidence is only rarely preserved as cross lamination in some thin sandstone beds.

Quartzose siltstone and fine to very fine-grained sandstone are present as medium to very thick beds, interbedded with lesser pelitic (schistose) lithologies. Individual sandstone beds are commonly up to 2 m, rarely 5 m, thick and internally structureless. Thick beds generally have sharp tops and bases in places; grading is preserved in thin to medium beds. There are rare ellipsoidal concretions, ~0.5 m long, probably originally calcareous, of dark amphibole hornfels with pale siliceous rims, similar to those seen elsewhere in the Surprise Bay Formation.

Structure

In large part the structural sequence set out here follows Cox (1973), who recognised five deformations near Cape Wickham. D1, which is the most pervasive, predates granite emplacement, whereas D2–D5 are later, spatially impersistent and weak outside the granite aureole. This, and the absence of regionally penetrative foliations associated with these phases, makes correlation of structures across the area rather speculative.

As discussed above, D1 and regional metamorphism are now considered to have occurred at ~1290 Ma (Berry et al. 2005), whereas D2 - D4 are probably minor, local events due to intrusion of the Cape Wickham Granite at ~760 Ma; D5 post-dates the granite.

D1

Between Cape Wickham and Phoques Bay, the primary foliation (coarse schistosity) is nearly everywhere subparallel to bedding, which dips predominantly steeply west and youngs to the east. The whole area presumably lies on the steeply overturned limb of a large scale isoclinal F1 fold. However, contact metamorphism obscures facing evidence and D1 at many places. Minor F1 fold closures are rare. D1 pre-dates granite intrusion since minor granitic intrusions, not significantly deformed, cut across bedding and the subparallel S1 foliation in many places (Cox, 1973).

Post-D1 boudinage

Symmetric boudinage of competent metasandstone beds is seen in several places. Tight neck folds involve both bedding and S1, implying a post-D1 age, but temporal relationships with D2–D5 are unknown. Boudin interspaces (and neck fold hinges) tend to plunge steeply northwest in steeply west-dipping bedding planes (4 out of 5 observations), a quite different orientation from the asymmetric foliation boudinage of D3 (see below).

D2

At scattered localities there are outcrop-scale upright, open to tight, gently plunging, N- to NE-trending folds of bedding and S1 schistosity which correspond to D2 of Cox (1973). Axial planar cleavage is often absent, but is locally seen as a coarse, patchy crenulation. These elements are grouped as D2 mainly based on similar axial plane orientation, although more than one phase may be present (Fig. 17).

D2 has deformed xenoliths in the granite, folded thin pegmatite sheets, and produced a foliation and mylonite zones in the granite (see Loc. 20). However, some small granitic bodies cut across S2.

D3

Cox (1973, 1989) assigned D3 to moderately to gently inclined open folds, which are also cut by minor granitic sheets and veins.

In recent MRT mapping, D3 has been assigned a curious group of outcrop-scale structures in thinly banded schist that appear to be of predominantly extensional

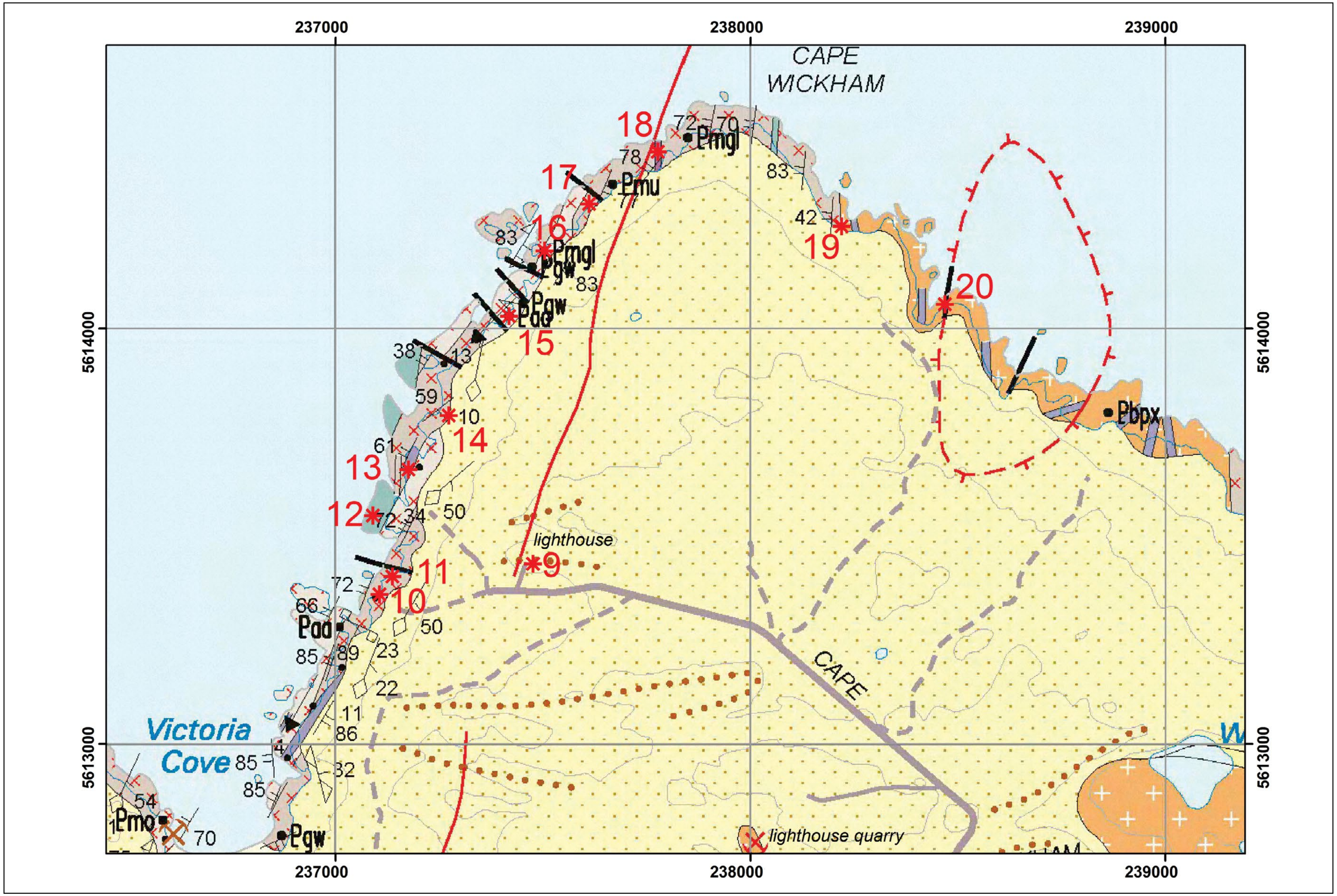

Figure 15. Map of Cape Wickham area, with 1 km grid and excursion stops shown. Grey- Surprise Bay Fm (dark-pelite, pale- quartzite), red- Cape Wickham Granite, green- amphibolite, purple- dolerite. From Calver & Everard (2012).

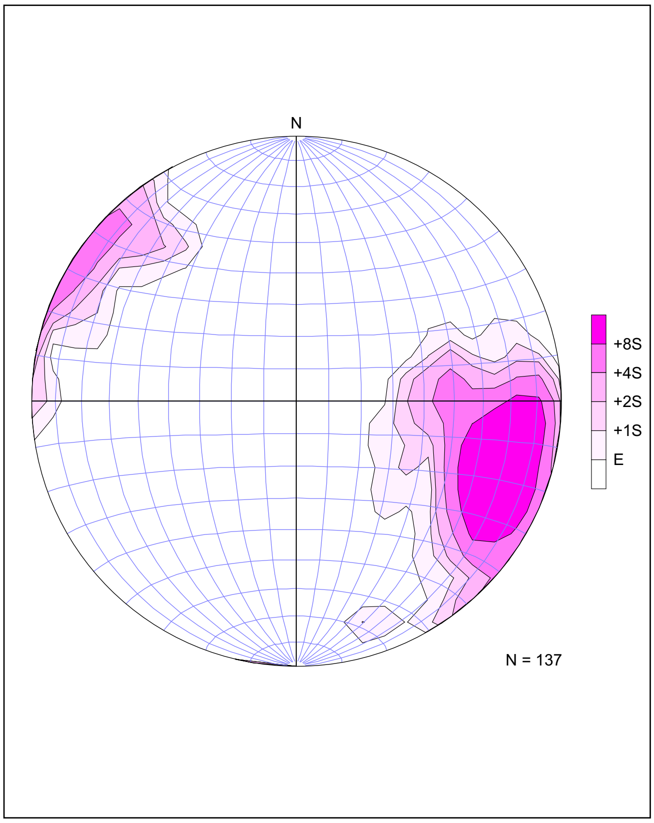

Figure 16. (Left). Equal-area plot of poles to bedding, Yellow Rock Beach to Cape Wickham area. From Calver & Everard 2014 (Figure 8A, p. 26, UR 2014/1).

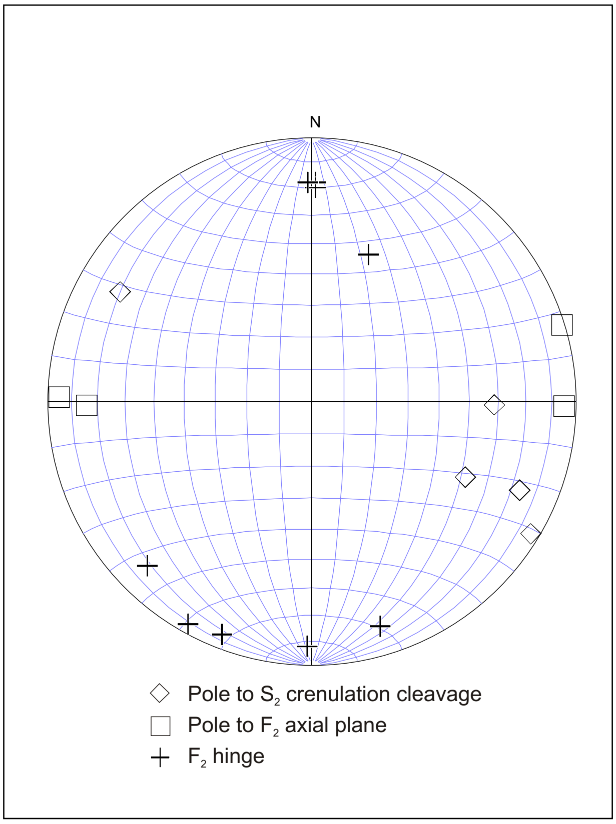

Figure 17. Equal-area plot of D2 structural elements, Cape Wickham area. From Calver & Everard 2014 (Figure 9, p. 26, UR 2014/1).

origin. The F3 folds, affecting bedding and the primary schistosity, are disharmonic, generally lack axial plane cleavage and have axial planes aligned with short vein segments, in a manner similar to the neck folds associated with boudin gashes (Figs. 20, 21). Viewed on outcrop surfaces approximately normal to the vein-bedding intersection, the veins are short (~50–150 mm) and inclined at 45–60° to bedding. The folds are more pronounced if associated with shorter, broader veins, an observation also consistent with boudinage. However the structures (veins + folds) differ from classical boudinage in that they appear more or less randomly distributed through the rock, and are not associated with any obvious compositionally discrete layers (Fig. 22). As well as the neck folds immediately beyond the terminations of the veins, there are in most cases gentle 'flanking folds' (Passchier, 2001) on either side of them. Flanking fold closures on either side are generally opposed so that they form verging 'S' or 'Z' structures with the vein occupying the short limb. Layers in the schist may be slightly displaced from one side of a vein to the other. Displacement is antithetic (i.e. 'a-Type' flanking folds, Passchier, 2001; Fig. 21). Viewed in the bedding plane, the veins are much longer, with a strong parallel alignment. They have an undeformed pegmatite-like fill of coarsely crystalline quartz, K-feldspar and (in some cases) tourmaline.

The veins (and the axial surfaces of the neck folds, and flanking folds where present) dip fairly consistently to the southeast or east (Fig. 18). In the area north of Victoria Cove, the fold hinges (and the parallel vein-bedding intersections) plunge gently south (and have 'S' vergence, down plunge). Elsewhere they plunge gently north elsewhere ('Z' vergence, down plunge). In rare cases, a weak patchy coarse crenulation cleavage is present, parallel to the axial plane of the neck folds (236887/5612968, 237141/5613549).

The D3 structures are very similar to the 'foliation boudinage' of Platt and Vissers (1980), and imply extension in the direction of foliation (S0 + S1) of the banded schists. In this case, the extension direction was more or less vertical in the plane of the banding (predominantly steep west dipping). The angle between the overall banding (S0 + S1) in the schist and the D3 structures (neck folds + veins) tends to be significantly less than 90°, indicating an element of non-coaxial shear (Platt and Vissers, 1980), in this case west-side-up. This is consistent with the vergence of the flanking folds. The veins imply brittle fracture and are filled by leucocratic minerals; the presence of tourmaline shows ambient fluid compositions were granitic, and a broadly syn-Wickham Granite age is implied for D3.

D3 as recognised here probably corresponds with D3 of Cox (1973, 1989). Cox (1973, p.124) remarked that "…there is localised recrystallization and formation of granitic sweat-out structures in the hinges of some F3 folds", although Cox seems not to have recognised the predominantly extensional nature of D3.

D4

As recognised by Cox (1973), D4 comprises open, upright folds with northeast trends (similar to D2), that overprint D3 structures. Only such fold was positively identified during the recent mapping (see Loc. 11).

D5

Late, open, upright, approximately east-west trending folds are assigned to D5 (Cox, 1973; Fig. 19). Other local manifestations of D5 are a weak, patchy crenulation cleavage, a down-dip lineation on steep west-dipping S0 + S1 surfaces and a weak alignment of retrogressed andalusite porphyroblasts. Thin granitic sills are affected. D5 features occur around Cape Farewell, and about 500 m north of Victoria Cove.

Metamorphism

Coarse recrystallisation of micas and quartz in schist overprints the S1 schistosity. In thin section these rocks also contain microcline, as larger anhedral crystals (2 mm) poikilitically enclosing other minerals (0.25–0.5 mm) and biotite. Quartz grains are equant, unstrained, granoblastic in places, and all phases are apparently undeformed. S1, if preserved, is a weak alignment of the micas.

Metamorphic spotting is locally present. Large ovoid 'mega-spots' (Plate 32) occur near the granite contact on Cape Wickham (Loc. 18).

Pseudomorphs of columnar porphyroblasts up to 30 mm long, probably originally andalusite, are locally abundant. XRD analysis shows that they have retrogressed to muscovite and minor chlorite. These are common in places distant from granite elsewhere on King Island where they also appear to pre-date S1, so here they are not necessarily of contact metamorphic origin. Dark greenish 2 mm porphyroblasts of probable amphibole are sparsely disseminated in some metasiltstone layers. There are rare ellipsoidal concretions, ~0.5 m long, probably originally calcareous, of dark amphibole hornfels with pale siliceous rims, also similar to those seen elsewhere in the Surprise Bay Formation.

Minor granitic intrusions

Granitic intrusive rocks are abundant as sheets, dykes, veins and irregular bodies, mostly from 50 mm to several metres wide, of granite, microgranite and pegmatite. Microgranite sills and sheets, 50–100 mm wide, are ptygmatically folded in some cases. Many small knots of pegmatite may be leucosomes, in some cases associated with extensional fracture, as shown for those associated with D3 (below). These are all thought to be more or less synchronous with intrusion of the Cape Wickham Granite.

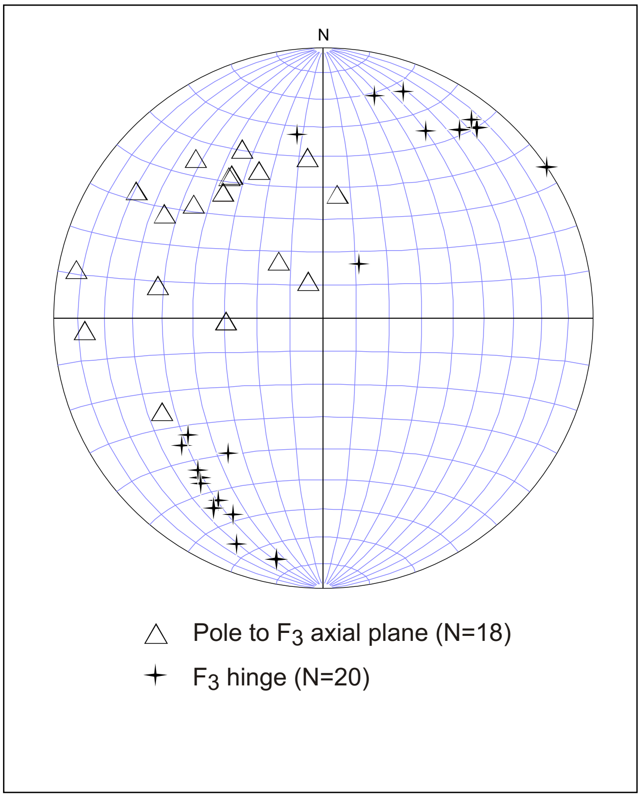

Figure 18. Equal-area plot of D3 structural elements, Cape Wickham area. From Calver & Everard 2014 (Figure 10, p. 27, UR 2014/1).

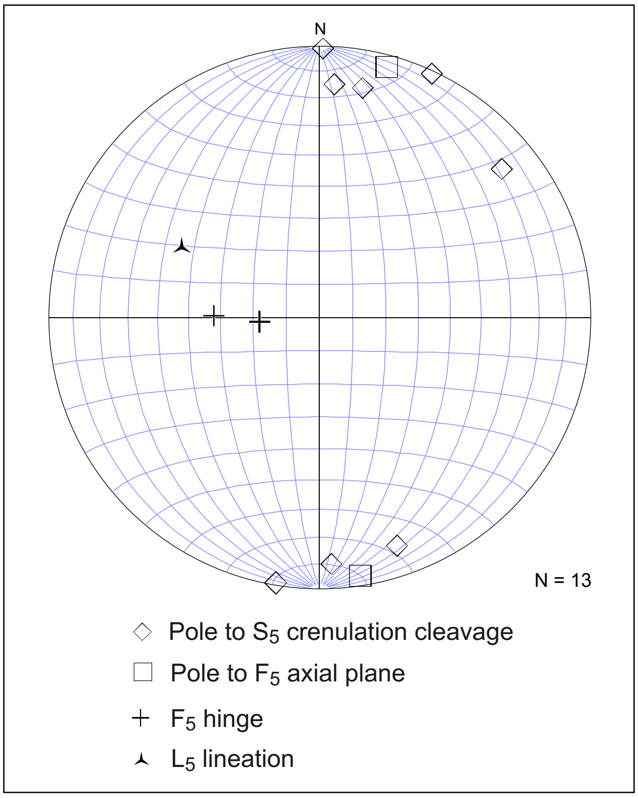

Figure 19. Equal-area plot of D5 structural elements, Cape Wickham area. From Calver & Everard 2014 (Figure 11, p. 27, UR 2014/1).

Figure 20. Short, leucocratic veins associated with disharmonic folds, assigned to D3 (237175/5613518). From Calver & Everard 2014 (Plate 26, p. 29, UR 2014/1).

Figure 21. D3 vein with well-developed flanking folds (237120/5613396). From Calver & Everard 2014 (Plate 28, p. 30, UR 2014/1).

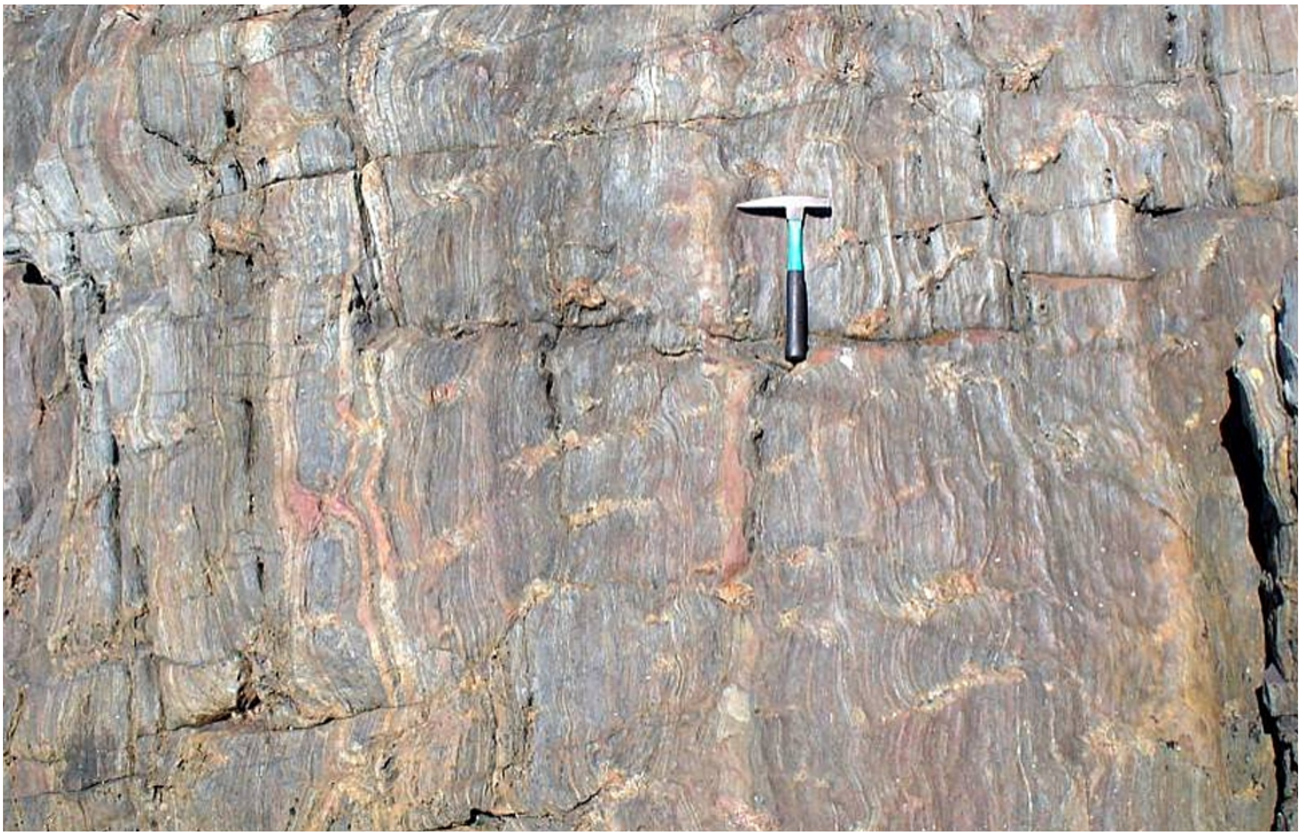

Figure 22. Outcrop surface with multiple examples of crudely aligned short veins and gentle disharmonic folding assigned to D3 (237120/5613396). From Calver & Everard 2014 (Plate 30, p. 30, UR 2014/1).

Minor mafic intrusions

Mafic sheets and dykes of at least two, possibly three different generations can be recognised. All have the chemical composition of variably, but usually strongly, fractionated tholeiitic basalt. Relative timing of intrusion can generally be determined by cross-cutting relationships with minor granitic intrusions and grade of metamorphism.

Amphibolite bodies, some more than 20 m wide, occur as concordant to subconcordant sheets. The smaller bodies are locally boudinaged. In thin section they consist largely of clear yellow-brown hornblende and plagioclase. Many are transected by minor granitic dykes. They are therefore are >760 Ma and, as they commonly carry a foliation attributed to F1, probably also pre-date regional metamorphism and D1 deformation at ~1290 Ma (Berry et al. 2005). One large body (see Loc. 15) has been dated at ~1370 Ma (U-Pb, zircon) by J. Mulder (pers. comm.).

At two localities (e.g. Loc. 13), fine-grained metadolerite bodies are cut by microgranite and pegmatite veins, yet these have turbid, greenschist facies textures and assemblages, distinct from the amphibolites. They may represent a minor episode of mafic magmatism sometime between ~1290 Ma and 760 Ma.

All mafic dykes that are demonstrably post-granite (i.e. transect minor granite dykes, or are within granite) have turbid, metadolerite textures. These are up to 15 m wide. The more fractionated varieties are feldspar-phyric (see Loc. 18).

Locatlites 9 - 20

Locality 9. The Cape Wickham lighthouse, 47 km from Currie and 75 km from Grassy, is Australia's tallest at 48 m. It was constructed in 1861 from the Cape Wickham Granite, extracted from an outcrop a few hundred metres away in the dunes. The contract was reputedly very profitable, as the original tender envisaged importing granite from Scotland. A sample from the same quarry was dated at 760 ± 12 Ma by Turner et al. (1998).

We will walk west to the foreshore and follow the coast for ~2.5 km, northward around Cape Wickham and across the granite contact to the first major shear zone in the granite, and return across the dunes, a total distance of about 4 km.

Locality 10. Foreshore west of the lighthouse.

GDA94 Zone 55: 237095mE/5613350
Zone 54: 752353mE/5613702mN

In thinly banded schist, bedding and primary schistosity (S1) are subparallel and dip steeply west (~020W72). Both are affected by gentle disharmonic F3 folds (plunging ~23 to 210). In their axial planes, tension gashes filled by short vein segments of coarse-grained quartz, feldspar and tourmaline. See above for detailed discussion.

Locality 11.

GDA94 Zone 55: 237130mE/5613395mN
Zone 54: 752391mE/5613745mN

50m north of Loc. 10 in similar schist, an open coupled synform-antiform, with a gently southwest plunging hinge and easterly vergence, rotates more D3 "tension gash" structures, and is thus assigned to D4. (Fig. 23). There are also at least two granitic dykes, one of which has intruded along a fault in the synformal axial plane. These suggest that the "last gasp" of granite magmatism was later than D4.

Locality 12.

GDA94 Zone 55: 237116mE/5613542mN
Zone 54: 752443mE/5613978mN

About 150m N of Loc 11, close to low water mark, a large amphibolite body has a sharp ± concordant eastern contact with a subvertically (~036E85) dipping sandstone unit. The amphibolite is cut by thin (~1 cm) microgranite dykes and is therefore >760 Ma. Nearby, bedding and schistosity and folded by more F3 (?) folds, plunging shallowly NNE.

Locality 13.

GDA94 Zone 55: 237166mE/5613631mN
Zone 54: 752387mE/5613892mN

About 140m N of Loc. 12, a large irregular mafic dyke 8-9 m wide, trending ~010, is cut by microgranite and pegmatite veins. Unlike most other pre-granite intrusions which are amphibolites, it has a doleritic texture and may have intruded after regional metamorphism at ~1290 Ma, but before ~760 Ma.

Locality 14.

GDA94 Zone 55: 237247mE/5613797mN
Zone 54: 752534mE/5614138mN

Another ~140m north and back in pelite, bedding and schistosity dip southeast (~050SE60). Here cross-lamination, which is rarely preserved in this sequence, shows that the beds are right-way-up. Walking north, abundant beach cobbles several metres above present high water mark may indicate a period of high sea-level, possibly during the last interglacial.

Locality 15.

GDA94 Zone 55: 237419mE/5614021mN
Zone 54: 752721mE/5614350mN

About 280m further on, a large irregular body of amphibolite is intruded by narrow veinlets (few cm) of fine-grained granite. Zircons extracted from the amphibolite returned a precise U-Pb date of ~1370 Ma (J. Mulder, pers. comm.). This is interpreted as an igneous age, but is indistinguishable from the youngest detrital zircons in the Surprise Bay Formation (1350 ± 90 Ma; Black et al. 2004).

Locality 16.

GDA94: Zone 55 237502mE/5614185mN
Zone 54: 752815mE/5614508mN

About 180m further on, a well-jointed dolerite dyke, trending ~010 and about 5m wide, occupies a slot in the Surprise Bay Formation. Bedding and schistosity mostly dip steeply east or southeast.

Locality 17.

GDA94 Zone 55: 237618mE/5614300mN
Zone 54: 752938mE/5614615mN

About 160m further on, the schist here contains scattered porphyroblasts, a few cm long, of retrogressed andalusite. About 10m to the east, the schist is intruded by a 1m granite dyke; to the west a unit of fine-grained quartzite extends to low water mark.

Locality 18.

GDA94: Zone 55 237776mE/5614424mN
Zone 54: 753104mE/5614728mN

About 200m west of the tip of Cape Wickham and 200m from Loc. 17, a north-south trending feldspar-phyric dolerite dyke, about 10 m wide, forms a prominent outcrop on the eastern side of a small inlet. It cuts across granitic veins in the schist and is therefore <760 Ma. Similar dykes are widespread in western King Island (e.g. Stokes Point excursion, Loc. 2), in both the Loorana Granite and Surprise Bay Formation. The schist nearby contains dark ovoid spots up to 50 mm across, with white margins, probably due to contact metamorphism as we approach the granite contact.

Locality 19.

GDA94: Zone 55 238224mE/5614241mN
Zone 54: 753539mE/5614516mN

The north-south trending contact of Surprise Bay Formation and Cape Wickham Granite is exposed in a small bay about 400m SE of Cape Wickham. The adjacent Surprise Bay Formation dips mostly west, but is chaotically deformed immediately adjacent to the contact. Another dolerite dyke intrudes the granite a few metres east of the contact.

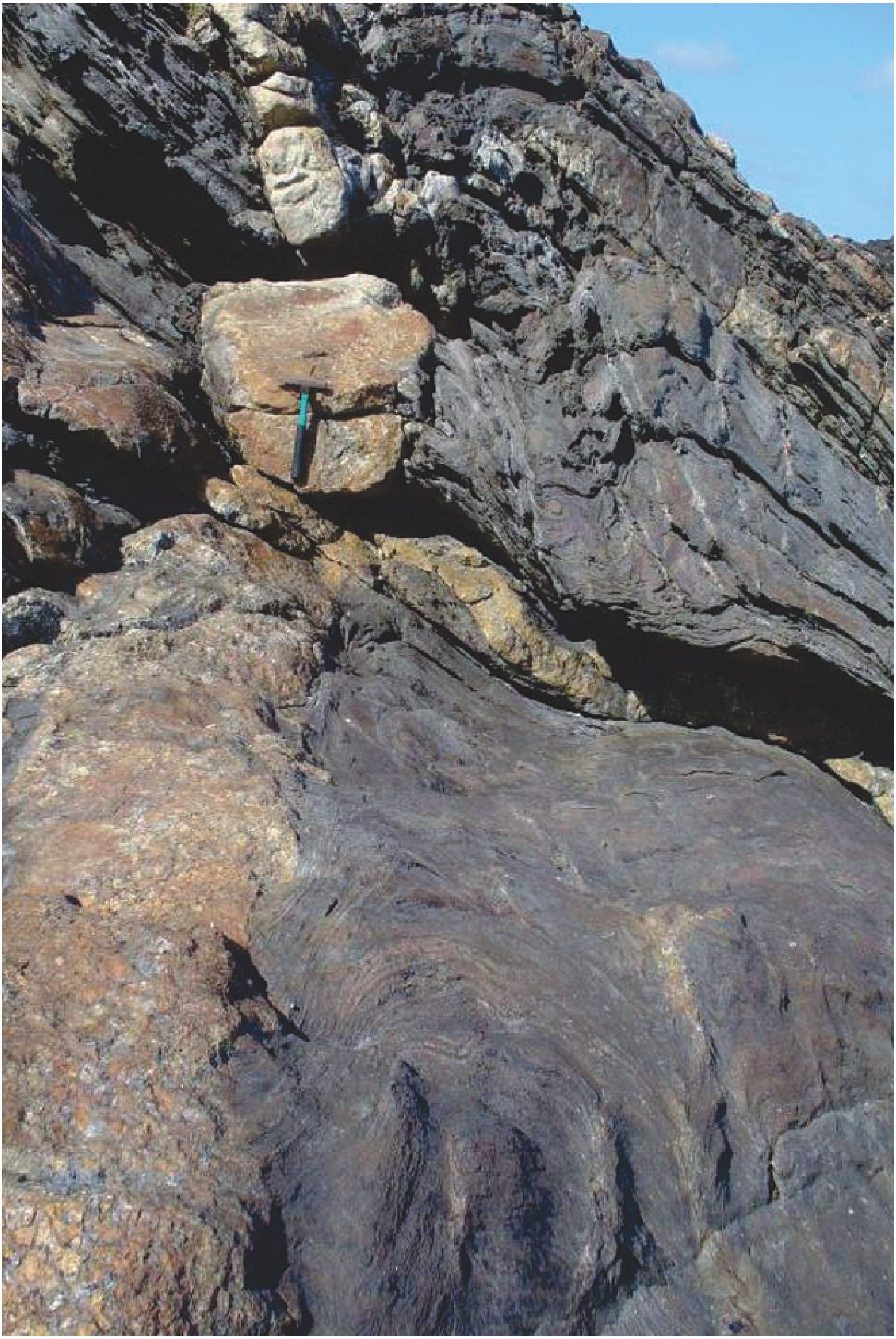

Figure 23. D4 fold, looking south; granite dyke (on which hammer sits) intrudes parallel and just left of anticlinal axial plane (237133/5613401). From Calver & Everard 2014 (Plate 31, p. 31, UR 2014/1).

Locality 20. Cape Wickham Shear Zone.

GDA94: Zone 55 238469mE/5614060mN
Zone 54: 753772mE/5614319mN

About 350m further on, just past yet another dolerite dyke and on the western side of a small bay, we come to a major shear zone in the granite, one of several studied in detail by Streit and Cox (1998):

"This moderately W-dipping mylonite zone has a sharply defined, high strain, eastern border against porphyritic granite (phenocrysts <3cm) (Fig. 24). Laminated mylonites and augen mylonites with porphyroclasts >2 mm long have an outcrop width of ~1 m, and are followed to the west by a 10-20m 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. Quartz veins on various states of deformation occur, but are rare and localised within the shear zone margins." Microstructures in the laminated mylonites "(sigma and delta-clasts; Passchier & Simpson, 1986) indicate oblique normal displacement with a dextral strike-slip component."

Oxygen isotope data from mineral pairs in the mylonite indicate an equilibrium temperature of 460° ± 15°C, consistent with the upper greenschist facies assemblage of K-feldspar-plagioclase-biotite-muscovite-quartz ± chlorite ± titanite ± epidote. Phengite compositions indicate minimum fluid pressures (PH_2O) of 550-750 MPa (Streit & Cox, 1998).

Dating of monazite from the mylonite suggests that the shear zone formed at ~730 Ma, soon after emplacement of the granite (Berry et al., 2022).

In the Cape Wickham Shear Zone, the eastern mylonites have lost Na_2O, K_2O and possibly some SiO_2, and gained ~0.5% CaO, relative to the granite protolith. This was interpreted as indicating an up-temperature (i.e. downward) fluid low at mid-crustal levels. In contrast, a dominantly strike-slip shear zone, ~3 km to the west near Disappointment Bay appears to have gained ~60% mass, chiefly SiO_2, during to upward-directed fluid flow (Streit & Cox 1998).

Head back across the dunes for ~700m at bearing ~230, to the Cape Wickham Road and the vehicles.

Figure 24. Eastern contact of shear zone in Cape Wickham Granite (~238470mE, 5614060mN).

CITY OF MELBOURNE BAY - COTTONS FLAT EXCURSION

The following is largely adapted from Calver (2012, 2018).

Grassy Group: Overview

The Grassy Group (Figs. 1, 25) is well exposed on the east coast for about 12 km north of Grassy, with an outlier at Fraser Bluff, SE of Naracoopa. The term was first used by Knight and Nye (1953) for the contact metamorphosed host rocks of the Grassy and Bold Head scheelite skarns, but was redefined more broadly by Calver (2012).

The base of the Grassy Group is an angular unconformity upon the Fraser Formation. The coastal exposures consistently dip and young steeply east or southeast. It consists of four dominantly sedimentary formations, described below, overlain by three mafic volcanic formations which comprise the Skipworth Subgroup (Figs. 26, 27).

The basal **Robbins Creek Formation** (Calver 2012), which we will not be visiting, is 80 – 100 m thick and consists of a locally developed basal conglomerate, followed by interlaminated black shale, grey-green to brown weathering siltstone and fine-grained lithic sandstone. The siltstone and sandstone are chloritic and probably volcaniclastic. Impersistent, conformable, altered basaltic units, some possibly intrusive but including definite thin flows, are locally present. Minor thin beds of impure limestone occur near the top.

Both glacial and mass-flow origins have been suggested for the overlying **Cottons Breccia** (see discussion, localities 27 and 28). However, dating of zircons from the uppermost part of the unit by chemical abrasion- thermal ionisation mass spectroscopy (CA-TIMS) yielded a weighted mean age of 636.41 ± 0.45 Ma, in close agreement with similar TIMS dates from ash beds close to the Ediacaran-Cryogenian boundary in Namibia (635.51 ± 0.82 Ma) and South China (635.23 ± 0.82 Ma) (Calver et al. 2013a and references therein). This, together with the apparent presence of dropstones appears to confirm that the Grassy Group records the worldwide "Snowball Earth" glaciation and subsequent rapid deglaciation at ~635 Ma.

The overlying **Cumberland Creek Dolostone** (Meffre et al., 2004) is best seen on the coast north of City of Melbourne Bay (Fig. 28), and is unfortunately not exposed in today's traverse. Its thickness varies markedly in response to growth faults, but is normally about 10m. Preiss (2000), Calver and Walter (2000) and Hoffman et al. (2009) noted its similarity to the distinctive 'cap carbonate' (Nuccaleena Formation) that sits on the glacial Elatina Formation (the 'Marinoan glacials') in South Australia. The correlation is supported by carbon isotope chemostratigraphy (Calver & Walter, 2000; Hoffman et al., 2009). Accordingly, the base of the Cumberland Creek Dolostone is taken as the base of the Ediacaran System on King Island.

The lowermost member is a laminated, very pale grey, pale yellow-brown weathering, fine-grained dolostone. Gentle sharp-crested anticlines (100–200 mm amplitude), vertically impersistent and with axial planes approximately normal to bedding, are seen at The Gut and elsewhere. Similar structures are found in cap carbonates in globally widespread localities, and have been interpreted as either giant wave ripples (Allen and Hoffman, 2005) or due to expansive crystallisation during early diagenesis (Gammon et al., 2005).

The middle member consists of impure thinly interbedded fine-grained dolostone and shale, locally with swaley cross-stratification. The uppermost member is dominantly shale and marly shale, with thin beds of fine-grained limestone. The top of the last limestone bed is taken as the base of the conformably overlying **Yarra Creek Shale.**

The **Yarra Creek Shale** (see localities 22 and 23) was intruded by the mafic intrusions (including the Grimes Intrusive Suite), some of which have peperitic margins. A date at 575 ± 3 Ma (U-Pb zircon, Calver et al. 2004) from the GIS suggests a significant lacuna of up to 60 Myr within or near the base of the YCS.

On King Island, as in mainland Tasmania and parts of southeastern Australia, 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 the volcanic succession (the **Skipworth Subgroup**) on King Island occurs about 100 m above the top of a probable Marinoan glacial correlative, the Cumberland Creek Dolostone (Calver & Walter, 2000; Calver et al., 2004). By contrast, 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).

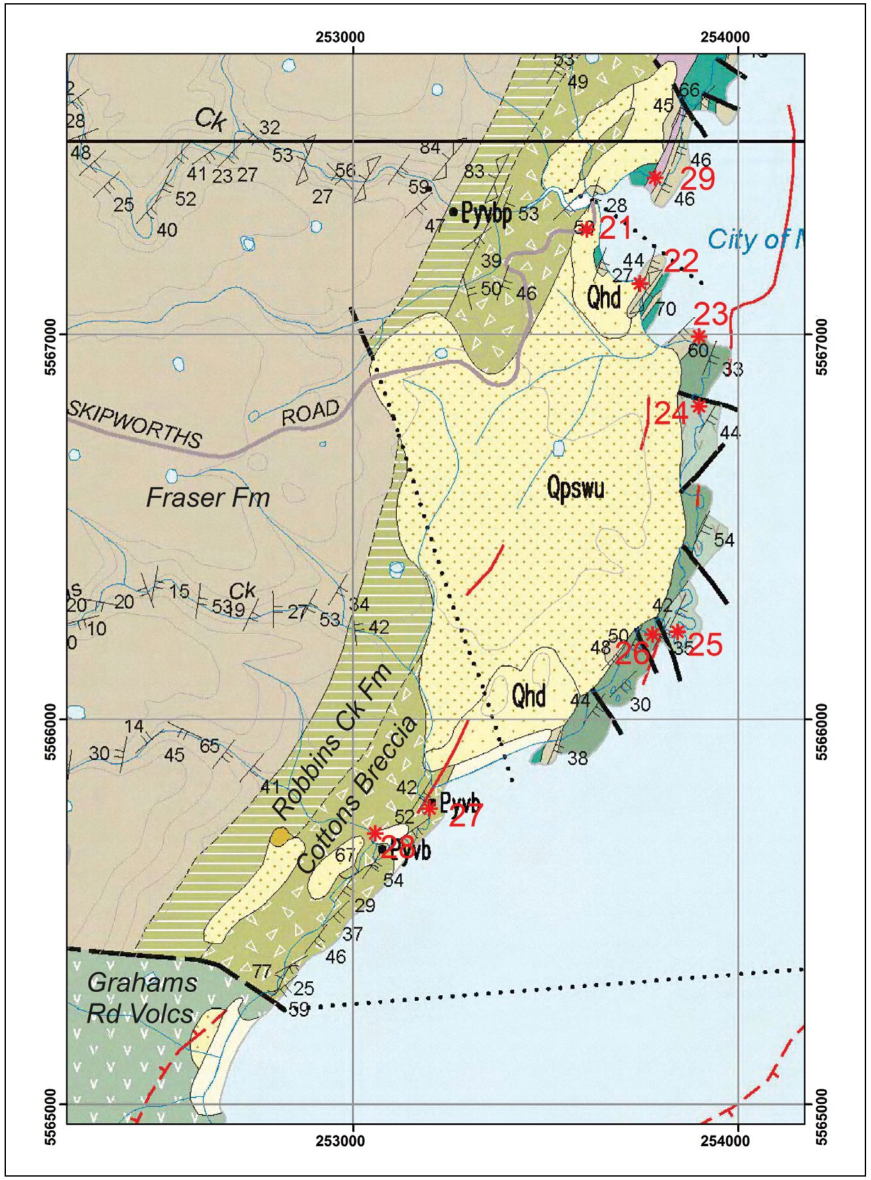

Figure 25. Map of City of Melbourne Bay- Cottons Creek area, with 1 km grid and excursion stops shown. Khaki- Yarra Creek Shale, pale green- City of Melbourne Volcanics, dark green- Shower Droplet Volcanics, purple-Grimes Intrusive Suite, bright green- other mafic intrusions, other units as labelled. From Calver (2008).

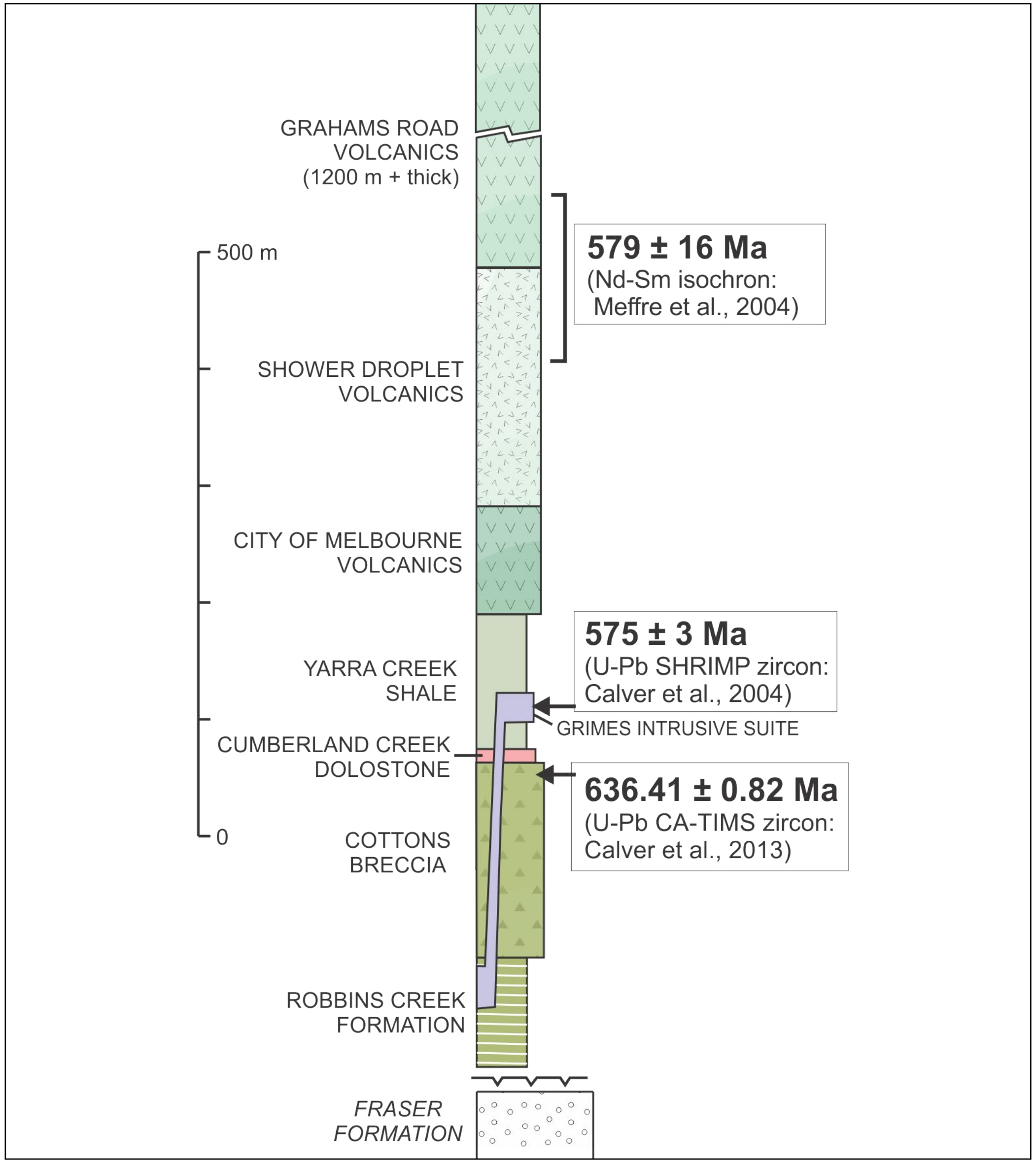

Figure 26. Stratigraphic column of the Grassy Group. Modified from Calver & Everard in Corbett et al. (2014, p. 74-77).

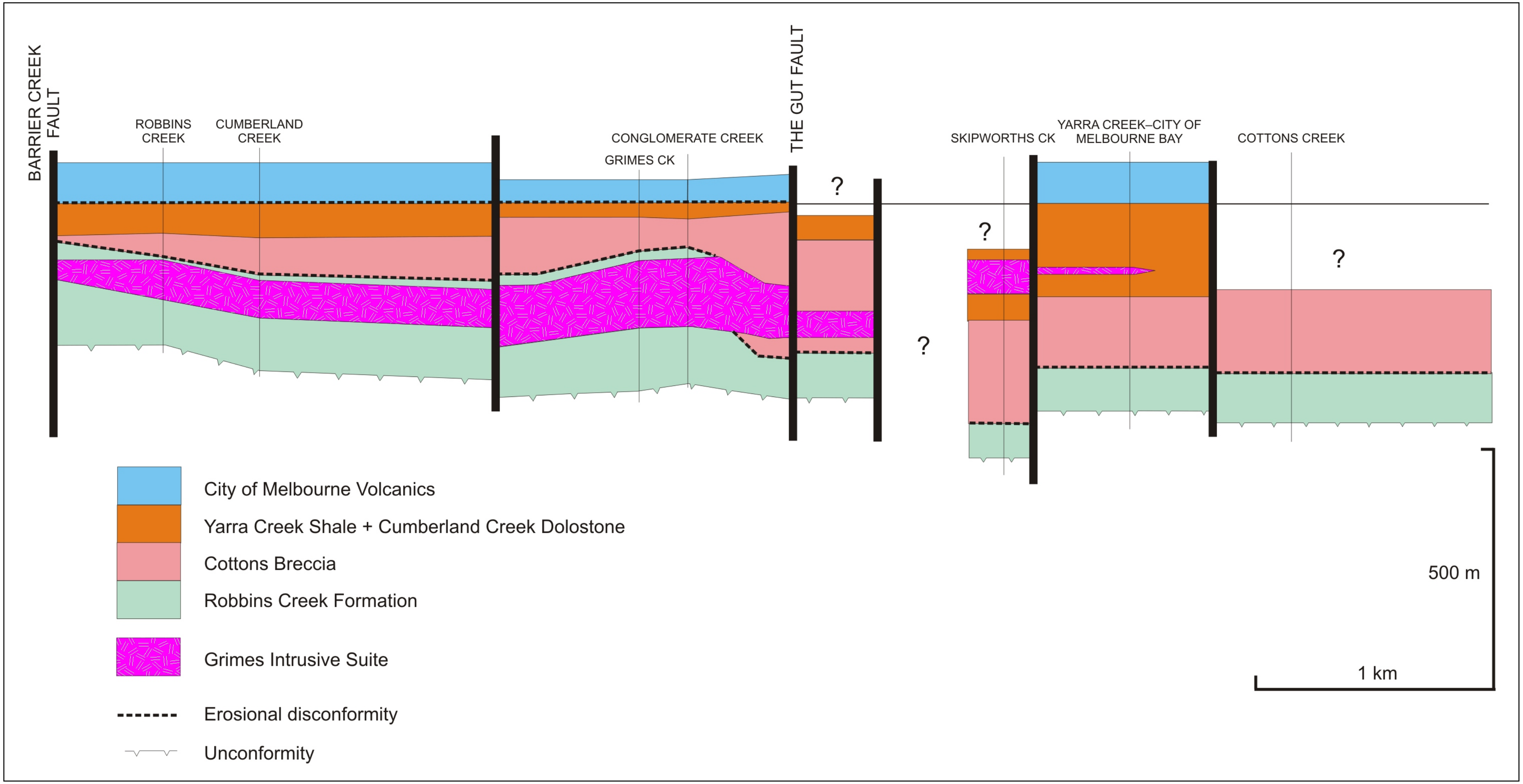

Figure 27. Diagrammatic structural profile of the Grassy Group looking southeast and down dip. Vertical exaggeration x 2; fault blocks drawn level at the base of the City of Melbourne Volcanics, basaltic sills removed. Dip of faults is uncertain. From Calver 2012 (Figure 24, p. 22, ER Grassy-Naracoopa).

Figure 28. Topmost beds of the Cottons Breccia (diamictite and red sandstone, right) conformably overlain by the Cumberland Creek Dolostone ("cap carbonate")(left), ~ 1.3 km N of City of Melbourne Bay (~254280mE, 5568360mN).

Locatlies 21 - 29

Locality 21. City of Melbourne Bay

GDA Zone 55: 253605mE/5567265mN

Leave vehicles in the car park at end of Skipworths Road. There are outcrops of the Cottons Breccia to the west of the car park, but there are much better outcrops later. Go through the gate to the beach and walk south for ~250m.

Locality 22. South headland of City of Melbourne Bay

GDA Zone 55: 253765mE/5567134mN

The Yarra Creek Shale (Calver et al. 2004) consists of uniform, poorly bedded, weakly fissile shale (mudstone) with rare, thin beds of carbonate and of mafic-volcanic sandstone. The formation is thickest here in the type section (between 100 m and 250 m; uncertain because of incomplete exposure and intercalated basaltic sills). The lower part of the formation is pale yellow-brown to grey-green, locally with black shale beds (see Loc. 29, below).

Direen & Jago (2008) showed that the Yarra Creek Shale (YCS) thickens towards the southeast, and represents a growth section, probably fault controlled. Calver (2012) also showed that the YCS has an inverse thickness correlation with an underlying mafic sill, which may also be responsible for part of the accommodation of this unit. Overall the YCS may represent a quiet water deep lake system, such as those found in the East African rift today.

The upper part of the formation, seen here, is predominantly oxidised red shale. Here, bedding dips moderately (~25 - 45°) east with a steeper (70° to subvertical) cleavage. The shale is intruded on the western side of the headland by a subconcordant intrusion, 1-2 m wide, of pale green tholeiitic basalt. There are two further sill-like intrusions, up to 20 m wide, on the southeast side of the point. The adjacent shale is pale green, possibly due to contact metamorphism, and the sills are chemically similar to the City of Melbourne Volcanics, seen at Loc. 23 on the next headland ~200 m to the southeast.

Locality 23.

GDA Zone 55: 253882mE/5566988mN

The uppermost 30 m of the Yarra Creek Shale, although rather poorly exposed, contains angular basalt fragments and is intruded by highly irregular dykes of altered basalt, in places with peperitic margins. This indicates that at least the upper part of the YCS was wet and unlithified when the City of Melbourne Volcanics were erupted into and over it.

The base of the City of Melbourne Volcanics (COMV) is taken as a volcanic breccia. Here at the type section, massive volcanic breccia and sandstone fines upwards to a metre of well-bedded fine-grained pale green volcanic sandstone at the top (253931/5566938). This is abruptly overlain by at least 60 m of pillow lava. The pillows are typically well formed, with an outer zone with characteristic radially orientated vesicles and a glassy non-vesicular rim ~20 mm thick (Fig. 29). Massive basalts are also present in the COMV (see Loc. 26).

The basalt is usually moderately to strongly magnetic (measured magnetic susceptibility up to 80 x 10^{-3} SI units, Table 3), in contrast to enclosing units, and a corresponding linear magnetic anomaly can be followed northward offshore.

Locality 24.

GDA Zone 55: 253917mE/5566810mN

About 180m south of Loc. 23 and just south of an ESE-trending inferred fault, we pass into the Shower Droplet Volcanics (SDV), a sequence of pale green picritic pillow lavas, which elsewhere conformably overlies the City of Melbourne Volcanics. The SDV extend northward parallel to the coast for ~ 6 km, offset by cross-faults, and form most of the faulted outlier at Fraser Bluff near Naracoopa, where they are overlain by the Grahams Road Volcanics (see below). The SDV also form Councillor Island, ~10 km N of Naracoopa (Everard et al. 1997).

The pillows (Fig. 30) tend to be irregular and more flattened than those of the COMV, and although vesicular, lack the distinct marginal zones of radially orientated vesicles characteristic of the latter. Many pillows of the SDV have central voids. The breccia units, largely of hyaloclastite origin (Solomon, 1968; Waldron and Brown, 1993), include isolated flattened pillows, thin flows and minor, well-bedded green volcanic sandstone (usually at the tops of the breccia units).

The Shower Droplet Volcanics are generally weakly magnetic, although a few examples of lavas with moderate magnetic susceptibility (up to 13 x 10^{-3} SI units) were recorded.

These picritic lavas consist of euhedral olivine phenocrysts (0.1–3 mm), entirely replaced by almost colourless chlorite, in a groundmass largely of quenched clinopyroxene and altered glass, with minor euhedral chromite. MgO is high — typically 11–21 wt%. Incompatible elements are very low (e.g. 0.2–0.4 wt% TiO_2) and there is marked LREE depletion (Waldron & Brown, 1993; Meffre et al., 2004; Fig. 31).

About ~200m further south, across another inferred fault, we pass back into the COMV. The two pillow lava sequences, dipping consistently southeast and juxtaposed by cross-faults, extend southward for almost 1 km.

To avoid an arduous coastal traverse, head inland to the edge of the paddocks and walk south to their corner (~253800/5566345) where a rough track leads through the scrub back to the coast.

Locality 25.

GDA Zone 55: 253824mE/5566214mN

On reaching the coast, the headland on the left (east) consists of a few metres of volcanic breccia and a spectacular example of picritic pillow lavas (Shower Droplet Volcanics).

Locality 26.

GDA Zone 55: 253780mE/5566218mN

The headland immediately to the west consists of mostly massive, although well-jointed, tholeiitic basalt (COMV). The massive and pillowed basalts are not significantly different in composition or mineralogy (Waldron & Brown, 1993). They consist of albitised plagioclase and clinopyroxene, often showing ophitic intergrowth, with interstitial green chlorite, titanomagnetite and epidote. They are tholeiites with low TiO_2 (0.4–0.8 wt%), low Zr, and LREE enrichment. Their chemistry reflects a depleted mantle source, and their Nd isotopic composition (εNd = -3.1 at 579 Ma) indicates extensive crustal contamination (Waldron & Brown, 1993; Meffre et al., 2004).

Here the massive basalt passes down-section (west) into wave-polished outcrops of volcanic breccia, and then back into the Yarra Creek Shale. The contact (e.g. in a landward embayment of the coastal cliff, 253683/5566162) is abrupt and conformable, although nearby the YCS again contains small basaltic intrusions with peperitic margins.

Locality 27.

GDA Zone 55: 253197mE/5565769mN

Walk past the remaining COMV and YCS outcrops and to the western end of a sandy beach to the mouth of Cottons Creek, at the start of outcrops of the Cottons Breccia.

Figure 29. Pillow basalt of City of Melbourne Volcanics. Outer zone of radially orientated vesicles is characteristic. Basalt youngs to upper right in photo. City of Melbourne Bay (253943/5566904). From Calver 2012 (Figure 36, p. 28, ER Grassy-Naracoopa).

Figure 30. Pillows in picrite (Shower Droplet Volcanics), south of City of Melbourne Bay (~238470mE, 5614060mN).

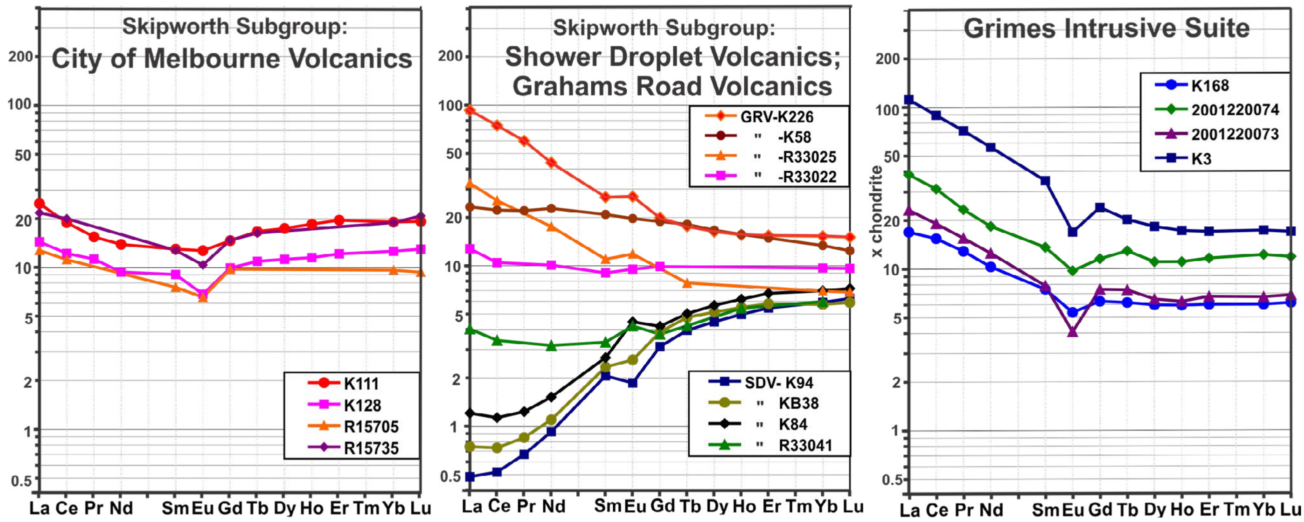

Figure 31. Comparative chondrite-normalised rare-earth element plots for members of the Skipworth Subgroup, and Grimes Intrusive Suite. From Figure 3.26, "The Geological Evolution of Tasmania", Corbett et al. (2014).

The Cottons Breccia (Jago, 1974) consists of diamictite, with minor sandstone, conglomerate and pebbly mudstone. Its origin has been controversial, with both glacial (Waterhouse, 1916; Carey, 1947; Solomon, 1968; Calver and Walter, 2000; Calver et al., 2004) and mudflow modes of deposition being proposed (Schermerhorn, 1974; Waldron and Brown, 1993; Direen and Jago, 2008; Direen et al. 2009). Under the glacial hypothesis, the unit represents the late Cryogenian "Snowball Earth" glaciation. (See also Hoffman et al. 2009 for an account of the development of the controversy and detailed descriptions of several sections).

The Cottons Breccia is approximately 150 m thick at City of Melbourne Bay, and is of variable and generally decreasing thickness going northwards (Fig. 27). There is an inverse relationship with the thickness of the underlying Robbins Creek Formation, suggesting an erosionally incised (disconformable) contact. Due to its calcareous composition, it is an important locus for scheelite skarn mineralisation at Grassy.

Three informal members are recognised by Calver (2012). Here we are in the upper diamictite-conglomerate member, which is here about 27 m thick, although it thins northward. It consists here of thick bedded, interbedded sandy conglomerate, diamictite and pebbly sandstone (Fig. 32). The sandstone, and matrix of the coarser rocks, is carbonate-poor and reddish in colour. Clasts are predominantly metasiltstone, although carbonates and other lithologies listed above are still present. The top of the upper member (base of the Cumberland Creek Dolostone) is not exposed here, but a four metre bed of closed-framework coarse conglomerate a few metres below the top of the exposure is similar to boulder conglomerate just below the top of the formation elsewhere, suggesting little if any section is missing.

A narrow (~1m) feldspar-phyric tholeiitic dyke, possibly related to the Grahams Road Volcanics, intrudes the conglomerate on the landward side.

Also here at the mouth of Cottons Creek, the conglomerate is underlain (to the west) by a green volcaniclastic sandstone, about 20 m thick, which constitutes the middle sandstone member of the Cottons Breccia. It is a thick-bedded, fine-grained grey-green, basaltic sandstone. No cross bedding is seen. It is significantly magnetic (measured magnetic susceptibility up to 59 x 10-3 SI units), giving rise to a small aeromagnetic anomaly. Seen in thin section, it is entirely composed of well-sorted angular to shard-like glassy fragments (50–100 µm), which are altered to chlorite, minor carbonate and fine-grained alteration products. The good sorting but highly angular nature of the volcanic detritus suggests some aeolian sorting of an ash plume followed by deposition in a largely ice-free body of water (in the waning stages of the glaciation?). The middle sandstone member also thins northward.

Fine-grained highly altered mafic dykes, up to about 300 mm wide, intrude the upper member of the Cottons Breccia just south of Cottons Creek. The dykes are discontinuous and divided into separate boudin-like sections with rounded terminations, suggesting intrusion into partially unconsolidated sediment (Fig. 33). They are therefore interpreted as penecontemporaneous with the Cottons Breccia.

Locality 28.

GDA Zone 55: 253050mE/5565700m

From Cottons Creek, walk SW over the small headland and along the beach to the mouth of a small creek.

We are now in the lower diamictite member, which forms the bulk of the Cottons Breccia. The matrix is dominantly carbonate, either calcareous or dolomitic. Clast size is up to 1 m, but commonly only pebble

Figure 32. Upper member of the Cottons Breccia at Cottons Flat [253195/5565741]. From Calver 2012 (Figure 28, p. 24, ER Grassy-Naracoopa).

Figure 33. Discontinuous dyke in Cottons Breccia, indicating intrusion before lithification of the sediment. Pen is parallel to bedding. Near mouth of Cottons Creek [253183/5565717]. From Calver 2012 (Figure 30, p. 24, ER Grassy-Naracoopa).

size. About 70% of clasts are carbonate, including dark grey, fine-grained limestone, white crystalline limestone/marble, pale to dark grey, fine-grained dolostone, and oolitic limy dolostone with large (3 mm) ooids. The clasts have a wide range (-2‰ to +10‰) of carbon isotopic compositions, which were interpreted as indicating a stratigraphically diverse source area (Hoffman et al., 2009). The remainder of the clasts are dominated by siliceous siltstone, metasiltstone and grey mudstone, many of them indistinguishable from typical Fraser Formation lithologies. Metasiltstone clasts with porphyroblastic chlorite, similar to a lithology in the Fraser Formation, are found at Cottons Beach, and it is noteworthy that the chlorite porphyroblasts are erosionally truncated at the surfaces of the clasts. Also noted amongst the clasts are black chert, red mudstone, basalt, red jasper and dacite (Jago, 1974; Waldron and Brown, 1993; Calver and Walter, 2000). The lower diamictite member is unstratified, although long axes of clasts tend to be subparallel to regional bedding and elsewhere (near Grimes Creek) exhibit a preferred WNW–ESE long-axis orientation (tilt corrected), suggesting an origin as a lodgement till (Hoffman et al., 2009).

The uppermost 20 m of the lower member at Cottons Beach exhibits facies variation not seen elsewhere (Hoffman et al., 2009). At the base of this section, massive carbonate-rich diamictite is abruptly overlain by 1.3 m of thinly planar-laminated mudstone and siltstone crowded with dropstones (Fig. 34). Higher up, thick beds of carbonate-rich diamictite predominate; these have weakly stratified matrices, and further interbeds of dropstone-rich laminite. The unstratified diamictite at the base of the section is interpreted as an ice-contact (lodgement) tillite; its sharp top represents the step-back of an ice-grounding line resulting in subsequent 'rain-out' of material from floating ice to produce melt-out tillites and dropstone-rich laminites (Hoffman et al., 2009).

Locality 29. (Time permitting)

GDA Zone 55: 253791mE/5567386mN

On returning to City of Melbourne Bay, walk northward past the car park and along the beach for ~250m.

(Just past the mouth of Yarra Creek, you will pass a cliff of sand. The lowermost metre of landward-dipping peaty sand contains plant fragments and has been dated by the thermoluminescence method at ~120,000 yr BP (early last interglacial), and is unconformably overlain by horizontally bedded brown sand. **Please don't disturb this important site.**)

At the second of two small promontories of the north side of the bay, the Yarra Creek Shale is intruded by a sill, about 15 m thick, of andesitic composition. The sill here is very fine-grained and featureless except for small (~5 mm) vesicles and chlorite-filled amygdales. This is the southernmost limit of the **Grimes Intrusive Suite** (GIS) (Meffre et al. 2004).

The main sill extends northward, parallel to the coast, for about 6 km, to Barrier Creek. From south to north it thickens, locally up to 150m, coarsens, and transgresses the Grassy Group stratigraphy downwards, through the Cottons Breccia into the Robbins Creek Formation. Its thickness varies inversely to that of the Yarra Creek Shale across various fault blocks (Fig. 27). Peperitic contacts with the enclosing sediments were reported by Meffre et al. (2004) and Crawford et al. (2009), although Calver (2012) considered that the Yarra Creek Shale was at least partly lithified at the time of intrusion. Further north, just south of Fraser Bluff near Naracoopa, a related sill about 250m thick has intruded at or near the base of the Grassy Group (Calver 2012).

The GIS is compositionally very variable due to crystal settling, chilling and alteration. The basal parts of thick sills are cumulate gabbros and wehrlite with abundant olivine, high MgO (up to 30%), Ni and Cr, yet relatively high incompatible elements and strongly enriched LREE. The central and upper parts are broadly andesitic and consist largely of plagioclase and pyroxene. Chromite crystals have clustered around vesicles, suggesting that they were attached to rising bubbles by surface tension and carried upward. The parental magma was probably a mixture of LREE-depleted picritic melt and LREE-enriched basaltic melt, contaminated by continental crust (Meffre et al., 2004).

Here and northward for about 100m, the overlying Yarra Creek Shale contains a distinctive ~16m thick interval of "stripey", thinly interbedded pale yellow-brown and black shale. Thin sections of the latter show wispy, anastomosing organic-rich seams, a microstructure characteristic of microbialite, i.e. fossil benthic microbial mats, similar to those seen in the Ediacaran of Central Australia (Calver & Walter 2000). On the easternmost headland, the "stripey" beds are overlain by red shale.

Grahams Road Volcanics

("Bold Head Volcanics of Meffre" et al. 2004)

This formation, which we will not be visiting, is the uppermost onshore unit of the Skipworth Subgroup. Although largely fault-bounded, chemically similar dykes intrude the SDV (Waldron & Brown 1993), and at Fraser Bluff near Naracoopa the SDV pass conformably upward into an outlier of basal GRV (Calver , 2012).

Figure 34. Dropstones in laminated calcareous siltstone, Cottons Breccia, Cottons Beach [253044/5565709]. From Calver 2012 (Figure 26, p. 24, ER Grassy-Naracoopa).

The GRV type section, between Cottons Beach and Bold Point, dips moderately (~50°) southeast and is ~1200m thick with no exposed base or top. The lower one-third consists of stacked thick flows of massive basalt with many zones rich in quartz-filled amygdales. The upper two-thirds is also dominantly (~85%) basalt, but is intercalated with at least 24 sedimentary units, 0.15 to 20 m thick, of volcaniclastic conglomerate and sandstone, some of which fine upward to rare reddish-brown siltstone and shale. Meffre et al. (2004) reported clasts of felsic volcanic and coarse-grained intrusive rocks in the GRV conglomerates. Pillow lavas are rare in the GRV although Direen and Crawford (2003) noted them at Bold Point.

The GRV are tholeiites with no marked depletion in incompatible elements, unlike the tholeiites of the City of Melbourne Volcanics. They are strongly magnetic, and with strong broad aeromagnetic anomalies extending offshore, suggesting that they are the base of a thick (several kilometres) east-dipping volcanic package (Direen and Crawford, 2003).

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ACKNOWLEDGMENTS

1. Much of this excursion guide is derived from previously published MRT reports, particularly Calver (2012) and Calver & Everard (2014).
2. Layout arranged by Chris Large.

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