Explanatory report for the Grassy and Naracoopa geological map sheets

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Cover: Coarse conglomerate bed at the top of the Cottons Breccia, The Gut.

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*1:25 000 Scale Digital
Geological Map Series
— Explanatory Report 5 —*

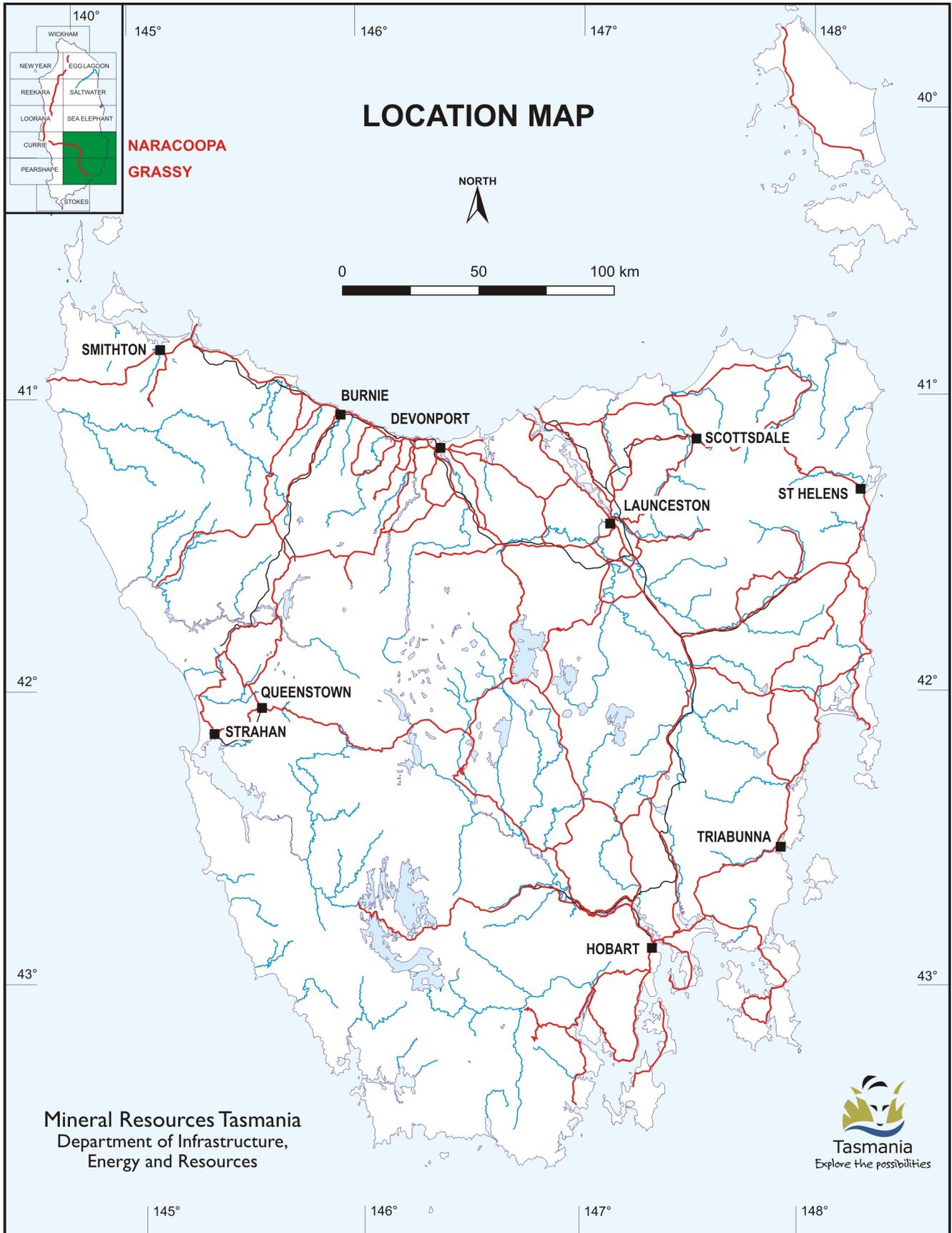# Explanatory report for the Grassy and Naracoopa geological map sheets

by C. R. Calver

October 2012

LOCATION MAP

NARACOOPA
GRASSY

NORTH

0   50   100 km

Mineral Resources Tasmania
Department of Infrastructure,
Energy and Resources

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CONTENTS

TABLES

FIGURES

SUMMARY

The Grassy, Naracoopa and part of the Pearshape 1:25 000 scale geological map sheets, covering the southern and eastern parts of King Island, were mapped by the writer in 2007–2009. The main conclusions arising from this work are:

1. The Fraser Formation, comprising the majority of basement of eastern King Island, is probably a weakly deformed correlate of the Mesoproterozoic (~1300 Ma) Surprise Bay Formation of western King Island.

2. Both formations are dominantly quartz-rich, fine-grained turbidites.

3. An inferred west-dipping thrust contact, here named the Pearshape Fault, has foreshortened the metamorphic and strain transition between these two formations.

4. Regional metamorphism and deformation in the Fraser Formation (D_1 and D_2) is shown to be pre-650 Ma; and D_1, at least, is probably Mesoproterozoic (as in the Surprise Bay Formation).

5. The Robbins Creek Formation is newly recognised at the base of the Grassy Group, with a basal unconformity on the Fraser Formation.

6. Minor late Cryogenian (~640 Ma) mafic volcanic rocks occur in the lower Grassy Group.

7. Further evidence was obtained for a glacial origin, and terminal Cryogenian age (?635 Ma), for the Cottons Breccia (a diamictite formation within the lower Grassy Group) (see Hoffman et al., 2009).

8. Growth faulting in the Grassy Group was augmented with the emplacement of the 575 Ma Grimes Intrusive Suite, which can be correlated with a stratigraphic level high in the Yarra Creek Shale.

9. A weak deformation of probable Cambrian (Delamerian) age affects the Grassy Group and parts of the Fraser Formation.

10. The Grassy Group is more extensive than previously recognised south of Lymwood, enhancing the prospectivity of this area for subsurface skarn-related mineralisation.

11. The potential for further skarn mineralisation has been insufficiently tested in the aureole north and west of the Sandblow Granite, where radial faults are likely to have been pathways for mineralising fluids.

The Surprise Bay Formation of western King Island is middle Mesoproterozoic (c. 1300 Ma: Black et al., 2004; Berry et al., 2005). It consists of at least three kilometres of fine-grained, quartz-rich sandy turbidite interbedded with pelite (schist). Locally, boudinage resulting from mild N–S extension preceded D_1. First-generation (F_1) folds are tight to isoclinal with gently north or south-plunging hingelines, are upward-facing and are overturned to the east. The S_1 axial planar cleavage comprises the primary schistosity in the Surprise Bay Formation. Garnet, muscovite, biotite and andalusite (retrogressed) comprise the syn-D_1 regional metamorphic mineral assemblage. D_1 has been dated at c. 1290 Ma by U-Th-Pb chemical monazite dating (Berry et al., 2005). Upright F_2 folds, approximately coaxial with F_1, are locally present with an associated crenulation cleavage. Minor dykes and sills of amphibolite, altered dolerite and mafic feldspar porphyry are common in the Surprise Bay Formation. Northwest of Millers Bay there is an intrusive contact with the Loorana Granite (748 Ma: Black et al., 1997). Regionally, this contact appears to be concordant, upon underlying, west-dipping and facing Surprise Bay Formation.

The unexposed contact between the Surprise Bay Formation and the Fraser Formation is regionally subparallel in strike to S_1 and S_2. It is inferred to be a west-dipping thrust, here named the Pearshape Fault.

The Fraser Formation makes up most of the Grassy and Naracoopa map sheets. Age constraints are broad (1400–650 Ma) but in contrast to previous interpretations, the Fraser Formation is here interpreted as a relatively weakly deformed correlative of the Surprise Bay Formation. A few kilometres or more thick, the Fraser Formation largely comprises fine-grained turbidites, dominated by thick-bedded or laminated, micaceous, fine-grained quartz sandstone, siltstone and grey-black mudstone. Thin microbialite (black shale) beds occur at the tops of many turbidite beds, and represent hemipelagic deposition. Near the Pearshape Fault, upright NNE-trending open F_2 folds are similar in trend to F_2 of the Surprise Bay Formation. S_2 here crenulates a weak bedding-parallel slaty cleavage (S_1). The effects of both D_1 and D_2 diminish eastward, and there is a central meridional zone with no cleavage and gentle, dome and basin structure. Regional metamorphism produced garnet, chlorite (in porphyroblast form, possibly retrogressed biotite), biotite and amphibole in the Fraser Formation. Massive actinolite and cummingtonite hornfels may have had a basaltic precursor. Gabbroic tholeiitic intrusive rocks in the Fraser Formation were converted to coarse-grained hornblende amphibolite. Garnet in the metasediments is pre-kinematic, while growth of other metamorphic minerals continued until syn-D_2. Regional-metamorphic garnet is restricted to a discrete western meridional zone, comprising a major F_2 anticline ('Lymwood Anticline') faulted against lower grade Fraser Formation to the west (fig. 1). The eastern limb of the Lymwood Anticline is unconformably overlapped by Grassy Group rocks near Mt Stanley. Thus D_1, D_2 and the regional metamorphism are older than ~650 Ma, and the most straightforward interpretation is that they are the same as those of the Surprise Bay Formation. Consistent with these observations, clasts identical to the Fraser Formation with pre-depositional chlorite porphyroblasts are found in the Cottons Breccia.

The Grassy Group (~650–570 Ma, late Cryogenian to Ediacaran) unconformably overlies the Fraser Formation, and dips south and east as a relatively narrow belt paralleling the east coast. The stratigraphic succession in the sub-greenschist facies, minimally deformed exposures on the east coast consists of:

(1) Robbins Creek Formation (new name): laminated chloritic siltstone and black shale with minor mafic lavas and thin basal conglomerate, unconformably overlying the Fraser Formation.

(2) Cottons Breccia: glacigene diamictite with clasts, dominantly of carbonate and metasiltstone, up to boulder size, and minor sandstone and conglomerate.

(3) Cumberland Creek Dolostone: a thin unit of laminated dolostone, shale and limestone.

(4) Yarra Creek Shale.

(5) City of Melbourne Volcanics: tholeiitic lavas and volcaniclastic rocks.

(6) Shower Droplet Volcanics: picritic lavas and volcaniclastic rocks.

(7) Grahams Road Volcanics: tholeiitic lavas with minor intercalated volcanic conglomerate and sandstone.

The Cottons Breccia and Cumberland Creek Dolostone are considered to be correlatives of the (glacial) Elatina Formation and its 'cap carbonate' (Nuccaleena Formation), respectively, of South Australia. The base of the Cumberland Creek Dolostone is therefore taken to represent the Cryogenian–Ediacaran boundary (Calver and Walter, 2000; Hoffman *et al.*, 2009), currently thought to be 635 Ma from dating outside Australia.

A sub-volcanic, gently transgressive sheet of intermediate composition (Grimes Intrusive Suite) intrudes the Yarra Creek Shale and older units, and has been dated at 575 3 Ma (Calver *et al.*, 2004). It is more mafic and thickest in the north, where it is lowest in the stratigraphy. This part is here named the Denbys Dolerite. The thickness of the Grimes Intrusive Suite is inversely related to that of the Yarra Creek Shale in different fault blocks, indicating that dilatation associated with emplacement was linked to growth faulting prior to deposition of the City of Melbourne Volcanics. A ~60 million year lacuna or condensed section is inferred within or at the top of the Yarra Creek Shale. In the south of the Grassy map sheet, poor exposure and contact metamorphism by the Sandblow Granite mean that the Grassy Group has there been mapped simply as a lower unit of metasediments and an upper unit of undifferentiated metavolcanics. Marble units corresponding to the lower carbonate-rich part of the Cottons Breccia and the Cumberland Creek Dolostone were the main locus of scheelite skarn mineralisation at Grassy and Bold Head. These prospective horizons remain poorly tested in the aureole west of Grassy. Unmetamorphosed, gently dipping, poorly exposed equivalents of the Grassy Group are more extensive, north of the Sandblow Granite, than previously recognised, and may be prospective at depth. Along the east coast (Bold Head to Fraser Bluff), the Fraser Formation and Grassy Group dip moderately SE and E; a weak NE-trending cleavage and upright minor folds are present in both units and represent a third regional deformation (D_3) which is inferred to be of Cambrian age (a correlate of the Tyennan or Delamerian orogenies of mainland Tasmania or southeast Australia).

The Sandblow Granite (formerly Grassy Granite or Granodiorite), dated at 351 Ma (early Carboniferous), is an ovoid pluton of monzogranite that intrudes the Grassy Group and Fraser Formation at the southern margin of the Grassy map sheet. The moderate dip of country rocks inwards towards the contact, and radial faults in the contact aureole, probably resulted from mild deformation during emplacement. The Bold Head Granite may be an outlier of the Sandblow Granite, offset by the Grassy River Fault. Several small outliers of microgranite were mapped, distant from the main pluton.

The world-class Grassy (No. 1 + Dolphin) scheelite ore body, mined between 1917 and 1991, is a skarn deposit in the proximal contact aureole of the Sandblow Granite, hosted in the lower Grassy Group. The smaller Bold Head deposit (1973–1984) lies in the aureole of the Bold Head Granite. The field has produced a total 60 000 t WO_3 from 11.5 Mt of ore, with considerable resource remaining. Hydrothermal alteration and minor mineralisation along the Barrier Creek Fault (eastern Naracoopa sheet) may be associated with a subsurface cupola.

A few Paleogene basalt plugs (eroded volcanic feeders) give rise to aeromagnetic anomalies in the northern part of the Naracoopa sheet. One, a basanite north of Adams Road, has been dated by K-Ar at 62 Ma (early Paleocene: Sutherland *et al.*, 2004). Between this time and the Miocene (c. 15 Ma), King Island was subjected to marine peneplanation. Rare erosional remnants of Miocene, shallow-marine foraminiferal limestone are found at elevations up to 70 masl, indicating notable post-Miocene uplift (in common with much of southern Australia). Incision of major streams into the Pegarah Plateau has taken place since then. There are widespread Pleistocene–Holocene deposits of surficial windblown sand. Pleistocene raised beach deposits and modern beach sands just north of Naracoopa have been exploited for rutile, ziron and ilmenite. The younger vegetated calcareous dunes in the west are an important local source of agricultural lime. There are widespread small surficial deposits of ironstone ('bog iron ore') in areas of groundwater resurgence in Proterozoic sedimentary rocks.
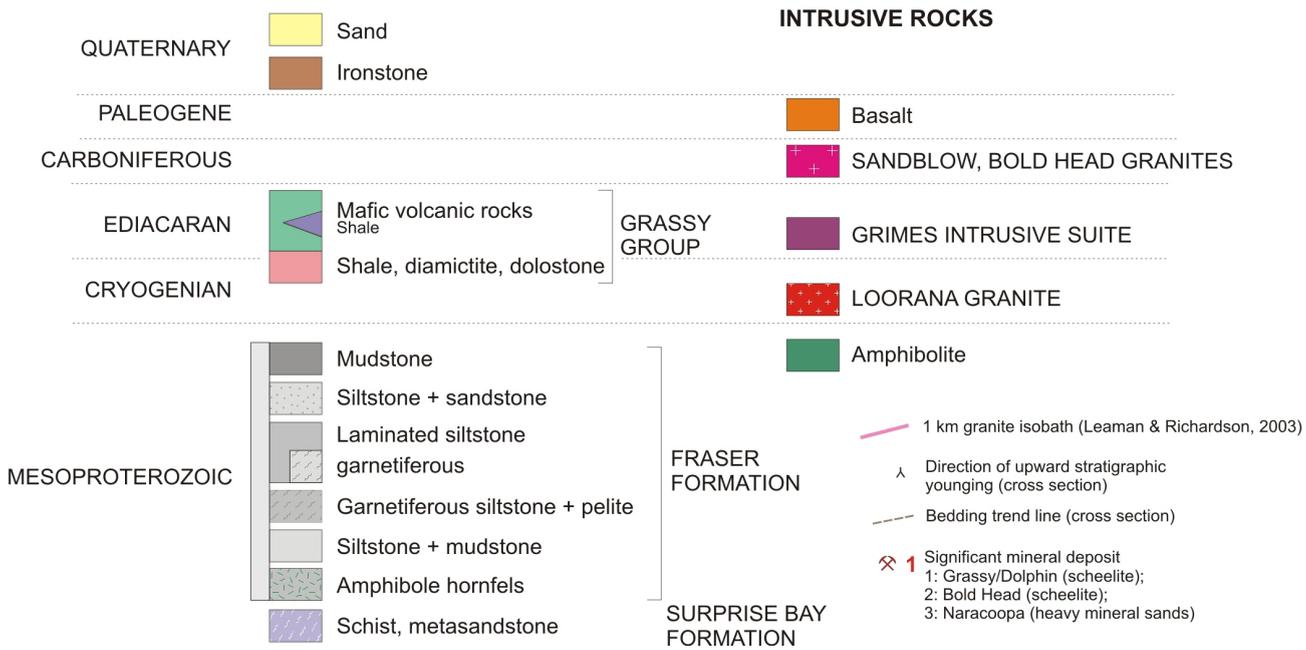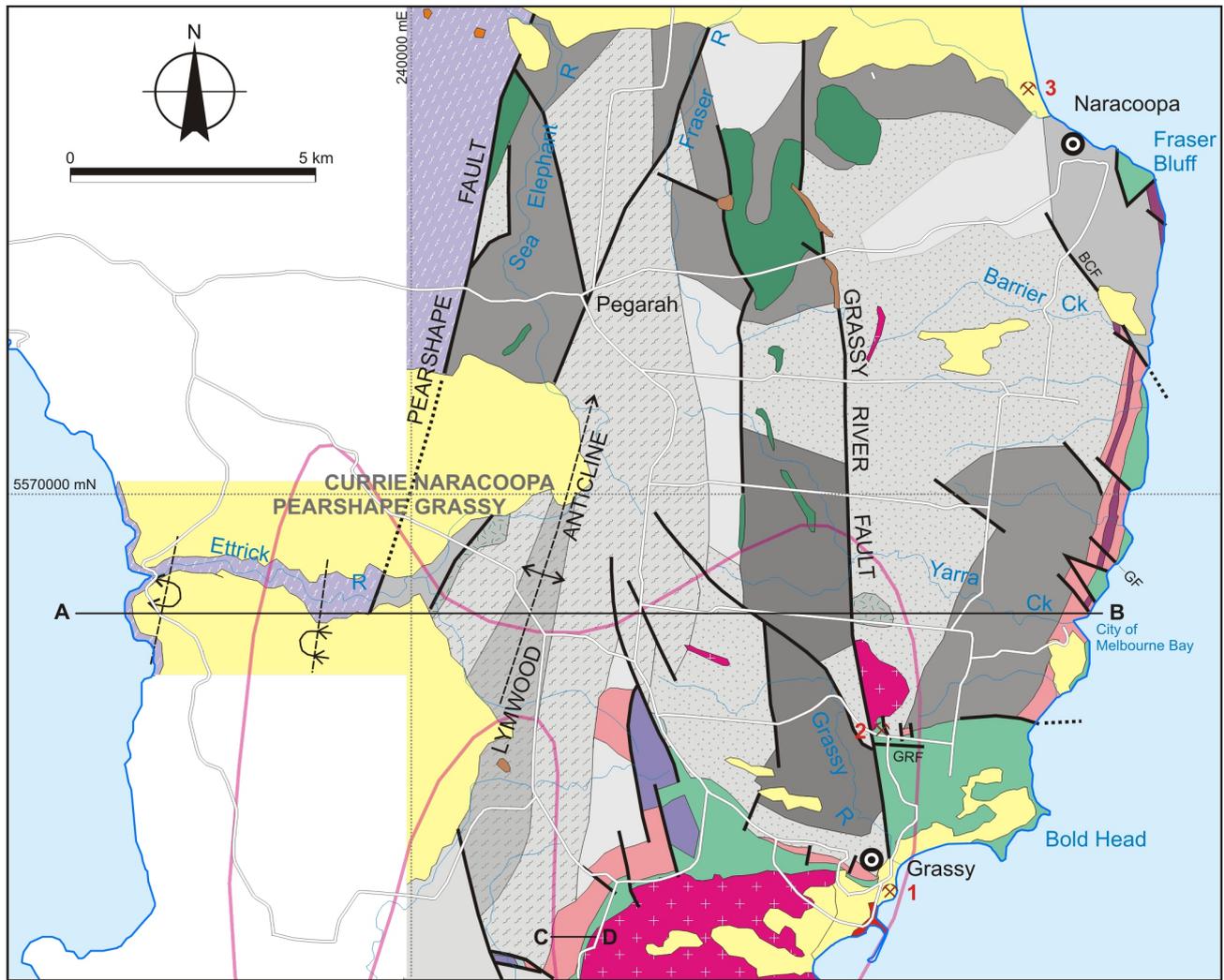
Figure 1

Simplified geological map and cross section of the Grassy–Naracoopa–northern Pearshape map sheet area.
For section C–D see Figure 42. BCF: Barrier Creek Fault; GF: Gut Fault; GRF: Grahams Road Fault.

INTRODUCTION

The Grassy, Naracoopa and part of the Pearshape 1:25 000 scale map sheets were geologically mapped by the writer in 2007–2009 (Calver, 2008a; 2010). The neighbouring Stokes and southern Pearshape map sheets were mapped by J. L. Everard in 2008–2009. This is the first Tasmanian Government geological survey mapping to be carried out on King Island, and was done as part of the *TasExplore* project.

Previous work

An early overview of the geology of King Island was given by Waterhouse (1916). The development of the Grassy and Bold Head scheelite deposits led to an extensive body of work on geological setting and aspects of ore formation and contact metamorphism and metasomatism. Useful summaries include Knight and Nye (1953), Edwards *et al.* (1956), Danielson (1975a), Brown (1975, 1989, 1990), Danielson and Brown (1976) and Green *et al.* (in press). Edwards *et al.* (1956), Kwak (1978a, b), and Kwak and Tan (1981a, b) explored aspects of ore formation and metasomatism in some detail. Large (1971) discussed the metasomatism and mineralisation at Bold Head. The most recent detailed study of the scheelite mineralisation is that of Wesolowski *et al.* (1988), who proposed that the major factors controlling the type of mineralisation were the intermediate redox state of the magmatic-hydrothermal system and the fairly deep level of emplacement (4–7 km) of the granitoids.

Numerous unpublished reports, mainly by Geopeko geologists between 1969 and 1990, deal with exploration, mapping and mine development at Grassy and Bold Head, and many of these are referenced in the *Economic Geology* section. Detailed mapping of the contact aureoles of the Sandblow and Bold Head granites was largely based on shallow grid drilling (Brown, 1975, 1981, 1983). Gresham (1972) described the regional geology and produced a generalised bedrock geology map of King Island at 1: 63 360 scale. Many mine plans, drill logs and other data were bequeathed to MRT on closure of the Grassy mine in 1991; scans of these are available in Turner (1993).

Unpublished reports providing useful overviews of the Naracoopa heavy mineral deposits are Neale and Salway (1975) and Gillett (1989).

Another major thread of geological investigation on King Island has been focussed on the well-exposed, unmetamorphosed Grassy Group equivalents on the east coast. Carey (1947) suggested correlation of the diamictite formation there with the Cryogenian glacial deposits of South Australia. Jago (1974) named this unit the 'Cottons Breccia' and described it in detail. Scott (1951) and Solomon (1968) described the petrology and eruptive structures of the mafic volcanic rocks. Waldron and Brown (1993) worked out the stratigraphy and discussed the petrochemistry of the volcanic and associated rocks. Calver and Walter (2000) correlated the Cottons Breccia with the Marinoan glacial phase (i.e. the Elatina Formation, of terminal Cryogenian age) of South Australia. Calver *et al.* (2004) dated the Grimes Intrusive Suite at 575 3 Ma, and discussed

implications for the age of the Marinoan glaciation. Meffre *et al.* (2004) described the petrogenesis and regional tectonic setting of the mafic volcanic rocks, dated them at 579 16 Ma (Nd-Sm isochron) and proposed that they mark the initiation of a volcanic passive margin. Direen and Jago (2008), in contrast to most previous workers, interpreted the Cottons Breccia as a non-glacial mass flow deposited in an active rift. In response, Hoffman *et al.* (2009) marshalled additional evidence for a glacial origin, and a terminal Cryogenian age, for this formation.

Jennings (1959) gave a detailed description of the coastal geomorphology of King Island with an emphasis on inferring past changes of sea level. Jerie *et al.* (2003) reviewed the island's physiography in discussing management of rivers and streams.

Climate, land use and physiography

Situated on the 40th parallel, King Island has a mild maritime climate and an annual rainfall of about 1000 mm. Most of the Grassy–Naracoopa map sheet area is improved pasture devoted to beef and dairy cattle. Some native forest, dominated by blue gum (*Eucalyptus globulus*), tea tree (*Melaleuca ericifolia*), banksia (*Banksia marginata*) and blackwood (*Acacia melanoxylon*) is preserved along the narrow valleys of the larger streams and in the Pegarah Forest, which also includes some radiata pine plantation. The small settlements of Naracoopa and Grassy today mainly service the tourism industry, although before 1991, Grassy housed the workforce for the Grassy scheelite mine.

Southeastern King Island mainly consists of a flattish or gently rolling plateau, 70–100 m in elevation, known as the Pegarah Plateau. Proterozoic bedrock, with a thick regolith of silty clay and a patchy cover of windblown sand, forms most of the plateau. Jerie *et al.* (2003) distinguished a higher level surface at ~120 m in the Mt Stanley–Lymwood area, with the highest point (Gentle Annie, 140 m) comprising a residual hill. The northern and southern margins of the Pegarah Plateau are relatively gentle, while surficial sheet and dune sands encroach from the west. A steep coastal escarpment marks the eastern edge of the plateau between Naracoopa and Grassy townships. A narrow (<500 m) coastal terrace at ~6–15 m above sea level is present in places at the foot of the escarpment, e.g. Cottons Flats and Naracoopa. This was produced by marine erosion at higher relative sea level stands during the last interglacial or earlier Pleistocene interglacial intervals (Jennings, 1959; Jerie *et al.*, 2003).

The generally subdued topography means that stream power is limited except where larger streams are steeply incised into the plateau margins, namely Sea Elephant River and Fraser River in the north, Barrier, Cumberland, Conglomerate and Yarra creeks to the east, and Grassy River in the south. A large proportion of freshwater discharge appears to be through groundwater systems, with the upper reaches of many streams being intermittent (Jerie *et al.*, 2003). Partly as a consequence of weak fluvial processes, there is relatively little topographic

differentiation of harder and softer rock types. The Bold Head and Sandblow granites, evidently less resistant to erosion, form gentle basins rimmed by the harder contact metamorphosed rocks of their aureoles. The metamorphosed siltstone subdivision of the Fraser Formation (Lfgl) is relatively resistant: the regolith is thinner on this unit, and in the Pegarah area, the upper part of the unit forms a gentle ridge comprising the drainage divide between the Sea Elephant and Fraser rivers.

King Island's Cenozoic geomorphic history has been characterised by successive uplift events interspersed with long stable periods of (largely marine) erosion (Jennings, 1959; Jerie et al., 2003). The Pegarah Plateau was probably formed by marine peneplanation in the Paleogene. A number of basaltic volcanic plugs are eroded to the level of the plateau; a date of 62 Ma on one of these (Sutherland et al., 2004) gives an older age constraint for the peneplanation. There are rare erosional remnants of Miocene fossiliferous limestone, including one at 75 m elevation (see below), suggesting that the bedrock plateau had been formed by then (and was at least partly covered by the sea). Uplift since the Miocene (in common with the rest of southern Australia: Sandiford, 2007) has led to the present elevation of the plateau and its partial dissection by down-cutting streams.

The Pegarah Plateau is onlapped in the west by a flat plain of stabilised aeolian sand (Qpsa). Still further west, younger vegetated dune sands ('New Dunes' of Jennings, 1959) encroach on the plain, with a steep, well-defined eastern limit. These calcareous dune sands cover much of Pearshape and Stokes map sheets. Smaller areas of more siliceous 'New Dunes' (shown as Qhd) occur on the coastal terrace at Grassy, at Bold Point and immediately inland of Fraser Beach. Longitudinal and parabolic dune forms are preserved. The 'New Dunes' were deposited in the colder, drier and windier conditions associated with the later stages of the last glacial period (Jerie et al., 2003).

Data sources

The Grassy and Naracoopa 1:25 000 scale geological maps, and the northern part of the Pearshape map, were compiled from field observations made between December 2007 and December 2009, with the aid of colour aerial photography, magnetics, radiometrics and previous detailed mapping in a few areas. The coverage of field observations is shown in Figure 2. Airborne magnetics and radiometrics were flown at 200 m line spacing for the Western Tasmanian Regional Minerals Program in 2001. Previous work referred to in compiling some areas of the maps is that of S. G. Brown (1975, 1983), Danielson (1975a), and Waldron and Brown (1993) (see responsibility diagrams on maps). A hand-held Garmin Etrex GPS was used with a typical accuracy of approximately 5 metres. Samples were studied with standard thin sectioning, X-ray diffraction (XRD) and X-ray fluorescence (XRF) methods. Forward modelling of aeromagnetic data was carried out with *Modelvision* and *Quickmag*.

All grid references in the text (and map grids) are GDA94 datum and are MGA co-ordinates in Zone 55, quoted in the form xxxxxx/yyyyyyy, where the first six numbers are metres east and the last seven numbers are metres north.

Acknowledgements
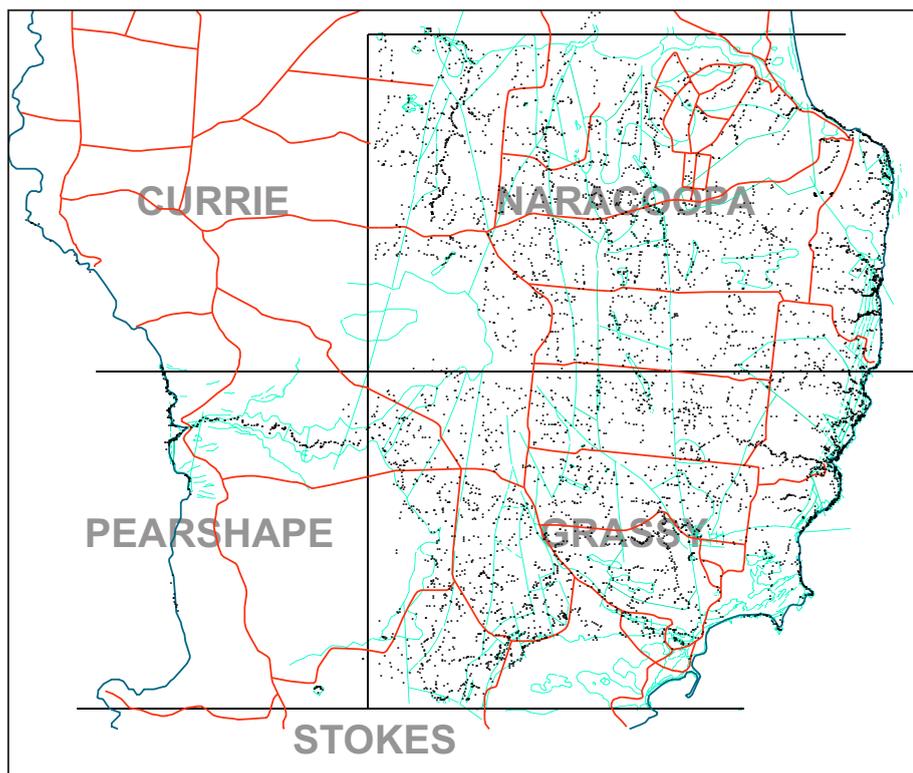
Figure 2

Mapped area covered by this report (Naracoopa, Grassy and northern Pearshape map sheets), and distribution of field observation points (n = 6155).

STRATIGRAPHY

Mesoproterozoic: Surprise Bay Formation (Lb)

Introduction

'Surprise Bay Formation' is the term for the meta-sedimentary and minor meta-igneous rocks of western King Island, with the type section in the Surprise Bay area (Calver and Everard, in prep.). Regionally, the formation is intruded by the Cryogenian Loorana and Cape Wickham granites, and faulted to the east against the Fraser Formation.

The Surprise Bay Formation is poorly exposed in the westernmost part of the Naracoopa map sheet, but is well exposed in the cross-strike Ettrick River section and along the west coast (Fitzmaurice Bay to Millers Bay) on the Pearshape map sheet. The unit consists of fine-grained (<0.25 mm) quartzose sandy turbidite and pelite, with minor mafic intrusive rocks, regionally metamorphosed to lower amphibolite grade. Its protolith was similar to the Fraser Formation, but the Surprise Bay Formation differs in having a strong schistose primary cleavage. On the Pearshape map sheet, a major F_1 isoclinal anticline and syncline (3 km apart) are overturned with their axial surfaces dipping steeply west (fig. 1). The three kilometre width of the overturned common limb is an approximate minimum thickness for the formation. To the west, west-facing Surprise Bay Formation is intruded by the Loorana Granite. Regionally, the granite contact appears to be concordant.

Age and correlation

Berry *et al.* (2005) carried out chemical U-Th-Pb dating of monazite in the Surprise Bay Formation in the Fitzmaurice Bay–Surprise Bay area. An age of 1287 ± 18 Ma was interpreted as an early regional Grenvillean metamorphic event. Detrital zircon dating by Black *et al.* (2004) shows the youngest population at c. 1350 Ma, so the depositional age of the formation should be between 1350 and 1287 Ma (Ectasian; mid-Mesoproterozoic). It is the oldest rock formation known on King Island (and in Tasmania). There are no known correlates in Tasmania or southeastern Australia, although the Fraser Formation is probably a less deformed equivalent (see below).

Metasandstone and schist (Lbs); dominantly pelitic schist (Lbp)

The succession in northern Pearshape is a quartz-rich, fine-grained sandy turbidite. Sandier, thicker-bedded intervals alternate with thinner-bedded, more pelitic intervals, each metres to tens of metres thick. Bouma ABC and BCD sequences are common in the sandstone beds (fig. 3). Amalgamated, thick sandstone beds locally form packages 25 m or more in thickness, comprising resistant units that form Ettrick Rock and the headlands north and south of Millers Bay. Individual sandstone beds within these units are up to 2.5 m thick. The turbidite beds have sharp planar bases. Load structures are rare, and grading is difficult to detect in the field, partly because of the fine grainsize of the sandstone. Facing is generally determined from cross lamination.

The finer grained intervals consist of parallel-laminated dark grey pelitic siltstone with starved ripples or lensing thin beds of fine-grained sandstone with cross lamination (fig. 4). Current directions shown by the cross lamination are approximately to the south.

Metamorphic minerals locally visible in the field include garnet (up to 1.5 mm) and probable retrogressed andalusite (up to 10 mm × 50 mm) (see *Structure and Metamorphism* section).

In thin section, a massive quartzose sandstone (R15814) shows an interlocking granoblastic mosaic of fine-grained (0.1–0.25 mm) quartz (80%) with biotite, muscovite, K-feldspar, plagioclase and chlorite. Pelitic siltstone and pelitic schist show subequal quartz and muscovite, the latter as 0.25–0.5 mm long plates strongly aligned in the schistosity, with minor biotite (similarly aligned) and brown tourmaline. Garnet is subhedral to euhedral, and S_1 is deflected around garnet porphyroblasts (fig. 5).

In the northern part of the Pearshape map sheet, the Surprise Bay Formation has been differentiated into a sandstone-rich unit (Lbs) and a pelitic unit (Lbp). Lbs includes the coastal exposures and most of the Ettrick River section, and the major F_1 anticline. Lbp occurs in the easternmost part of the Ettrick River section, and includes the major F_1 syncline.

Mesoproterozoic: Fraser Formation (Lf)

Introduction

A thick Proterozoic succession of mildly deformed mudstone and siltstone makes up most of eastern King Island, including most of the Grassy and Naracoopa map sheets (fig. 1). This succession was named the 'Fraser Formation' with a type section at the southern end of Fraser Beach, Naracoopa, by Direen and Jago (2008). They described the type section as "…at least 390 m thickness…of buff to grey cross-bedded quartzites, grey interbedded laminar graded siltstones, and rare conglomerates".

As examined by the writer, the type section consists of a monotonous succession of laminated, pale grey quartzose fine-grained siltstone (fig. 6). Similar rocks were mapped west along the shore as far as the mouth of the Fraser River, and south to the Barrier Creek Fault (shown on the map as Lfl). No conglomerate was found in this succession (in contrast to Direen and Jago, 2008), which dips and faces predominantly east and is at least around one kilometre thick. Similar, laminated quartz siltstone also forms a belt extending down the western side of the Naracoopa and Grassy map sheets, from North Pegarah Road south to Red Hut Point and Seal Point, but contains metamorphic garnet (Lfgl). The term 'Fraser Formation' is here applied to all the mildly deformed mudstone, siltstone and fine-grained sandstone (and metamorphic equivalents) between the Pearshape Fault to the west, and the unconformity at the base of the Grassy Group. This accords with the apparent intention of Direen and Jago (2008) for the term to apply to
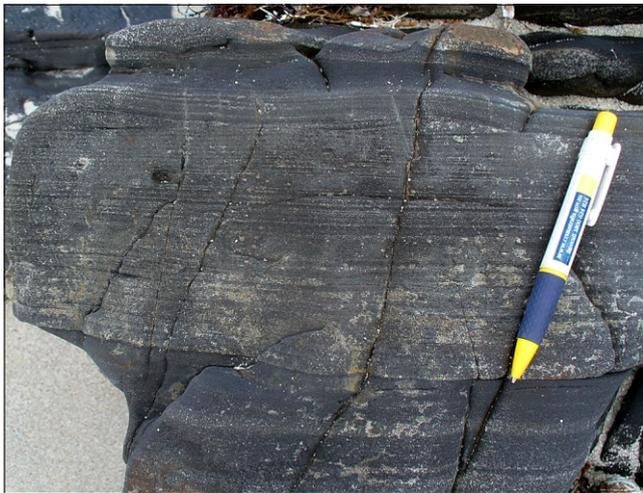
Figure 3

Surprise Bay Formation: sharp-based fine-grained sandstone bed with Bouma BCD subdivisions, enclosed by silty pelite; Millers Bay [234275/5569042].

Figure 4

Lensing cross-laminated siltstone laminae in pelite, Surprise Bay Formation; Millers Bay [234275/5569042].
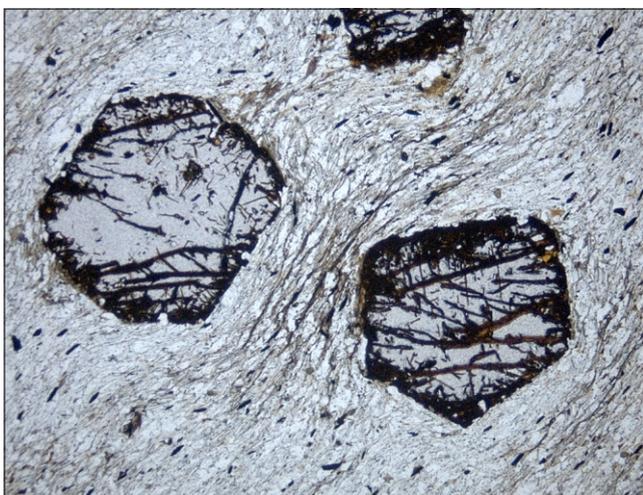
Figure 5

Strong deflection of S_1 schistosity around garnet porphyroblasts in Surprise Bay Formation. Thin section R15012, plane polarised light.

Figure 6

Plane-laminated quartz siltstone of the type section of the Fraser Formation at Fraser Beach [254229/5577146].

Figure 7

Quartzose metasiltstone (Lfgl). Pale green chlorite porphyroblast kinked by S_2; smaller garnet and olive-green biotite. Thin section R013119, plane polarised light.

Figure 8

Outcrop of Lfi. Medium grey mudstone with spaced S_2 cleavage, overlain by thin layer of black shale (hemipelagic microbialite), then sharp based pale siltstone bed. Seal River [239860/5561507].

the regional "basement succession to the Grassy Group". Apart from the laminated siltstone (Lfl, Lfgl) mentioned above, important mappable units identified in the course of the mapping include thick-bedded mudstone (Lfn), thick-bedded siltstone to very fine-grained quartzose sandstone (Lfs), and amphibole hornfels (Lfa, Lfc). The Fraser Formation lacks indicators of shallow marine deposition, and the typical sedimentary structures of Lfn and Lfs are those of fine-grained turbidites.

Regional metamorphic grade is of upper greenschist to lower amphibolite grade, although (unlike the Surprise Bay Formation) the Fraser Formation cannot be described as schist or even phyllite, because of the absence of strong foliation. Some of the rocks (Lfgl, Lfa) could be described as hornfels, but are not of contact metamorphic origin.

Based on predominant lithology, the Fraser Formation is divided into seven mappable units described below. Stratigraphic order is uncertain because of faulting and poor exposure. Lfgp (garnet grade interbedded pelite and siltstone) may be the oldest unit. It occurs in the core of the Lymwood Anticline (fig. 1) and is inferred to be conformably overlain by Lfgl (garnet-grade laminated siltstone). Lfn (mudstone) appears to conformably overlie Lfgl, north of Pegarah. Lfs (siltstone-sandstone) is inferred to be conformably overlain by Lfn near Yarra Creek. Lfs, Lfn and Lfi (interbedded siltstone and mudstone), together comprising about 70% of the outcrop area of the Fraser Formation, are interpreted to be mainly fine-grained turbidites.

Age and correlation

Calver and Walter (2000) suggested correlation of the Fraser Formation, on general lithologic grounds, with the Rocky Cape Group of northwest Tasmania (c. 1000–750 Ma), while Direen and Jago (2008) suggested the Fraser Formation is a "younger, post-Wickham Orogeny cover sequence" (i.e. <760 Ma). Here, the Fraser Formation is described in detail for the first time, and it is shown that probably neither of these suggestions is correct. The Fraser Formation is unlike the Rocky Cape Group in lithology and palaeoenvironment. The Rocky Cape Group was deposited in relatively shallow marine shelf environments ranging from tidal to storm wave-base, with abundant medium-grained cross-bedded quartzarenite (Calver et al., in press). The more distal units of the Rocky Cape Group have evidence of deposition within storm wave-base, such as gutter casts and graded, wave-rippled fine-grained sandstone beds; and clastic dykes are abundant. None of these features is seen in the Fraser Formation. The Fraser Formation largely comprises turbidites, similar in composition and sedimentary facies to the Surprise Bay Formation. It is also locally of similar metamorphic grade, and only differs significantly from the Surprise Bay Formation in its milder deformation. The Fraser Formation and Surprise Bay Formation contain comparable detrital zircon age populations, although the populations are in different proportions. The Fraser Formation is younger than 1440 Ma from detrital zircon dating (Black et al., 2004, p. 890). The main deformation (D_1, D_2) and regional metamorphism in the Fraser Formation is here shown to be pre-Grassy Group in age, and thus older than the Cambrian Tyennan Orogeny, which is the main deformation event that affects the

Proterozoic rocks of mainland Tasmania (Turner et al., 1998). The simplest interpretation of the available evidence is that the Fraser Formation is a correlate of the Surprise Bay Formation, and also mid-Mesoproterozoic in age (Calver, 2009).

Garnet-bearing, interbedded pelite and siltstone (Lfgp)

This unit forms a NNE-trending antiformal belt up to 1.5 km wide in the west of the Grassy map sheet. No contacts are exposed. The belt tapers northwards and is interpreted as the core of a major, gently north-plunging F_2 anticline (Lymwood Anticline) flanked to the east and west by apparently conformably overlying laminated metasiltstone (Lfgl).

Lfgp consists of thinly interbedded or interlaminated, grey silty pelite and lesser, paler grey or white, quartzose metasiltstone. The bedding generally imparts a banded appearance to the rock. Lamination is planar-parallel. A weak cleavage (S_2) at an angle to bedding may be discernible in outcrop. In places quartzose metasiltstone is predominant with little or no pelite, identical to Lfgl. Sparsely disseminated garnet, up to 1 mm in diameter, is commonly present. Garnets tend to be larger and more abundant in pelitic layers. Porphyroblasts of chlorite, up to 3 mm in size, are locally present.

In thin section the pelite layers consist predominantly of fine-grained white mica (20–70 m) and minor quartz. Chlorite porphyroblasts are thickly discoidal in shape, and some are altered to iron oxide. Narrow columns of tourmaline up to 300 m long are present. Quartz siltstone layers are locally pure and granoblastic, and may contain flakes of brown biotite. There is a foliation parallel to bedding (S_1), defined by a preferred orientation of the white mica in the pelite layers. The weak inclined cleavage (S_2) seen in outcrop is resolved as a weak crenulation in thin section (e.g. R013132).

Garnet-bearing, laminated quartzose siltstone (Lfgl)

This unit is very similar to the laminated siltstone of the Fraser Formation type area at Naracoopa (Lfb) except that it is of higher metamorphic grade, containing garnet. Lfgl comprises a stratigraphic unit about one kilometre thick, that appears to conformably overlie Lfgp (contact not exposed). The two units are folded into the regional Lymwood Anticline (fig. 1). Lfgl consists of pale grey to grey-green (weathering to white), tough, uniform fine-grained quartzose metasiltstone. Planar-parallel lamination is usually present, although little or no compositional variation is apparent, unlike Lfgp. In a few places (such as the small quarry on Old Grassy Road; 242106/5567975) the rock is an entirely massive, very fine-grained quartzite. Disseminated fine-grained (<0.25 mm) biotite of metamorphic origin is often visible under the hand lens. Garnet is often too small to be visible in the field, but is present (up to 200 m) in most thin sections. Pale grey silty pelite is seen in places, often with conspicuous dark green porphyroblastic chlorite (1–2 mm). One outcrop (243037/5566561) contains a thin bed with abundant chlorite in the form of plumose aggregates 2 mm long, which

from their morphology are probably altered amphibole porphyroblasts similar to those in unit Lfa. Extensive coastal exposures of Lfgl on Red Hut Point (Stokes map sheet) show common soft-sediment slumping.

Thin sections show predominant hornfels-textured (granoblastic polygonal) quartz silt (<50 m) and abundant platy metamorphic muscovite, also <50 m. Biotite is usually present, olive-green or brown, forming 10–20% of the rock and up to 200 m (fig. 7). Tabular chlorite porphyroblasts up to 1 mm long are found in some samples, usually with abundant quartz inclusions. Sparse (<1%) garnet up to 200 m is present in most. In a couple of examples (R013124, R013119), a weak foliation (probably S_2) at an angle to bedding is present. This comprises a preferred orientation of muscovite and biotite, and is associated with kinking of the cleavage planes of the large chlorite porphyroblasts (fig. 7).

Lfgl is about one kilometre thick on the eastern limb of the Lymwood Anticline. A magnetic marker horizon near the stratigraphic top of the unit, along the eastern limb of the anticline, is associated with a prominent linear aeromagnetic anomaly, 14 km long, offset in places by faults, which has been a considerable aid to mapping (see *Magnetic Interpretation*). The magnetic unit is adjoined to the west (underlain) by a magnetically subdued unit about one kilometre wide. The magnetic unit in outcrop is a tough, grey metasiltstone-hornfels with a measured magnetic susceptibility of up to 21 10^{-3} SI units. In thin section (R013122) this rock is similar to other Lfgl samples but has coarse (400 m) euhedral opaques.

Laminated quartzose siltstone (Lfb)

This unit is well exposed on the coast at Naracoopa and north of Barrier Creek. As mentioned above, it includes the type section, a monotonous succession of laminated, pale grey quartzose fine-grained siltstone (fig. 6), a description that suffices for nearly all of this area. Bedding at Naracoopa dips moderately east or northeast; minor upright NE-plunging F_3 folds have a weak axial planar cleavage. Lamination is dominantly planar-parallel, but in a few places there are low-angle truncations and scour-and-fill structures. At 253806/5576852 there is a train of starved ripples along a bedding plane, of slightly coarser grainsize than the siltstone (also seen at Red Hut Point). In places there are chlorite porphyroblasts (1 mm) which in thin section can be seen to pre-date the F_3 cleavage.

The monotonous laminated siltstone at Naracoopa continues along shore to the west as far as a small beach (in front of the 'Naracoopa Holiday Units') which probably conceals a minor fault (253403/5577669). West of this, medium to thick graded beds of siltstone and silty mudstone, probably turbidites, appear in the sequence. Some of these beds have basal load casts and ragged intraclasts of mudstone. Thin black shale beds (probably hemipelagic microbialites, see below) are found at the top of some of the turbidite beds, and rare clastic dykes are present.

Coastal outcrop of Lfb around the mouth of Barrier Creek and 1–2 km northwards is strongly indurated, perhaps a result of silicification associated with hydrothermal alteration along the Barrier Creek Fault (see below).

Consequently the coastal escarpment is very steep here, and aptly named 'The Wall'.

Interbedded quartzose siltstone and grey mudstone (Lfi)

This unit occurs in the far west of the Grassy map sheet, where it is largely covered by sandy floodplain deposits (Qpsa), and extends west into the Pearshape sheet where it crops out in the Pearshape quarry and in the Ettrick River. There, it is inferred to be faulted against the Surprise Bay Formation to the west. The eastern contact with units Lfp, Lfl and Lfa on the Grassy map is not exposed and is also inferred to be a fault, because of structural discordance and the lower metamorphic grade of Lfi relative to the other units. Upright, major NNE-trending F_2 folds (wavelength c. 300 m) are seen in Lfi, subparallel to the larger Lymwood Anticline, but no overall vergence is discernible (see cross section, Grassy map sheet and fig. 1). The unit is very pale quartzose siltstone, interbedded and interlaminated with grey shaly mudstone, and minor black shale. Many siltstone layers have sharp, planar bases and weak grading (fig. 8). S_2 is generally visible in mudstone layers as a spaced cleavage (fig. 8) or crenulation cleavage. S_1 is an inconspicuous slaty cleavage in mudstone, penetrative but weak, and subparallel to bedding. In thin sections the siltstone has detrital quartz and muscovite in an abundant matrix of fine-grained sericite. Parallel-orientated sericite in mudstone layers comprises the weak slaty cleavage (S_1). In one sample, porphyroblasts of chlorite (0.5–1 mm long), whose original growth overprinted S_1 and pre-dated S_2 (fig. 9), are present.

Mudstone (Lfn)

Lfn, dominantly thick-bedded mudstone, has been mapped in four main areas:

(1) in the west of the Naracoopa sheet (Sea Elephant River area) between the Pearshape Fault to the west and the higher grade (Lfgl) unit to the east, with which it also shares a faulted contact;

(2) a faulted, poorly exposed area in the central north of the Naracoopa sheet, where to the west the mudstone appears to conformably overlie unit Lfgl;

(3) a meridional belt in the central Grassy sheet, that dips gently SSE and is bounded on the east by the Grassy River Fault; and

(4) an eastern belt mainly on the Grassy sheet that dips east and underlies the Grassy Group.

It is uncertain whether these occurrences represent the same, or separate stratigraphic units. No garnet is known, and rare metamorphic biotite and chlorite are distributed across the areas. S_1 and S_2 are well developed in the Sea Elephant River area (fig. 10), but in the other areas, deformation is very mild and cleavages are weak or absent. Lfn in the eastern belt (area 4) appears to be approximately 800 m thick. About 1000 m may be present in area 3 given an average dip of about 15° south. Elsewhere thicknesses are difficult to estimate. There is good outcrop in the Sea Elephant and Grassy rivers, and Yarra Creek.

The predominant rock type of Lfn is a dark grey to black, pyritic, thick-bedded, uniform, slightly silty mudstone,
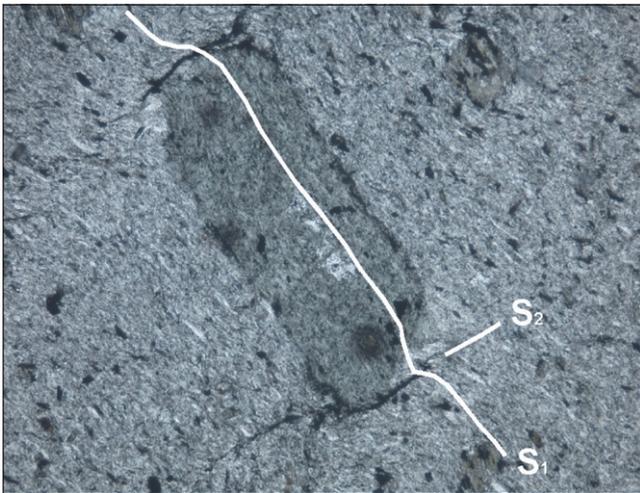
Figure 9

Cleaved mudstone of Lfi. Slaty cleavage (S_1) overgrown by a chlorite porphyroblast, which pre-dates the weak crenulation cleavage (S_2). Thin section R013155, plane polarised light. Field of view 2 mm.

Figure 10

Mudstone overlain by microbialite. Weak penetrative slaty S_1, and crenulation (S_2) in mudstone. Sparse platy ?porphyroblasts replaced by iron oxide. Field of view 6 mm. Thin section R15005, plane polarised light.

Figure 11

Unit Lfn: sharp-based bed of fine-grained siltstone with planar lamination and climbing-ripple cross-lamination, grading up into mudstone. Near Yarra Creek [252633/5568719].

Figure 12

Two turbidite units, Fraser Formation; Bouma subdivisions indicated in one; note uppermost thin hemipelagic black shale bed (Ep). Seal Point [241485/5555418].

Figure 13

Load casts and flame structure at base of siltstone bed, unit Lfs. Near Cumberland Creek [251210/5570679].
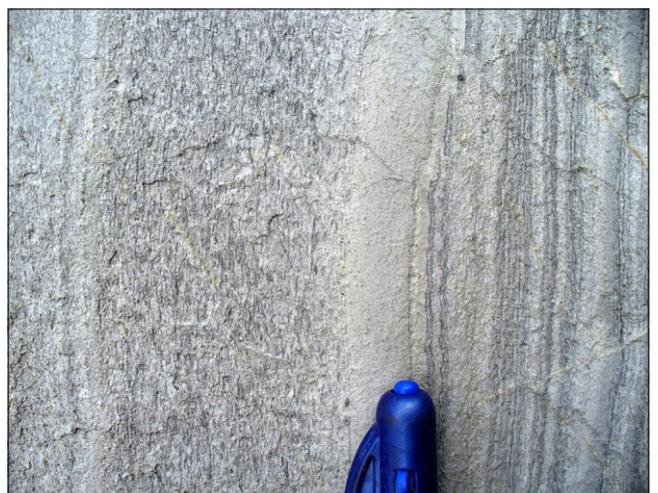
Figure 14

Siltstone with undisturbed microbialite laminae (right), and siltstone bed crowded with tiny ragged rip-up clasts of microbialite (left of centre). Millwood pit [253380/5575332].

weathering to pale grey. Bedding, which is often difficult to find, is typically manifest as sporadic bundles of thin, pale siltstone laminae. Locally, minor sharp-based thin beds of quartzose siltstone are present with planar lamination, cross lamination and climbing-ripple cross lamination, grading up into mudstone (fig. 11). The presence of muddy siltstone foresets (fig. 11) suggests rapid deposition from suspension. Bedding in otherwise massive silty grey mudstone may also be discerned by the presence of sporadic thin beds of black shale. The black shale beds have sharp, parallel upper and lower contacts and a microstructure of anastomosing seams (fig. 10), just visible with the hand lens. They are probably microbialites formed from benthic microbial mats, although not necessarily indicative of the photic zone (e.g. Schieber, 1986; Logan et al., 1999). Presence of the microbialite beds is indicated as 'Lfnb' on the observations spreadsheet.

The sedimentary features suggest a muddy turbidite mode of deposition, characterised by a typical Bouma BCE sequence, with B and C sometimes poorly developed or missing, grading up into a thick turbiditic mudstone (Et), topped by a thin hemipelagic microbialite layer (Ep), not always present (fig. 12).

A plane-laminated mudstone facies is present in a quarry on 'Barratts Farm', Pegarah (248183/5574527) and as float at a couple of places nearby (indicated as 'Lfnl' on the observations spreadsheet). This may represent a period of more or less persistent hemipelagic deposition.

In thin section, uncleaved mudstone from Yarra Creek is essentially a fine-grained (20 m) intergrowth of white mica, quartz and minor chlorite. There is no discernible cleavage or metamorphism beyond crystallisation of mica and chlorite (with no discernible preferred orientation) and growth of sparse narrow columns (150 m long) of tourmaline. The black shale microbialite beds consist of fine-grained white mica, with a dusting of fine opaques (graphite + pyrite?) concentrated into anastomosing thin dark seams. Several samples contain platy grains up to 0.7 mm long replaced by iron oxide; possibly originally biotite porphyroblasts (fig. 10). A sample of mudstone with contact-metamorphic spotting from the Grassy River (K123) has fine-grained (100 m) metamorphic brown biotite, distinctly coarser than the 'groundmass' of white mica and quartz, but the mineralogy of the spots cannot be determined.

Quartzose siltstone (Lfs)

The main occurrence of this lithology is a large area east of the Grassy River Fault, where it appears to stratigraphically underlie mudstone (Lfn) at Yarra Creek and west of Naracoopa township. Lfs in this area is at least one kilometre thick, assuming no undetected faulting. Four smaller, poorly exposed areas of Lfs lie west of the Grassy River Fault. In the lower reaches of the Grassy River, Lfs appears to overlie mudstone (Lfn) and is unconformably overlain by the Grassy Group. Probably more than one stratigraphic unit of Lfs is therefore present. Lfs is generally poorly exposed. Best exposures are along the Grassy Reservoir access road, Robbins Creek and Barrier Creek. Contact-metamorphosed (massive, silicified, quartzitic) Lfs is exposed in the northern wall of the Grassy open-cut mine.

Lfs is thick-bedded to massive, pale grey to white, micaceous quartz siltstone. Lfs differs from Lfb (laminated quartzose siltstone) in its generally coarser grainsize and less common planar lamination. In places the grainsize is up to very fine sand grade (c. 0.1 mm). Flakes of detrital muscovite (0.5 mm), with no discernible preferred orientation, are visible in hand specimen. Interbedded grey mudstone (similar to Lfn) is present in many places. In such cases bedding or lamination tends to be planar, and the siltstone layers are sharp based and weakly graded. Some thick siltstone beds have basal load casts (fig. 13). There are rare thin beds of black shale (microbialite). A few siltstone beds contain abundant ragged, shred-like intraclasts of the microbialite (fig. 14). The lack of internal structure of most of the siltstone beds, and the sedimentary structures associated with the mudstone interbeds, are consistent with a predominant turbidite mode of deposition.

Thin sections show detrital grains of quartz and muscovite with minor sodic plagioclase, K-feldspar and tourmaline. Irregular brown biotite (50 m), probably predominantly of metamorphic origin, may comprise up to 20% of the rock, and secondary chlorite may also be present. One sample (R009697) contains sub-equant inclusion-rich muscovite porphyroblasts (up to 1 mm).

Amphibole hornfels (Lfa, Lfc)

These are massive, tough, grey rocks, fine grained but for 5–20% porphyroblasts consisting of plumose aggregates, often bowtie shaped, of amphibole. The rocks resemble dolerite in the field, but were identified as 'metasiltstone' on the initial map editions because of the abundance of fine-grained quartz in the groundmass. However their chemical composition indicates a mafic protolith, and the less specific descriptor 'hornfels' is more appropriate, although in most cases the rocks appear to result from regional rather than contact metamorphism. Two varieties were differentiated on the type of amphibole making up the porpyroblasts; actinolite hornfels (Lfa) and cummingtonite hornfels (Lfc).

Actinolite hornfels (Lfa) comprises a 200–500 m wide belt near Missons Road (northwestern Grassy map) on the western side of the Lymwood Anticline. The contacts are not exposed and are probably faulted. The rock type also occurs as isolated outcrops at Pegarah (243560/5574094) and Fraser River (245270/5577241) on the Naracoopa map, along the same inferred NNE-trending fault (or system of faults) that bounds the Missons Road occurrence. An isolated occurrence is also found near Naracoopa township (252374/5577647). The rock is massive and uniform except for sparse ellipsoidal siliceous concretions a few centimetres long. The actinolite porpyroblasts are conspicuous bowtie-shaped radiating aggregates up to 8 mm long (fig. 15). In thin section, these are arrays of sub-parallel, gently curved, columnar to acicular crystals up to 50 m wide. The porphyroblasts poikilitically enclose much groundmass quartz, chlorite and biotite. They show the weak green pleochroism and maximum extinction angle (~20°) characteristic of actinolite. The abundant groundmass is of fine-grained (20–30 m) chlorite and quartz, and brown biotite up to 100 m. A whole-rock XRD determination
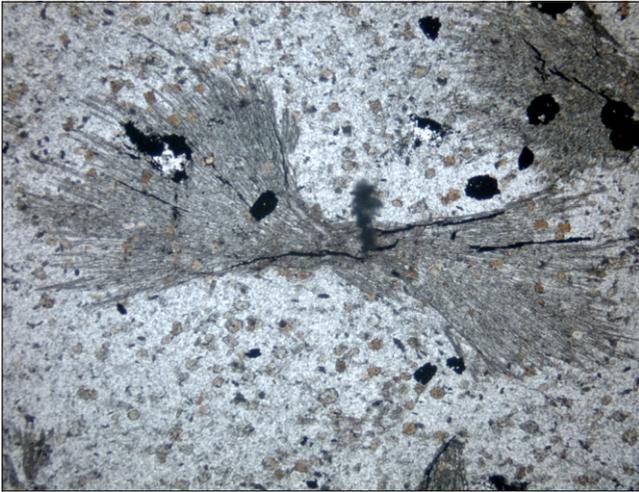
Figure 15

Bowtie-shaped actinolite plumes in Lfa; groundmass of fine-grained quartz, biotite (brown) and chlorite. Thin section R15010, plane polarised light. Field of view 6 mm.

Figure 16

Lfc: Plumose cummingtonite porphyroblasts in matrix of brown biotite and clear quartz. Thin section R009689, plane polarised light. Field of view 4 mm.

(K180) gave chlorite, quartz, plagioclase, (Ca-?) amphibole, mica and clinopyroxene.

At Mount Stanley Road (243037/5566561), a small outcrop of laminated quartz siltstone (Lfgl) includes a thin concordant bed with abundant dark green plumose aggregates identical in appearance to those of Lfa, although a thin section shows these have retrogressed to chlorite. This thin bed is presumably of sedimentary (mafic-volcaniclastic?) origin.

One area of cummingtonite hornfels (Lfc) was mapped within the contact aureole and just north of the Bold Head Granite. Lfc is similar to Lfa, but is richer in quartz and the porphyroblasts are cummingtonite rather than actinolite. Like Lfa, this is a massive brownish-grey rock with sparse siliceous concretions. In thin section there are porphyroblasts up to 3 mm long of colourless to very pale brown amphibole, with prismatic, inclusion-rich cores authigenically overgrown by fibrous overgrowths of the same mineral (fig. 16). The porphyroblasts are identified petrographically as cummingtonite (maximum extinction angle 19°; second order interference colours). Abundant smaller porphyroblasts of biotite (200 m) are present and the matrix appears to be mainly fine-grained (20–30 m) granoblastic quartz and biotite, although XRD also detected significant plagioclase and chlorite. A finer-grained variety (R009694) contains smaller (1 mm) cummingtonite porphyroblasts, which are nearly all fibrous in form, often as bowtie-shaped aggregates. This unit is surrounded by weakly contact-metamorphosed (spotted) siltstone associated with the Bold Head Granite and is interpreted as a contact metamorphic rock (a cummingtonite-biotite-quartz hornfels) overlying granite at shallow depth.

This area of Lfc was described as a tremolite hornfels, probably originally a siliceous carbonate-rich horizon, by Brown (1974). It has also been interpreted as a contact metamorphosed basaltic lava (Crawford, 1994).

Two analyses of the actinolite hornfels and one of the cummingtonite hornfels are very similar to one another, with 54–56% SiO_2 (Table 1). Together with high iron (9–11% FeO), magnesia (6–8% MgO), Cr (119–145 ppm) and Ni (74–86 ppm), this suggests a mafic to intermediate igneous
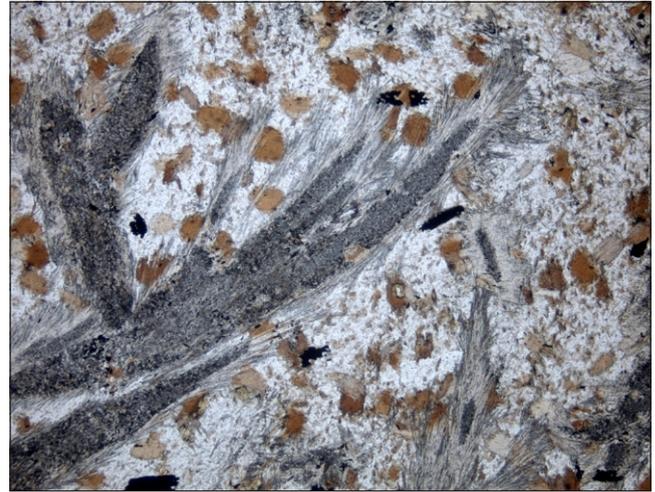
protolith. The analyses are similar to that of a dolerite that intrudes the Fraser Formation near Fraser Bluff (R013188; see *Proterozoic dolerite*).

Very similar rocks occur in the Surprise Bay Formation, e.g. unit Lbac on the Stokes map sheet (Everard, 2011).

Cryogenian–Ediacaran: Grassy Group

Introduction

The Grassy Group is well exposed on the east coast, north of Bold Head, and is also well known as the 'mine series' hosting the Grassy and Bold Head scheelite-skarn ore bodies. The term 'Grassy Group' was first used by Knight and Nye (1953) for the contact metamorphosed host rocks in the open-cut mine. They state (p. 1223): "The Grassy Group is divided by a strong transverse fault — No. 3 Fault — into two parts which differ in lithology and strike. Immediately north of the fault occurs muscovite hornfels striking 40°, and dipping 40° SE. South of the fault are the host beds of the ore body which, except at their extreme eastern end, strike 90° and dip at 30° to 60° S."

Subsequent and current interpretations of the open cut geology have the hornfels north of the No. 3 Fault belonging to the 'Quartzite' succession, i.e. to the Fraser Formation (e.g. Danielson, 1975a). The type area of the Grassy Group is therefore here revised to constitute the exposures in the open-cut mine and environs, between the No. 3 Fault and the contact with the Sandblow Granite. The informal stratigraphic succession recognised in the 'mine series' (e.g. Danielson, 1975a; Danielson and Brown, 1976; Large, 1971) is shown in Figure 17.

The Grassy Group on the east coast is thicker, well exposed and essentially unmetamorphosed, and seven formations have been recognised: the Robbins Creek Formation; the Cottons Breccia (Jago, 1974); the Cumberland Creek Dolostone; the Yarra Creek Shale (Calver et al., 2004); the City of Melbourne Volcanics (Meffre et al., 2004; = 'lower tholeiite sequence' of Waldron and Brown, 1993); the Shower Droplet Volcanics (Meffre et al., 2004; = 'picrite sequence' of Waldron and Brown, 1993); and the Grahams
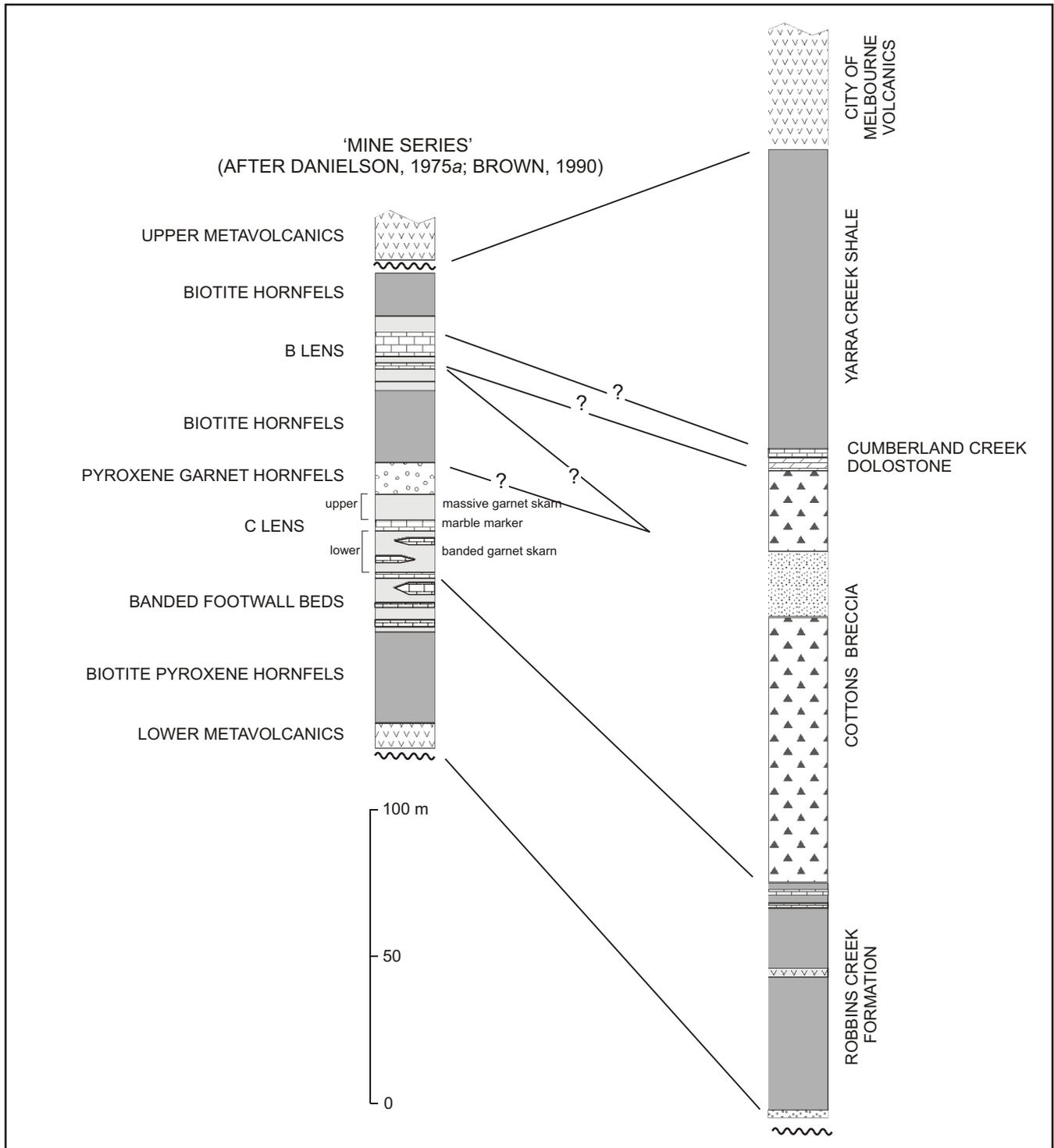
Figure 17

*Diagrammatic stratigraphic columns of the Grassy Group in the Grassy–Bold Head mines ('mine series') and
in the City of Melbourne Bay area (excluding sills), showing suggested correlation.*

Road Volcanics (= 'upper tholeiite sequence' of Waldron and Brown, 1993; = 'Bold Head Volcanics' of Meffre *et al.*, 2004). A supplementary type section for the Grassy Group is here nominated in Yarra Creek and along the southern side of City of Melbourne Bay, from the basal unconformity at 253254/5567336 to 253900/5566700. This section includes significant exposures of all of the units except the Cumberland Creek Dolostone and the Grahams Road Volcanics.

From the open-cut mine west to Red Hut Road, the Grassy Group lies within the contact aureole of the Sandblow Granite. It is strongly contact metamorphosed and metasomatised and, except for the open-cut mine, poorly exposed. The Grassy Group in this area has been divided into a lower metasedimentary unit (Lys) and an upper metavolcanic unit (Lyv).

The Grassy Group was, in error, referred to as the 'Currie Group' by VandenBerg *et al.* (2000) and Cayley *et al.* (2002).

Age and correlation

Distinctive attributes of the Cottons Breccia and overlying Cumberland Creek Dolostone show that the top of the Cottons Breccia corresponds to the end of the last great 'snowball Earth' glaciation, and thus to the boundary between the Cryogenian and Ediacaran systems on King Island (Calver and Walter, 2000; Hoffmann *et al.*, 2009). From dating in South China and Namibia, this boundary is c. 635 Ma (Hoffman *et al.*, 2004; Condon *et al.*, 2005). Calver *et al.* (2004) correlated the Cottons Breccia with the >582 Ma Croles Hill Diamictite of northwest Tasmania, but the implied mismatch with the dated overseas Cryogenian–Ediacaran successions means this correlation is not generally accepted.

Calver *et al.* (2004) dated the Grimes Intrusive Suite at 575 3 Ma (SHRIMP U-Pb on zircon). The Grimes Intrusive Suite appears to be petrogenetically linked to the City of Melbourne Volcanics (Meffre *et al.*, 2004), and field evidence (see below) shows it is older than the City of Melbourne Volcanics and correlates with a stratigraphic level at or just below the top of the Yarra Creek Shale. Four Nd-Sm isotopic analyses from the Shower Droplet Volcanics and one from the Grahams Road Volcanics yielded an isochron age of 579   16 Ma (Meffre *et al.*, 2004). However, on the isochron plot, the single Grahams Road Volcanics point is distant from the four others which by themselves do not form a convincing isochron. Hence the validity of the isochron rests on an assumption that the two formations are similar in age.

An implication of the above age constraints is that the Yarra Creek Shale represents a lengthy time interval (c. 60 m.y.) and may include a significant lacuna or disconformity.

Equivalents of the lower, sedimentary part of the Grassy Group (including the Cottons Breccia) are not seen in the index Neoproterozoic succession (Togari Group) of northwest Tasmania. There, a succession of shale and volcaniclastic sandstone (the lower Keppel Creek Formation) separates probable Sturtian and Gaskiers-equivalent diamictites (i.e. Julius River Member and Croles Hill Diamictite, respectively). The Skipworth Subgroup is of the same or similar age to the Spinks Creek Volcanics (Calver *et al.*, in press).

The Cottons Breccia, Cumberland Creek Dolostone and Yarra Creek Shale are correlated with the Elatina, Nuccaleena and lower Brachina Formations, respectively, of South Australia (Calver and Walter, 2000). No volcanic rocks are known from the index Ediacaran successions of South Australia, but the c. 586 Ma Mt Arrowsmith Volcanics of western NSW (Crawford *et al.*, 1997) are possible correlates of the mid-Ediacaran mafic volcanic rocks of Tasmania.

Base of the Grassy Group

Regionally, the base of the Grassy Group is an angular unconformity upon the Fraser Formation, with the Grassy Group resting on different units of the Fraser Formation in different areas (see *Structure and Metamorphism* section). The unconformity is exposed in two places. In Yarra Creek the unconformity (fig. 18) is planar, with no noticeable sub-unconformity weathering of the underlying mudstone of

the Fraser Formation (Lfn). The overlying conglomerate of the basal Robbins Creek Formation is three metres thick, with subrounded cobbles and pebbles of grey silty mudstone identical to the underlying Fraser Formation. Three metres of conglomerate similarly overlies siltstone (Lfs) in Cumberland Creek.

Direen and Jago (2008) figured a purported unconformity between the Fraser Formation and Shower Droplet Volcanics (a picrite unit high in the Grassy Group) on the coast southeast of Naracoopa jetty (their Figure 3). However this outcrop, at 254588/5577043, is entirely within the Shower Droplet Volcanics, and consists of east-dipping agglomerate overlying massive, jointed picrite lava (fig. 19). Outcrop of picrite lava continues along the coast for 120 m northwest of this outcrop. Then there is a gap in exposure (30 m), then abundant outcrop of Fraser Formation. Both

Figure 18

Basal conglomerate of Robbins Creek Formation (Grassy Group) unconformably overlying thick-bedded mudstone of Fraser Formation at level of hammer handle. Yarra Creek [253254/5567336].

Figure 19

Picritic agglomerate overlying jointed massive picrite lava, 250 m SE of Naracoopa Jetty [254588/5577043]. This outcrop was figured by Direen and Jago (2008, their Figure 3) and incorrectly interpreted as an unconformity of Shower Droplet Volcanics upon Fraser Formation.

units are notably fractured near the concealed contact, which is interpreted to be a fault.

Robbins Creek Formation (Lysr)

The Robbins Creek Formation (new name) is the oldest unit of the Grassy Group in the eastern coastal strip between Cottons Creek and Barrier Creek. Some earlier workers noted this formation without naming it or explicitly recognising its unconformable relationship with the Fraser Formation. Solomon (1968) noted a 90 m thick unit underlying the Cottons Breccia of "grey-green mudstone, partly dolomitic, partly varve-like, with thin spilite flows and tuff bands", which corresponds to the Robbins Creek Formation. The 'laminated siltstone' of Waldron and Brown (1993) by and large refers to the Robbins Creek Formation. It probably corresponds to the footwall biotite pyroxene hornfels and lower metavolcanic rocks in the Grassy and Bold Head 'mine series'.

The Robbins Creek Formation consists of laminated shale and siltstone, with locally developed basal conglomerate. 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. The formation is about 100 m thick in its type section in Robbins Creek. The Yarra Creek reference section, described below, is about 80 m thick.

In the Yarra Creek section, a few cobble and boulder-sized clasts are present just above the unconformity, but most of the basal conglomerate is pebble grade, and derived from the underlying Fraser Formation. The conglomerate, three metres thick, is adjoined to the east by an altered picritic intrusive rock about 20 m wide. Then follows a seven metre stratigraphic gap, then laminated shale and siltstone (40 m), then another gap in exposure. Here as elsewhere, the dominant rock type is black shale thinly interbedded and interlaminated with paler siltstone and fine-grained lithic sandstone. The rock weathers to grey-green or pale brown (fig. 20). Some siltstone laminae are graded and have load-casted bases. The siltstone and sandstone is notably poor in quartz, and altered to fine-grained chlorite, and probably originated as mafic detritus (fig. 21). It is distinctly less siliceous than the siltstone of the Fraser Formation. Convolute lamination is seen in one bed and rare isolated ripples are present. A weak but distinct subvertical cleavage (S_3) is present. Near the top of the exposure, on the south bank of the creek (253349/5567323), is a 0.7 m thick conformable unit of altered fine-grained basaltic rock. Approximately along strike about 80 m to the southwest, thin, weathered and altered, irregularly lensing mafic flows are seen within the shale in a track cutting exposure. The uppermost 20–30 m of the formation is not exposed.

In the uppermost few metres of the formation in Robbins Creek, Cumberland Creek and Grimes Creek, thin beds of impure limestone are interbedded with the shale.

From Conglomerate Creek north to Cumberland Creek, a sill up to 150 m thick of Grimes Intrusive Suite (Lyg) intrudes at a level 10 to 20 m below the top of the Robbins Creek Formation. Mild contact metamorphism of the limestone and shale of the upper Robbins Creek Formation is seen above the sill in Grimes Creek.

Figure 20
Typical Robbins Creek Formation near Yarra Creek [253326/5567246].
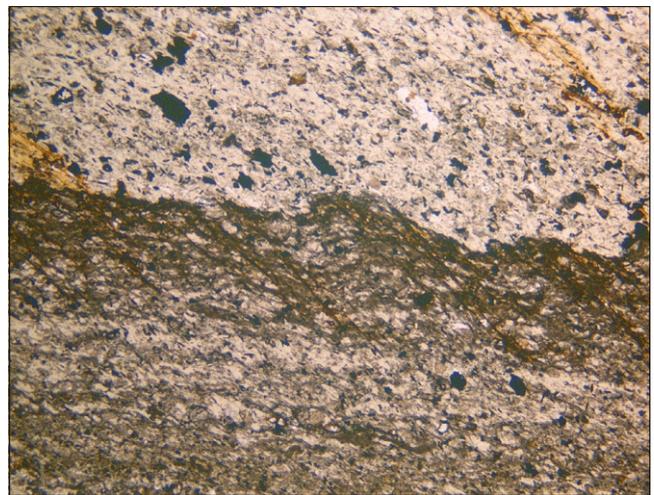
Figure 21
Laminated dark shale of Robbins Creek Formation, showing S_3 cleavage. Nearly all the non-opaque silt-sized grains are chlorite, and probably altered mafic-volcanic detritus. Thin section R009680, plane polarised light. Field of view 7 mm.

The most northerly outcrop of Robbins Creek Formation is seen on the coast just south of Fraser Bluff. Here, a 250 m thick sill of the Denbys Dolerite (Grimes Intrusive Suite) intrudes at or near the base of the Robbins Creek Formation. Between the highest Fraser Formation outcrops and the lowest Denbys Dolerite, there is a gap of several metres that may represent unexposed basal Robbins Creek Formation. The top of the Denbys Dolerite sill is overlain by 15 m of hornfelsed, laminated (banded), green, black and yellow-brown shale, correlated with the Robbins Creek Formation. The shale is concordantly overlain by a basaltic intrusive rock (see later section), whose upper contact is covered by the sea.

In the inland, western part of the Grassy map sheet, south of Lymwood, a 0.7   1.2 km area shown as undifferentiated Grassy Group sedimentary rocks probably belongs to the Robbins Creek Formation. Sparse float and one outcrop (244050/5565651) consist of unmetamorphosed, plane-laminated grey shale and minor labile siltstone and sandstone very similar to the type Robbins Creek Formation. Bedding in the single outcrop dips very gently

southwest. In contrast, adjoining areas to the west, north and south assigned to the Fraser Formation, are east-dipping mudstone and garnetiferous metasiltstone. To the east, this area is inferred to be faulted against mudstone of the upper Grassy Group (Lyvs).

The Robbins Creek Formation appears to be disconformably overlain by the Cottons Breccia, although the contact is not exposed (see below). The Robbins Creek Formation is probably not much older than the Cottons Breccia. The two units contain compositionally similar mafic volcanic rocks. The Robbins Creek Formation is lithologically somewhat similar to the Tapley Hill Formation of the Adelaide Geosyncline, which is between 659 and 635 Ma in age (Grey *et al.*, 2011).

Mafic volcanism associated with the Robbins Creek Formation

Thin flows are seen in Yarra Creek (as mentioned above) and good exposures of thin flows are also found in Cumberland Creek. At 254571/5571655, in the upper part of the formation, an exposure of several metres of typical laminated shale and siltstone contains two conformable fine-grained altered basaltic units about 250 mm thick. The upper one is a flow, because it has an abrupt rounded termination associated with soft-sediment disturbance, and onlap of bedding onto the top of the flow (fig. 22). These two units have ~15% euhedral phenocrysts (3 mm), probably formerly clinopyroxene, in a fine-grained intersertal plagioclase-rich groundmass, but both are almost wholly altered to sericite and chlorite (R013110, R013198). Lower in the succession nearby, laminated shale-siltstone contains

Figure 22
Nose of thin basaltic flow in Robbins Creek Formation. Note disturbed bedding immediately to right of flow. Cumberland Creek [254571/5571655].

minor thin graded beds of immature mafic-volcaniclastic granule conglomerate (thin section R13197). Analyses of the two thin flows show distinctly higher alkalies and TiO_2 than the Grimes Intrusive Suite, City of Melbourne Volcanics and Shower Droplet Volcanics (fig. 23, Table 2).

In Conglomerate Creek, Grimes Creek and Robbins Creek, the basal 20–40 m of the formation is predominantly altered basaltic rocks, but the contacts are poorly exposed and it is difficult to say whether these are intrusive rocks or flows. A sample from Grimes Creek (R013109) is texturally similar to
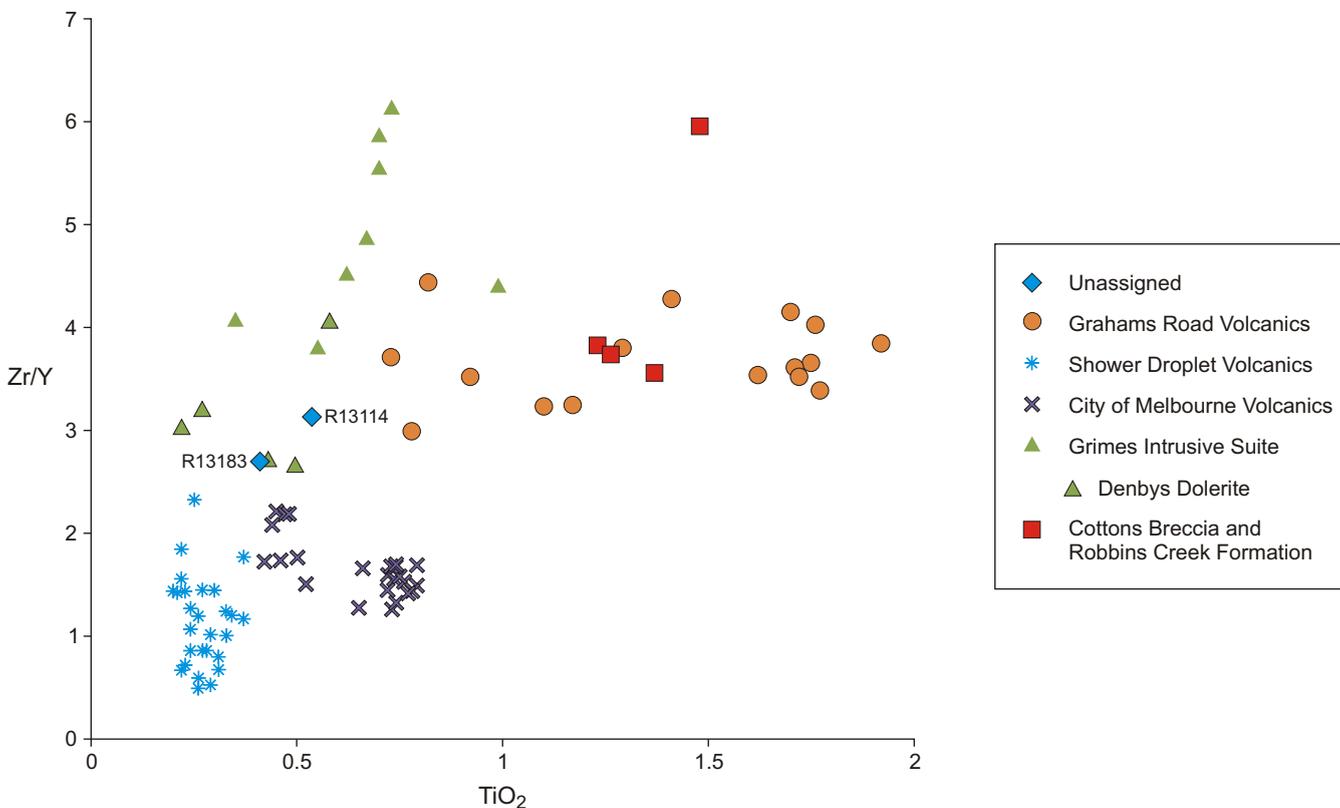
Figure 23
TiO_2 vs Zr/Y of igneous units of the Grassy Group and associated intrusive rocks (from Waldron and Brown, 1993; Meffre et al., 2004; Calver et al., 2004; J. Everard, geochemistry database; and this work).
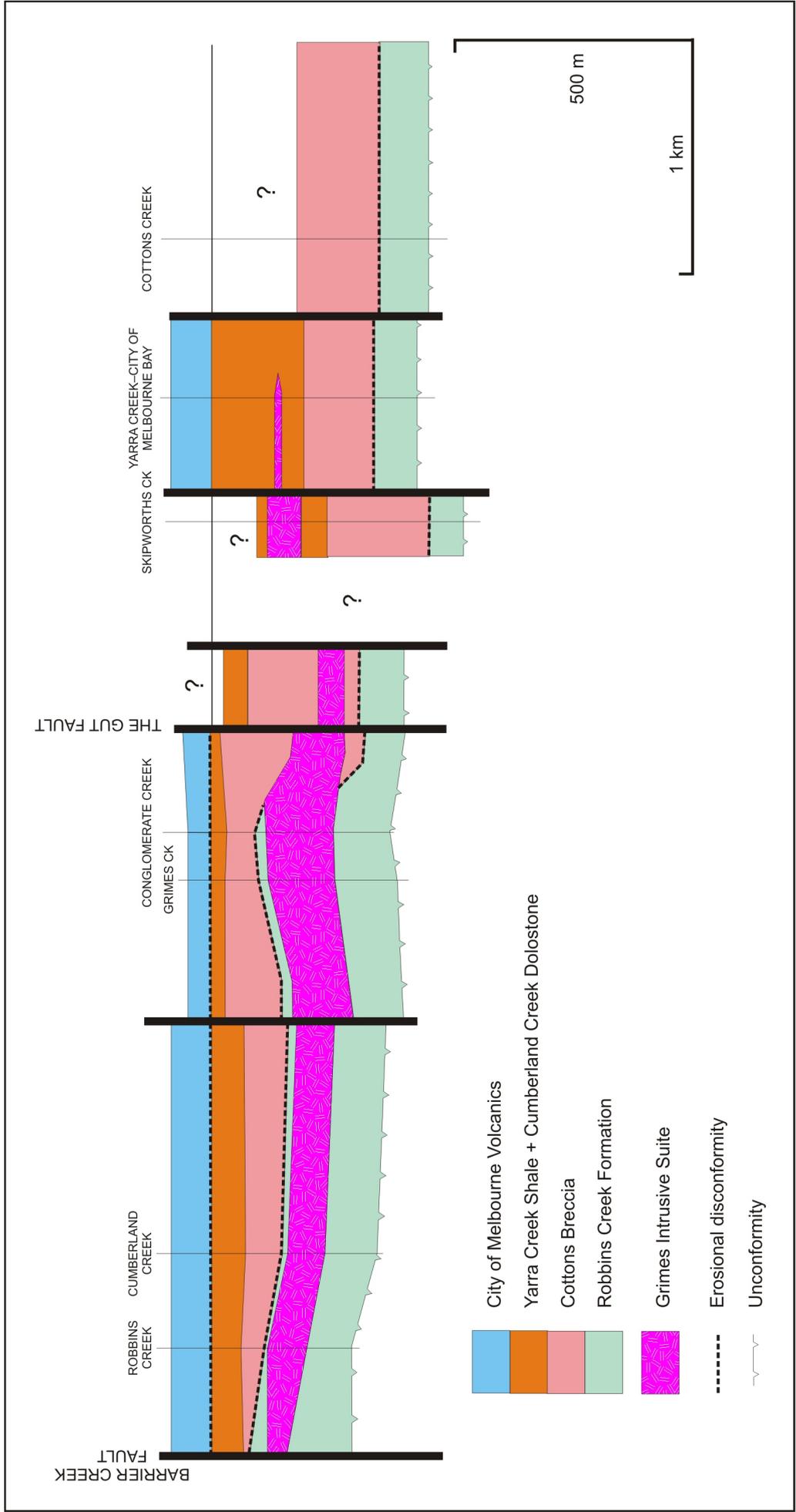
Figure 24

*Diagrammatic structural profile of Grassy Group looking southeast and down-dip, vertical exaggeration x 2;
fault blocks drawn level at base of City of Melbourne Volcanics; basaltic sills removed. Dip of faults is uncertain.*

the thin Cumberland Creek flows, with 20% equant subhedral phenocrysts (1 mm) and glomerocrysts, probably originally clinopyroxene but wholly replaced by granular quartz, in a plagioclase-rich intersertal groundmass. An analysis of a sample (R013114) from Robbins Creek is unrelated to the proven flows (e.g. only 0.5% TiO_2); it is probably an intrusive rock related to Skipworth Subgroup magmatism (fig. 23; see later section).

Cottons Breccia (Lysc)

The Cottons Breccia (Jago, 1974) consists of diamictite, with minor sandstone, conglomerate and pebbly mudstone. Its origin has been controversial, with either glacial (Waterhouse, 1916; Carey, 1947; Solomon, 1968; Calver and Walter, 2000; Calver et al., 2004) or mudflow modes of deposition being proposed (Schermerhorn, 1974; Waldron and Brown, 1993; Direen and Jago, 2008). Some further work on the Cottons Breccia was undertaken by the writer in collaboration with P. F. Hoffman and G. P. Halverson. The resulting paper (Hoffman et al., 2009) contains an account of the development of the controversy, detailed descriptions of several sections, a discussion of the sedimentology, and further evidence of a glacial origin. Here, a brief regional overview of the formation is given, and evidence for basaltic magmatism during deposition is outlined.

No exposure of the base of the Cottons Breccia has been found. Poor outcrop and float straddling the contact near Grimes Creek (254589/5570122) includes float of mudstone with laminae of granule conglomerate, possibly a transitional lithology between Robbins Creek Formation and Cottons Breccia. However an inverse relationship between the

Figure 25
Lower, carbonate-rich member of Cottons Breccia, Cumberland Creek [254776/5571748].

thickness of the two formations (fig. 24) suggests an erosionally incised (disconformable) contact.

The Cottons Breccia is approximately 150 m thick at City of Melbourne Bay, and is of variable and generally decreasing thickness going northwards (fig. 24). There is excellent outcrop of the upper part of the formation in coastal exposures, particularly at Cottons Beach, The Gut and around the mouth of Grimes Creek. The lower part is not so well exposed in creek sections.

In the 'mine series' of the Grassy mine (and Bold Head mine) areas, the 'pyroxene garnet hornfels' and possibly the 'C lens' (totalling about 50 m thick) are considered to be equivalent to the Cottons Breccia. The calcareous composition of the unit has made it an important locus of skarn mineralisation (see later section; fig. 17). A few exposures of contact metamorphosed Cottons Breccia (Lyscx) are found in the Mount Stanley–Red Hut Road area. These are diamictite–calc-hornfels in which most of the clasts are altered to white calcite marble (see later section).

Three informal members can be recognised in the eastern coastal sections:

(1) a lower diamictite member, comprising the bulk of the formation, in which carbonate clasts predominate and with a carbonate-rich, grey matrix;

(2) a middle sandstone member of volcaniclastic sandstone; and

(3) an upper diamictite-conglomerate member, usually reddish coloured and with a predominantly non-carbonate clast population.

The middle and upper members are best developed in the south (Cottons Flat), and wedge out northwards to be absent at Cumberland Creek and further north.

In the lower diamictite member, the matrix is dominantly carbonate, either calcareous or dolomitic. Maximum clast size is variable from place to place, up to one metre, but commonly only pebble 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 very wide range (-2‰ to +10‰) of carbon isotopic compositions, 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, identical to Lfb, are found at Cottons Beach, and it is noteworthy that the chlorite porphyroblasts are erosionally truncated at the surfaces of the clasts (sample R013165). 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 also exhibit (near Grimes Creek) a preferred WNW–ESE long-axis orientation (tilt corrected), suggesting an origin as a lodgement till (Hoffman et al., 2009). Good exposures of the lower diamictite member are seen in Cumberland Creek (fig. 25), on the coast at Cottons Beach and at the mouth of Grimes Creek. In Cumberland Creek

Figure 26

Dropstones in laminated calcareous siltstone, Cottons Breccia, Cottons Beach [253044/5565709].

Figure 27

Isolated boulder in a sandstone bed within the Cottons Breccia, at the mouth of Grimes Creek [254584/5569597].

Figure 28

Upper member of the Cottons Breccia at Cottons Flat [253195/5565741].

Figure 29

Coarse conglomerate bed at the top of the Cottons Breccia, The Gut [254356/5568447].

Figure 30

Discontinuous dyke in Cottons Breccia, indicating intrusion before lithification of the sediment. Pen is parallel to bedding. Near mouth of Cottons Creek [253183/5565717].

and Robbins Creek the lower diamictite unit appears to comprise the whole, or almost the whole, formation. In Robbins Creek, a six metre thick unit of plane-laminated khaki shale and siltstone, lacking lonestones, occurs just below the top of the formation.

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. 26). 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).

The middle sandstone member is well exposed at Cottons Flat and at the mouth of Cottons Creek, where it is about 20 m thick. It is a thick-bedded, fine-grained grey-green, mafic-volcanic sandstone. No cross bedding is seen. It is significantly magnetic (measured magnetic susceptibility up to 59 $\times$ 10^{-3} SI units), giving rise to a small aeromagnetic anomaly in the Cottons Creek area. A thin section (R013167) is entirely composed of well-sorted angular to shard-like glassy fragments 50–100 μm in size, altered to chlorite, minor carbonate and fine-grained alteration products. An analysis of this rock is basaltic (Table 2; see below). 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. North of Cottons Creek, the middle sandstone member is thin and possibly discontinuous. A green sandstone bed at The Gut is similarly composed of altered mafic shards and is a probable correlate. Zircon extracted from this bed for SHRIMP dating was meagre and of basement origin (M. Wingate, pers. comm.). The middle sandstone member at the mouth of Grimes Creek is one metre thick and contains a boulder-sized lonestone (fig. 27).

The upper diamictite-conglomerate member is about 27 m thick at Cottons Creek–Cottons Flat. It consists here of thickly bedded, interbedded sandy conglomerate, diamictite and pebbly sandstone (fig. 28). 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. To the north, diamictite increases at the expense of conglomerate and sandstone in the upper member. At The Gut and Grimes Creek foreshore, 20–25 m of weakly stratified, reddish, carbonate-poor diamictite represents the upper member. A 1–2 m thick bed of clast-supported, cobble-boulder (<400 mm) conglomerate occurs a few metres below the

top of the Cottons Breccia at Cottons Flat (as mentioned above), Yarra Creek (seen immediately west of the City of Melbourne Bay car park), The Gut (fig. 29) and the Grimes Creek foreshore. At The Gut, this conglomerate bed fines upward into 1–2 m of red, plane-laminated sandstone, in turn overlain by Cumberland Creek Dolostone which has a rapidly transitional (<100 mm) lower contact.

Magmatism during Cottons Breccia deposition

The tuffaceous, shard-rich sandstone comprising the middle sandstone member indicates contemporaneous volcanic activity. An analysis is similar to the thin lavas in the Robbins Creek Formation (fig. 23).

Fine-grained 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. 30). The dykes are therefore interpreted as penecontemporaneous with the Cottons Breccia. A thin section (R013166) shows abundant 0.5 mm plagioclase laths, almost entirely altered to fine-grained indeterminate material, in intersertal texture with an abundant turbid mesostasis of chlorite, opaques and fine-grained alteration products. An analysis (R013166, Table 2) is similar to the middle volcanic sandstone member and to the Robbins Creek lavas. Caution is required in interpreting the analyses of these highly altered rocks, but a cross-plot using the high field strength elements Zr, Y, and Ti (fig. 23) shows that these late Cryogenian basaltic rocks associated with the Robbins Creek Formation and Cottons Breccia have distinctly more evolved compositions than the mid-Ediacaran Grimes Intrusive Suite, City of Melbourne Volcanics and Shower Droplet Volcanics.

Cumberland Creek Dolostone (Lysd)

The Cumberland Creek Dolostone (Meffre *et al.*, 2004) conformably overlies the Cottons Breccia. 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 and Walter, 2000; Hoffman *et al.*, 2009). Accordingly, the base of the Cumberland Creek Dolostone is taken to be the base of the Ediacaran System on King Island. Detailed descriptions of the formation are given in Calver and Walter (2000) and Hoffman *et al.* (2009). Newly reported here are marked lateral thickness variations in response to growth faulting.

The formation is well exposed on the coast at The Gut and again between Conglomerate Creek and Shower Droplet Rock (best section just south of the mouth of Grimes Creek). The only other known exposures are in Cumberland Creek and Robbins Creek. A small outcrop (242269/ 5560318) and bouldery float (242998/5560305) of dolostone west of Red Hut Road probably belong to the Cumberland Creek Dolostone. Generally about 10 m thick in total, the Cumberland Creek Dolostone can be divided into three intergrading units.
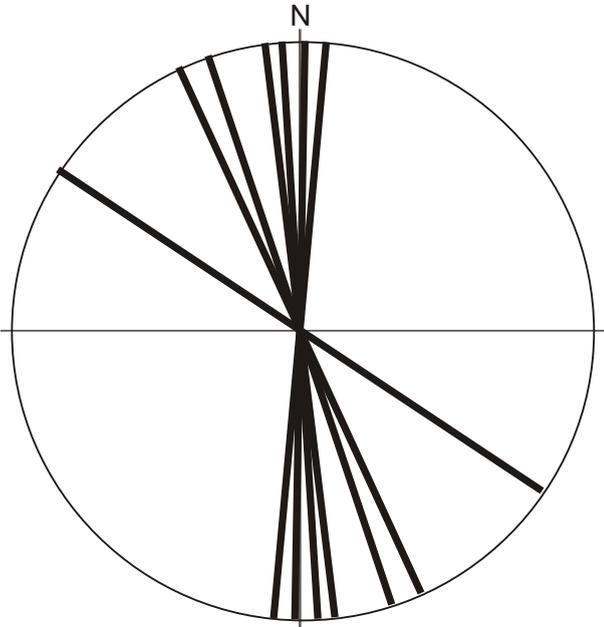
Figure 31

Tilt corrected orientations of seven intraformational anticlinal crests in the Cumberland Creek Dolostone at The Gut.

Figure 32

Local unconformity within Cumberland Creek Dolostone, near the mouth of Grimes Creek [254600/5569519]. Unconformity is at level of hammer head in foreground, and indicated by person in middle distance. Boulders of reddish Cottons Breccia in right foreground.

(1) The basal unit is a laminated, very pale grey, fine-grained dolostone that weathers to a pale yellow-brown colour. Gentle sharp-crested anticlines (100–200 mm amplitude), vertically impersistent and with axial planes approximately normal to bedding, are seen in a few places (best seen at The Gut). These 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 anticlines in the Cumberland Creek Dolostone have a tilt-corrected, preferred north–south orientation (fig. 31), like those in South Australia (Hoffman and Li, 2009). A local unconformity occurs within this unit on the Grimes Creek foreshore, suggesting syndepositional tectonism (fig. 32).

(2) The second unit is thinly interbedded, impure fine-grained dolostone and shale. Swaley cross-stratification is seen in some dolostone beds at The Gut. The dolostone beds commonly become more pure towards their tops and have sharply defined, irregular upper surfaces suggesting lithification and mild erosion at the sea floor.

(3) The third unit 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.

Just north of The Gut, a NW-trending fault (here named the Gut Fault) coincides with an abrupt northward thinning of the Cumberland Creek Dolostone and Yarra Creek Shale. The Cumberland Creek Dolostone is reduced to 200 mm of thinly interbedded mudstone and dolostone (fig. 33). Going northwards, both units thicken again, although the Cumberland Creek Dolostone is not exposed until one kilometre further north at the mouth of Conglomerate Creek, where the usual thickness of about 10 m is found (fig. 24).
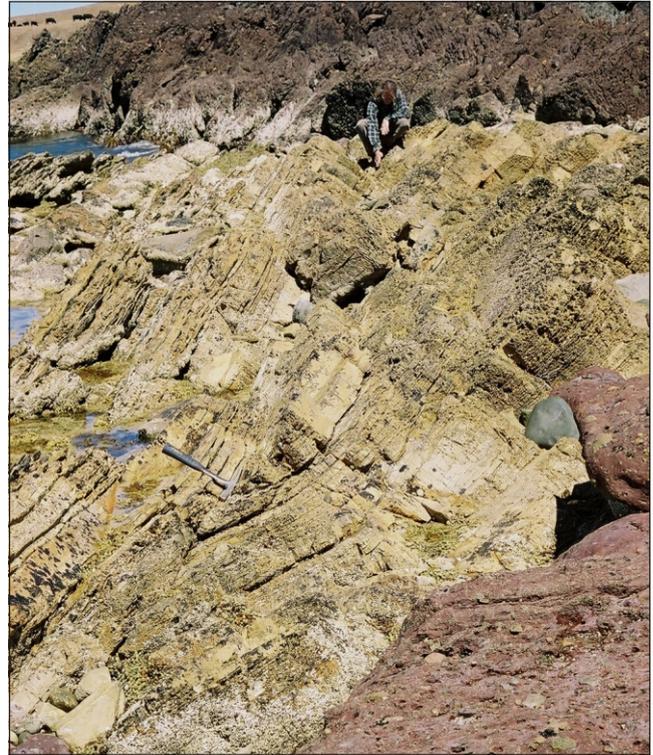
Yarra Creek Shale (Lysy)

The term Yarra Creek Shale was introduced by Calver *et al.* (2004) for the shale that transitionally overlies the Cumberland Creek Dolostone and is overlain by the City of Melbourne Volcanics. It consists of uniform, poorly bedded, weakly fissile shale (mudstone) with rare, thin beds of carbonate and of mafic-volcanic sandstone. The formation is thickest at the type section at City of Melbourne Bay (between 100 m and 250 m; uncertain because of incomplete exposure and the presence of basaltic sills of uncertain aggregate thickness). The lower part of the formation here is pale yellow-brown to grey-green in colour, with distinctive black shale beds in a 16 m thick interval exposed on the north side of City of Melbourne Bay. There is an upward transition to red shale, seen in the easternmost outcrops on the north side of City of Melbourne Bay. Red shale predominates in the upper part of the formation, and is well exposed on the south side of the bay. The uppermost 30 m of the formation, poorly exposed on the southern headland of the bay, consists of shale intruded by highly irregular dykes of altered basalt, in places with peperitic margins. This is overlain by the lower volcanic breccia unit of the City of Melbourne Volcanics. Good exposure of this contact, and of the peperites (fig. 34), is seen 800 m to the south (253683/5566162), where the contact is abrupt and conformable.

The black shale beds have the distinctive microstructure (wispy, anastomosing organic-rich seams) of microbialites (fossil benthic microbial mats) (Calver and Walter, 2000).

Figure 33
Highly attenuated Cumberland Creek Dolostone overlying grey diamictite on interpreted shoulder of upfaulted block just north of The Gut [254438/5568569].

Figure 34
Irregular dykes of altered basalt (pale green) in uppermost Yarra Creek Shale, northern end of Cottons Beach [253539/5565964].

Similar beds at a corresponding stratigraphic position in lower Ediacaran sequences in mainland Australia have been ascribed to sulphide-oxidising bacteria (Logan *et al.*, 1999). An unsuccessful attempt was made in 2007 to date the black shale beds at City of Melbourne Bay, using the Re-Os isochron method (R. Creaser, pers. comm.).

There is a striking variation in thickness of the Yarra Creek Shale, apparently in response to penecontemporaneous movement on faults (fig. 24). An abrupt northward thinning is associated with the Gut Fault. The formation is at least 40 m thick south of the fault (top covered by the sea). Immediately south of the fault, at 254438/5568569, two thick (few metre) beds of coarse-grained lithic sandstone, with scattered rafts of mudstone, are found within the Yarra Creek Shale and probably represent debris shed from the active fault scarp. Immediately north of the fault, the formation is only 15 m thick and rests on a very thin (~30 mm) equivalent of the Cumberland Creek Dolostone (see previous section). Here the Yarra Creek Shale is pale yellow-brown, with rare thin pale grey dolostone beds and sparse microbialite laminae. The topmost metre is slump folded and is overlain by the lower breccia unit of the City of Melbourne Volcanics, with a sharp, slightly irregular contact. The thin dolostone beds (sample R15026) may reflect siliciclastic sediment starvation, as the 15 m thick shale represents a ~60 m.y. time interval (see previous section). Minor thin graded beds of coarse-grained mafic-volcaniclastic sandstone are found near the top of the Yarra Creek Shale 60 m to the north. Slumped beds and minor thin carbonates are also present here. The formation thickens northwards, attaining 25 m at the mouth of Conglomerate Creek, and about 50 m at Cumberland Creek and Robbins Creek, not including a 30 m thick sill (compositionally similar to the City of Melbourne Volcanics) in the middle of the formation. A few metres below the top, at the mouth of Robbins Creek, a 0.5 m slumped bed with ragged intraclasts is overlain by a 0.5 m graded bed of mafic-volcanic conglomerate and sandstone. About 150 m to the north, the upper contact of the Yarra Creek Shale with massive lava of the overlying City of Melbourne Volcanics is a sharp irregular surface with about 0.5 m of relief. The Yarra Creek Shale may

be notably thicker (~100 m) in a poorly exposed area on the coastal escarpment just south of Barrier Creek. Barrier Creek contains a short faulted section of the Yarra Creek Shale, north of which no more outcrop is known.

The equivalent unit to the Yarra Creek Shale in the 'mine series' is probably the biotite hornfels unit above the B lens (fig. 17; see below).

Skipworth Subgroup (Lyv)

The volcanic rocks of the upper Grassy Group have been combined under the name Skipworth Subgroup by Meffre *et al.* (2004). Waldron and Brown (1993) recognised three units (the 'lower tholeiite sequence', 'picrite sequence' and 'upper tholeiite sequence'). Formal stratigraphic names for the same three units were introduced by Meffre *et al.* (2004) and are used below, except for their 'Bold Head Volcanics' which has been renamed Grahams Road Volcanics because of the previously existing name 'Bold Head Granite'.

The petrology, eruptive structures, geochemistry and petrogenesis of these rocks have been described by previous workers (Scott, 1951; Solomon, 1968; Waldron and Brown, 1993; Direen and Crawford, 2003; Meffre *et al.*, 2004) and these aspects are only briefly summarised here. Newly documented here are:

(1) stratigraphic trends in composition within the City of Melbourne Volcanics and the Shower Droplet Volcanics; and

(2) a stratigraphic contact (previously unknown) between the Shower Droplet Volcanics and the Grahams Road Volcanics.

City of Melbourne Volcanics (Lyvt)

Two units make up the City of Melbourne Volcanics (= 'lower tholeiite sequence' of Waldron and Brown, 1993); a lower unit of fragmental rocks (volcanic breccia and sandstone), and an upper unit of tholeiitic lava. The lava can be further divided into massive and pillowed types. At the type section on the south side of City of Melbourne Bay, the lower unit, about 27 m thick, is of massive volcanic breccia and sandstone fining upwards to a metre of well-bedded,

Figure 35

Contact (arrowed) between lower volcaniclastic unit and upper lava unit of the City of Melbourne Volcanics, just north of the Gut Fault (254474/5568559). Note tube vesicles above 10 mm chilled margin.

Figure 36

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).

Figure 37

Base of the upper lava unit of City of Melbourne Volcanics, with load-casted contact on underlying volcanic sandstone of lower unit. North of Cottons Beach (253704/5566110).

Figure 38

Ropy or pahoehoe-textured upper flow surface in Shower Droplet Volcanics, upper part of type section north of Shower Droplet Rock (255081/5570294).

Figure 39

Pillow lava of Shower Droplet Volcanics. Facing is right way up. Headland between City of Melbourne Bay and Cottons Beach (253871/5566262).

fine-grained pale green volcanic sandstone at the top (253931/5566938). This is abruptly overlain by the upper unit, 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. 36). The lower 10 m of the lava unit is massive at the northern end of Cottons Beach. Nearby, load cast-like structures at the base of the lava show that the bedded green sandstone forming the top of the lower unit was unlithified when the lava flowed over it (fig. 37) (also seen at the corresponding horizon just north of the Gut Fault at 254474/5568554).

The thickness of the formation varies, although not as much as that of the Yarra Creek Shale. Immediately north of the Gut Fault, the lower fragmental unit is only five metres of coarse volcaniclastic sandstone; the upper unit is 57 m of massive lava (fig. 35). The coarse volcaniclastic sandstone here has a sharp erosional contact upon Yarra Creek Shale. At the mouth of Conglomerate Creek, 19 m of volcanic breccia and sandstone (enclosing a 5 m thick lens of pillow lava) is overlain by 25 m of pillow lava. The lower fragmental unit is absent at the mouth of Cumberland Creek and further north and the formation consists of 90 m of massive lava. About 150 m north of the mouth of Robbins Creek, inclined tube vesicles just above the basal contact indicate a flow direction approximately to the south.

The basalt is usually moderately to strongly magnetic (measured magnetic susceptibility up to 80 $\times$ 10^{-3} SI units, Table 3), in contrast to enclosing units, and a corresponding linear magnetic anomaly can be followed (offset by mapped faults) from the northern end of Cottons Beach to terminate against the offshore projection of the Barrier Creek Fault (fig. 1) (see *Magnetic Interpretation*).

The massive and pillowed basalts are not significantly different in composition or mineralogy (Waldron and 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 and Brown, 1993; Meffre *et al.*, 2004).

A comparison of 23 available analyses (Waldron and Brown, 1993; Meffre *et al.*, 2004; J. L. Everard, unpubl.; this work) shows two distinct groupings: eight analyses are relatively mafic, with 8–9% MgO and 0.4–0.5% TiO$_2$, while the remainder are slightly more fractionated, with 5–7% MgO and 0.7–0.8% TiO$_2$ (fig. 23). The mafic group includes:

(1) sills within the Yarra Creek Shale at Skipworths Creek and Robbins Creek (see below);

(2) the lower breccia unit in two places;

(3) possibly the lava unit just north of Cottons Beach (sample K2O3 of Meffre *et al.*, 2004).

The more fractionated group, apparently the younger, includes all other analyses of the main lava unit, both massive and pillowed.

Shower Droplet Volcanics (Lyvp)

The Shower Droplet Volcanics (Meffre e*t al.*, 2004) (= 'Picrite Sequence' of Waldron and Brown, 1993) is well exposed along the east coast at several places, from south of City of Melbourne Bay to Cumberland Creek. In this area the formation overlies the City of Melbourne Volcanics, but its top is not exposed, and lies offshore. A faulted section of Shower Droplet Volcanics lies west of Fraser Bluff (Naracoopa map sheet); here the base of the formation is faulted out, but the top — a conformable contact with the Grahams Road Volcanics — can be seen. The Shower Droplet Volcanics comprises most, or all, of the poorly exposed undifferentiated volcanic rocks (Pyv) in the Grassy–Mount Stanley–Red Hut Road area.

The type section, about 250 m thick, extends from just south of the mouth of Cumberland Creek to Shower Droplet Rock (Naracoopa map sheet). Massive basalt of the City of Melbourne Bay Volcanics is overlain by pillow lavas of the Shower Droplet Volcanics at 255086/5571671. The pillow lavas, about 10 m thick, are overlain by a similar thickness of unsorted, poorly stratified volcanic breccia and minor volcanic sandstone. Similar pillow lavas and breccias alternate higher in the succession, with pillow lavas dominating from ~80 m to ~200 m above the base of the formation. The pillows tend to be irregular and more flattened than those of the City of Melbourne Volcanics, and although vesicular, lack the distinct marginal zones of radially orientated vesicles characteristic of the latter. Many pillows of the Shower Droplet Volcanics 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 uppermost part of the lava-dominated part of the succession is of stacked thin (0.1–2 m) vesicular flows with chilled margins. This is overlain by the uppermost ~50 m of exposed section, which consists of well-bedded, coarse-grained volcaniclastic sandstone with thin tabular flows (~0.1 m), many of which have well-preserved ropy tops (fig. 38). These ropy or pahoehoe surfaces have been cited as evidence of subaerial eruption (Waldron and Brown, 1993; Meffre *et al.*, 2004). The base of this uppermost unit occurs at 255152/5570790 and can followed south along strike to Shower Droplet Rock (254892/5570103). At this locality there is a 0.5 m thick bed of welded lapilli tuff (the 'shower droplet rock' of Scott, 1951, p. 117).

The lower part of the Shower Droplet Volcanics is well exposed again on the headland between Conglomerate Creek and The Gut. Here, volcanic breccia abruptly overlies basalt of the City of Melbourne Volcanics, and similar to the type section, breccias and pillow lavas alternate up-section with the lavas becoming predominant. About 10 m of interbedded volcanic breccia and sandstone occurs at the base of the formation south of City of Melbourne Bay. The basal breccia rests abruptly on pillow basalt of the City of Melbourne Volcanics, but there is no erosional truncation of the underlying pillows at the contact. This breccia and sandstone unit is overlain by at least 60 m of dominantly pillow lava (fig. 39).
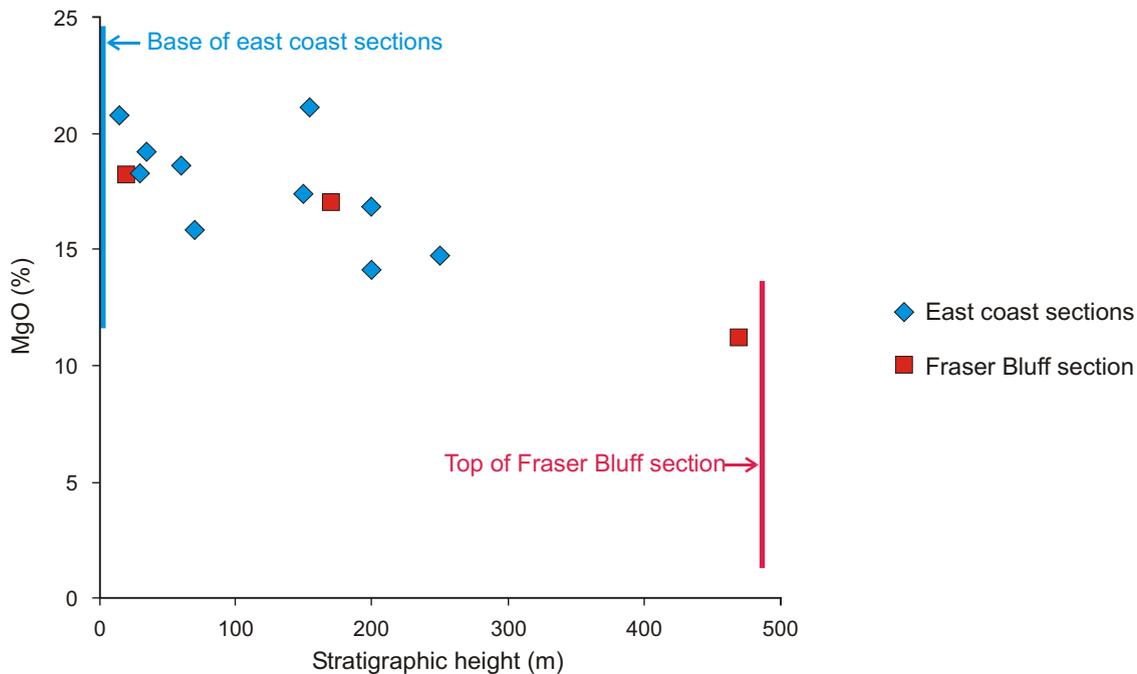
Figure 40

Variation in MgO content with stratigraphic height above base of formation, Shower Droplet Volcanics lavas. Analytical data from Meffre et al., 2004; Everard, unpublished, this work. Analyses of dykes and 'beach boulders' excluded.

A well-exposed fault-bounded section of picritic volcanic rocks between the Naracoopa jetty and Fraser Bluff is about 450 m thick. Petrochemical trends (see below) suggest that the lower half of this section correlates approximately with the type section. The section consists mainly of thin (0.5–1 m) lavas, with lesser intercalated open-framework volcanic breccia with a fine-grained (1–2 mm) matrix carrying the S_3 tectonic foliation. There is rare agglomerate (fig. 19), and a 10 m thick, banded mudstone bed, overlain by a doleritic sill six metres thick, at 254667/5577045. Two ropy-topped (pahoehoe) flows were seen in the upper half of the section. In the uppermost 50 m of this section, thick (several metres or more) massive flows predominate. An analysis of one of these flows (R013175) is relatively low in MgO (11.2%) and compositionally more evolved than other samples.

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

The picritic lavas of the Shower Droplet Volcanics 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 and Brown, 1993; Meffre et al., 2004). There is a tendency for the lavas to evolve to less primitive compositions with time (stratigraphic height). MgO averages 18.5% in the lowest 100 m of the formation, while the youngest sample, just below the top of the formation at Fraser Bluff, is 11.2% MgO. Overlapping compositional trends suggest that the lower part of the Fraser Bluff fault block correlates approximately with the type section (fig. 40).

Grahams Road Volcanics (Lyvg)

This formation has been previously referred to as the 'Upper Tholeiite Sequence' (Waldron and Brown, 1993) and the 'Bold Head Volcanics' (Meffre et al., 2004). The formation comprises a roughly square, fault-bounded area (3 km   3 km) at Bold Head. No base or top to the formation are exposed here, and Waldron and Brown (1993) inferred the Grahams Road Volcanics to be younger than the Shower Droplet Volcanics, as the latter unit is intruded by dykes compositionally similar to the Grahams Road Volcanics. A short section (50 m) of basal Grahams Road Volcanics occurs at Fraser Bluff, conformably overlying the Shower Droplet Volcanics.

The type section is the well-exposed coastal outcrop between Cottons Beach and Bold Point. Inland, the formation is poorly exposed and is bounded to the west by the Grassy River Fault. To the north, in the vicinity of the Bold Head mine, a major east-west fault (the Grahams Road Fault of Brown, 1982a, 1982e, 1983: ~300 m south-side down displacement, fig. 1) separates Grahams Road Volcanics from south-dipping, undifferentiated, older volcanic rocks and 'mine series' (i.e. lower Grassy Group metasediments) to the north. Evidence for the Grahams Road Fault is entirely from drilling and underground mine mapping (Brown, 1983) as surface exposure is negligible in this area. At Cottons Beach, another major east-west fault separates Grahams Road Volcanics from Cottons Breccia and (further inland) Fraser Formation. Strong, broad aeromagnetic anomalies trend SW–NE across the mapped area of Grahams Road Volcanics, and a similar pattern continues seaward east of Bold Head. The trend of the anomalies accords with the observed northeast strike of the formation in the coastal outcrops, which dip moderately (c. 50°) to the southeast. The offshore magnetic anomalies suggest that the Grahams Road Volcanics is part of a thick

(several kilometres) package of east-dipping volcanic rocks (Direen and Crawford, 2003).

The type section is about 1200 m thick and is over 90% exposed. Two informal members can be differentiated. The first, comprising the lower one-third of the type section, consists of massive basalt with many zones rich in quartz-filled amygdales (stacked thick flows), and no intercalated sedimentary rocks. The basalt is strongly magnetic (MS up to 122 10^{-3} SI units). The second member, comprising the upper two-thirds of the section (south of 252600/5564150) is marked by similar, massive amygdular and non-amygdular basalt but has numerous intercalations of volcaniclastic conglomerate and sandstone. Twenty-four such sedimentary units were recorded, ranging from 0.15 m to 20 m thick, comprising in total about 15% of the upper member. The conglomerate is closed-framework, consisting of rounded pebbles and cobbles of basalt (fig. 41). The volcaniclastic sandstone is coarse to fine grained, the latter in one example with cross lamination suggestive of wave action.

The sedimentary units tend to fine upwards, and there is rare reddish-brown siltstone and shale. Several of the sedimentary units have a thin (<0.3 m) basal bed of reddish-brown siltstone, filling irregularities in the underlying basalt and abruptly overlain by conglomerate. A conglomerate unit about 10 m thick on Bold Point (253084/5563468) contains, in addition to basalt clasts, rare (1%) clasts of a whitish fine-grained rock of felsic appearance (top left, fig. 41). Probably the same conglomerate crops out along strike to the southeast, on the tip of the southern point of Bold Head (252175/5562346) where it contains about 5% of the whitish clasts. In thin section one of these (R15036) is an altered basaltic rock type. Nevertheless, Meffre *et al.* (2004) recorded clasts of felsic volcanic rocks with embayed quartz phenocrysts, and of coarse-grained felsic intrusive rocks, in conglomerates of the Grahams Road Volcanics.

Basalt in the upper member is less magnetic than in the lower (MS up to 36 10^{-3} SI units, and mostly less than 10 10^{-3} SI units), except for the uppermost exposed basalt on the end of Bold Point which is 96 10^{-3} SI units. Observed variation in magnetic susceptibility through the type section is broadly consistent with the aeromagnetic anomalies. Pillow lavas were not observed in the Grahams Road Volcanics, although Direen and Crawford (2003) noted them at Bold Point.

About 50 m of massive basalt assigned to the Grahams Road Volcanics overlies the Shower Droplet Volcanics at Fraser Bluff. The top of this section is covered by the sea. In places there are quartz-filled amygdales, and the uppermost exposure is a bed of volcaniclastic conglomerate. An analysis (R013176) is very similar to the Grahams Road Volcanics of the Bold Head area.

The basalts consist of albitised plagioclase and calcic clinopyroxene, with actinolite overgrowths in places. Some flows are porphyritic with phenocrysts of zoned, albitised, partly sericitised plagioclase (up to 6 mm) and diopside (1.5–2 mm) (Waldron and Brown, 1993). The rocks are tholeiites with no marked depletion in incompatible elements, unlike the tholeiites of the City of Melbourne Volcanics.

Figure 41

Volcaniclastic conglomerate in the Grahams Road Volcanics. Note whitish pebble of felsic appearance, upper left. Bold Point [252175/5562346].

Ferruginous silty mudstone (Lyvs)

A wedge-shaped area (0.8 2 km), northwest of Gentle Annie (245400/5563800), consists of white-weathering, purplish-grey to dark grey hard mudstone, massive or faintly parallel-laminated, slightly micaceous, with rare labile silty laminae. A thin section (R013138) shows a ferruginous sandy mudstone. Most of the sand grains are altered to fine-grained chlorite and are probably altered mafic volcanic detritus. Detrital quartz is minor.

This area adjoins Grassy Group volcanic rocks to the south, and an area of probable Robbins Creek Formation to the west. Previous maps show it as Fraser Formation. It is here assigned to the Grassy Group, because:

(1) It is unmetamorphosed and lithologically unlike the Fraser Formation, particularly in the presence of probable altered volcanolithic grains.

(2) Bedding dips gently, in variable directions, discordant to the mapped Fraser Formation nearby.

(3) The magnetic anomaly associated with the volcanic rocks to the south continues under the southern part of this area, suggesting it is underlain by volcanic rocks.

This unit (Lyvs) probably corresponds to a mudstone unit (the 'upper pelitic sediments') within the volcanic succession intersected in Geopeko drilling (Brown, 1975). It has no known correlate on the east coast.

A small faulted outlier assigned to Lyvs occurs in Mount Stanley Creek. This occurrence is lithologically very similar to the area northwest of Gentle Annie (thin section R013145). Bedding dips southwest and these outcrops appear to overlie a small area of mafic volcanic rocks, which in turn overlies dolostone (Cumberland Creek Dolostone?) and Cottons Breccia.

Extending from just south of Gentle Annie to Mount Stanley Road is an area of dominantly contact metamorphosed mudstone (hornfels) shown as Lyvsx, i.e. the contact-metamorphosed equivalent of Lyvs. This is a dominantly massive (uniform) or faintly parallel-laminated, dark grey to black, hard, spotted, very fine-grained hornfels

and baked mudstone. A thin section (R013126) shows a spotted, fine-grained hornfels of biotite, quartz and abundant granular opaques; within the spots, poikiloblastic cordierite (confirmed with XRD) replaces biotite.

Contact metamorphosed lower Grassy Group, including the 'mine series' (Lysx)

The lower sedimentary part of the Grassy Group, contact metamorphosed by Carboniferous granite, occurs in the Mount Stanley–Grassy area and in the vicinity of the old Bold Head mine. It is poorly exposed (except for parts of the open cut mine that remain unflooded), and is mainly shown on the map as a single undifferentiated unit (Lysx). Its mapped distribution is mostly from Geopeko mapping (Brown, 1975), derived from intensive auger drilling. Lysx includes the well documented 'mine series' that hosts the scheelite ore bodies at Grassy and Bold Head.

The 'mine series' stratigraphy at the No. 1 (open cut) and Dolphin mines is summarised in Figure 17 (from Danielson, 1975a; Brown, 1990). Overall the sequence is thinner and richer in carbonate than the sections exposed on the east coast. The units vary strongly in thickness within the extent of the mine. Mineralogy is strongly altered, as detailed by Edwards *et al*. (1956), Large (1971) and Kwak (1978a, b). Mudstones have been converted to fine-grained biotite hornfels and biotite-pyroxene hornfels. Mafic volcanic rockss are metamorphosed to tremolite-forsterite-phlogopite-chlorite-magnetite assemblages. Carbonates, including dolostones, have been converted to coarse-grained calcitic marbles (Large, 1971). The grade of metamorphism is hornblende-hornfels facies.

The Lower Metavolcanics, Biotite Pyroxene Hornfels and Banded Footwall Beds (fig. 17) are probably equivalent to the Robbins Creek Formation. The Banded Footwall Beds likely correspond to the thinly interbedded limestone and shale in the upper part of the Robbins Creek Formation. Correlation of the C lens (mineralised garnet skarn and marble) is uncertain. It may have no equivalent in the east coast sections, or it may correspond to the lower part of the Cottons Breccia that includes intervals of relatively pure carbonate-in-carbonate diamictite. The C lens is the main mineralised horizon at Grassy. The Pyroxene Garnet Hornfels contains pods of marble in a fine-grained matrix of grossularite and diopside; it has long been considered a metamorphic equivalent of the Cottons Breccia (Edwards *et al*., 1956; Large, 1971). Minor scheelite mineralisation is present in the lower part of this unit. The B lens may correlate with the Cumberland Creek Dolostone, and the underlying biotite hornfels could be a mudstone unit at the top of the Cottons Breccia such as is seen at Robbins Creek. The overlying Biotite Hornfels correlates with the Yarra Creek Shale. The Upper Metavolcanics is equivalent to the Skipworth Subgroup (here probably just the picrites of the Shower Droplet Volcanics). The contact at the base of the Upper Metavolcanics is an erosional unconformity cutting down into the underlying stratigraphy (Edwards *et al*., 1956; Gresham, 1972), and northwest-trending faults cutting the mine series appear to pre-date the volcanic rocks (Wesolowski *et al*., 1988). Similar relationships can be identified in the east coast sections, where growth faults affect mainly the units below the volcanic rocks, and where the base of the volcanics is locally an erosional surface, upon Yarra Creek Shale of highly variable thickness (fig. 24).

The structure of the 'mine series' in the No. 1 and Dolphin mines is summarised by Danielson (1975a) and Brown (1989). The mineralised sequence forms a gentle anticline plunging about 30° to the southeast, offset by several northwest-trending faults. The Dolphin ore body is limited to the south and southeast by the Sandblow Granite and to the east by the Grassy River Fault, a north-trending steep normal fault with east-side-down and/or sinistral movement. Detailed plans and sections from mine mapping and drilling are found in Butjor (1973), Danielson (1975b), Anon. (1978), Brown and Potter (1980), Brown (1982b), Butjor (1978) and Turner (1993).

The mine series in the Bold Head mine has a similar stratigraphy to that of the No. 1 and Dolphin mines, and is up to 200 m thick. A marble-skarn unit in a narrow fault block immediately west of the Boundary Fault has been identified as a separate 'A lens' stratigraphically higher than the B lens (Large, 1971; Danielson, 1975a), but it is in fact an upfaulted correlate of the B lens (Brown, 1990). A 'middle metavolcanics' unit 15–40 m thick (possibly a sill) overlies the B lens. The hanging-wall biotite hornfels overlying the B lens (Yarra Creek Shale equivalent) in the Bold Head area is up to 100 m thick (Brown, 1990). Significant mineralisation occurs in both the B and C lenses here.

The Bold Head 'mine series' dips about 17°S, with locally steeper drag against the Boundary and Grahams Road faults to the east and south respectively (Brown, 1981; Anon., 1980). The steep Grahams Road Fault (fig. 1) has a 300 m throw (south-side down) bringing Grahams Road Volcanics against the mine series. The Boundary Fault dips 75°E and downthrows to the west at least 200 m, bringing Fraser Formation against the mine series on the eastern side of the mine block (Anon., 1980). There is a steep intrusive boundary of the mine series with Bold Head Granite to the north and west. The Boundary and Grahams Road faults do not significantly offset the granite intrusive boundaries. The mine sequence is mapped at surface 500 m further east from drilling (Brown, 1981), but does not crop out, is unmineralised and the drill holes are poorly documented.

In the absence of much outcrop, information on Lysx in the Sandblow Granite aureole west of the open cut is mainly from exploration drilling by Geopeko (Brown, 1975). In the Investigator 6 area (about one kilometre west of the open cut), Lysx is about 140 m thick from drilling and dips about 15° south. Six hundred metres further west ('Investigator 6/4') the sequence is only 50 m thick (e.g. DDH INV 6/4-1) and dips 25° south; further west Lysx appears to wedge out beneath the volcanic rocks (Lyv) in an area where surface information is very poor. This is confirmed in drill hole PDH26 on Grassy Road at 246660/5563523, in which volcanic rocks rest directly on 'quartzites' (Fraser Formation) at a depth of 133 m (Brown, 1975). However only one kilometre further west (DDH 214, just south of Gentle Annie) at least 90 m of slightly contact metamorphosed Lysx is present, underlying volcanic rocks at a depth of 130 m (no detailed log or core survives). Similarly at least 120 m of Lysx was intersected in DDH 218 on Mount Stanley Road, and further west, a 'normal'
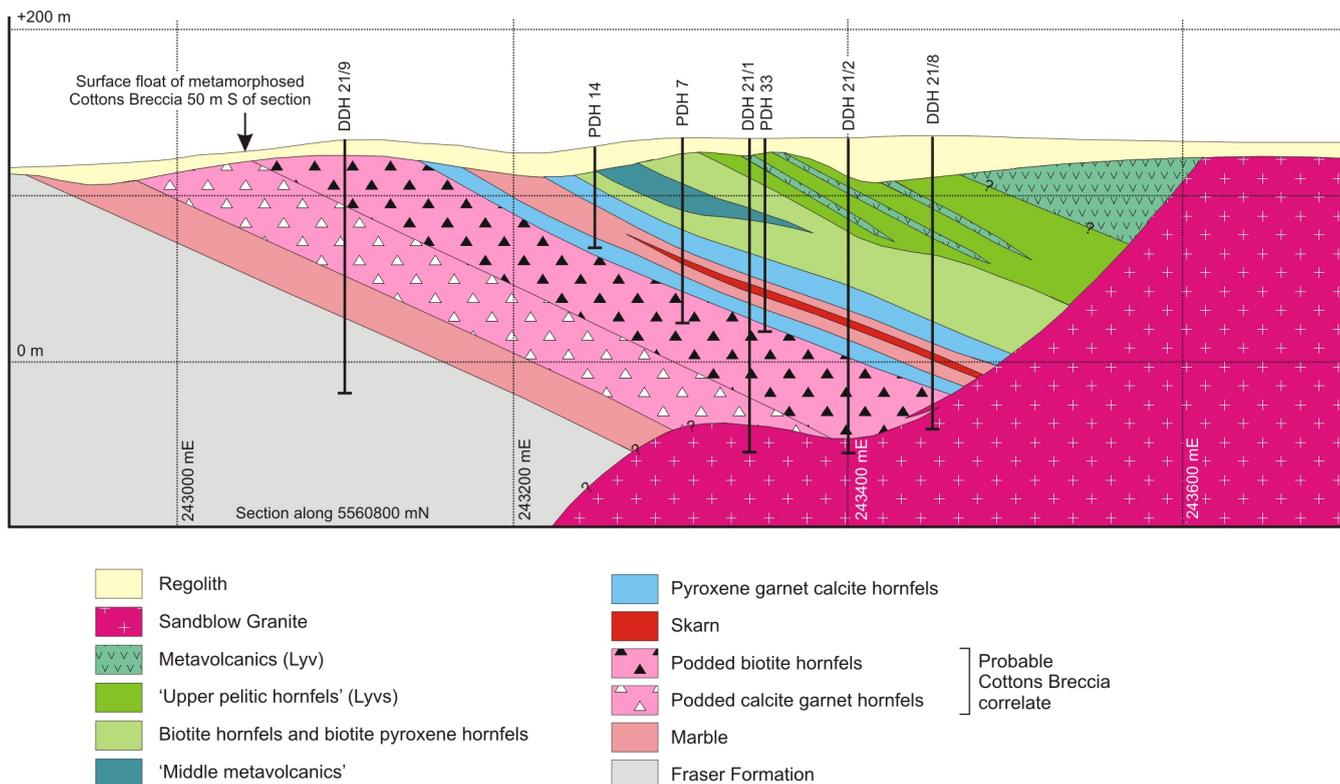
Figure 42

East–west cross section of 'Investigator 21' area (see Figure 1 for location). Adapted from Brown (1975).

thickness of 150–200 m of 'mine sequence' is again present. Closer to the granite contact at 'Investigator 23', drilling intersected volcanic rocks (Lyv) and hornfelsed upper pelitic sediments (Lyvsx) above granite at 110–115 m depth. Minor scheelite mineralisation is here found in carbonate-rich horizons within Lyvsx (Brown, 1975).

At Investigator 3 (Mount Stanley Road), the granite contact dips about 30°N. A 20 m thick 'middle volcanics' unit probably corresponds to rare surface float of a medium-grained intrusive rock (245312/5562370). The sediments dip about 20°S. About 110 m of Lysx is present below the 'middle volcanics'.

Extensive drilling in the Red Hut Road area has outlined the geology on the west side of the Sandblow pluton (Brown, 1975). Surface information (float and outcrop) is rare. About 200 m of 'mine series' (Lysx) is shown by the drilling, and the sequence dips 20–30°E or SE, towards the granite contact, which dips 30–45°W or NW (fig. 42). The lower part of Lysx is in places dominantly 'podded' biotite hornfels and garnet calcite hornfels (e.g. DDH Investigator 21/9: 'podded calcite garnet hornfels' between 38.7 and 81.5 m, similar to the Pyroxene Garnet Hornfels of the open cut). This corresponds to bouldery float and rare outcrop shown on the map as contact-metamorphosed Cottons Breccia (Lyscx) in the west of this area. Lyscx contains angular clasts, up to 100 mm, of carbonate (white sucrosic crystalline marble, usually weathered out), metasiltstone, paler hornfels and secondary quartz replacement, in a fine-grained grey hornfelsic matrix. It is evidently a contact metamorphosed, sparse diamictite with dominantly carbonate clasts. A thin section (R013149) is predominantly diopside with minor calcite and plagioclase. Most clasts are of coarse-grained (1 mm) diopside and calcite, a few are fine-grained quartz or altered plagioclase. XRD also detected grossular, epidote, chlorite and a natrolite group mineral. Bouldery float of thin-bedded carbonate at 242998/5560305 is probably a Cumberland Creek Dolostone correlative.

Scheelite mineralisation at 'Investigator 21' (estimated 200 000 t at 0.47% WO_3 and 0.14% Mo) is associated with calcite hornfels and garnet hornfels just above the 'podded' units, likely an horizon equivalent to the Cumberland Creek Dolostone (fig. 42). As mapped by Brown (1975), the 'upper volcanics' contain significant intervals (which are volumetrically predominant in places) of biotite-quartz hornfels interpreted as pelitic metasediments. Some of this hornfels is mapped instead as Lysx on the Grassy map, i.e. the base of the volcanics is in places further west on Brown's (1975) map.

In the Mount Stanley area Lysx is characterised by rare float and outcrop of tough, black or dark green, fine-grained (<0.25 mm) hornfels, thinly bedded in many cases. Metamorphic spotting is not common. Thin sections show a fine-grained intergrowth of actinolite as columnar to fibrous aggregates, biotite, quartz, altered feldspar and opaques. Two sections (R013127, R013147), of dominantly actinolite, may have a volcanic protolith.

Undifferentiated metabasalts (Lyv)

Undifferentiated basaltic rocks of the upper Grassy Group (= Skipworth Subgroup) and minor associated intrusive rocks occur in the Mount Stanley–Little Annie–Grassy area and near the old Bold Head mine. Most of these rocks are contact metamorphosed to some degree, but there is no

obvious field criterion (such as metamorphic spotting) to allow the aureole to be mapped in Lyv, as it has been in the sedimentary rocks.

Analyses in the Grassy mine area are picritic (Edwards *et al.*, 1956), suggesting the City of Melbourne Volcanics may be absent here. Lyv throughout the Grassy–Mount Stanley–Red Hut Road area is probably predominantly, or entirely picrite (Shower Droplet Volcanics).

Lyv, mapped mainly from sparse float, comprises mainly tough, massive, uniform, fine-grained (<1 mm), grey-green basaltic rocks. In places, small ovoids of dark green chlorite may be amygdules. Thin sections (e.g. R013151) show a fine-grained intergrowth of actinolite, chlorite and minor epidote. An analysis of this rock is picritic (Table 2). Float at 246489/5563672 on Grassy Road is, in thin section (R013106), seen to be a picritic hyaloclastite of irregular, altered, formerly probably glassy fragments, with abundant phenocrysts and glomerocrysts, formerly probably euhedral olivine, altered to epidote, actinolite and quartz. In a few places there is float of fragmental volcanic rocks (not mapped, but identified on the observations spreadsheet). At 244018/5561618 (near the base of Lyv just west of Red Hut Road), there is float of open-framework volcanic breccia with fragments up to 100 mm across.

Medium-grained (1–2 mm) massive mafic rocks are also found in this area. Some can be mapped as apparently concordant, sill-like bodies within Lysx, and are shown as intrusive rocks (Lyvb) on the map. A thin section of one (R13150) shows augite, largely replaced by fibrous actinolite, in a groundmass of fine-grained chlorite; an analysis of this rock is picritic (Table 2).

Magnetic susceptibilities are variable and generally high (Table 3). The generally strong response on the TMI image merges with the adjacent, similarly magnetic Sandblow Granite.

Neogene

Limestone (Tm)

Mr J. Davis showed me some fragments of porous, fossiliferous limestone dug out of a dam on his property near Ettrick River (239445/5569038, northern Pearshape map sheet). A thin section (N58) shows a weakly cemented, porous bioclastic limestone of bryozoan, foraminiferal and indeterminate fossil fragments, with sparse, well-rounded quartz sand grains. A palaeontological assessment of this sample by Professor P. Quilty is given in Appendix 1. Miocene limestone is known from several other localities on King Island (Crespin, 1945; Jennings, 1959; Quilty, 1972). This occurrence is of interest as it appears to be from the highest elevation yet recorded (c. 75 masl) on King Island. Miocene marine rocks are known from as high as 160 masl in northwest Tasmania (Quilty and Seymour, 2010).

Semiconsolidated coarse-grained sand and gravel (TQsg)

In the northwest of the Naracoopa map, at about 60 m elevation, there is outcrop (242963/5579564) of semi-consolidated closed-framework pebble-cobble gravel with subrounded clasts up to 200 mm diameter of mudstone,

Figure 43

Ironstone outcrop: note vuggy, cemented conglomeratic texture.

siltstone (Fraser Formation), schist (Surprise Bay Formation) and vein quartz. Similar cobbles are found as sparse lag in the generally sandy soils of the surrounding area. Nearby (at 242693/5579234), at a similar elevation, boulders and outcrop in a dam are of semi-consolidated well-sorted coarse-grained quartz sandstone with sparse pebbles of siltstone and mudstone. The sandstone is massive or parallel laminated. These deposits are probably high-level shoreline (beach) sediments laid down during post-Miocene uplift.

Quaternary

Ironstone (Qf)

Outcrops and bouldery float of ironstone are common across the Pegarah Plateau. In places the ironstone forms small plateaux raised 1–2 m above surrounding country. Ironstone has been extracted on a small scale in many places for surfacing roads and cow lanes.

The ironstone is a surficial deposit. Exposed profiles, typically about two metres thick, show an upper solid dark red-brown ironstone with small voids (fig. 43), grading down into earthy, limonitic, rubbly yellow-brown ironstone, often with inclusions of quartz sand grains and iron-stained angular bedrock fragments. The ironstone is thought to be formed by oxidation and precipitation of dissolved iron in reduced groundwater that reaches the surface ('bog iron', typically of goethite and minor magnetite).

Ironstone bodies mapped in the centre of the Naracoopa sheet, straddling Pegarah Road, are aligned along 2.5 km of the inferred northern extension of the Grassy River Fault. These deposits probably result from a locally elevated flux of groundwater from the fractured fault rocks. Named the 'Investigator 15' prospect by Brown (1974), these deposits are associated with small aeromagnetic anomalies. Analysed samples lacked anomalous base metal values, but were up to 53.4% Fe, 5.1% Mg and 0.7% Mn (Brown, 1974). Mapped ironstone deposits near Brumbys Road (246341/5576100) and near Conglomerate Creek (251910/5569745) also coincide with small aeromagnetic anomalies. Measured magnetic susceptibility is up to 62 $\times$ 10^{-3} SI units (Table 3).

Stabilised aeolian sand of coastal plain (Qpsa)

Broad sandy flats mapped as Qpsa extend from the western parts of the Grassy and Naracoopa map sheets (where the sand sheets cover the Proterozoic bedrock), westward to where they are in turn covered by younger vegetated dunes (Qhd) on the Pearshape map sheet. Low radiometric response has been used as an aide in mapping Qpsa. Excavations to two metres depth show humic-stained, weakly cohesive, fine to medium-grained quartz sand.

Older dune sand and minor clay, peat and gravel (Qpswu)

These areas consist mainly of leached, pale grey fine-grained quartz sand. They correspond to the 'Old Dunes' of Jennings (1959). Dune morphology is generally not preserved. Some areas are near the coast, while others are well inland on the Pegarah Plateau; all are dark on radiometric images. Many isolated patches of pale grey, fine-grained quartz sand subsoil are found on the Pegarah Plateau (observations spreadsheet), but most do not form mappable areas.

A section about 15 m thick of sand, gravel and peat is exposed in the southwest wall of the open cut at Grassy (249036/5562040). This is predominantly medium to coarse-grained, bedded, semiconsolidated quartz sand with some brown, humic-stained beds and 300 mm of sandy peat near the top. A bed of rounded cobble gravel at the base of this section, resting on metavolcanic basement, is at about 25 masl.

Further southwest, 16 auger holes between the open cut and Sandblow Point showed 0.25–0.3 m of humus underlain by 0.8 to 3.7 m of white, fine-grained quartz sand, then brown clayey sand (Mathison, 1992).

Vegetated dune sand (Qhd)

Vegetated dune sand, with longitudinal, parabolic and U-dune crests preserved, occurs adjacent the east coast at Fraser Beach, Bold Head and Grassy Harbour, and covering much larger areas in the west (Pearshape map sheet). These areas correspond to the 'New Dunes' of Jennings (1959). The sand is siliceous on the east coast, but calcareous in the west (Jennings, 1959). The western area has a dark pink (slightly potassic) response on the KThU RGB radiometric image, probably resulting from a relatively fresh granitic component.

Beach and dune sand; shingle (Qhb, Qhbg)

These include modern beach sands and gravel, which on the western side of Grassy Bay are derived from wave reworking of the mine dump adjoining to the west.

Mine tailings, landfill, etc. (Qhm)

Mine tailings and overburden cover areas south and east of the open cut. The area of mine tailings to the east of the open cut comprises a 500 m wide area reclaimed from the sea. Some of the Grassy mine tailings, and those adjacent to the Bold Head mine decline, are currently being used as road material. Fine tailings have accumulated in a shallow tailings pond, now dry, behind the dune north of Grassy Bay.

INTRUSIVE ROCKS

Proterozoic(?) mafic intrusive rocks in the Surprise Bay Formation

Minor mafic dykes and sills in the Surprise Bay Formation can be differentiated into three types: amphibolites, altered dolerites and mafic feldspar porphyries. None of these rocks show S_1 cleavage. At least some of the altered dolerites and feldspar porphyry are Cryogenian or younger (post-Loorana Granite).

Amphibolite (R15804, Ettrick River) consists of dark green hornblende (1 mm) with minor plagioclase and opaques. The rock appears fresh in thin section, unlike the other types. As the hornblende is of metamorphic origin, this rock likely pre-dates regional metamorphism, which is thought to be c. 1290 Ma in the Surprise Bay Formation (Berry *et al.*, 2005).

Altered dolerites from widespread localities (R15006, R15805, R15809, R15810, R15813) are of variable grainsize (up to 2 mm), with fine-grained chlorite and other alteration products usually replacing most or all of the ferromagnesian minerals and much of the plagioclase. R15006 and R15805 still preserve clinopyroxene. An altered dolerite dyke north of Millers Bay (at 233979/5569908) is 30 m wide and splits into two narrower dykes going northwards. A five-metre wide altered dolerite dyke at Ettrick Bay (234238/5567993) cuts a small body of granitic pegmatite and so is probably post-Loorana Granite, i.e. <748 Ma.

Feldspar porphyry consists of abundant tabular plagioclase (labradorite) phenocrysts up to 15 mm long in flow alignment, in a dark green fine-grained groundmass. No ferromagnesian minerals are preserved in thin section (R15812). A 20 m wide sill of this porphyry occurs on the south shore of Ettrick Bay and is seen again on the coast 600 m along strike to the south. A similar porphyry intrudes (and therefore post-dates) the Loorana Granite at 231473/5573248 on the Currie map sheet.

Proterozoic hornblende amphibolite (Laa)

Several coarse-grained amphibolite bodies, probably regionally metamorphosed gabbroic intrusive rocks within the Fraser Formation, were mapped in the central and western Naracoopa map sheet and north–central Grassy map sheet. This rock type is more erosionally resistant than the Fraser Formation and occurs as sparse bouldery float. Being regionally metamorphosed, the amphibolites are probably Mesoproterozoic (c. 1300 Ma).

No contacts with the Fraser Formation are exposed. Most of the mapped amphibolite bodies lie within the central, gently south-dipping area of the Fraser Formation (domain 4, see below). Narrow (<100 m) elongate bodies (e.g. crossing Robbins Road) could be dykes. The two large irregular bodies in the central north Naracoopa sheet could be gently dipping, relatively thin sills (see *Structure* section). A drill hole (DDHR01 at 247700/5574500 and inclined at 45°SE) just inside the southeast mapped margin of the large Pegarah amphibolite body encountered 'black shale and quartzite'

(Fraser Formation) at ten metres, showing that this contact dips gently northwest (Leckie, 1968).

The amphibolite is massive, black and coarsely crystalline (up to 10 mm), weathering to pale brown. Thin sections consist mainly of green hornblende as coarse anhedra enclosing laths of plagioclase (~20%), minor opaques (~5%) and very minor brown biotite. The plagioclase in R013121 is approximately An_{42} (andesine) (optical determination). Two analyses from the largest body and one from a smaller intrusion southeast of Pegarah (Table 1) indicate a moderately fractionated, low-K tholeiitic magma, relatively depleted in incompatible elements.

The amphibolites have low magnetic susceptibility (measured at up to 1.2 10^{-3} SI units). The narrow dyke-like bodies do not show up on images of total magnetic intensity, while the larger bodies have a subdued lumpy signature that is not readily distinguished from the surrounding Fraser Formation (fig. 44). The amphibolite along the Pearshape Fault just west of Sea Elephant River (242000/5578000) has a stronger aeromagnetic response; modelling indicates an effective magnetic susceptibility of around 7 10^{-3} SI units and a steep westerly dip (see *Magnetic Interpretation*).

The five kilometre wide 'Pegarah gravity high' covers the two large bodies between Pegarah and Naracoopa (Young and Mathison, 1994).

Proterozoic dolerite (Lmd)

There are minor, isolated occurrences of altered medium-grained mafic rocks, probably dolerite dykes, within the Fraser Formation and Surprise Bay Formation on the Naracoopa map sheet. Float associated with amphibolite (Laa) southwest of Pegarah is wholly altered to chlorite and minor secondary quartz (R15013). Other samples (R013188, R15006) preserve clinopyroxene and plagioclase. The least altered occurrence (R013188) is found as bouldery float inland from Fraser Bluff. Similar, more altered dolerite crops out in Denbys Creek, 900 m to the south. A thin section of R013188 shows an equigranular dolerite (1 mm grainsize) of columnar augite and feldspar and anhedral quartz. An analysis is distinctly more felsic (54% silica) than the amphibolite (Laa), and similar to the amphibole hornfels of the Fraser Formation (Lfa, Lfc).

Ediacaran Grimes Intrusive Suite (Lyg, Lygc, Lygd)

The Grimes Intrusive Suite is the name given (Meffre *et al.*, 2004) to sheets and sills of variable but broadly intermediate composition that intrude the lower Grassy Group north of City of Melbourne Bay. The sills were shown as 'dolerite' on some early maps (e.g. Gresham, 1972). They were analysed and described by Waldron and Brown (1993), who referred to them as 'syenite dykes'. Meffre *et al.* (2004) demonstrated a petrogenetic link to the Skipworth Subgroup, which is supported by dating (575   3 Ma for the Grimes Intrusive Suite: Calver *et al.*, 2004; and 579   16 Ma for the upper two
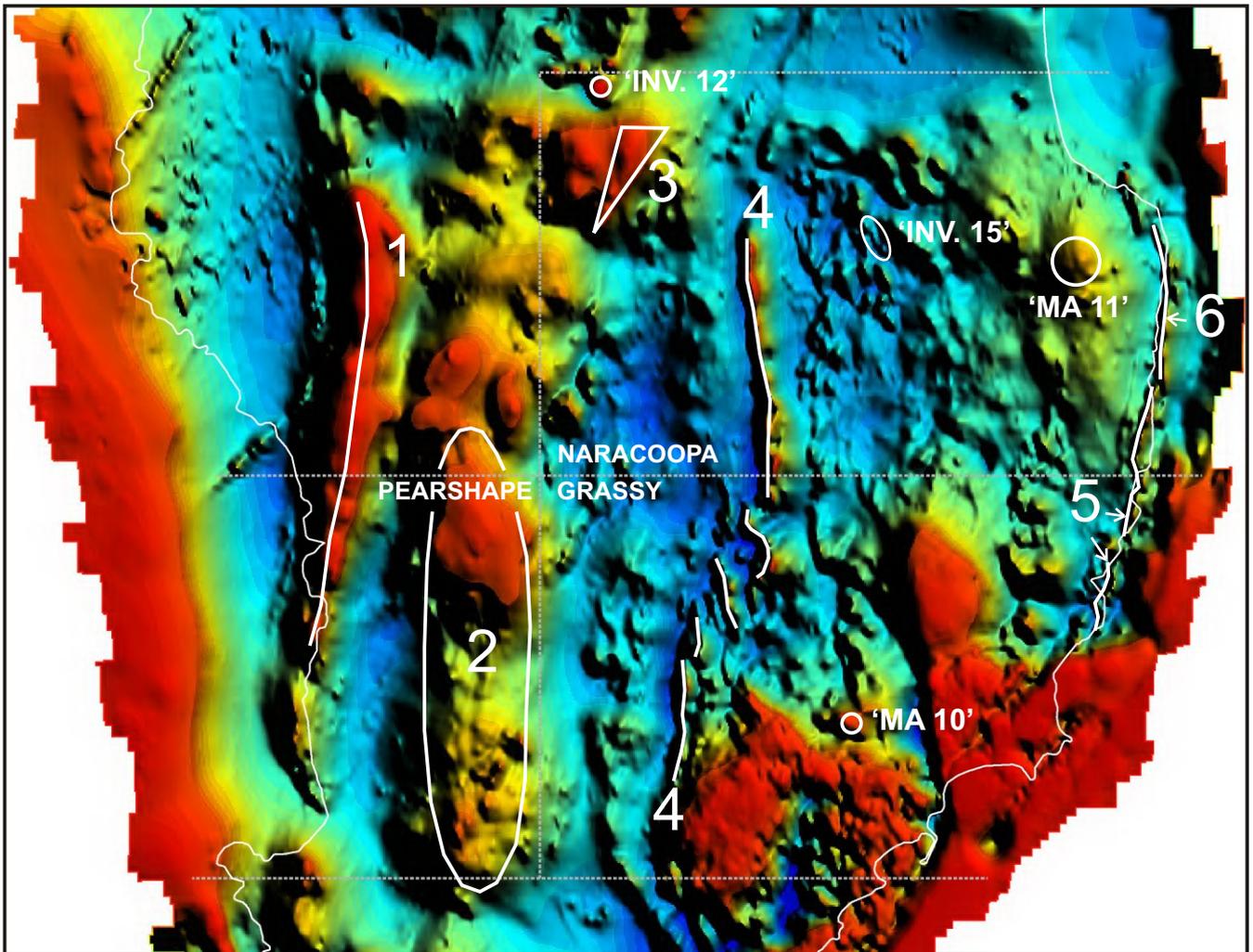
Figure 44

*Aeromagnetic anomaly image (total magnetic intensity) of southern King Island,
with numbered anomalies corresponding to discussion in text.*

units of the Skipworth Subgroup: Meffre *et al*., 2004). The new mapping shows:

(1) the Grimes Intrusive Suite between the Barrier Creek Fault and City of Melbourne Bay is a single sheet that gently transgresses up through the stratigraphy from north to south (fig. 24);

(2) a more mafic phase, here named the Denbys Dolerite, occurs further north (Fraser Bluff to Barrier Creek Fault);

(3) emplacement of the Grimes Intrusive Suite was associated with faulting;

(4) the timing of emplacement correlates with a stratigraphic level high in the Yarra Creek Shale.

Denbys Dolerite (Lygd, Lygc)

The Denbys Dolerite, here defined, is a 250 m thick sill of dolerite and gabbro intruding the lowermost Grassy Group just south of Fraser Bluff. The name is derived from nearby Denbys Creek (255200/5575000). The type section extends from the stratigraphically lowermost outcrops of gabbro on the escarpment (at 255175/5575850) eastward to the coast, where the upper contact is exposed around 255430/5576000. The lower contact is not exposed, and a covered interval a few metres wide between highest Fraser

Formation outcrop and lowest gabbro could conceal basal Robbins Creek Formation below the gabbro. The top of the sill is a conformable contact with overlying contact-metamorphosed laminated shale assigned to the Robbins Creek Formation. The basal cumulate (Lygc), a coarse-grained (3 mm) black gabbro, is about 100 m thick. A thin section (R013185) shows coarse orthopyroxene and clinopyroxene poikilitically enclosing serpentinised olivine, with minor biotite. Meffre *et al*. (2004) also noted chromite and phlogopite. Lygc is strongly magnetic (unlike other parts of the Grimes Intrusive Suite), with a measured magnetic susceptibility of up to 52 $\times$ 10^{-3} SI units. A corresponding linear magnetic anomaly extends southward from the coastal outcrop, to just offshore of The Wall, terminating at the offshore projection of the Barrier Creek Fault. The dolerite (Lygd), comprising the rest of the sill above the basal cumulate, is about 150 m thick. This is a grey, coarse-grained rock dominantly of columnar clinopyroxene up to 4 mm long with an abundant mesostasis of quartz generally showing micrographic intergrowth with probable feldspar, and minor plagioclase and biotite.

The basal cumulate gabbro is 45–49% SiO_2 and 16–30% MgO, with relatively high incompatible element abundances, and strongly enriched LREE (two analyses by Meffre *et al*.,

2004). Three analyses of the dolerite are 52–53% SiO_2 and distinctly more mafic than the intermediate phase of the Grimes Intrusive Suite (Table 2).

Intermediate phase (Lyg)

South of Barrier Creek, the intermediate phase (Lyg) intrudes at a level near the top of the Robbins Creek Formation. It thickens from about 80 m (Robbins Creek, Cumberland Creek) to 147 m in Conglomerate Creek. Just south of Conglomerate Creek it transgresses upwards to a level within the Cottons Breccia. Just south of The Gut, relationships are obscured by faulting and lack of outcrop, but at Skipworths Creek the sheet re-appears at a level within the Yarra Creek Shale, where it may be c. 80 m thick. Another fault is crossed further south, then the Grimes Intrusive Suite is seen as a 15 m thick sill within the Yarra Creek Shale on the northern side of City of Melbourne Bay. This is its southern known limit (fig. 24).

Lyg is well exposed in Conglomerate Creek. A basal cumulate, about 40 m thick, is present but not distinguished on the map. This is an altered, more or less equigranular gabbro or dolerite, dominantly clinopyroxene (2 mm) with lesser plagioclase (5 mm) and opaques. A cumulate sample from the stratigraphically lowermost outcrop in Conglomerate Creek was dated by SHRIMP (U-Pb on zircon) at 575 3 Ma (Calver et al., 2004). The dated sample (R005945) has clinopyroxene and amphibole in thin section but is largely altered to fibrous chlorite and minor talc. The main mass of the sill is a massive, pale to medium grey, very fine-grained microdiorite with needle-like phenocrysts of plagioclase up to 10 mm long. Thin sections show an open mesh of 20% needle-like plagioclase phenocrysts and a similar proportion of a columnar phase (3 mm, probably clinopyroxene) entirely replaced by chlorite and hornblende. The groundmass is quench-textured (fibrous to snowflake textured) and mainly chlorite, plagioclase and quartz (XRD determination).

The much thinner (15 m) southern extremity of the intrusion is well exposed on the north shore of City of Melbourne Bay and for about 200 m north. Here the rock contains chlorite-filled spheroidal amygdules about 5 mm in diameter, which are concentrated in the upper part of the sill. The rock, pale grey and aphanitic with acicular plagioclase phenocrysts, is similar to, but finer-grained than the predominant Conglomerate Creek microdiorite. In thin section it is quench-textured, with about 10% skeletal hollow plagioclase needles (up to 3 mm   0.1 mm) in an irresolvable groundmass with a fibrous, feathery texture in which at least some of the crystallites are feldspar. XRD of sample R002630 indicates predominant chlorite, quartz and plagioclase, and minor K-feldspar and mica. There are sparse microphenocrysts of chromite (0.3 mm) that in one sample are concentrated at the edges of the amygdules (also observed by Meffre et al., 2004). Upper and lower contacts are well exposed. The sill here intrudes Yarra Creek Shale consisting of interbedded pale yellow-brown and black shale. The lower contact is planar to gently undulose. The upper contact has, at one location (253842/5567517), a straight-sided dyke-like apophysis, normal to bedding, and displaying a right-angle bend in plan view, suggesting the enclosing shale was consolidated and jointed at the time of the intrusion (Calver et al., 2004). No peperitic contacts were observed on Grimes sills (cf. Meffre et al., 2004, p. 181).

About 20 m stratigraphically higher than the Grimes sill on the north shore of City of Melbourne Bay, a second but much thinner (<300 mm), irregular sheet of grey-white, aphanitic rock intrudes the Yarra Creek Shale, just below the upward transition from pale yellow-brown to red shale. This can be followed for about 40 m, transgressing generally downwards to the south by several metres. Concordant sections alternate with steeply discordant sections, and small examples of wedging, stoping (fig. 45) and differential dilatation associated with movement of the country rock on a small steep fault (fig. 46) can be seen. (The latter process, on a regional scale, appears to have accompanied the intrusion of the main sheet; see Figure 24). The contacts are in places irregular, but neither joint-bounded nor peperitic. The host sediment was probably weakly consolidated at the time of intrusion.

The upper and middle parts of the sills of the intermediate phase are 57–64% SiO_2 and are thus broadly andesitic in terms of SiO_2 content (Waldron and Brown, 1993; Meffre et

Figure 45

Small sill of Grimes Intrusive Suite, north shore of City of Melbourne Bay, showing wedging and incipient stoping (contacts accentuated with white dashed line) [253855/5567441].

Figure 46

Small sill of Grimes Intrusive Suite, north shore of City of Melbourne Bay, showing differential dilatation associated with small fault (F) in sediments above the sill [253842/5567427].

al., 2004). However the high MgO, Cr and Ni contents indicate partial derivation from mafic sources (Meffre et al., 2004). An analysis of the dated basal cumulate sample (R009545) is similar to the two analyses from Lygc (the basal cumulate of the Denbys Dolerite). It is not clear whether the Denbys Dolerite sill was originally laterally continuous with the intermediate phase prior to faulting, or if there were two intrusions of slightly different ages. Overall, the Grimes Intrusive Suite is enriched in radiogenic Nd and has low Nd (Meffre et al., 2004). Meffre et al. (2004) showed that the composition of the Grimes Intrusive Suite is consistent with derivation from three components: crustal, picritic and enriched basaltic melts.

Age relationship with the Grassy Group

The age relationship of the ~575 Ma Grimes Intrusive Suite to the Grassy Group is relevant to the issue of age constraints on the base of the Ediacaran System, which are very poor in Australia even though the Flinders Ranges (S.A.) is the site of the GSSP (Global Stratotype Section and Point) (Knoll et al., 2004; Calver et al., 2004; Calver, 2008b, 2009). Meffre et al. (2004) considered the Grimes Intrusive Suite to be older than the City of Melbourne Volcanics, as intrusions are apparently restricted to the Yarra Creek Shale and older units. These authors also showed that there are compositional similarities (such as evidence for significant crustal contamination) between the Grimes Intrusive Suite and the City of Melbourne Volcanics. Peperitic margins to the Grimes sills were noted by Meffre et al. (2004) and Crawford et al. (2009), implying near-contemporaneity with enclosing sediments. My own observations on the margins of the stratigraphically highest sills just north of City of Melbourne Bay indicate that the Yarra Creek Shale was at least partly lithified at the time of intrusion (Calver et al., 2004, and above).

The mapping shows that the thickness of the Yarra Creek Shale varies from ~15 m to >100 m, with abrupt changes coinciding with northwest-trending faults. The sill comprising the intermediate phase of the Grimes Intrusive Suite (Lyg) varies in thickness (~15–150 m), in an approximately inverse relationship with the thickness of the Yarra Creek Shale in different fault blocks (fig. 24), indicating that its emplacement was related to, and in part the cause of, the fault movements that affected the Yarra Creek Shale. The thickness of other units, including the Cottons Breccia and City of Melbourne Volcanics, is less affected by penecontemporaneous fault movement. This evidence shows that the Grimes Intrusive Suite is older than the City of Melbourne Volcanics, but younger than at least the lower part of the Yarra Creek Shale, which it intrudes (Calver, 2008a; 2009). Its emplacement likely corresponds to the erosional break at the top of the Yarra Creek Shale north of the Gut Fault (fig. 24), and to an unidentified horizon within the upper part of the Yarra Creek Shale in the City of Melbourne Bay section.

Ediacaran basaltic intrusive rocks (Lyvb)

Basaltic dykes and sills are common in the Grassy Group, and many have been linked compositionally or petrographically with Skipworth Subgroup units (Waldron and Brown, 1993; Meffre et al., 2004). Tholeiitic (Lyvbt) and picritic (Lyvbp)

intrusive rocks are differentiated on the Grassy and Naracoopa maps. Because of cartographic limitations, only a small proportion of occurrences are shown on the maps (see *Observations* spreadsheet for the complete data).

Tholeiitic intrusive rocks (Lyvbt)

Sills compositionally similar to the City of Melbourne Volcanics intrude the Yarra Creek Shale in two separate areas; Robbins Creek–Cumberland Creek and City of Melbourne Bay. In Robbins Creek, a 30 m thick sill occurs in the middle of the Yarra Creek Formation and may be continuous with a similar body in Cumberland Creek. A thin section (R013113) shows a fine-grained (0.1 mm) intergranular texture of dominantly clinopyroxene and lesser columnar plagioclase up to 0.5 mm long, secondary chlorite and carbonate, and chlorite-filled amygdules 0.5 mm in diameter. Two sills intruding red mudstone on the southern shore of City of Melbourne Bay are 10 and 20 m thick, and related to the City of Melbourne Volcanics (Waldron and Brown, 1993). About 500 m to the north, thicker basaltic bodies intrude the Yarra Creek Shale around the mouth of Skipworth Creek. An analysis from here and one from Robbins Creek show that these sills belong to the more mafic subgroup of the City of Melbourne Volcanics, relating them specifically to the lower breccia unit (see above). Sills are absent from the thin, upfaulted Yarra Creek Shale between these occurrences.

Dykes up to six metres wide, related to the Grahams Road Volcanics, are locally found in the Shower Droplet Volcanics and older units. These commonly have feldspar phenocrysts (Waldron and Brown, 1993) and are usually strongly magnetic. At Cottons Beach (253033/5565562) a distinctive basaltic dyke, 0.3–2 m wide, with abundant rounded feldspar phenocrysts up to 10 mm in size, intrudes Cottons Breccia and can be followed for 250 m, transgressing up through the stratigraphy going north. Dykes related to the Grahams Road Volcanics have a strong preferred tilt-corrected northeast strike (fig. 47).

Picritic intrusive rocks (Lyvbp)

An altered picritic sill about 20 m thick is found in Yarra Creek just above the basal conglomerate of the Robbins Creek Formation. This is a massive, pale grey, granular talc-carbonate rock. A thin section from the lowest five metres shows a cumulate texture with glomerocrysts of former olivine, outlined by a dusting of iron oxide, wholly altered to talc and chlorite; the only remaining primary mineral is minor rounded and embayed chromite. Several other small picritic intrusions were identified by Waldron and Brown (1993).

Undifferentiated basaltic intrusive rocks (Lyvb)

Of many recorded occurrences, two undifferentiated basaltic intrusive rocks are worthy of note. A massive basaltic body concordantly overlies Robbins Creek Formation 700 m south of Fraser Bluff, with its top covered by sea. This unit is of subequal fresh augite (0.5 mm) and subophitically enclosed, wholly altered laths, probably originally plagioclase, with much fine-grained chloritic alteration product. There are minor spherical chlorite-filled

A: Dykes coeval with Cottons Breccia

N = 4

B: Grimes Intrusive Suite

small syn-intrusion fault

apophysis at top of sill

N = 5

C: Dykes associated with Grahams Road Volcanics

N = 9

D: Dykes associated with Skipworth Subgroup (undifferentiated)

lower tholeiite

N = 13
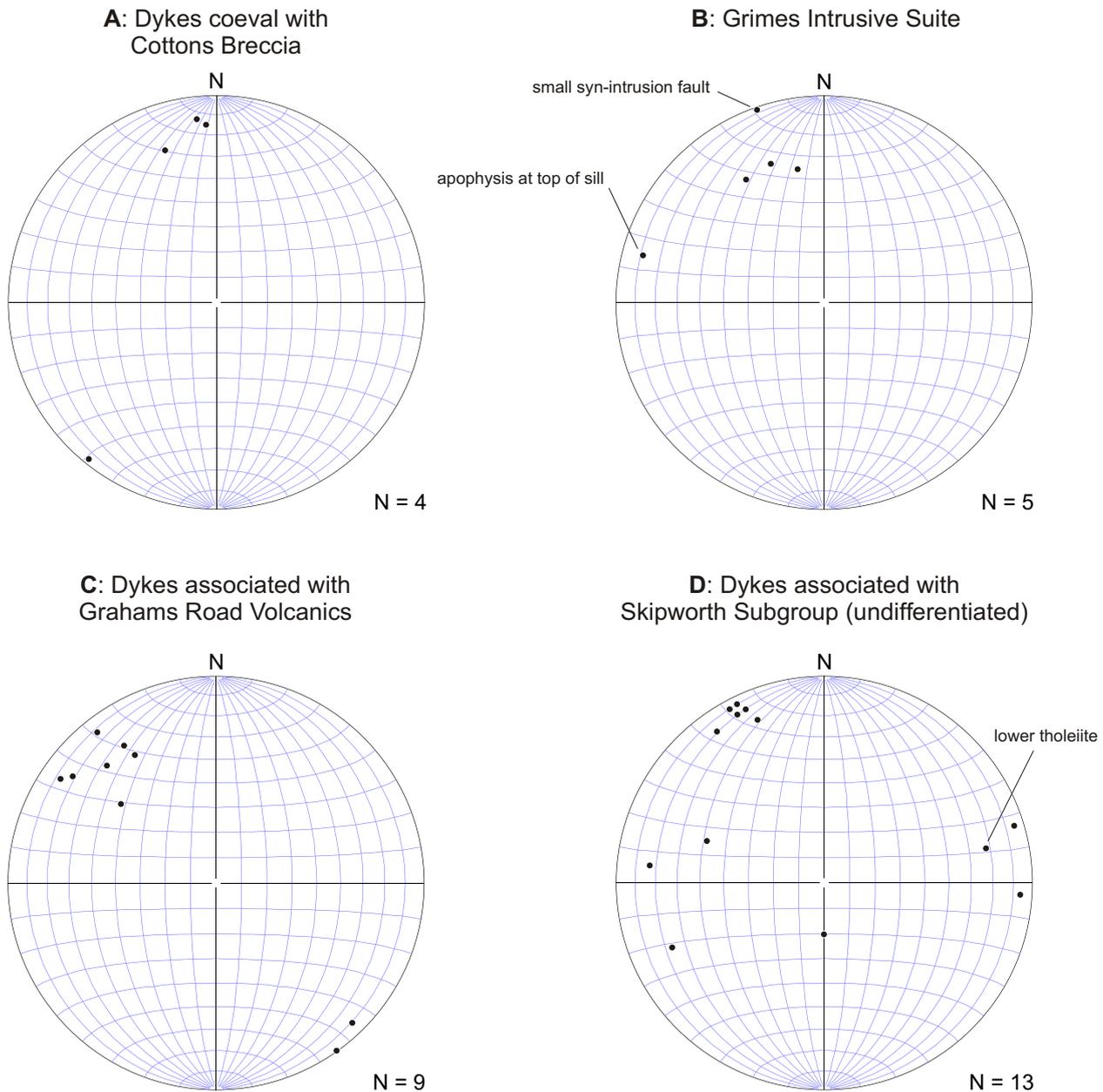
Figure 47

Equal area projection of dyke orientations, tilt corrected by rotating bedding of adjacent country rock to horizontal.

amygdules (0.5 mm). An analysis (R013183) is difficult to classify with the other units (fig. 23) and is similar in some respects to the more mafic grouping of the City of Melbourne Volcanics.

Another three metre thick concordant body in the Robbins Creek Formation in Robbins Creek (R013114) is an equigranular rock (~1 mm), dominantly plagioclase, with much secondary chlorite and carbonate, and an originally mafic(?) equant phase entirely replaced by chlorite. Small (0.7 mm) spherical amygdules filled with chlorite and carbonate are present. An analysis of this sample is similar to the Denbys Dolerite (fig. 23).

Carboniferous monzogranite (Dgns) and microgranite (Dgnsf)

Carboniferous monzogranite, here named the Sandblow Granite (formerly Grassy Granite or Grassy Granodiorite),

forms an ovoid pluton seven kilometres wide southwest of Grassy. Very similar monzogranite comprises the ~1 km^2 Bold Head Granite, which is probably an outlier of the same pluton offset by movement on the Grassy River Fault (Wormald, 1990; Black *et al.*, 2005). Modelling of gravity data suggests that the granites underlie much of the western Grassy map sheet and Pearshape map sheet at depths of one to two kilometres, deepening rapidly to about nine kilometres towards the east coast (Leaman and Richardson, 2003; section, fig. 1).

The close association of the granites with scheelite mineralisation has led to a number of previous detailed studies (Edwards *et al.*, 1956; Wesolowski *et al.*, 1988; Wormald, 1990). Wesolowski *et al.* (1988, p. 241) state: "Generally, the granitoids consist of 10% to 15% euhedral alkali-feldspar phenocrysts up to 2 cm by 3 cm by 1 cm in a coarse matrix with average grain size of around 2 mm to 3 mm. The matrix consists of quartz, oligoclase, alkali

feldspar, biotite and hornblende". Emplacement occurred at pressures of approximately 1 to 2 kb and depths of four to seven kilometres (Wesolowski *et al.*, 1988). The Sandblow Granite is 'a relatively oxidised, magnetite-bearing, unfractionated, I-type hornblende-biotite monzogranite', dated at 350.8   1.7 Ma or early Carboniferous (SHRIMP U-Pb on zircon) (Black *et al.*, 2005). It is the youngest known of the Tasmanian Devonian–Carboniferous granites, and is the least felsic in western Tasmania (SiO_2~68–69%).

The new mapping has shown a number of microgranite dykes (Dgnsf) up to 1.2 km long on the Grassy and Naracoopa maps that are distant from the Sandblow and Bold Head granites. These are based on mapping of sparse float (see *Observations* spreadsheet) and one outcrop. In addition, a number of single, isolated surface fragments of microgranite are shown on the map as 'notable float'. Typical thin sections (R013153, R13193) show phenocrysts of euhedral hornblende, K-feldspar and rounded quartz in a groundmass of feldspar, hornblende, quartz, chlorite and alteration products.

Indications of possible subsurface granite, Barrier Creek area

Hydrothermal alteration is associated with the Barrier Creek Fault. Outcrop of brecciated City of Melbourne Volcanics near the fault on the coast is strongly carbonate altered. The Fraser Formation and Yarra Creek Shale are strongly silicified here. The Barrier Creek Ag-Pb-Zn lodes are found inland, close to the fault (see *Economic Geology*). Further inland the fault passes near the Millwood quarries where quartz veins up to two metres wide, and disseminated tourmaline (sample R013190), are found in the Fraser Formation. The Millwood quarries directly overlie the summit of a long wavelength 60 nT magnetic anomaly (MA11, fig. 44, see *Magnetic interpretation*) that has been attributed to a subsurface granite cupola (Brown, 1974). However gravity-based modelling shows granite to be deep here (6–9 km: Leaman and Richardson, 2003).

Feldspar porphyry of uncertain age

A small outcrop of altered feldspar porphyry occurs in Yates Creek (248333/5577268). A thin section (R15004) shows feldspar phenocrysts up to 2 mm in size partly replaced by epidote and chlorite. The groundmass is of altered feldspar and chlorite. Quartz is absent. Assignation to Dgnsf (as shown on the map) is doubtful. Short intersections of feldspar porphyry were noted in the Irelands Farm prospect drill holes (Leckie, 1968).

Cretaceous lamprophyre (Kal)

A lamprophyre dyke intruding the Shower Droplet Volcanics on the coast south of Cumberland Creek (255012/5571383) is described by Waldron and Brown (1988). It is 520 mm wide and strikes to 055°, and contains high grade metamorphic xenoliths. Probably the same dyke was dated by McDougall and Leggo (1965) at 143   3 Ma (Early Cretaceous) (Waldron and Brown, 1988).

Paleogene basaltic rocks (Tb, Tbb)

Basalt float is scattered over a gentle knoll one kilometre north of Adams Road in the northwest corner of the Naracoopa sheet. This basalt, a basanite, has been dated at 62 Ma (Sutherland *et al.*, 2004). A thin section shows fine-grained (0.1 mm) basalt, of titanaugite, plagioclase and opaques with phenocrysts of olivine and augite, with no vesicles or amygdules. The magnetic susceptibility of the basalt is about 8 10^{-3} SI units (Table 3). Modelling of profiles from ground magnetometer traverses by Calver (1998) showed the basalt to be a vertical cylindrical plug about 150   250 m in area. A very similar result arises from Quickmag modelling of the strong circular aeromagnetic anomaly associated with this body (fig. 48). Normal magnetisation and strong remanence (Koenigsberger ratio c. 10) can be inferred.

A similar 'bullseye' magnetic anomaly occurs nearby about one kilometre to the northwest, at the edge of the map sheet, but no outcrop or float could be found. This anomaly can also be modelled as a vertical pipe, and a similar concealed near-surface Paleogene basalt plug is inferred.

TMI

75 % Line

50 % Line

25 % Line

King Island

Logo 2

Pipes
Adams Rd anomalies

Perspective

0km   1km

MRT   encom

No	Depth	Susc.	Width	Dip	Easting	Northing
1	-8	0.070830	133	90.0	241191	5579349
2	-8	0.070830	211	90.0	241215	5579347
3	-8	0.070830	254	90.0	241239	5579345
4	-8	0.070830	279	90.0	241262	5579342
5	-8	0.070830	291	90.0	241286	5579340
6	-8	0.070830	291	90.0	241310	5579338
7	-8	0.070830	279	90.0	241334	5579335
8	-8	0.070830	254	90.0	241357	5579333
9	-8	0.070830	211	90.0	241381	5579330
10	-8	0.070830	133	90.0	241405	5579328

Model name	QM-Model * 8
Av. depth	-8
Av. susc. (SI)	0.070830
Av. dip	90.0
Av. width	234
Grid cell size	40.00
Mag. intensity	61015
Mag. declination	11.9
Mag. inclination	-70.5
Quality regional	100
Quality geol. noise	99
Anomaly Overlap	100
Quality inversion	52
Total Quality	97

Figure 48. *Quickmag interpretation of the 'Investigator 12' basaltic plug near Adams Road, northwest corner of Naracoopa map sheet.*

Introduction

The Surprise Bay Formation and the Fraser Formation are probably correlates (see previous section), differing mainly in the much higher strain state of the Surprise Bay Formation. In that unit, D_1, dated at c. 1290 Ma (Berry *et al.*, 2005), produced isoclinal folds and a well-developed schistosity, while the Fraser Formation has only a weak slaty cleavage in the west and no detectable D_1 deformation elsewhere. Regional metamorphism that accompanied D_1 is of lower amphibolite facies in the Surprise Bay Formation, and in part of the Fraser Formation, but much of the Fraser Formation is of greenschist facies. The two formations meet along a major N–S, inferred west-dipping thrust here named the Pearshape Fault. D_2, in at least the Surprise Bay Formation, may be about the same age as the Cape Wickham Granite (760 Ma: Cox, 1989; Turner *et al.*, 1998). D_3, probably Cambrian in age, produced cleavage and an east-facing monocline in the Fraser Formation and Grassy Group on the east coast.

Surprise Bay Formation

Boudinage

Coastal exposures of west-dipping and facing Surprise Bay Formation north of Millers Bay show boudinage of some sandstone beds within pelitic intervals (fig. 49). Most boudin necks have quartz gashes. Strong refraction of S_1 around the quartz gashes shows that the boudinage is pre-D_1. Quartz gashes, rather than being perpendicular to bedding, are rotated anticlockwise and thereby signify an element of sinistral (top to south) shear during extension (Goscombe and Passchier, 2003). Most boudin necks plunge steeply southeast, at a high angle to the S_0/S_1 intersection, which plunges moderately north in this area (fig. 50). Maximum extension direction shown by the boudinage was therefore approximately north–south. Minor extensional faulting subparallel to bedding, perhaps associated with the boudinage, is also present in this area.

Equal Area (Schmidt)

○ S_0/S_1 intersection
● Boudin necks

Figure 50

Equal-area stereoplot showing orientation of boudin necks and local calculated S_0/S_1 intersection lineation, Surprise Bay Formation, Millers Bay.

D_1

The Surprise Bay Formation is characterised by a strong schistose primary cleavage (S_1), which is well developed everywhere except for some massive sandstones and recrystallised contact metamorphic rocks. S_1 is generally at a low angle or subparallel to bedding (reflecting tight to isoclinal F_1 folding), and is axial planar to uncommon, minor (outcrop scale) tight to isoclinal F_1 fold closures (fig. 51), and two major regional F_1 folds.

The regional structure of the Surprise Bay Formation on the northern Pearshape map sheet is dominated by a major F_1

Figure 49

Boudinage in Surprise Bay Formation, north of Millers Bay [233986/5569805].
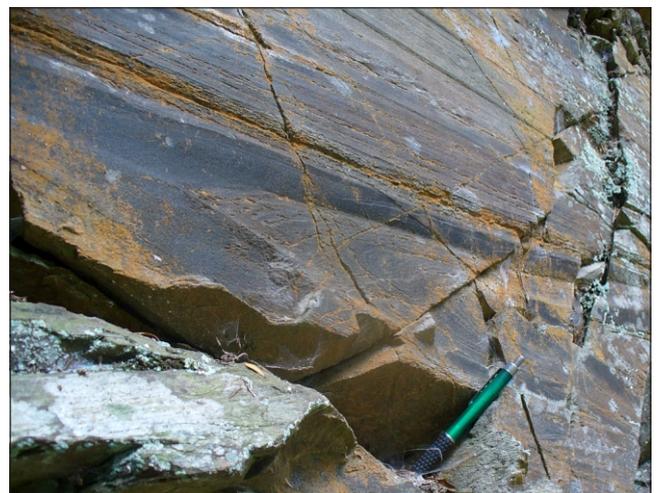
Figure 51

Tight minor F_1 fold closure in Surprise Bay Formation, Ettrick River [237217/5568324].

Surprise Bay Formation, northern Pearshape map sheet

■ Measured minor F_2 hinge
□ Measured minor F_1 hinge

(a) Bedding (S_0) N = 111

16%
8%
4%
2%
0.5%

(b) S_1 cleavage N = 82

8%
4%
2%
1%

(c) Bedding-S_1 intersection lineation N = 58

8%
4%
2%

(d) S_2 cleavage N = 10

16%
8%
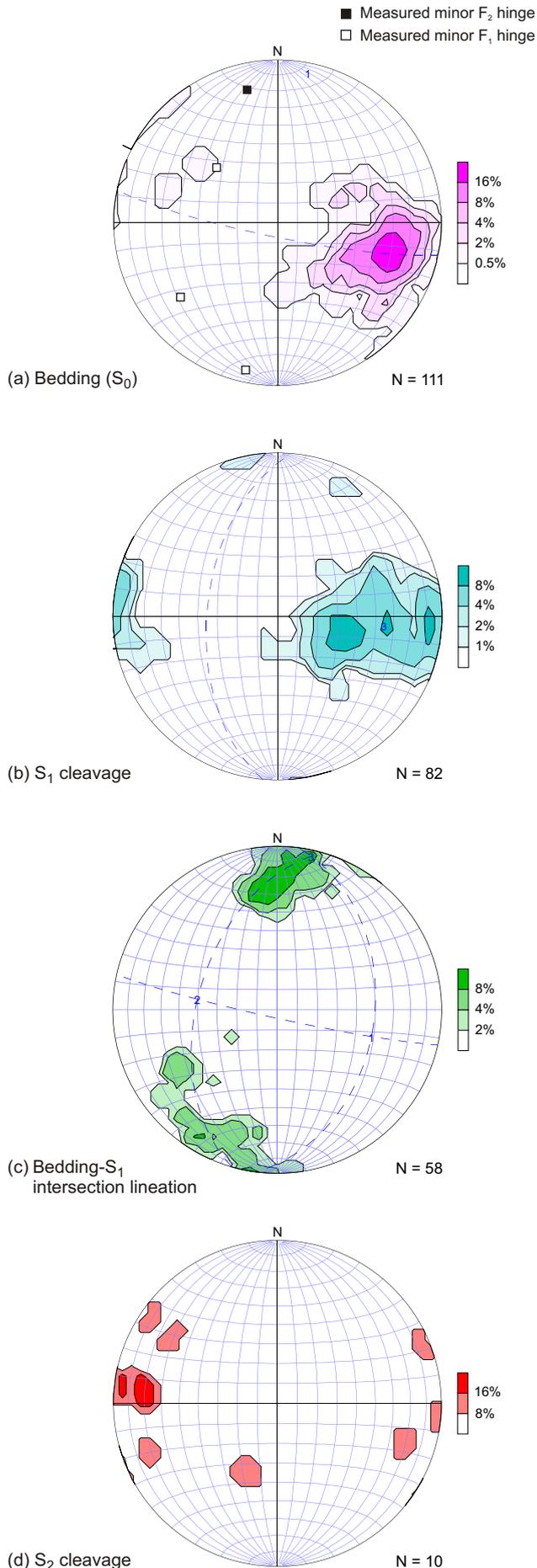
isoclinal anticline, with a steeply west-dipping axial surface and sub-horizontal hinge, trending NNE through Dripping Wells and the lower Ettrick River; and a similarly orientated syncline, three kilometres to the east, in the upper Ettrick River (fig. 1). The overturned common limb between the two hinge lines is recognised mainly by the shallower dip of S_1 in relation to bedding, in a few places confirmed by overturned (east-facing) cross lamination. The few measured minor F_1 fold hinges and numerous calculated S_0/S_1 intersection lineations are sub-horizontal to moderately north or south plunging (fig. 52).

Regional metamorphism associated with D_1

Garnet, up to 1.5 mm, is locally present (fig. 53). The main schistosity, defined by platy muscovite and biotite, is deflected around the garnet porphyroblasts (fig. 5). Garnet is evidently pre-kinematic. Columnar porphyroblasts up to 10 50 mm in size, almost square in cross section, are locally abundant. They are entirely retrogressed to fine-grained muscovite, margarite and chlorite (XRD determination), but their morphology suggests they formed as andalusite (fig. 54). These porphyroblasts occur in pelitic schist but not sandstone. In places they show a preferred alignment in S_1, and S_1 deflects around them, implying a pre or early D_1 age. The garnet and retrogressed andalusite show a disjunct regional distribution not obviously related to known granite distribution (fig. 53). These phases reflect low amphibolite facies metamorphism prior to or early in D_1.

D_2

A post-S_1 crenulation cleavage is locally present in the Surprise Bay Formation, with a similar (N–S) strike to S_1, but a subvertical to steep easterly dip. Outcrop-scale, upright, open to tight F_2 folds, parallel in style, with strongly fanning S_2 and plunging gently north, are seen on the coast at Dripping Wells (e.g. 234757/5566771; fig. 55).

Cryogenian contact metamorphism

An intrusive contact of the Loorana Granite with west-dipping and facing Surprise Bay Formation is exposed at the southern end of Sandfly Beach (northern edge of Pearshape map sheet). This contact is irregular in outcrop, with rafts of metasediment in the granite, but regionally the contact appears to be conformable or nearly so (consistent with aeromagnetic trends), trending offshore to the south and reappearing on the south side of Fitzmaurice Bay. A contact metamorphosed zone about 100 m wide is present in the Surprise Bay Formation adjacent to the granite at the northern edge of the Pearshape map sheet, marked by recrystallisation and the disappearance of S_1 and of small scale sedimentary structures such as planar and cross lamination, and the appearance of unaligned coarse (2 mm) poikiloblastic muscovite (e.g. thin section R15811), accompanied by thin veins and knots of microgranite and pegmatite. (No garnet or retrogressed andalusite were seen in this zone. These minerals have a broader, unrelated distribution and belong to the earlier phase of regional metamorphism).

Figure 52

Equal area stereoplots of the Surprise Bay Formation, northern Pearshape map sheet. (a) bedding and minor fold hinges; (b) S_1 cleavage; (c) S_0/S_1 intersection lineations; (d) S_2 cleavage.

Garnet (red)
Retrogressed ?andalusite (blue)

Chlorite
(porphyroblastic)

in clast in Cottons Breccia

Biotite

Figure 53

Observed distribution of:

(a) garnet (excluding metamorphic aureoles of Sandblow and Bold Head granites) and retrogressed andalusite;

(b) porphyroblasts (>0.25 mm) of chlorite;

(c) biotite (excluding metamorphic aureoles of Sandblow and Bold Head granites).

Figure 54
*Porphyroblasts of retrogressed probable andalusite,
Surprise Bay Formation, Millers Bay [234179/5569325].*

Figure 55
*F_2 fold in Surprise Bay Formation,
Dripping Wells [234757/5566771].*

Fraser Formation

Pearshape Fault

The contact between the Surprise Bay Formation and the Fraser Formation is not exposed, but is inferred to be a fault, for which the name 'Pearshape Fault' is here proposed. The nature of this boundary has previously been a matter of conjecture (e.g. Calver and Walter, 2000; Direen and Jago, 2008). In the Ettrick River, the eastward change from pelitic schist of the Surprise Bay Formation to weakly cleaved mudstone and siltstone of the Fraser Formation takes place within an unexposed gap of 40 m across strike. S_1 and S_2 are subparallel in strike to the mapped regional trend of the fault. Schistosity (S_1) dips west in the Surprise Bay Formation, while S_2 near the fault is subvertical (Ettrick River) or moderately west dipping (Sea Elephant River). The aeromagnetic anomaly associated with the amphibolite body along the Pearshape Fault just west of the Sea Elephant River suggests it (and the fault) dip west at 72° (fig. 56). Minor faults are common in outcrop of the Fraser Formation in the Pearshape quarry, inferred to be within a few hundred metres of the Pearshape Fault. These faults dip moderately northwest (fig. 57). These observations suggest that the Pearshape Fault is a west-dipping thrust (perhaps related to D_2) that has foreshortened the metamorphic/strain transition between the Surprise Bay and Fraser formations.

Regional structure, Fraser Formation

The structure of the Fraser Formation can be described in terms of six roughly meridional, largely fault-bounded domains, numbered 2 to 7 (fig. 58). The earlier (Mesoproterozoic?) deformations seen in the Surprise Bay Formation (D_1 and D_2) are limited to the westernmost domains 2 and 3. The centre (Domain 4) is relatively undeformed, while a weak later (Cambrian?) deformation, D_3, mainly affects the eastern domains (5–7) (fig. 59).

Domain 2, of mainly mudstone (Lfn), adjoins the Pearshape Fault in the west of Naracoopa map sheet. Here S_2 is a strongly developed crenulation cleavage, dipping moderately west, and axial planar to F_2 minor folds that are upright to steeply overturned to the east and very gently north plunging

(fig. 58). The earlier cleavage (S_1) tends to be masked by S_2 in outcrop, but can be seen in a few places as a slaty cleavage subparallel to bedding (fig. 10). A second, later crenulation, probably belonging to S_3, was seen in one outcrop. A poorly exposed area of siltstone (Lfgl) in the north of this domain appears to represent the north-plunging nose of a major anticline with a subvertical eastern limb. This could be a faulted-off section of the Lymwood Anticline.

Domain 3 shares a faulted boundary with Domain 2 and extends as far west as the Pearshape Fault on the Pearshape sheet. It is dominated by the regional, upright, gently north-plunging F_2 Lymwood Anticline (fig. 58). In the westernmost area of interbedded siltstone and mudstone (Lfi), which is faulted against the Lymwood Anticline (but nevertheless included in Domain 3), S_1 is present as a weak slaty cleavage subparallel to bedding, and S_2 is a crenulation or seamed cleavage (less intense than in Domain 2), axial planar to upright north-trending folds. These folds have wavelengths of about 200–400 m in the Ettrick River section (see cross section, fig. 1). The Lymwood Anticline, mainly expressed in the more competent garnetiferous quartz siltstone (Lfgl) unit, is much larger (half wavelength > 3 km). Its dihedral angle is about 70°. Because of faulting, the eastern limb is areally much more extensive than the western limb. S_1 is not detectable in outcrop, only being seen as a weak bedding-parallel fabric in a few thin sections. S_2 is a weak cleavage in outcrop and is not always present. Thus there is a decline in intensity of D_1 and D_2 going east across domains 2 and 3.

With evidence for S_1 being somewhat equivocal in the area of the Lymwood Anticline, supporting evidence for its axial planar cleavage being S_2 (not S_1) comes from the relative age of the widespread chlorite porphyroblasts. West of the Lymwood Anticline, chlorite porphyroblasts overgrow (post-date) S_1 (e.g. fig. 9) and are overprinted (cleaved) by S_2. The axial planar cleavage of the Lymwood Anticline overprints chlorite porphyroblasts, consistent with its assignation as S_2 (fig. 7) and this major regional fold as belonging to D_2.
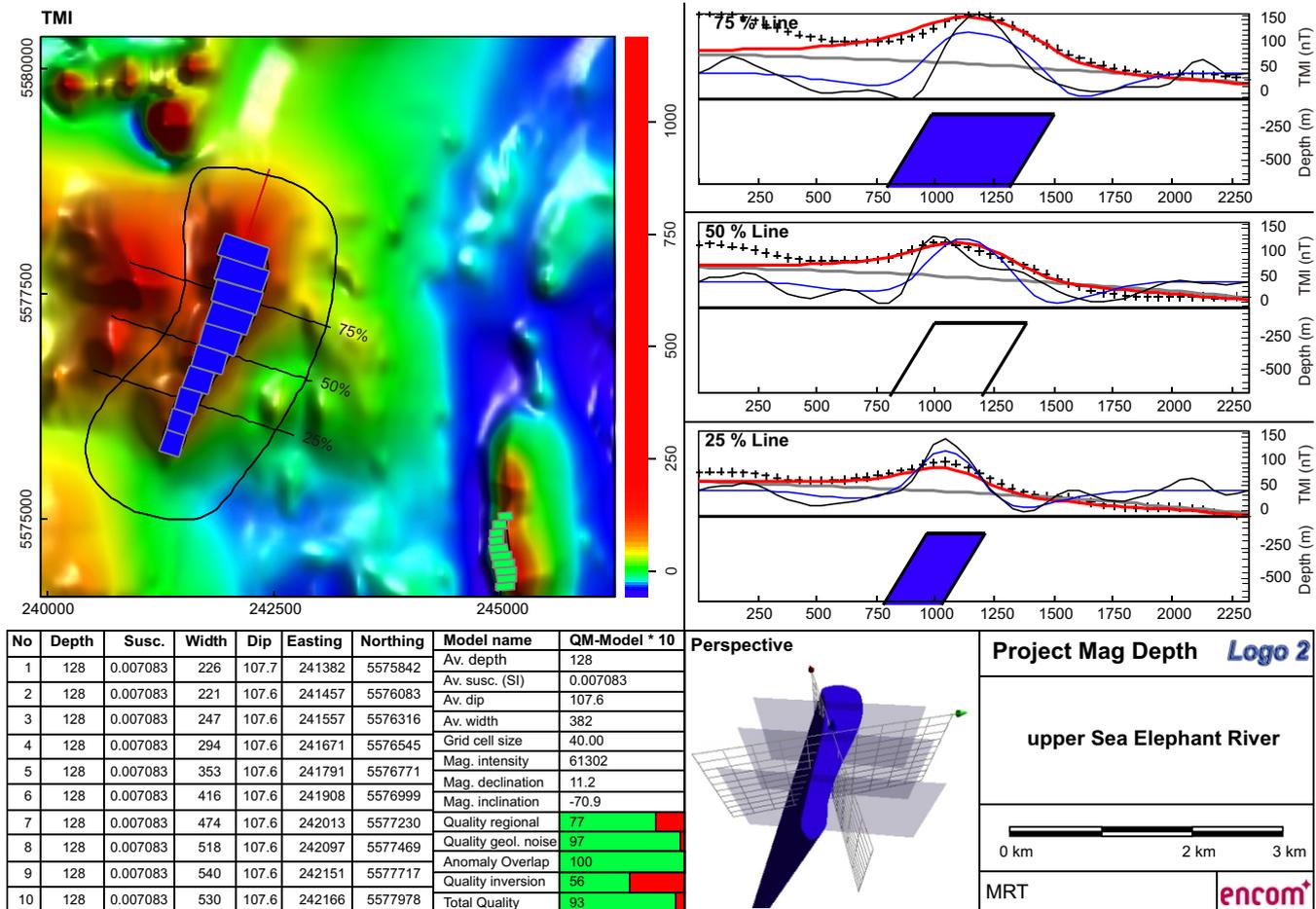
Figure 56

Quickmag interpretation of the aeromagnetic anomaly over the amphibolite body west of the Sea Elephant River on the Naracoopa map sheet, interpreted to be bounded on the west by the Pearshape Fault.

The table within Figure 56:

No	Depth	Susc.	Width	Dip	Easting	Northing
1	128	0.007083	226	107.7	241382	5575842
2	128	0.007083	221	107.6	241457	5576083
3	128	0.007083	247	107.6	241557	5576316
4	128	0.007083	294	107.6	241671	5576545
5	128	0.007083	353	107.6	241791	5576771
6	128	0.007083	416	107.6	241908	5576999
7	128	0.007083	474	107.6	242013	5577230
8	128	0.007083	518	107.6	242097	5577469
9	128	0.007083	540	107.6	242151	5577717
10	128	0.007083	530	107.6	242166	5577978

Model name	QM-Model * 10
Av. depth	128
Av. susc. (SI)	0.007083
Av. dip	107.6
Av. width	382
Grid cell size	40.00
Mag. intensity	61302
Mag. declination	11.2
Mag. inclination	-70.9
Quality regional	77
Quality geol. noise	97
Anomaly Overlap	100
Quality inversion	56
Total Quality	93

Project Mag Depth — Logo 2

upper Sea Elephant River

0 km — 2 km — 3 km

MRT — encom

Poles to minor faults, Pearshape Quarry

Equal Area (Schmidt)

Axial — N = 7

Figure 57

Equal area stereoplot of poles to minor faults, Pearshape Quarry.

The Grassy Group near Mount Stanley dips south and southeast, and its base transects the eastern limb of the Lymwood Anticline. Similarly, near Gentle Annie, sparse outcrops of the Grassy Group have gentle dips, variable in direction, in contrast to the moderate to steep easterly dips in adjacent Fraser Formation outcrops. A northwest-dipping cleavage recorded in an outcrop similar to the Robbins Creek Formation (Grassy Group) at 244050/5565651 is orientationally similar to S_3 (see below) rather than the S_2 in the adjacent Fraser Formation. These observations indicate that D_2 pre-dates the Grassy Group. That is, D_1 and D_2 in the Fraser Formation are older than c. 650 Ma.

The boundary between domains 3 and 4 lies in a zone of very sparse exposure, but an imprecisely located, north–south fault seems to be required to separate the moderately east-dipping beds on the eastern limb of the Lymwood Anticline (Domain 3) from the mainly gently south-dipping beds of Domain 4. Domain 4 is a N–S zone a few kilometres wide, central to both map sheets, in which the Fraser Formation is essentially undeformed and almost entirely lacks cleavage. With some variation, there is a prevailing gentle (approximately 15°) southerly dip (fig. 58). Bedding is right-way-up. Some steeper (up to 70°) southerly dips are seen in the far south, near the Sandblow Granite. The single recorded cleavage in this domain (at 245656/5565337) could be S_3 (unassigned on the map). A large body (3.5 km²) of amphibolite extends across the northern part of Domain 4 at
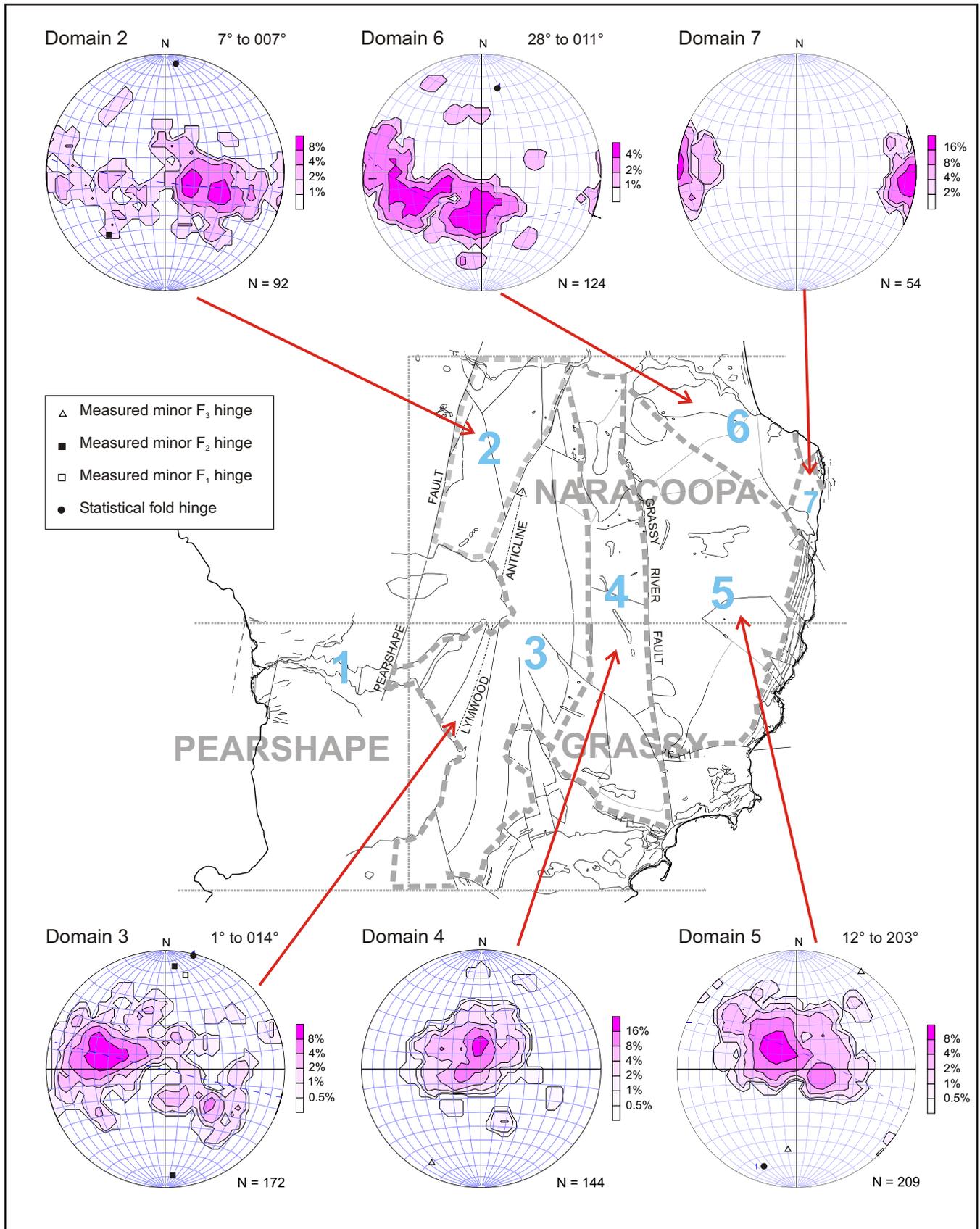
Figure 58

Structure in the Fraser Formation: domains and equal-area stereoplots of poles to bedding.
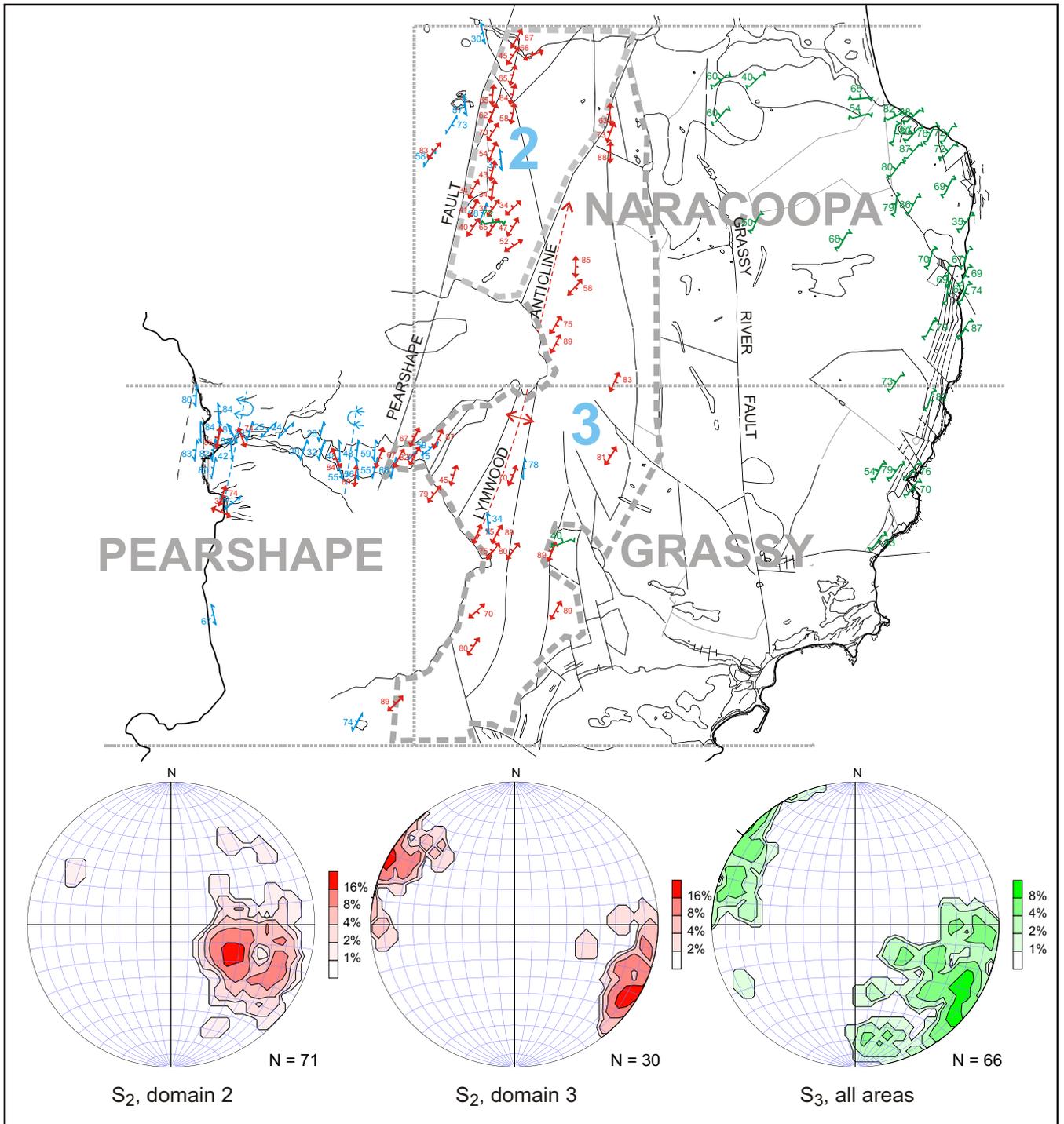
Figure 59

*Cleavage distribution over mapped area: S₁ (blue), S₂ (red) and S₃ (green);
each cleavage spatially averaged on 500 m grid; and equal-area projections of S₂ and S₃.*

Pegarah Road. Its contacts with the Fraser Formation are not exposed, but it is bounded to the east and west by inferred faults. The gentle southerly dip of bedding to the north and south of the amphibolite suggests it could be a relatively thin (c. 200 m), gently folded, south-dipping sill, although drill hole DDHR01 indicates that its southeast boundary dips gently to the northwest (previous section). The lack of aeromagnetic response is consistent with a relatively thin body.

Domain 5 extends from the Grassy River Fault to the unconformity at the base of the Grassy Group. The Grassy River Fault's location is uncertain on the Naracoopa sheet

because of sparsity of outcrop and similarity of Fraser Formation lithologies on either side. It is located on the basis of weak aeromagnetic features, linear ironstone bodies near Pegarah Road (thought to be located on zones of groundwater resurgence and hence fractured bedrock — see previous section), and the mild structural discordance of gently south-dipping v. west-dipping beds on either side of the inferred position of the fault near Laterite Road. Domain 5 is dominated by gently to moderately southeast-dipping, right-way-up bedding. The statistical fold girdle shows a gentle SSE plunge (fig. 58). Gentle folds of this orientation in Yarra Creek (see cross section) are associated with a weak

axial planar cleavage that dips steeply west. The folds verge west and have a wavelength of about 200 metres. Very similar deformation affects the Grassy Group immediately to the east. Therefore this deformation post-dates S_2 of domains 2 and 3; it is assigned to D_3 which must be younger than the Grassy Group (<575 Ma). D_1 and D_2 appear to be entirely absent from the central (4) and eastern domains (5–7) (fig. 59).

A large amphibolite body (1.5 km^2) occurs at Zwar Creek in the far northwest of Domain 5. Its contacts with the Fraser Formation are not exposed. Bedding to the south, west and north of the body dips gently away from it. There is no exposure to the east. The body could be a dome or a sill (as proposed for the large amphibolite in Domain 4) in the nose of a very gently northwest-plunging, open major anticline.

Domain 6 lies north of Domain 5 and is differentiated from it on the basis of moderately north to east-dipping bedding, and moderately NNE-plunging minor folds. The weak axial planar cleavage dips steeply northwest, and being also present in the Grassy Group to the southeast of Naracoopa township, is assigned to S_3. A very open warp or anticline along the boundary between domains 5 and 6 may be responsible for the change in dip (and F_3 fold plunge) between the domains, as is evident around the Zwar Creek amphibolite body. Elsewhere outcrop is very poor.

The small Domain 7 encompasses outcrop around The Wall on the east coast, where bedding in the Fraser Formation is subvertical and east-facing. Moderately west-dipping S_3 cleavage is present. The steep dip is attributed to a D_3 monocline. Dip is similarly steep (75°E) in the Grassy Group just south of Fraser Bluff.

Regional metamorphism

The Fraser Formation has undergone low to medium grade regional metamorphism. The distribution of metamorphic mineral phases identifiable in the field — chlorite, garnet and biotite — is shown in Figure 53. Metamorphic amphibole is characteristic of mapped units Laa, Lfa, and Lfc. A western meridional strip coinciding with the Lymwood Anticline is of lower amphibolite facies (garnet zone) while the rest of the formation is probably upper greenschist facies (biotite zone). As in the Surprise Bay Formation, garnet formation preceded development of the S_1 cleavage. Chlorite porphyroblasts are post-D_1 and pre-D_2, while some biotite is syn-D_2 (fig. 60).

Garnet

With one exception, garnet is only seen in units Lfgl and Lfgp, which comprise the Lymwood Anticline in the western part of Grassy and Naracoopa map sheets (fig. 53). The garnet zone thus delineated is faulted against lower grade rocks on its western side, but the eastern side appears to be a metamorphic transition coinciding approximately with the stratigraphic top of Lfgl. The garnet in Lfgl is pale pink, sparse, euhedral to slightly corroded, and about 0.1 mm, rarely 0.5 mm, but is locally more abundant and larger (1 mm) in Lfgp, particularly the pelitic layers. Locally, S_2 (e.g. in R15802) and probable S_1 (bedding parallel, in R15801) are both seen to deflect around garnet porphyroblasts. A chlorite porphyroblast in R15802 overgrows a euhedral garnet, confirming that garnet is the earlier phase.
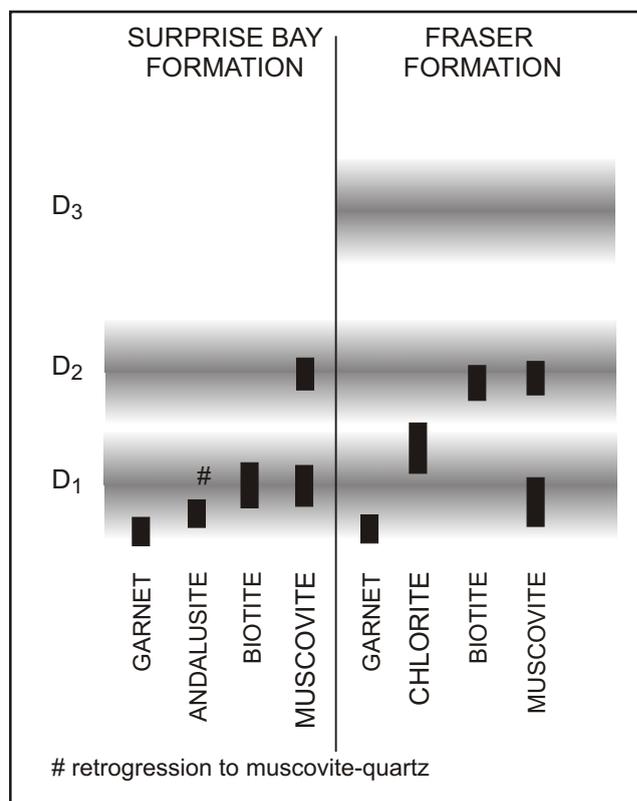
Figure 60

Inferred temporal relationships of metamorphic mineral phases and cleavage forming events.

Chlorite

Porphyroblasts of dark green chlorite 0.25–3 mm, usually 1–2 mm long and readily visible in outcrop, are widespread, although apparently rare in the eastern part of the Grassy map sheet (fig. 53). Chlorite (and biotite, see below) were observed much more frequently in siltstone (Lfb, Lfs, Lfgl) than in mudstone (Lfn). This may be partly because of the easier visibility of these dark minerals in paler host rock, and also that platy porphyroblasts in many mudstones — possibly originally biotite or chlorite — have been altered to iron oxide (e.g. R013104, R15002, R15015, R15016). No chlorite porphyroblasts were seen in the Surprise Bay Formation. In the Grassy Group they only exist in clasts, lithologically identical to laminated quartz siltstone of the Fraser Formation (Lfb), in the Cottons Breccia. These porphyroblasts are erosionally truncated at the surfaces of the clasts (sample R013165), showing that chlorite porphyroblast growth pre-dated deposition of the Grassy Group, i.e. is > c. 650 Ma.

The chlorite porphyroblasts are shaped as thick plates (oblongs with ragged ends in thin section). Rarely, roughly hexagonal basal sections can be made out; these are monocrystalline with good basal mineral cleavage. Inclusions of quartz are common, in some cases concentrated at the centre of the porphyroblast. Quartz inclusions may be notably coarser than the detrital grains in the surrounding rock, and are therefore not poikilitically enclosed detrital grains (R013141). Inclusions of epidote may also be present (R013119). Chlorite is not generally known as a porphyroblast-forming mineral (e.g. Mason, 1978, p. 122), so these may have grown as biotite before pseudomorphous

retrogression to chlorite. Biotite-to-chlorite retrogression would release SiO_2, which could explain the quartz inclusions (G. Green, pers. comm.). In the westernmost part of the Grassy sheet, the porphyroblasts overprint S_1 and therefore post-date it (fig. 9). In many samples where the porphyroblasts are present together with one or other of the later crenulation cleavages, the porphyroblasts can be seen to pre-date S_2 and S_3 in thin sections. Typically, the mineral cleavage in the chlorite porphyroblasts is kinked in accord with the S_2 or S_3 crenulation (fig. 7).

Biotite

Biotite is widely distributed across the Fraser Formation, although absent from the mudstone (Lfn) of the eastern Grassy sheet and some smaller areas (fig. 53). Biotite is visible in outcrop as tiny disseminated dark grains and in thin section as abundant, ragged grains, brown or less commonly olive-green, around 100 m in size. Biotite and muscovite show a preferred alignment in S_2 (fig. 7). Therefore the biotite is thought to be syn-S_2 and hence younger than the chlorite porphyroblasts, which may represent retrogressed, older biotite (see above). Inferred temporal relationships of metamorphic mineral phases and cleavage-forming events are shown in Figure 60.

Amphibole

Coarse-grained hornblende amphibolite (shown as Laa on the maps) is widespread as intrusive bodies within the Fraser Formation (previous section). The abundant dark hornblende in these rocks is a characteristic mineral of amphibolite facies metamorphism, and it appears that much of the Fraser Formation outside the garnet isograd (fig. 53) is of borderline lower amphibolite facies. It may be inferred that the intrusive rocks were emplaced before peak regional metamorphic conditions during D_1.

Porphyroblasts of amphibole in a hornfelsic groundmass of quartz + biotite + chlorite + plagioclase are characteristic of the mapped units Lfa (in which the porphyroblasts are actinolite) and Lfc (in which the porphyroblasts are cummingtonite). The mineralogy suggests upper greenschist facies regional metamorphism of a fine-grained mafic protolith (previous section). These rocks lack cleavage and it is difficult to relate their paragenesis to the rest of the Fraser Formation.

Grassy Group

Basal unconformity

The basal contact of the Grassy Group was observed in Yarra Creek (fig. 18) and Cumberland Creek. In Yarra Creek, bedding in the basal conglomerate and underlying Fraser Formation are approximately parallel, although bedding in the Fraser Formation further down-section tends to strike about 20° clockwise of bedding in the Grassy Group and is more shallowly dipping. A similar discordance is evident in stereoplots of bedding in Domain 5 in the Fraser Formation (fig. 58) and adjacent Grassy Group to the east (fig. 61). An area now assigned to Grassy Group south of Lymwood is characterised by very gentle (7–13°) southerly or westerly dips; surrounding Fraser Formation rocks inferred to underlie this area dip more steeply (37–64°) E–SE. Regionally, the Grassy Group overlies different units in

Poles to bedding, Grassy Group, Cottons Beach to Barrier Creek

Minor F_3 hinge
N = 159
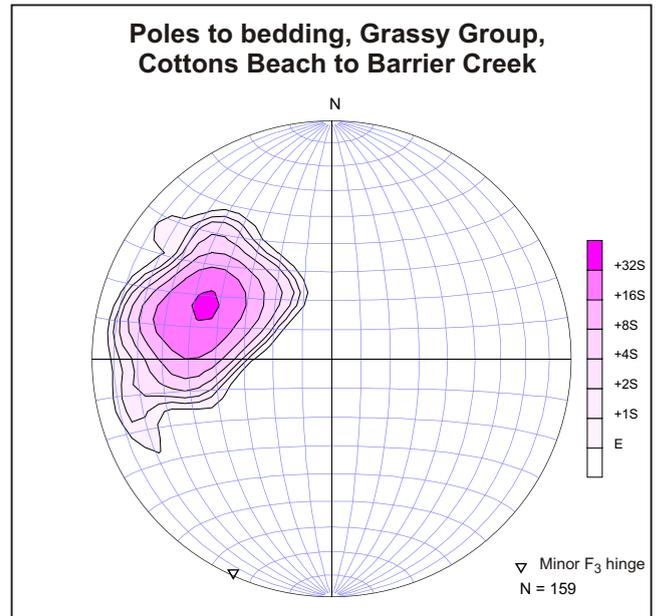
Figure 61

Equal area stereoplot of poles to bedding in Grassy Group, east coast between Cottons Beach and Barrier Creek.

the Fraser Formation (mudstone (Lfn) on the southern part of the east coast; siltstone (Lfs) north of Grimes Creek and between Grassy township and Gentle Annie; metasiltstone (Lfl) west of Red Hut Road), reflecting pre-Grassy Group D_1 and D_2 folding and faulting in the Fraser Formation.

Syndepositional extension

As outlined above, lateral changes in the thickness of units in the Grassy Group and of the Grimes Intrusive Suite along the east coast appear to coincide with mapped northwest-trending faults (fig. 24). These include the faults just north of City of Melbourne Bay, at The Gut, and just south of Shower Droplet Rock. The Barrier Creek Fault was probably also active during Grassy Group deposition, as it marks the southern limit of the Denbys Dolerite and possibly the northern limit of the City of Melbourne Volcanics. The dips of these faults could not be determined in the field, but if they were steep normal faults during Grassy Group deposition, their tilt-corrected trend must have been approximately NNW. This would imply a $_3$ (least stress) direction trending ENE. However some of these faults show relatively large displacements in the Fraser Formation, so they may have been pre-existing faults, reactivated during Grassy Group deposition.

A more reliable indicator of extension direction is the preferred orientation of syn-Grassy Group dykes. Several ages of these are present. Tilt-corrected orientations are shown in Figure 47. Four dykes interpreted to be penecontemporaneous with the Cottons Breccia have variable but predominantly ENE trends (fig. 47a). A thin sheet of Grimes Intrusive Suite just north of City of Melbourne Bay has short steep sections with an ENE trend, likewise the minor syn-intrusion fault shown in Figure 46. The dilatation direction indicated by the apophysis at the top of the main sill is ESE (fig. 47b). Dykes identified as associated with the Grahams Road Volcanics have a strong preferred tilt-corrected northeast trend (fig. 47c). All these dyke sets

tend to dip steeply SE–SSE (tilt corrected). Undifferentiated dykes have variable tilt-corrected orientations, but many cluster with the other ENE-trending dykes (fig. 47d). A long-lived stress state with $_3$ trending NW or NNW is evident, quite different from that suggested by the trend of the faults.

Cambrian (?) D$_3$ event

A steep northeast-trending cleavage is present in the Grassy Group on the east coast, and in the adjoining Fraser Formation over a large area, and is assigned to S$_3$ (fig. 59). This cleavage is weak and impersistent in the Fraser Formation and occurs as axial planar to open, NNE-plunging minor folds in the Fraser Formation on the foreshore at Naracoopa, and open, west-verging folds of about 200 m wavelength at Yarra Creek (section, fig. 1). S$_3$ is pervasive in the dark shale of the Robbins Creek Formation (fig. 21), and moderately well developed in the Yarra Creek Shale and volcaniclastic rocks in the Shower Droplet Volcanics. It is not seen in the more competent rocks (diamictite, basalt). S$_3$ is axial planar to a minor west-verging fold in the Robbins Creek Formation (fig. 61). Going west, S$_3$ in the Fraser Formation trends more ENE and dips moderately northwest (central north of Naracoopa sheet; fig. 59). A late crenulation dipping NNW in the Fraser Formation in the Sea Elephant River (western Naracoopa map sheet) is the most westerly recorded development of S$_3$. A similarly orientated cleavage in an isolated outcrop of Robbins Creek Formation one kilometre southwest of Lymwood in the central-west of the Grassy map sheet is assigned to S$_3$. The Grassy Group mudstones in this area (Lyvs) are otherwise uncleaved and bedding dips gently to the west and south. The moderate E–SE dips in the Grassy Group along the east coast are interpreted as a D$_3$ monocline.

Direen and Jago (2008) did not recognise the evidence for compressional deformation in the Grassy Group, and attributed the E–SE dips along the east coast to fault block rotation.

The Grassy Group has been subjected to lower greenschist facies metamorphism, as shown by the presence of actinolite, prehnite, sericite, epidote and chlorite in the volcanic rocks (Meffre et al., 2004).

Age of regional metamorphism and D$_1$–D$_3$

Chemical U-Th-Pb dating of syn-D$_1$ monazite showed that D$_1$ in the Surprise Bay Formation was Mesoproterozoic (1287 18 Ma) in age (Berry et al., 2005). Amphibolite facies mineral assemblages including garnet were regarded as syn D$_1$. (However in contrast to our observations they conclude that the porphyroblastic andalusite overgrows S$_1$). The mineralogy and mineral chemistry reported by Blackney (1982) from the Surprise Bay area is consistent with

metamorphism at 500°C and 300 MPa. D$_2$ has not been directly dated. D$_2$ in the Surprise Bay Formation is probably the same phase as D$_2$ in the Fraser Formation, which pre-dates the Grassy Group, i.e. is >c. 650 Ma (see above). D$_2$ may be a late phase of the Mesoproterozoic event, or be related to the emplacement of the Cryogenian (748–760 Ma) granites of western King Island (Cox, 1989; Turner et al., 1998).

D$_3$ is younger than the Grassy Group (i.e. <570 Ma), and by analogy with deformation affecting Proterozoic to early Cambrian rocks in northwest Tasmania, could be either Cambrian (Tyennan–Delamerian Orogeny) or Devonian (Tabberabberan Orogeny). Aeromagnetic data show that Proterozoic rocks of King Island may be structurally continuous with the (largely subsurface) Selwyn Block of central Victoria, which is thought to have been deformed in the Cambrian Tyennan Orogeny but remained relatively undeformed in the Devonian (Cayley et al., 2002). D$_3$ on King Island is therefore tentatively dated as Cambrian.

Carboniferous deformation associated with granite intrusion

Around the northern and western sides of the ovoid pluton of the Sandblow Granite, the regional strike of the Grassy Group is parallel to the contact, and bedding dips moderately towards the contact. Further north, beyond the aureole, dips in the Grassy Group are gentle and in no particular direction. A similar effect is seen in the Fraser Formation, e.g. gentle dips in the Grassy River area (Domain 4, fig. 58) and steeper southerly dips west of Grassy township. Faults, radial to the pluton, displace the Grassy Group in places without much affecting the granite contact. It is likely that the faults, and the pluton-ward dip of rocks near the granite, are deformation associated with emplacement of the intrusion. The pattern is suggestive of subsidence of the country rocks through stoping (Wesolowski et al., 1988) or magma drawdown. The opposing dips of bedding and of the granite contact (fig. 42) appear to be too gentle for a mechanism involving compressive deformation associated with ballooning of the intrusion.

A zone of contact metamorphism was mapped around the Sandblow and Bold Head granites, based on hornfelsing in the Grassy Group and spotting in the Fraser Formation, described above. The width of the zone varies from ~1 km on the west of the Sandblow pluton to ~2 km on the northern side, and from ~1.5 km on the northern side of the Bold Head Granite to ~0.5 km on its eastern side. The variation is probably mainly related to changes in the attitude of the granite contact, and accords with the variation in attitude that can be inferred from the modelled one kilometre granite isobath (fig. 1; Leaman and Richardson, 2003).

MAGNETIC INTERPRETATION

A Total Magnetic Intensity (TMI) image of southern King Island, derived from the survey flown in 2001 at 200 m line spacing for the Western Tasmanian Regional Minerals Program, is shown as Figure 44. A partial interpretation is given here. Earlier magnetic surveys picked up many of the anomalies, and some have been followed up by drilling and other investigations, chiefly by Geopeko Ltd.

As an aid to interpretation, magnetic susceptibility determinations were made at 166 sites in the field with a hand-held meter. Five measurements were made at each site and the maximum and average values for each mapped unit are tabulated (Table 3).

The western part of the TMI image is dominated by a strong southward-tapering linear anomaly extending from five kilometres east of Currie southwards to Fitzmaurice Bay (Anomaly 1, fig. 44). Outcrop on this anomaly near the mouth of the Ettrick River and at Dripping Wells consists of unexceptional Surprise Bay Formation. The anomaly coincides with the axis of the major, isoclinal anticline, so it may correspond to a blind conformable magnetic unit within the Surprise Bay Formation. The northern part of this anomaly can be modelled as a subvertical tabular body with its top some 200 m below surface (fig. 62).

A large, north-trending long wavelength anomaly in the easternmost Pearshape map sheet (Anomaly 2, fig. 44) coincides approximately with the Pearshape Fault and with shallow (<1 km) granite inferred from gravity data (Leaman and Richardson, 2003). The anomaly may indicate shallow granite of oxidised (magnetic) type similar to the Sandblow and Bold Head granites. Smaller, superimposed anomalies may be due to mafic intrusive rocks or surficial ironstone. The Pearshape Fault is not well defined on the magnetics, and coincides with a generalised eastward transition to lower-amplitude, shorter wavelength anomalies over the Fraser Formation. In the northwest of the Naracoopa sheet, a wedge (<500 m wide) of amphibolite along the Pearshape Fault can be modelled as a steeply west-dipping wedge (Anomaly 3; fig. 56). The magnetic signature of the Fraser Formation is generally subdued but with many small anomalies, at least some of which are due to surficial ironstone deposits. The pelitic units (Lfgp, Lfn) generally appear to be characterised by a more 'lumpy' magnetic signature than the siltstones. A strong linear anomaly (4 on fig. 44) extending from Brumbys Road in the north to near Red Hut Road in the south is (as mentioned above) a conformable magnetic unit within Lfgl (garnet grade laminated quartz siltstone), offset in several places by faults. Outcrop of metasiltstone on the anomaly has a magnetic susceptibility up to 21 10^{-3} SI units. The anomaly can be modelled at 5 570 000 mN as a tabular unit dipping east at 40°, in accord with regional bedding orientation (fig. 63). This anomaly was auger drilled by Geopeko in three places: where it crosses the Pegarah Road ('Magnetic Anomaly No. 6'), and two places near Lymwood ('Investigator 9' and 'Investigator 10'). Only siltstone, without any anomalous metal values, was encountered (Brown, 1974).

The sub-circular anomaly 1.5 km northwest of Grassy township (247560/5563840) was tested by percussion drilling to 52 m; only mildly contact metamorphosed Fraser Formation was intercepted ('Magnetic Anomaly 10' of Brown, 1987; 'MA 10' on fig. 44).

The long-wavelength magnetic high south of Naracoopa ('Magnetic Anomaly 11' of Brown, 1974); 'MA 11' on fig. 44) was drilled (percussion hole PDH 52), intercepting only Fraser Formation (dominantly grey-green to black, quartz-rich siltstone, to 92 m TD). Brown (1974) suggested this anomaly may reflect a subsurface granite, in accord with disseminated tourmaline in the Fraser Formation at the centre of the anomaly, and hydrothermal alteration along the Barrier Creek Fault (previous section). However there is no gravity evidence for a cupola here (Leaman and Richardson, 2003).

The City of Melbourne Volcanics is more magnetic (maximum magnetic susceptibility 71 10^{-3} SI units) than enclosing units, and the formation gives rise to a narrow magnetic marker horizon extending from Cottons Beach, offset by mapped faults, as far north as the Barrier Creek Fault (anomaly 5 on fig. 44). A similar, offset anomaly continues to the north of the offshore extension of the Barrier Creek Fault, but coming ashore further north is seen to belong to the basal cumulate of the Denbys Dolerite (anomaly 6). The Barrier Creek Fault appears to be the northern limit of the City of Melbourne Volcanics anomaly, and is the southern limit of the anomaly related to the thick basal cumulate of the Denbys Dolerite.

The basal cumulate of the Denbys Dolerite is about 100 m thick, magnetic (maximum MS 52 10^{-3} SI units), and dips steeply east. The along-strike magnetic anomaly just offshore of The Wall can be modelled using very similar parameters (fig. 64).

The Grahams Road Volcanics is strongly magnetic (maximum magnetic susceptibility 122 10^{-3} SI units) and gives rise to strong magnetic anomalies in the Bold Head area. The northeast strike of the volcanic rocks here is evident in the grain of the magnetics, in accord with outcrop observations. Extensive offshore anomalies lie parallel to the southeast coast of King Island and are inferred to belong to the same or a similar volcanic succession, many kilometres in thickness (Direen and Crawford, 2003). The undifferentiated contact metamorphosed volcanic rocks in the aureole of the Sandblow Granite also have generally high magnetic susceptibility.

The magnetite-bearing, I-type Sandblow and Bold Head granites give rise to strong positive magnetic anomalies. The Sandblow Granite has an irregular central zone of low magnetic response. The anomaly associated with the Bold Head Granite suggests that the northeast margin is gently dipping, in accord with the wider contact metamorphic zone mapped there.

Of a cluster of four small but high amplitude sub-circular anomalies near the northwest corner of the Naracoopa sheet, the largest ('Investigator 12') is associated with surface

TMI

75 % Line

50 % Line

25 % Line

Perspective

No	Depth	Susc.	Width	Dip	Easting	Northing
1	183	0.028467	330	90.0	235201	5572441
2	287	0.028467	330	90.0	235167	5572259
3	329	0.028467	330	90.0	235147	5572078
4	327	0.028467	330	90.0	235138	5571896
5	295	0.028467	330	90.0	235135	5571715
6	249	0.028467	330	90.0	235134	5571534
7	207	0.028467	330	90.0	235131	5571353
8	185	0.028467	330	90.0	235122	5571171
9	197	0.028467	330	90.0	235102	5570989
10	262	0.028467	330	90.0	235067	5570807

Model name	QM-Model * 13
Av. depth	252
Av. susc. (SI)	0.028467
Av. dip	90.0
Av. width	330
Grid cell size	40.00
Mag. intensity	61302
Mag. declination	11.2
Mag. inclination	-70.9
Quality regional	97
Quality geol. noise	98
Anomaly Overlap	100
Quality inversion	41
Total Quality	96

Project Mag Depth *Logo 2*

South Rd

MRT

0km   2km   3km

encom

Figure 62. *Quickmag interpretation of aeromagnetic anomaly 1 (fig. 44), South Road area.*
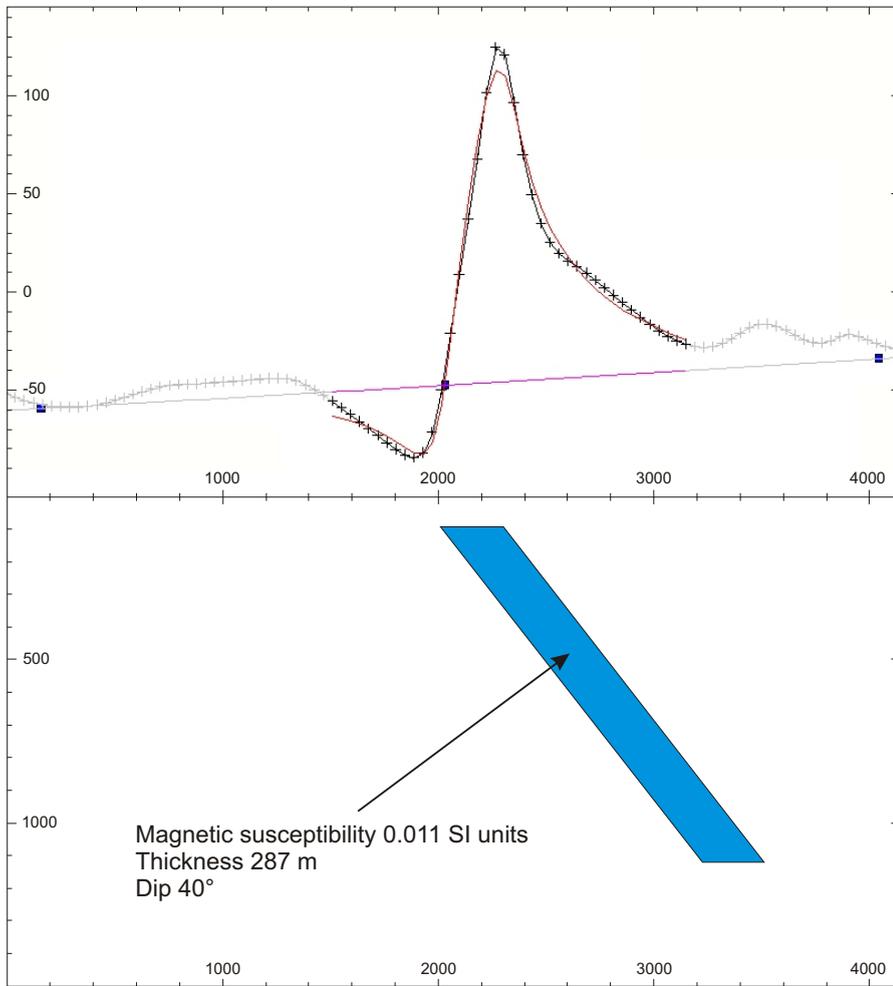
Figure 63
TMI modelling across anomaly 4 (fig. 44), along 5570175 mN between 243490 mE and 247630 mE.

Magnetic susceptibility 0.011 SI units
Thickness 287 m
Dip 40°

float of Paleogene basalt. The 'Investigator 12' anomaly is modelled as a 200 m wide vertical basalt plug cropping out at surface (Calver, 1998; fig. 48), in accord with the mapping.

Geopeko's 'Investigator 15' prospect (Brown, 1974) is a group of small linear anomalies coinciding with mapped ironstone outcrops north and south of Pegarah Road, just west of Parenna on the Naracoopa sheet. Mapped ironstone

bodies give rise to small anomalies in several other places, e.g. near Brumbys Road (246341/5576100) and near Conglomerate Creek (251910/5569745). Most recorded ironstone occurrences are evidently too small to register on the aeromagnetic image. The ironstone has a measured magnetic susceptibility of up to 62 $\times$ 10^{-3} SI units.
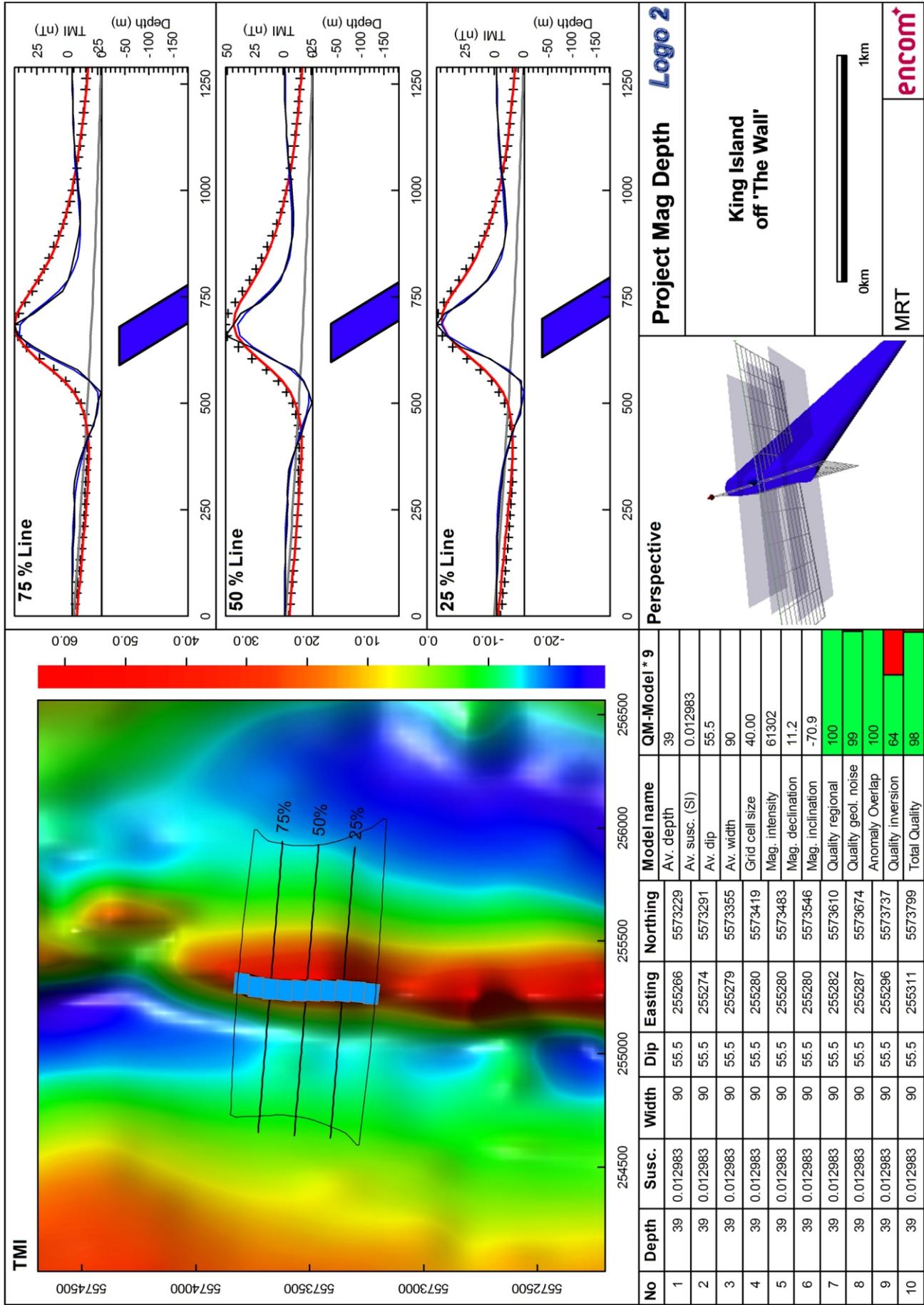
Figure 64. *Quickmag interpretation of linear magnetic anomaly attributed to basal cumulate of Grimes Intrusive Suite, just offshore of The Wall.*

TMI

75 % Line

50 % Line

25 % Line

Perspective

Project Mag Depth *Logo 2*

King Island off 'The Wall'

MRT   encom   0km — 1km

No	Depth	Susc.	Width	Dip	Easting	Northing	Model name	QM-Model * 9
1	39	0.012983	90	55.5	255266	5573229	Av. depth	39
2	39	0.012983	90	55.5	255274	5573291	Av. susc. (SI)	0.012983
3	39	0.012983	90	55.5	255279	5573355	Av. dip	55.5
4	39	0.012983	90	55.5	255280	5573419	Av. width	90
5	39	0.012983	90	55.5	255280	5573483	Grid cell size	40.00
6	39	0.012983	90	55.5	255280	5573546	Mag. intensity	61302
7	39	0.012983	90	55.5	255282	5573610	Mag. declination	11.2
8	39	0.012983	90	55.5	255287	5573674	Mag. inclination	-70.9
9	39	0.012983	90	55.5	255296	5573737	Quality regional	100
10	39	0.012983	90	55.5	255311	5573799	Quality geol. noise	99
							Anomaly Overlap	100
							Quality inversion	64
							Total Quality	98

ECONOMIC GEOLOGY

Tungsten

Mining history

The Grassy (No. 1 + Dolphin) scheelite ore body was discovered in 1904 by Tom Farrell, outcropping on the (then) shoreline of Grassy Bay near the eastern end of what is now the abandoned open-cut mine. Mining took place from 1917–1920 and 1938–1990, with development of the open cut (No. 1 ore body) after 1942. The mine was operated by King Island Scheelite (1947) Ltd until purchased by Geopeko Ltd (a subsidiary of Peko-Wallsend Ltd) in 1969. The Dolphin ore body is located seaward of the original shoreline and it was not until the late 1960s that sufficient reclamation had taken place to allow exploration of the Dolphin deposit, essentially a deeper eastward continuation of the No. 1 ore body. The underground Dolphin mine was opened on a sub-sea portal within the open cut in 1973. The Bold Head deposit, three kilometres to the north, was discovered from drilling on a soil geochemical anomaly in 1968, and development commenced in 1974. The ore from both deposits was milled and put through a gravity separation and flotation plant on the coast at Grassy. The scheelite concentrate was initially shipped from Currie, and after 1972, from the upgraded port of Grassy. The mines employed up to 300 people in the early 1970s, with the population of Grassy peaking at 767 in 1971. Production from the open cut was phased out in 1974. Low tungsten prices led to the closure of the Bold Head mine in 1984 and the Dolphin mine in November 1990, by which time the field had produced a total 60 000 t WO_3 from 11.5 Mt of ore. Remaining resources in the Dolphin mine are 4.76 Mt at 1.29% WO_3 at a 0.7% cut-off grade, and at Bold Head are 1.65 Mt at 0.96% WO_3 at a 0.5% cut-off grade (Fudge, 1990; Green *et al.*, in press).

The potential of the Dolphin deposit is currently being assessed to support a new mining operation, by a joint venture between King Island Scheelite Ltd and Hunan Nonferrous Metals Ltd.

Exploration

Early exploration drilling west of the open cut was undertaken by King Island Scheelite (1947) Ltd between 1947 and 1955. The Dolphin ore body, east of the open cut, began to be outlined by drilling from the Grassy sea dump in the 1960s.

An intensive exploration program for carbonate replacement scheelite and tin mineralisation was undertaken by Geopeko Ltd in the late 1960s and early 1970s, under Exploration Licence 15/66. This included a regional drilling program, regolith geochemistry, geological mapping and an aeromagnetic survey. Most of this exploration effort was undertaken in the aureoles of the Sandblow and Bold Head granites. This phase of exploration is summarised by Brown (1975, 1987). In 1971–1974, the distribution of the major rock units over most of the poorly exposed aureole of the Sandblow Granite was defined by a 50   100 m grid of auger holes (Brown, 1975; 1982*b*). Regolith (C horizon) geochemical sampling defined a number of anomalous W

values. Fifty-nine percussion drill holes and 38 diamond-drill holes were also drilled, mainly at a number of prospects defined by the auger drilling or regolith sampling. These prospects in the aureole of the Sandblow Granite were named (going clockwise around the granite) Investigator 24, 2, 21, 22, 3 and 23 (Brown, 1975). Minor W and Mo mineralisation was found in carbonate-rich parts of the 'mine series' (= lower sedimentary part of the Grassy Group, shown as Lysx on the Grassy map), especially 'podded' varieties in the lower mine series that are probably equivalent to the Cottons Breccia (previous section). The largest deposit found in the Sandblow Granite aureole, Investigator 21, contains an estimated 200 000 t of 0.47% WO_3, the ore being present as a thin (3 m) skarn horizon within the mine series (fig. 42). The lower part of the mine series (including the prospective Cottons Breccia horizon) remained poorly tested by this program. Further follow up diamond drilling took place in the late 1970s, and another aeromagnetic survey was undertaken in 1980.

Regional exploration for tin-tungsten-molybdenum mineralisation at this time included regional geological mapping (Gresham, 1972), magnetic surveys, regional geochemical soil sampling, and reconnaissance auger drilling along roads. The regional auger drilling records were unfortunately lost. A number of prospects were identified away from the Sandblow Granite aureole (Brown, 1974). Ground magnetic gravity and IP surveys were done over many prospects. Some magnetic anomalies were followed up with mapping, auger drilling and geochemistry with generally no results of interest. Some linear magnetic anomalies (Investigator 6, 9, 10) were found to be magnetic metasiltstone in the Fraser Formation (previous section). The prospects known as Investigator 4, 16 and 17, in the northeastern part of the Bold Head Granite aureole, were auger tested, with minor base metal anomalies being recorded (Brown, 1974). The large magnetic anomaly south of Naracoopa was percussion-drilled, and ironstone at Investigator 15 was auger drilled, with no anomalous metal values recorded.

With the downturn in the tungsten market after 1981, exploration became confined to the immediate mine areas. Effort was concentrated on development of, and exploration immediately adjacent to, the Bold Head and Dolphin deposits. The complex structural and replacement features required an intensive underground drilling and mapping program to be undertaken for development control. Deep drilling began testing the southern extension of the Dolphin ore body in 1982, but was later restricted due to the downturn (Brown, 1982*b*, *c*, *d*, 1984, 1986). Offshore EL21/78 was designed to include the southern extension of the Dolphin ore body and the southern offshore contact of the granite — the hypothetical 'Teredo prospect' (Brown, 1982*e*). The latter has still not been directly tested.

VLF-EM, ground magnetic and gravity surveys were undertaken in the Bold Head mine area in 1982/83. A gravity low was found southeast of the Bold Head ore body, possibly

signifying a granite cupola, but has not been drill tested (Sumpton, 1982; Brown, 1983).

There was a recovery in tungsten prices in the early 2000s. EL19/2001 was taken out over southeast King Island by Australian Tungsten Pty Ltd. RL2/1998 over the Dolphin mine area is held by King Island Scheelite Ltd, and most of this is now under application as Mining Lease 1M/2006. A higher resolution aeromagnetic survey has recently been undertaken, and further drilling in the Dolphin deposit area has been directed at re-opening the mine in the near future.

Prospectivity

The setting of the Dolphin and Bold Head deposits consists of a thick mine series host abutting a granite contact with some flattening of the contact beneath the mine series, in close proximity to major faults. Cusps or embayments in the granite contact are thought to be prospective. However there is not much density contrast between granites and the Proterozoic rocks, and gravity alone is generally of insufficient resolution to detect prospective configurations of the granite contact (Deakin and Richardson, 1977; Brown, 1987).

Potential exists in the Dolphin mine for additional resources below -300 m RL (Brown, 1990). Drilling has defined the total potential of the Bold Head ore body block (bounded by the Boundary Fault, Grahams Road Fault and Bold Head Granite), where there are resources remaining, but the area south of the Grahams Road Fault remains untested (Brown, 1990).

Mineralisation may have no surface expression in most of the Sandblow Granite aureole area (as the mineralised skarns will be in the subsurface close to the granite contact). The generally shallow drilling carried out by Geopeko in the 1970s left most of this area poorly tested. Faults in the aureole exhibit a radial pattern about the pluton, suggesting they may be tensional faults associated with emplacement of the granite. If so they are likely to have carried ore-bearing hydrothermal fluids, and adjacent calcareous units will represent favourable targets. Wesolowski *et al.* (1988) showed that the plunging anticline of the No. 1/Dolphin ore body appears to have channelised the flow of mineralising fluids. Similar fault-drag folds will tend to be present on the upthrown side of faults.

The Grassy map sheet shows an additional area of Grassy Group (c. 2 km²) in the area west of Grassy Road, south of Lymwood, compared to previous maps. Although outside the aureole of the Sandblow Granite, this area is now prospective at depth because gravity modelling shows granite within one kilometre of the surface (Leaman and Richardson, 2003).

Gold and base metals

The Barrier Creek lodes were found in 1904; their early history is given in Blake (1935). Two adits can still be seen on the west bank of the creek (at 254677/5573280). There is no record of any production. A series of quartz-sulfide (carbonate) veins were tested by adits and shallow shafts. The veins host Pb, Zn, As, Ag and Au mineralisation. The veins are only a few centimetres wide and mineralisation does not appear to extend into the host siltstone (Young and

Mathison, 1994). Waterhouse (1916) appears to refer to this as 'the old No. 1 mine', and describes an adit 160 feet long driven on a quartz vein 18–24 inches (450–600 mm) wide that had 'a little galena, some pyrite and traces of arsenopyrite and sphalerite'. Blake (1935) referred to two or three lodes striking NW–SE, and 6 to 30 inches (150–760 mm) wide. The mineralogy was described as quartz with arsenopyrite, sphalerite, galena, pyrite and chalcopyrite. The lodes are considered unlikely to be of economic significance (Brown, 1987). Reconnaissance sampling shows that no appreciable mineralisation extends into the country rocks (Mathison, 1991).

Abandoned workings known as 'McKie's Gold Mine' were noted by Waterhouse (1916). A shaft was said to be sunk on a gold-bearing quartz reef, 2 miles (3.2 km) from Pegarah Road. This may be the prominent quartz reef mapped just west of the Sea Elephant River (242000/5576000). Modern reconnaissance has found no detectable gold here or at the Sea Elephant River mine (Mathison, 1991).

An IP and base metal geochemical anomaly just south of Pegarah Road ('Irelands Farm prospect') was followed up with diamond drilling in about 1968. Two inclined holes were drilled; low anomalous base metal values were encountered in pyritic black shale of the Fraser Formation (Leckie, 1968).

Peko Exploration Ltd took out EL 54/1989 to search for base metal and gold mineralisation away from the granite, including shear-related gold deposits and McArthur River style (sedimentary exhalative) lead-zinc deposits. Reconnaissance Huminex water and soil geochemistry, and rock-chip sampling were undertaken. Results from the environs of the old Barrier Creek, Sea Elephant River and Fraser River prospects were not encouraging (Mathison, 1992). Thick regolith and surficial cover, and prevalent agricultural use of trace element enriched superphosphate, makes water or shallow soil geochemistry ineffective over much of the island.

North Exploration also sought McArthur River style Pb-Zn mineralisation, under EL 26/1992. Gravity, ground magnetic, limited rock-chip sampling and mapping were done. Results were deemed not encouraging for base metals (Young and Mathison, 1994).

Pacific Nevada Pty Ltd targeted Proterozoic iron-formation Cu-Au and sediment-hosted (stratiform) Cu under exploration licences that covered most of King Island in the late 1990s. Limited stream sediment and rock-chip sampling was undertaken (Reid and Westbrook, 1998).

Prospectivity

The weakly developed surface drainage system, thick regolith and widespread sandy cover present particular challenges to exploration programs based on regional geochemical sampling.

The Sandblow Granite has a relatively high gold content, and has some chemical similarities to monzonitic A-type granites which are prospective for Mo, W, Bi, U, REE and Au mineralisation (Wormald, 1990). There is potential for Au-rich base metal skarns and Au-quartz mineralisation associated with fault zones up to five kilometres away from the granite (Wormald, 1990). The Grassy River Fault, the
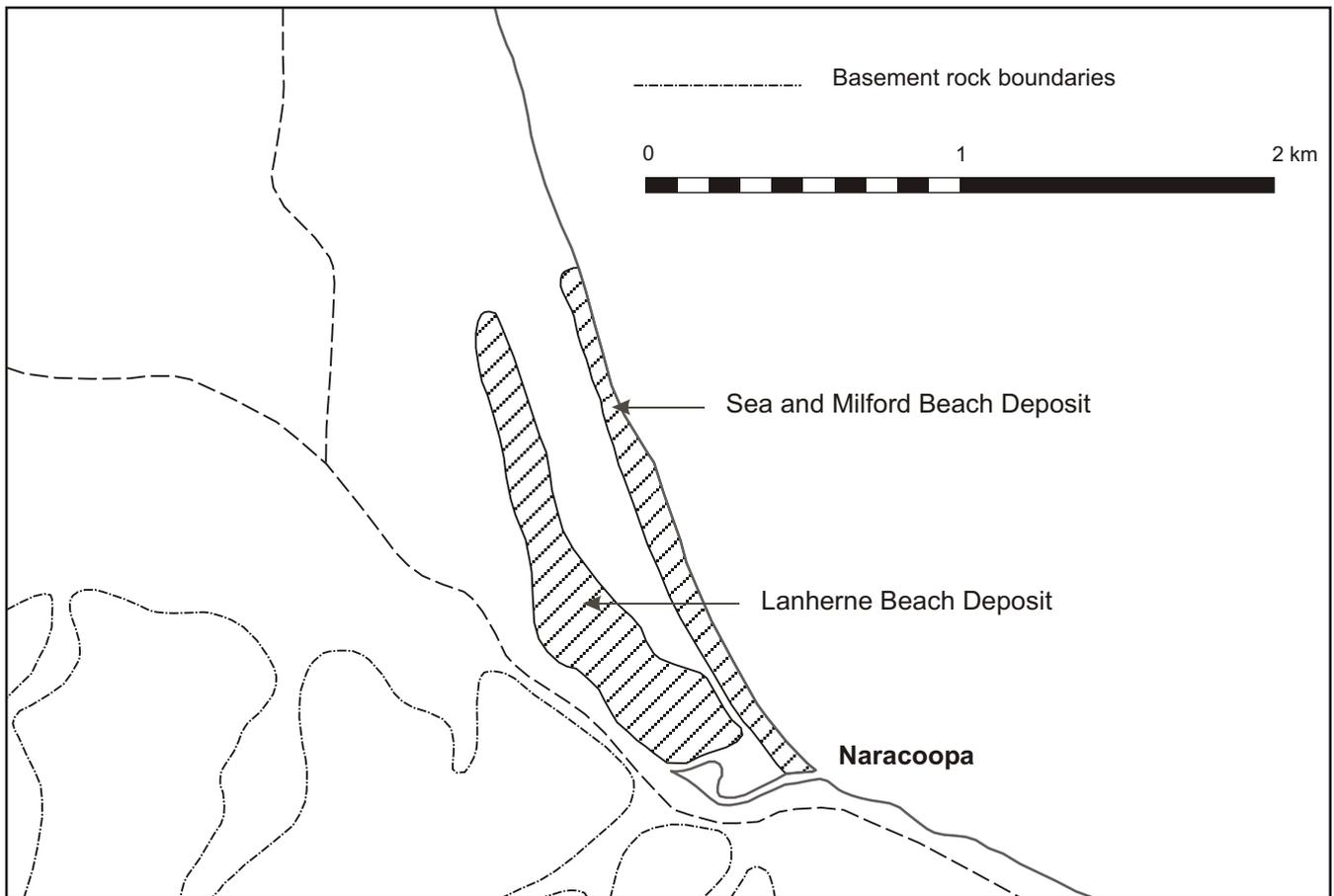
Figure 65
Historical heavy mineral deposits in the Naracoopa area. (from Owen, 1988).

north-trending faults in the Mount Stanley–Lymwood area, and the Barrier Creek Fault are prospective for such fault-related mineralisation. Gravity and magnetics suggest similar granite may have intruded along the Pearshape Fault.

Various sill-like Proterozoic mafic intrusive rocks could be prospective for magmatic Ni-Cu and Platinum Group Element mineralisation (Crawford *et al.*, 2009). One such unit is the mapped gabbroic cumulate variant (Lygc) of the Denbys Dolerite which extends over a strike length of four kilometres from Fraser Bluff to offshore of Barrier Creek. The larger amphibolite bodies (Laa) may also be prospective.

Mineral sands and tin

The black heavy mineral sands along the coast north of Naracoopa were initially prospected for tin. In 1905, the British Flag Prospecting and Mining Syndicate NL recovered 5½ tons from workings 150 m north of the Fraser River mouth, but very little other production of tin has been recorded (Blake, 1929; Neale and Salway, 1975).

An investigation by the Department of Mines in 1928 focussed on a terrace parallel to and immediately inland of the modern beach, two metres above high water mark, ~30 m wide and extending at least two kilometres north of the Fraser River mouth. This is the 'Milford Beach' of later workers (fig. 65). High concentrations of ilmenite were found in bores, although only a few bores contained notable cassiterite (Blake, 1929).

Further test boring in the 1950s by King Island Scheelite (1947) Ltd and Mt Isa Mines Ltd showed a substantial resource of heavy minerals (rutile, zircon, minor tin and monazite) in the raised beach sands (Garretty, 1952). In 1965 the Canadian company Mt Costigan Mines took over the leases and evaluated them with a systematic auger drilling program. By 1967, resources of 63 000 t of rutile and 53 000 t of zircon had been outlined, in both the modern beach and two older raised beaches named the Milford and Lanherne beaches (fig. 65) (Anon., 1967). A subsidiary, Naracoopa Rutile Ltd, was formed in 1968 to mine the deposits. The modern and Milford beach sands were successfully mined in 1969–1971, but the company went into receivership in 1972 due to operational problems associated with mining the partly indurated and iron-stained Lanherne beach deposit (Oliver *et al.*, 1972). The operation was bought by Buka Minerals, the plant revamped and mining continued until 1977 under Buka subsidiary, Kibuka Mines Pty Ltd (Neale and Salway, 1975). Total production from 1969 to 1977 was 20 000 t of rutile and 23 000 t of zircon from 3.07 Mt of sand. Considerable resource remains. The magnetic tailings, comprising mostly ilmenite and garnet with lesser quantities of rutile and zircon, were stockpiled.

Exploration Licence 28/1985 was taken out over the area by Sanidine NL, and in joint venture with PekoWallsend Ltd and National Mineral Sands Pty Ltd, Sanidine carried out further resource definition by drilling (Dove and Lee, 1988) and a detailed feasibility study (Gillett, 1989). Total Indicated and Inferred resources at 1.5% heavy mineral cut off (including

tailings) were estimated at 38 000 t of rutile, 43 000 t of zircon, and 20 000 t of leucoxene in a total 670 000 t heavy mineral and 6.5 Mt of sand (Gillett, 1989). Australian Titanium Minerals Ltd held title over the deposits in the late 1990s, and in 1998, Tasmanian Titanium Pty Ltd was granted mining lease 1673P/M over the Naracoopa and Cowper Point deposits (now held by Dr Allan J. Bond and Associates Pty Ltd). In early 2012 preparations were underway to resume production from the ilmenite-rich tailings stockpile.

A typical heavy mineral suite from the Naracoopa deposits contains rutile (5–9%), zircon (6–14%), leucoxene (3–7%), ilmenite (18–28%), 'leucoxenised ilmenite' (8–13%), garnet (5–10%), tourmaline (16–25%), epidote (2–6%), staurolite (4–6%), and minor chromite, kyanite, monazite, corundum, and other silicates (Gillett, 1989). Traces of scheelite have also been recorded (Dove and Lee, 1988). The magnetic minerals, which make up about 60–70% of the total suite, consist mainly of ilmenite. The non-magnetic fraction is 60–75% by volume rutile, zircon and leucoxene. Bottrill and Baker (2008) found that fine-grained pseudorutile is a major constituent of the 'leucoxene'.

The deposits appear to have been derived from the Proterozoic metasediments and igneous intrusive rocks which are the basement rocks for most of the area drained by the Fraser and Sea Elephant rivers. The ilmenite and chromite are probably derived from the amphibolite bodies inland of Naracoopa and the Ediacaran mafic intrusive and volcanic rocks along the coast to the south.

Lanherne Beach forms a terrace eleven metres above high water mark, and is considered to be an accumulation of beaches with at least three vertically-stacked beaches as shown by horizons of cobbles and buried soils. Milford Beach is considered to be the accreting storm barrier to the present day Sea Beach (Dove and Lee, 1988).

Exploration further north of the main deposits has shown that the mineral content of the sand generally diminishes northwards from the mouth of the Fraser River. Two lower grade, as yet unexploited deposits, have been outlined southwest of Cowper Point (beyond the northern boundary of the Naracoopa map) (Neale and Salway, 1975; Owen, 1988; Dove and Lee, 1989).

Intermittent exploration has taken place for heavy minerals in the sea bed sediments in Sea Elephant Bay offshore of Naracoopa. Shallow sub-sea drilling was carried out by Ocean Mining AG in 1966 (Anon., 1968) and in 1976 by Amdex Mining Ltd (Neale, 1976). In 1997, Mapping and Hydrographic Surveys Pty Ltd carried out a hydrographic survey comprising echo sounder bathymetry and boomer seismic at the southern end of Sea Elephant Bay. Also in 1997, Australian Titanium Minerals Ltd engaged Stitt and Associates to conduct a reconnaissance sea floor sampling program. Sampling at 20 sites was restricted to the surface

two metres and a maximum grade of 24.7% heavy minerals was obtained. Present data indicate that an area of some 60 ha, offshore from the southern end of Fraser Beach, contains surficial enrichment of total heavy mineral averaging approximately 5% (Morrison, 2000), but deeper sands have not been adequately sampled.

Prospectivity

There is only limited potential to add to the known heavy mineral resource in the Naracoopa area (Gillett, 1989), although the offshore sands remain largely untested.

Lime sand and silica sand

Lime sand is an important part of the agricultural economy on King Island, with regular applications required to maintain the pH of soils under pasture on the Pegarah Plateau and elsewhere. The lime sand is sourced from the extensive calcareous dune sands (Qhd) of western King Island. These are mostly vegetated and extend up to four kilometres inland, and contain up to 70% $CaCO_3$ (Hughes, 1954) in the form of comminuted shell material.

Geopeko Ltd investigated the sand deposits of the 'old dunes' (Qpswu) southwest of Grassy in 1991–1992 (Mathison, 1992). Mapping and limited auger drilling showed a few million tonnes of low iron silica sand. Market conditions and the logistical difficulties of export from the island did not favour further investigation.

Construction materials

The supply of gravel for road construction and concrete aggregate has been problematic on King Island. Alluvial gravels are poorly developed, and over most of the island bedrock is covered by several metres or more of stone-free clayey regolith or windblown sand. Bedrock quarries in mudstone and siltstone (Fraser Formation) at Pearshape, and in weathered granite at Reekara, have encountered problems with acid drainage. Demand is created by the extensive network of private farm tracks as well as the council-maintained public roads. Past, current and potential quarry sites are discussed by Calver (1998).

Most of the road gravel and concrete aggregate on southern King Island is now sourced by the King Island Council and private operators from mine waste dumps, composed of metavolcanic rocks and hornfels, adjacent to the old Grassy open cut and the Bold Head mine. Beach shingle in Grassy Bay, derived by erosion from the adjacent Grassy sea dump, is also used. Intermittent extraction has occurred from pits in mudstone/siltstone (Fraser Formation) on Millwood Road. In many places landowners have worked deposits of ironstone on a small scale, or less commonly, opened small pits in bedrock.

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Table 1

Whole-rock analyses of intrusive rocks and amphibole hornfels associated with the Fraser Formation

Reg. No.	R009689	R013131	R15022		R17522	R15014	R013188
Lab. No.	20110043	20110044	20090258	980665	20110355	20110353	20110045
Field No.	K26	K190	K184	B5A	K348	N50	K323
Lithology	hornfels	hornfels	hornfels	amphibolite	amphibolite	amphibolite	dolerite
Unit	Lfc	Lfa	Lfa	Laa	Laa	Laa	Lmd
Location	Yarra Creek Rd	Old Grassy Road	Missons Road	Pegarah Road	Pegarah Road	SE of Pegarah	Fraser Bluff
mE (GDA)	249733	240999	241593	247113	246929	242340	254842
mN (GDA)	5567373	5568620	5569295	5574185	5574399	5573376	5575897
SiO_2 (%)	55.25	53.58	56.41	46.63	47.47	48.34	54.29
TiO_2 (%)	1.07	1.06	1.04	1.14	1.40	1.73	0.58
Al_2O_3 (%)	14.72	15.01	14.86	15.45	14.53	13.49	14.48
Fe_2O_3 (%)	1.08	1.78	1.81	1.22	15.86	17.09	1.12
FeO (%)	11.1	9.8	8.80	12.09	0.00	0.00	7.0
MnO (%)	0.17	0.19	0.20	0.22	0.24	0.26	0.12
MgO (%)	7.73	7.08	6.05	8.08	7.09	5.72	5.58
CaO (%)	3.05	3.46	2.27	9.66	9.91	9.62	8.97
Na_2O (%)	2.03	2.12	1.31	2.09	2.21	2.02	3.21
K_2O (%)	1.36	1.55	1.59	0.3	0.32	0.44	1.06
P_2O_5 (%)	0.12	0.12	0.14	0.12	0.10	0.12	0.10
SO_3 (%)	0.30	0.55			0.05	0.05	0.37
CO_2 (%)	0.1	0.1	0.10	0.09	0.00	0.00	0.2
H_2O^+ (%)	1.92	3.62	4.85	2.72	0.93	1.06	2.91
TOTAL	**100.00**	**100.02**	**99.43**	**99.81**	**100.11**	**99.94**	**99.99**
LOI	1.09	3.18	3.97		0.93	1.06	2.70
Item (ppm)							
As	20	30	24		bdl	bdl	<3
Ba	350	370	264	93	30	61	195
Bi	3	2	2		2	4	1
Ce	48	45	41		9	15	40
Cl	<0.2	<0.2	0.007		0.004	0.006	<0.2
Co	49	48	45	59	58	52	30
Cr	145	145	119	155	155	180	48
Cs	14	10	8		3	bdl	<3
Cu	83	77	165	92	100	68	6
Ga	21	20	20	21	21	23	16
La	41	28	26		8	9	20
Mo	<1	<1	<1		bdl	1	<1
Nb	8	8	10		3	4	10
Nd	26	23	23		18	11	11
Ni	86	82	74	120	82	43	6
Pb	8	11	9	0	4	3	4
Rb	72	76	103	30	23	25	33
S	0.12	0.22	0.04		0.17	0.14	0.15
Sb	<2	<2	3		2	3	2
Sc	41	34	35	46	46	59	42
Sn	2	2	2		2	2	<2
Sr	210	260	232	150	130	170	42
Th	<2	2	3	17	bdl	bdl	5
U	2	3	3	0	1	1	2
V	310	290	275	340	400	510	210
W	<2	<2	<2	0	bdl	bdl	3
Y	29	26	21	27	32	38	27
Zn	135	140	118	120	125	150	50
Zr	110	110	124	59	74	89	100

Reg. No.	R013110	R13198	R002629	R013167	R013166	R013173	R009545	R009544	R13133
Lab. No.	20080205	20090266	990511	20090261	20090260	20090263	20010343		20110349
Field No.	K96	K360	P20	K274	K273	K293	220073	220074	K195
Lithology	basalt flow	basalt flow	sandstone	sandstone	dyke	diorite	gabbro	dolerite	dolerite
Unit	Lysr	Lysr	Lysc	Lysc	Lysc	Lyg	Lyg	Lygd	Lygd
Location	Cumb'land Ck	Cumb'land Ck	The Gut	Cottons Bch	Cottons Bch	Barrier Creek	Congl. Creek	Fraser Bluff	Fraser Bluff
mE (GDA)	254572	254548	254313	252925	253184	254594	254303	255457	255441
mN (GDA)	5571656	5571644	5568485	5565454	5565718	5573345	5569515	5575773	5575619
SiO$_2$ (%)	54.84	45.29	39.78	49.24	39.63	53.24	45.886	52.139	51.69
TiO$_2$ (%)	1.26	1.23	1.78	1.37	1.48	0.55	0.288	0.496	0.43
Al$_2$O$_3$ (%)	20.00	17.49	13.04	12.68	16.14	15.71	8.328	14.813	15.18
Fe$_2$O$_3$ (%)	1.70	0.95	0.73	3.47	3.27	1.50	1.237	1.971	8.37
FeO (%)	4.80	9.00	11.84	8.50	6.00	6.40	8.46	6.998	0.00
MnO (%)	0.04	0.10	0.11	0.09	0.11	0.16	0.156	0.178	0.15
MgO (%)	3.35	4.78	9.84	10.15	5.48	6.34	22.185	7.204	7.53
CaO (%)	0.72	5.07	8.16	1.98	9.33	7.48	5.867	9.482	10.92
Na$_2$O (%)	5.47	4.80	0.24	1.50	3.13	2.14	0.077	2.053	1.96
K$_2$O (%)	3.76	2.30	0.8	2.50	2.90	1.81	0.019	1.577	0.75
P$_2$O$_5$ (%)	0.11	0.12	0.23	0.13	0.19	0.09	0.05	0.072	0.07
SO$_3$ (%)	0.03		0.61				0.335	0.235	0.03
CO$_2$ (%)	0.10	3.80	5.93	2.70	7.40	0.40			0.00
H$_2$O$^+$ (%)	3.22	4.23	6.58	5.05	4.32	3.33			2.58
TOTAL	**99.40**	**99.16**	**99.67**	**99.36**	**99.38**	**99.15**	**99.433**		**99.66**
LOI	2.78	7.03	11.2	6.81	11.05	3.02	6.784		2.58
Item (ppm)									
As	bdl	8	0	3	5	9	1.3	-0.5	bdl
Ba	570	545	170	396	111	384	18	292	150
Bi	bdl	2	0	3	2	1	0.1	-0.1	bdl
Ce	bdl	11	30	10	60	38	15.4	25.29	24
Cl		0.009		0.031	0.018	0.009			0.012
Co	29	58	41	55	43	35			36
Cr	460	412	71	197	40	244	2876	152	180
Cs		3		17	2	4	0.76	2.32	bdl
Cu	125	148	55	172	17	21	130	23	16
Ga	20	18	22	17	20	15	7.8	13.8	13
La	bdl	11	0	20	31	22	7.17	11.9	9
Mo	bdl	<1	0	<1	<1	<1	1.1	2.3	bdl
Nb	8	9	15	7	31	10	4	6.1	6
Nd	bdl	9	0	6	23	16	7.5	11	7
Ni	78	126	78	81	25	44	737	43	40
Pb	bdl	2	0	3	5	4	0.9	4.5	6
Rb	110	54	34	52	91	59	4.8	77.4	36
S	0.1	0.03		0.02	0.04	0.03			0.02
Sb		<2		<2	3	<2	0.1	-0.1	bdl
Sc	53	55	39	50	36	48	23	46	44
Sn	bdl	1	0	1	2	<2	1.6	1.8	2
Sr	67	90	47	47	100	224	11.9	117.9	115
Th	bdl	<2	16	<2	1	3	2.1	3.5	3
U	bdl	1	0	<1	2	2	0.66	0.9	2
V	380	384	300	343	263	236	134	233	230
W	bdl	<2	0	1	<2	1			bdl
Y	20	19	30	23	27	27	13.5	24	22
Zn	86	99	125	94	140	70	99.7	77.5	63
Zr	75	73	135	82	161	103	46	64	60
Ag							-0.01	0.02	
Be							0.2	1.1	
Cd							0.06	0.15	
Dy							2.08	3.54	
Er							1.41	2.43	
Eu							0.299	0.713	
F							107	401	
Gd							1.93	2.98	
Ge							1.7	1.9	
Hf							1.1	1.7	
Ho							0.45	0.79	
Lu							0.22	0.38	
Pr							1.89	2.84	
Sm							1.53	2.65	
Ta							0.2	0.4	
Tb							0.35	0.61	
Yb							1.39	2.54	

Reg. No.	R13182	R013114	R013183	R013168	R013150	R013175	R13151	R13176	R17520
Lab. No.	20110352	20080206	20090265	20090262	20090259	20090264	20110350	20110351	20110354
Field No.	K315	K108	K316	K282	K238	K298	K245	K299	K48
Lithology	dolerite	basaltic sill	basaltic sill	sill	intrusive	picrite	basalt	basalt	basalt
Unit	Lygd	Lyvb	Lyvb?	Lyvbt	Lyvbp	Lyvp	Lyvp	Lyvg	Lyvg
Location	Fraser Bluff	Robbins Creek	Fraser Bluff	Robbins Creek	Mt Stanley	Fraser Bluff	Mt Stanley	Fraser Bluff	Cottons Bch
mE (GDA)	255361	254675	255463	254914	244596	255127	245479	255223	252643
mN (GDA)	5576255	5572254	5576003	5572501	5562249	5576734	5562601	5576679	5564960
SiO_2 (%)	53.32	52.20	47.37	49.83	43.28	47.15	42.35	50.78	48.01
TiO_2 (%)	0.58	0.54	0.41	0.47	0.20	0.37	0.28	0.92	1.72
Al_2O_3 (%)	15.07	14.71	12.69	14.09	8.88	14.59	12.71	15.74	13.90
Fe_2O_3 (%)	8.57	1.31	1.74	1.61	2.11	4.81	11.24	10.80	14.61
FeO (%)	0.00	8.10	7.90	7.50	6.90	3.90	0.00	0.00	0.00
MnO (%)	0.14	0.16	0.18	0.16	0.13	0.14	0.16	0.20	0.21
MgO (%)	6.30	8.20	12.74	8.80	23.44	11.19	17.85	7.78	6.60
CaO (%)	7.10	2.78	8.00	11.15	7.11	10.77	10.17	5.36	9.16
Na_2O (%)	2.49	4.08	0.48	1.72	0.16	2.58	0.61	2.96	3.66
K_2O (%)	2.44	0.46	3.42	0.80	0.03	0.17	0.24	1.00	0.15
P_2O_5 (%)	0.09	0.08	0.05	0.07	0.02	0.08	0.02	0.22	0.16
SO_3 (%)	0.04	0.01					0.02	0.04	0.03
CO_2 (%)	0.00	1.70	0.20	0.20	0.10	0.10	0.00	0.00	0.00
H_2O^+ (%)	3.60	5.11	3.91	3.03	6.72	3.90	3.77	3.99	1.97
TOTAL	99.74	99.44	99.09	99.43	99.08	99.75	99.42	99.79	100.18
LOI	3.60	5.91	3.23	2.40	6.05	3.57	3.77	3.99	1.97
Item (ppm)									
As	bdl	bdl	2	<3	5	3	bdl	bdl	bdl
Ba	420	230	519	525	24	90	67	250	69
Bi	1	bdl	1	1	3	1	2	2	4
Ce	41	bdl	7	11	<5	27	bdl	59	18
Cl	0.011		0.01	0.008	0.009	0.011	0.010	0.017	0.009
Co	31	35	61	43	92	49	80	44	51
Cr	240	1100	1386	376	2650	1005	3300	410	110
Cs	3		6	1	1	5	6	bdl	3
Cu	11	64	73	72	115	60	bdl	16	110
Ga	16	16	13	13	8	11	10	18	20
La	22	bdl	11	<6	1	25	bdl	34	12
Mo	bdl	bdl	<1	<1	<1	<1	bdl	bdl	1
Nb	10	3	2	6	2	23	2	16	9
Nd	22	bdl	12	2	<7	5	bdl	27	13
Ni	38	250	323	118	1256	281	880	47	74
Pb	4	bdl	3	1	1	2	3	3	bdl
Rb	110	11	172	24	4	8	11	54	8
S	0.01	0.0	0.02	0.04	0.02	0.02	0.00	0.00	0.00
Sb	bdl		<2	<2	2	2	bdl	bdl	bdl
Sc	33	49	38	50	32	47	45	37	45
Sn	2	bdl	1	<2	1	1	bdl	2	2
Sr	140	290	96	162	<1	191	65	130	210
Th	4	bdl	<2	<2	<2	1	bdl	bdl	bdl
U	2	bdl	1	1	<1	1	bdl	1	1
V	195	290	212	280	161	228	180	250	410
W	bdl	bdl	<2	<2	<2	<2	bdl	bdl	bdl
Y	27	21	17	20	9	18	15	34	26
Zn	64	83	74	67	55	59	64	100	115
Zr	110	66	46	44	13	32	13	120	105

Table 3

Magnetic susceptibility measurements with hand-held meter

Unit	Formation/lithology	Mean (10^{-3} SI)	Stand. deviation (10^{-3} SI)	Maximum (10^{-3} SI)	n
Qf	Ironstone	47.2	21.6	62.4	10
Tb	Basalt	8.3	1.5	10.6	9
Dgnsf	Microgranite	0.2	0.2	0.5	20
Lyv	Skipworth Subgroup (metabasalt)	12.5	13.1	43	75
Lyv	Skipworth Subgroup (metabasaltic, probable intrusive rock)	15.4	13.0	40	40
Lyvb	Basaltic intrusive rocks (undifferentiated) in Grassy Group	12.0	25.6	85	60
Lyvbt	Basaltic intrusive rocks related to Grahams Road Volcanics	2.4	2.3	4	10
Lyvg	Grahams Road Volcanics	40.7	33.7	122	115
Lyvgc	Conglomerate in Grahams Road Volcanics	1.8	1.4	2.8	10
Lyvp	Shower Droplet Volcanics	2.5	4.3	13.4	45
Lyvbt	Basaltic intrusive rocks related to City of Melbourne Volcanics	0.7	0.0	0.7	15
Lyvt	City of Melbourne Volcanics	21.2	23.0	70.9	90
Lyg	Grimes Intrusive Suite (GIS)	0.6	0.2	1.1	50
Lygc	Gabbroic cumulate at base of GIS	51.4	0.5	51.7	10
Lyscs	Volcanic sandstone within Cottons Breccia	35.0	34.0	59	10
Lmd	Doleritic intrusive rock in Fraser Formation	0.7	0.0	0.7	15
Laa	Amphibolite	1.0	0.1	1.2	45
Lfn	Fraser Formation: mudstone	0.3	0.1	0.3	30
Lfs	Fraser Formation: siltstone	0.5	0.4	0.7	10
Lfgl	Fraser Formation: garnet-bearing siltstone	1.5	4.5	20.9	105

APPENDIX 1
Report on three thin sections from King Island

P. G. Quilty

John Everard, Mineral Resources Tasmania, left three thin sections at the School of Earth Sciences office on 8 April 2010. Comments are as follows.

N58 — Sartoris Road (293 000 mE, 5 568 900 mN) 1 km southeast of Currie, c. 75 masl

A shallow-water, high porosity, bryozoal calcarenite with echinoid spines, broken bivalve and gastropod remains and scattered, rounded quartz grains. Foraminifera are few and far between and unidentifiable because of diagenetic effects. All seen are benthic forms and of no age diagnostic value. It represents deposition in a few metres water depth in a high energy environment to account for the broken remains and rounded grains. There has been considerable overgrowth of fine carbonate on the carbonate fossils acting as cement.

N59 — 243 000 mE, 5 604 000 mN: about 3 km ESE of Egg Lagoon, from shallow drill hole, c. 10 masl

This is also a bryozoal calcarenite but has several significant differences from N58. It is finer grained, perhaps even higher porosity but is bedded (possibly an artefact of orientation of the thin section) and there is a rough alignment of the bryozoan fragments. Other components include calcareous algae, echinoids, broken bivalves and finer quartz grains. There are also foraminifera, both benthic and planktonic, suggesting slightly deeper water deposition than N58, perhaps in the 20–50 m range. The environment was less robust than that of N58.

Foraminifera include *Lenticulina* and *Guttulina*.

One thin section (unfortunately poorly preserved) is an equatorial section through what appears to be *Tenisonina tasmaniensis* which I described from Cape Grim (Quilty, 1980) and found recently with Dr D. Seymour from Temma. The identification is tentative. If correct, it suggests an Early Miocene age consistent with sediments already described around the island (Quilty, 1972).

KE1226 — 241 870 mE, 5 558 980 mN: lower Stanley Creek, north of Colliers Swamp, c. 25 masl

Highly porous bryozoal calcarenite with aligned fragments. Also echinoids, broken molluscs (both bivalve and gastropod) and highly rounded terrigenous grains, including beautiful schist. Very minor calcareous algae. Foraminifera rare and basically unidentifiable (small *Haplophragmoides*, *Cibicides*); a couple of encrusting forms akin to *Acervulina*. Cavities between grains are filling with sparry calcite.

Comment

The three thin sections have much in common and appear to represent an episode of sedimentation, probably during the Early Miocene, well known around the margin of Tasmania (Quilty and Seymour, 2010).

All accumulated in high energy coastal environments within the photic zone. There are minor differences in content and depth of deposition.

An interesting feature is that N58 in particular, at 75 masl, suggests elevation of the island, consistent with other evidence from around northern Tasmania.

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[9 April 2010]