AUSTRALIAN JOURNAL OF EARTH SCIENCES
https://doi.org/10.1080/08120099.2022.2032340

The tabular Strathbogie batholith in central Victoria

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ABSTRACT

The southern boundary of the high level, discordant, Devonian Strathbogie batholith in central Victoria includes two near-linear sections that strike east–west, and one north–south. Field mapping has delineated the 100 km southern boundary with 2200 waypoints taken where granite and hornfels are within 10 m of one another. There is 790 m of topographic relief along the southern boundary and, where the mapping is overlain on contours, there are intervals that reflect a steep-dipping contact and others that reflect near-horizontal contacts. Of the latter, some reflect the granite roof and others the floor. Complementary evidence from mineralogic and textural data indicates a strong correlation between the interpreted roof of the granite and the abundance of tourmaline, aplite and pegmatite. When combined, the roof and floor intervals indicate a batholith thickness up to 350 m; nowhere along the southern boundary can a thickness of 1 km be demonstrated. Along the southern boundary, at least, the batholith shape is a thin, tabular and extensive composite granite sheet analogous to a *pizza* rather than a *pipe*. The roof of the granite is nearly horizontal in both east–west and north–south sections, and the plateaux today are close to the batholith roof. On regional and local scales, granite emplacement was determined by pre-existing anisotropies, such as master joint sets, across which the propagation of magma-filled fractures (granite sheets) was arrested. The emplacement records a fine balance between magma pressure, and the interplay of lower confining (overburden) pressures and pre-existing anisotropies that also facilitated roof uplift. The opportunistic magmas used the slightest variations of those parameters. This interpretation of the Strathbogie batholith matches examples in the Himalaya and Chilean Andes but differs markedly from the portrayal of very large batholiths beneath Cu–Au porphyry systems.

KEY POINTS

1. The boundary of the Strathbogie batholith can be mapped in moderately outcropping terrain to an accuracy of 10 m or better.
2. Steep intervals of the boundary are interspersed with near-horizontal intervals that delineate the granite floor and roof along the 100 km of the southern boundary.
3. The batholith, at least near its southern boundary, comprises near-horizontal sheets of <500 m aggregate thickness.
4. The boundary determined by geophysics is adequate for regional studies but has been misleading in three-dimensional interpretations.

ARTICLE HISTORY
Received 20 November 2021
Accepted 16 January 2022

KEYWORDS
Strathbogie batholith; granite; hornfels; boundary; tabular sheets; Devonian; southeast Australia; Lachlan Orogen; step-and-stair geometry

Introduction

There is a long history of investigation and speculation about the mechanisms of and controls on granitic magma emplacement (*e.g.* Clemens & Mawer, 1992; Cruden, 2006; Cruden & Weinberg, 2018; Menand, 2011; Pitcher & Berger, 1972; White *et al*., 1974). The three-dimensional (3D) shape of an intrusion informs magma emplacement, but on this matter, there are widely disparate interpretations of the geometry of intrusive bodies, from steep-sided plutons with large vertical depth extent to tabular, sheet-like granite plutons, and it is possible that both are correct in different settings.

Historically, textbooks and journal articles have depicted intrusions as akin to open-ended batholiths with steep sides, many kilometres vertical extent and commonly without defined floors (Figure 1a). For example, this trend is widespread in economic geology including the literature on Cu–Au porphyry deposits, which invokes large magma chambers as the metal sources and small, pipe-like, near-vertical plutons as orebody hosts (*e.g.* Sillitoe, 2021, figure 1). A different view is held by many igneous and structural geologists

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Editorial handling: Chris Fergusson
Supplemental data for this article is available online at https://doi.org/10.1080/08120099.2022.2032340.

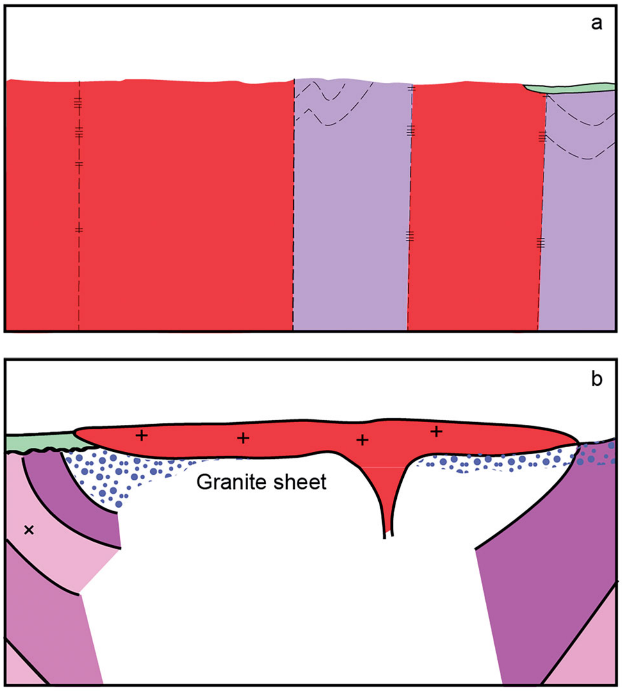

Figure 1. Two interpretations of granitic intrusions into folded metasedimentary rocks. (a) One common interpretation of a pipe-like intrusion (red) with great depth and steeply dipping contacts against wall rocks (purple); this representation is based on published sections for the western Strathbogie–Seymour region. (b) An alternative pizza-shape interpretation, which invokes thin granite sheets and a contact with wall rocks that has variable dips, depending upon proximity to the roof, walls or floor of a sheet.

who describe sheets of granitic rocks (Figure 1b; Coetzee & Kisters, 2018; Cruden, 1998; Hall & Kisters, 2016; McCaffrey & Petford, 1997; Searle *et al*., 2009; Searle, 2013; Searle & Treloar, 2019) and who doubt the existence of the large chambers dominated by magma with only subordinate crystals (*e.g.* Clemens, 2012; Lundstrom & Glazner, 2016). Others have inferred sheet-like forms for dolerite intrusions in the Karoo of South Africa (Du Toit, 1920) and the USA (Holz, 1952). Sheets have also been inferred for many granitic bodies (Farina *et al*., 2010) including from the Sierra Nevada Mountains in the USA (Bartley *et al*., 2012; Mahan *et al*., 2003), the Borborema Province in Brazil (Archanjo & Fetter, 2004), and the Donegal batholith in Eire (Price & Pitcher, 1998/1999). For most Cu–Au porphyry deposits, seismic studies have not been able to delineate the large bodies of magma implicated in the traditional view of their genesis; however, there are large reservoirs dominated by crystals with subordinate magmatic liquids (*e.g.* Pritchard & Gregg, 2016). Resolving these problems of composition, volume and geometry is not simply an exercise in granite enquiry but can inform our understanding of the rare but catastrophic large silicic eruptions, and genesis of some of the world's major ore deposits.

The two-dimensional shapes of intrusions can be gleaned from airborne and satellite imagery but inferences on the shape at depth have generally relied on direct studies in alpine regions or indirect geophysical methods such as gravity, seismic and magnetic surveys (*e.g.* Cruz *et al*., 2021). Drilling and mining both provide useful information on depth extent, but such data are quite restricted spatially. However, the introduction of some modern technologies has added detailed field mapping to the list of methods that can be used to constrain the 3D shapes of intermittently outcropping bodies where there is only moderate (non-alpine) relief. Global positioning systems (GPS) and geographic information systems (GIS) have been especially important and have led to a major advance compared with traditional field mapping onto air photos or the use of pace-and-compass and plane-table approaches (Marjoribanks, 1997).

The default interpretation of plutons as steep-sided, vertical bodies has been challenged with independent lines of evidence that suggest that many intrusions may be near-horizontal sheets of limited depth extent (Figure 1b), and with a *step-and-stair* geometry of flat and steep intervals on various scales (*e.g.* Francis, 1982; Knox, 1954; Menand, 2011). This alternative interpretation (to that of pipes) has given rise to descriptive terms such as *pizza* to describe the sub-horizontal sheet-like forms of plutons (this scenario still entertains the existence of pipe-shaped plutonic bodies). Environments in which the third dimension is exposed include the following:

- Alpine regions can expose deep cross-sections of granitic intrusions (*e.g.* Cruden, 1998), and some of these have near-horizontal contacts with surrounding metasedimentary rocks, *e.g.* Himalayas (Searle, 2013), and the Torres del Paine in southern Chile (Michael, 1991).
- Open-pit mines can be considered as modified land surfaces that expose the depth component as mining progresses, and drilling can supplement the mapping of the open pits. Some such pits provide examples in which mining has progressed through circular intrusions to reveal that the overall shape is disk-like or lenticular, with a thickness up to a few 100 m and with low to moderate dips. Examples from the Archean Yilgarn Craton include the Spotted Quoll nickel deposit at Forrestania, Discovery pit at Bronzewing gold mine, Nim 3 pit at Jundee gold mine and Marvel Loch gold mine (Kohler & Phillips, 2003; Kohler *et al*., 2003; Phillips & Vearncombe, 2011; Powell & Phillips, 2017; Prichard *et al*., 2013).

Many of these examples, both in alpine settings and from mining operations, demonstrate a *step-and-stair* geometry, as described previously for the mafic Whin Sill of northern England (Francis, 1982; Goulty, 2005). The open pit at Marvel Loch in Western Australia is particularly interesting because three moderately dipping pegmatite dykes, each several metres thick, are exposed in the pit walls and underground, and these show *step-and-stair* features with orthogonal deflections on a scale of a few metres (Powell & Phillips, 2017, figure 2c).

Previously, the *pipe* interpretation has been made for the western end of the Strathbogie batholith—the largest batholith in central Victoria. Based on geophysical and radiometric interpretations (Edwards *et al*., 1997), this intrusion, and several others nearby, have been depicted with steep sides to over 1 km depth (Figure 1a). However, the results of our field mapping around the Strathbogie batholith do not support the pipe-like geophysical interpretation. Our focus is on the 100 km southern margin within the context of the longer-term Strathbogie Granite Project (Clemens & Phillips, 2014; Phillips & Clemens, 2013). The advantages and disadvantages of this present study area are discussed, results of the mapping presented in various map sheets (supplemental data) and some conclusions drawn about granite emplacement and 3D shapes.

Glossary of terms used

Some terms are used here to describe where granitic rocks and hornfels are juxtaposed, and much of the terminology follows that used in a pilot study of the Tallarook plateau (Phillips, 2017).

Batholith is used to convey the areal extent of the Strathbogie granitic rocks (it is almost 2000 km^2), but the term carries no connotations regarding the third dimension (Figures 2 and 3).

Granite is used to include the main silicic igneous rocks of the batholith, encompassing the stricter petrological terms 'monzogranite' and 'syenogranite', and all their mineralogic and textural variations.

Hornfels means the contact-metamorphosed Paleozoic rocks found within the thermal aureole of the batholith, and most specifically the high-grade hornfelses that occur immediately adjacent to the granite.

Boundary is used to describe the line on the ground that can be mapped, separating granite from hornfels.

Contact is reserved for the surface across which the granite and hornfels are juxtaposed. It may be planar, with or without offsets, and horizontal, vertical or any intermediate orientation. In some exposures, globally and in the Strathbogie batholith, the local orientation of the contact can be inferred directly from mapping. Additional information from detailed mapping of the boundary has made it possible to interpret the two-dimensional nature of the contact, and to test whether contact orientations in single outcrops are representative over extended distances.

The boundary (line) is referred to as *flat* if it approximately follows contour lines; the contact (plane) is referred to as *(near-) horizontal* if it has a shallow dip.

Section is used as a subdivision for the different geographic parts of the boundary, each of several kilometres in length, and the term is primarily used to facilitate systematic description.

Southern boundary refers to the margin of the Strathbogie batholith, from the Goulburn River at Greenslopes to Barjarg

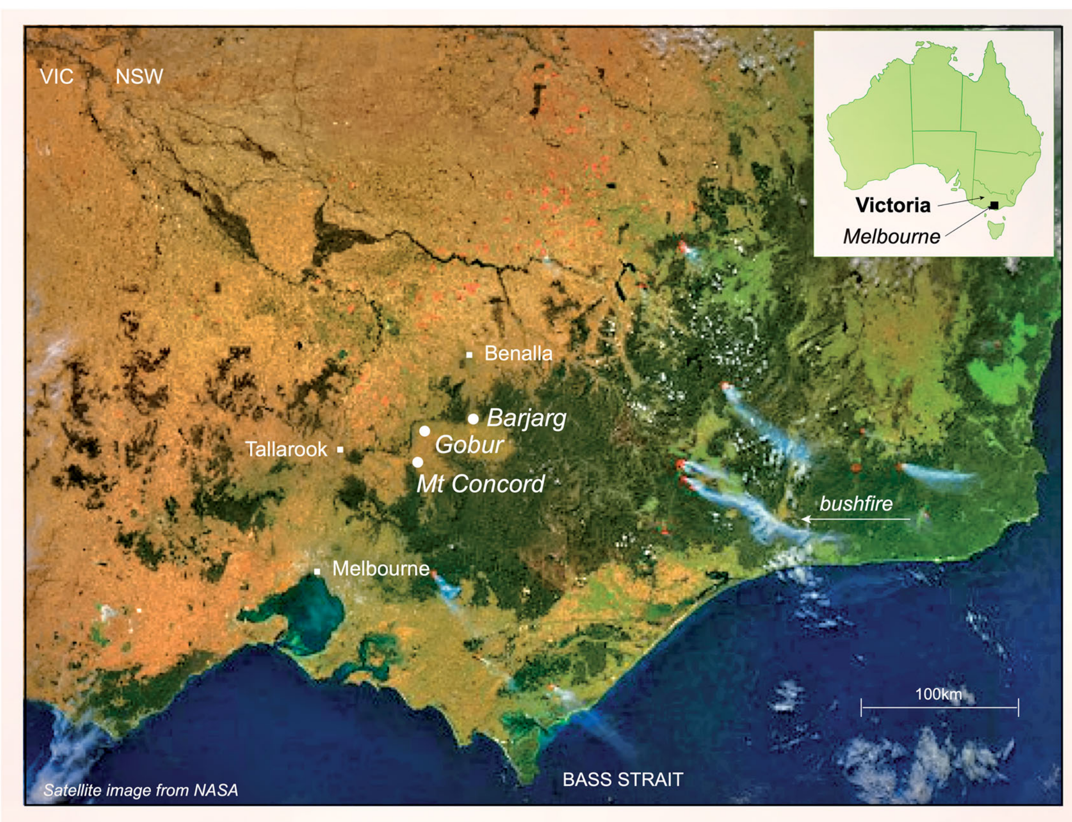

Figure 2. Landsat image of Victoria with location in southeast Australia (inset). The Strathbogie batholith lies between Benalla, Tallarook, Mt Concord, Gobur and Barjarg. Right angle bends at Mt Concord and Gobur are highlighted by the vegetation along the plateau edges. Image from NASA: https://www.nasa.gov/mission_pages/fires/main/world/20130326-victoria.html.

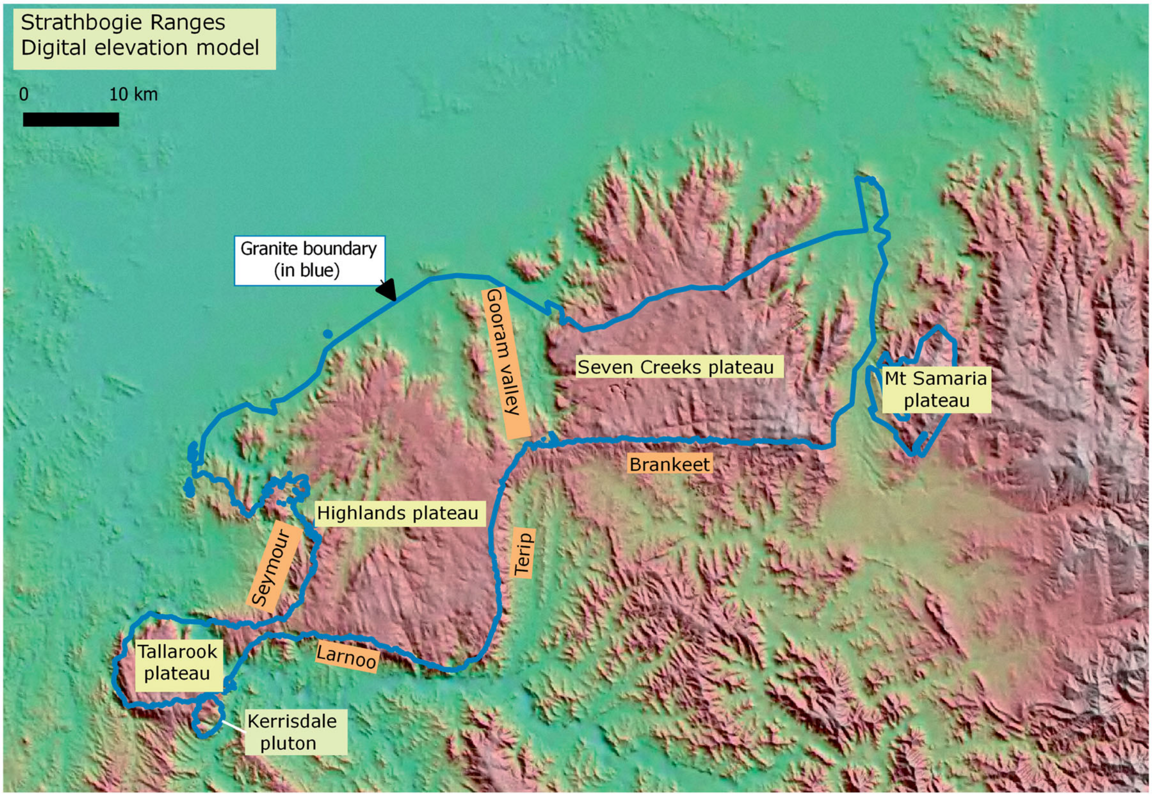

Figure 3. Digital elevation model showing the four plateaux of the Strathbogie batholith. Three sections of the southern boundary (Larnoo, Terip and Brankeet sections) are each over 20 km long. The Gooram valley separates the Highlands and Seven Creeks plateaux and includes three parallel watercourses. The Seymour section has been documented previously (Phillips *et al*., 2002) as has the Tallarook plateau (Phillips, 2017). The Kerrisdale pluton is separated from the Tallarook plateau by 200 m of hornfels (i.e. Munsra screen).

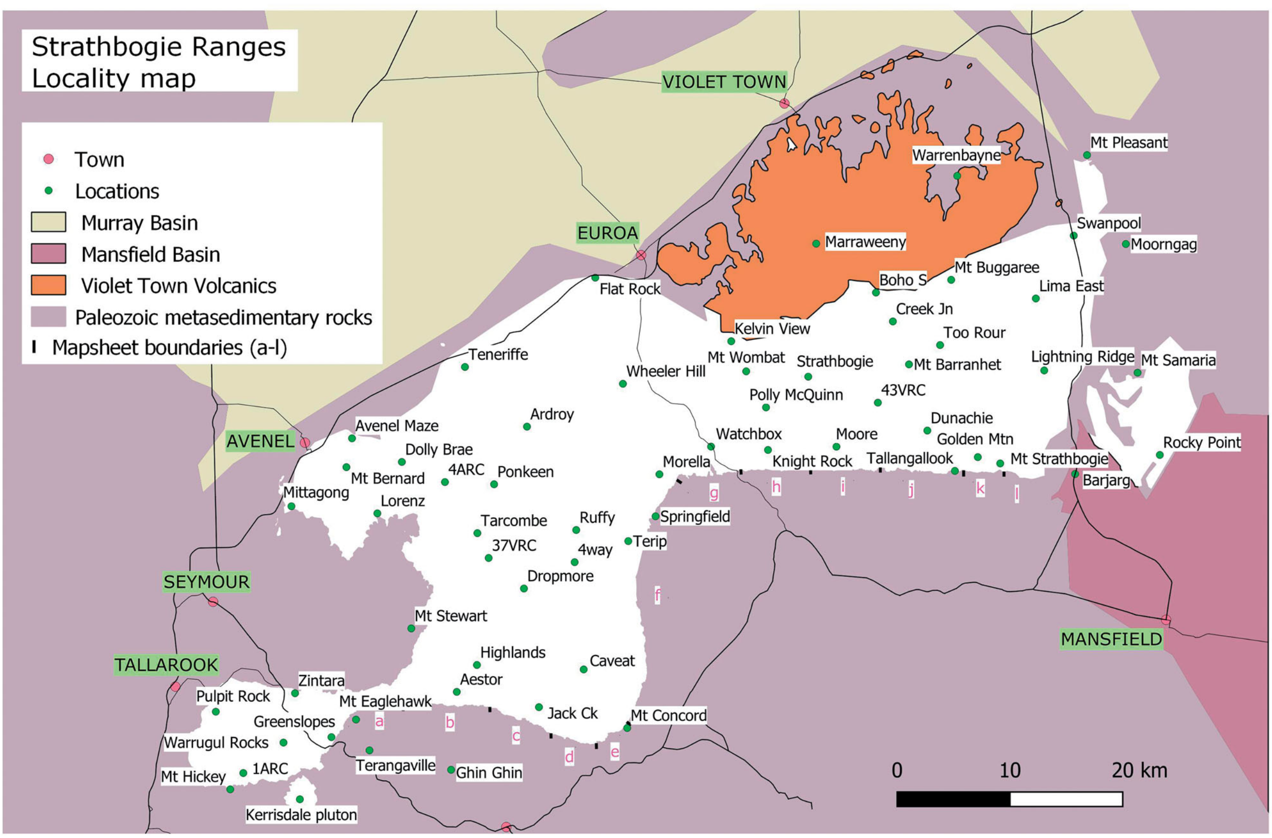

Figure 4. Map of major geological entities surrounding the Strathbogie batholith (white), and locality names used in this paper. The set of online map sheets span the southern boundary with small tick marks at their approximate overlap positions.

(Figure 4), and comprises three components (the Larnoo, Terip and Brankeet sections). The separate Seymour section refers to the granite boundary in the west, from the Goulburn River at Zintara to Avenel.

Interval is used for a part of the boundary that has constant geometry relative to contours (either parallel or oblique to these) and is generally of tens to hundreds of metres in map length.

Segments are groupings of small numbers of intervals along the southern boundary that parallel contours and have a relatively consistent character, particularly their elevation. Segments are used to group together the multiple intervals to convey the broader structural picture.

Map sheets are arranged west to east along the southern boundary, and each covers several kilometres. They are provided in supplemental data, and their extents are indicated on Figure 4.

Earlier field mapping has been published as six map sheets for the Tallarook plateau and Kerrisdale pluton (Phillips, 2017), and this information is incorporated here in the interpretation. Mapping of the boundary along the Seymour section is incorporated semi-quantitatively.

Map grid EPSG:28355 GDA94 MGA zone 55 is used, and waypoints were recorded in the field with respect to the WGS84 datum. No correction to GDA94 or to MGA2020 was deemed necessary for this project.

Bearings are from true north.

Strathbogie Igneous Complex is used to cover the Strathbogie batholith and Violet Town Volcanics, following the terminology of White (1954) and Phillips and Clemens (2013).

Strathbogie Ranges is a loosely defined term used to describe the uplands of the Strathbogie Igneous Complex. Although the granite is continuous, the uplands include four plateaux that are geographically separated by watercourses (Figure 3).

Gooram valley is the major north–south-trending depression between the Highlands and Seven Creeks plateaux, occupied by several north-flowing watercourses.

Regional setting of the Strathbogie batholith

Paleozoic rock sequences make up much of eastern Australia and, in the southeast, abundant clastic metasedimentary, and silicic volcanic and granitic rocks comprise the Lachlan Orogen (Birch, 2003; Korsch, 2017; VandenBerg *et al*., 2000). In central Victoria, the Tabberabberan Orogeny deformed the Cambrian to Middle Devonian sandstones, siltstones and shales with minor limestones and conglomerates. Shortly thereafter, the Late Devonian volcanic and plutonic rocks were emplaced (Cas *et al*., 2003, p. 185; Maher *et al*., 1997). One of the larger bodies of granite is the 100 km-long, high-level, discordant Strathbogie batholith. This granite was intruded with most of its southern boundary at a high angle to the north-northwest-striking fold axes and regional trends of bedding.

Beneath the exposed Paleozoic rocks of central Victoria lies the 20–25 km-thick Proterozoic to Cambrian Selwyn Block of metamorphic rocks that are dominantly andesites, dacites, greywackes, and pelites (Figure 5). The presence of the Selwyn Block has been inferred largely from geophysics (Cayley *et al*., 2002), the chemistry of igneous enclaves in the granitic rocks (Clemens & Phillips, 2014; Clemens *et al*., 2017) and the presence of high metamorphic grade pelitic mineral assemblages in schistose xenoliths in the granites (Phillips *et al*., 1981). However, there are a few isolated outcrops of the Cambrian rocks (Birch, 2003). The Governor

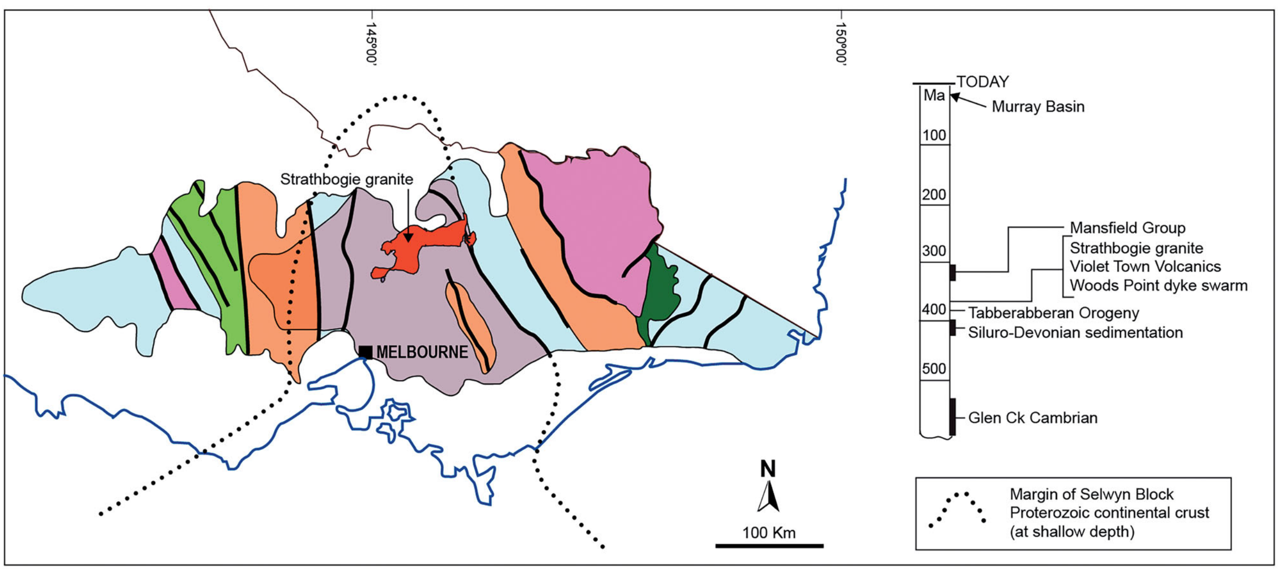

Figure 5. Map of the distribution of Paleozoic rocks across Victoria with major faults that separate different structural zones, based upon age, rock type and deformation style (VandenBerg *et al*., 2000) and mineralogic domains shown in different colours (Hughes & Phillips, 2015). The Strathbogie batholith (in red) lies within the Melbourne Zone (central mauve-grey area) in which the Devonian was a period of particularly active sedimentation, deformation and igneous activity. The Melbourne Zone is inferred to be underlain mainly by the Proterozoic to Cambrian Selwyn Block with its inferred subsurface boundary indicated by the dotted line.

Fault, an inferred terrane boundary, is mapped near the eastern margin of the Strathbogie batholith (Willman *et al.*, 2002).

At 373.5 ± 0.3 Ma, the Strathbogie batholith is slightly younger than the Violet Town Volcanics at 374.0 ± 0.3 Ma (Clemens & Phillips, 2014; Tulloch *et al.*, 2017) and the adjacent Tolmie Igneous Complex (377 ± 2 Ma; Clemens *et al.*, 2011) to the northeast. The peridotitic to dioritic Woods Point Dyke Swarm (375 ± 4 Ma; Bierlein *et al.*, 2001) is to the southeast and trends north-northwest towards the batholith but still separated from it by 30 km. The depth of emplacement of the Strathbogie batholith is inferred to be 1–2 km based on melting phase relationships and metamorphic assemblages in the hornfels (Phillips *et al.*, 1981). Southeast of the batholith are Upper Devonian to Carboniferous purple to red siltstones, sandstones, and conglomerates of the Mansfield Group (Cas *et al.*, 2003, p. 177). These are weakly deformed and unconformably overlie the granitic rocks of the Strathbogie batholith (Cas *et al.*, 2003). Much of the northwestern margin of the batholith is covered by unconsolidated sands and silts of the Cenozoic Murray Basin and, in this area, hornfels cropping out proximal to granite is scarce.

Lithological types within the Strathbogie batholith

Several lithological types of granite occur within the batholith, but mappable boundaries between these are rare. The main types are:

- coarse-grained porphyritic granite with K-feldspar phenocrysts, mostly 3 to 5 cm long. This type is common around Highlands and southern parts of the batholith,
- cordierite granite that is coarse-grained and has very few phenocrysts of feldspar,
- a mixture of granitic rock types including layered *aplite* sheets, pegmatite dykes, vugs and tourmaline rosettes (stars),
- porphyritic microgranite, and
- Kerrisdale microgranite in the far southwest.

Despite these textural variants, most batholith rocks are monzogranites with minor variation in the modes of K-feldspar, plagioclase and quartz, which are all around 25–30 modal %, biotite and cordierite, each 2–10%, and there is sporadic garnet and tourmaline, with minor ilmenite, apatite, monazite, xenotime, zircon and pyrrhotite (Hergt *et al.*, 2002; Phillips *et al.*, 1981). Plagioclase is oligoclase to andesine and primary muscovite is absent. Whole-rock chemical data for the Strathbogie granitic rocks and their enclaves are summarised in Clemens and Phillips (2014; see online data contained therein).

Recognition of cordierite in the batholith dates to Baker (1940), and both cordierite and garnet are distributed widely throughout the batholith, including near its margins, and near the inferred granite roof and floor. Most of the cordierite throughout the batholith is inferred to be of magmatic origin (Phillips *et al.*, 1981). Some of the evidence for this is derived from the Kerrisdale microgranite pluton where it is within 200 m of the main granite of the Tallarook plateau (Phillips, 2017, figures 12 and 13). Here, the magmatic quartz is much finer-grained in the Kerrisdale microgranite than in the main Tallarook granite (mostly 1–5 mm, compared with 7–15 mm), and this is mirrored in the cordierite grainsizes (1–5 mm compared with 5–20 mm). The magmatic cordierite in the granitic rocks is tabular and euhedral, contrasting with the cordierite, found in pelitic hornfelses and enclaves, which is ovoid and poikiloblastic, with inclusions of biotite, quartz and ilmenite. The magmatic cordierite is also texturally different from cordierite in the foliated high-grade metapelitic xenoliths, which is anhedral and has inclusions of sillimanite and hercynite. More generally in the batholith, the cordierite is finer-grained in porphyritic microgranite than in coarse-grained porphyritic granite.

In the field, there are some common features that demonstrate that the different granite types define sub-horizontal sheets (Figure 6; Phillips & Clemens, 2013), even though mapping of boundaries is not always possible. Such evidence includes small hills capped by aplite, perched paddocks, small gorges cutting through layers of cordierite granite into porphyritic granite and sub-horizontal sheets of aplite. The perched paddocks, which are widespread across the plateaux, are hectares to a few square kilometres in area, and are exploited for agriculture. Generally, the flatter grassy areas defining the perched paddocks are deeply weathered coarse-grained granite, whereas aplite as tors to 1 m diameter form the steeper rocky borders to these paddocks.

In this terrain, the movement of granite tors is mainly vertical and occurs as the supporting soil is eroded away. Lateral migration downslope is limited, as evidenced by the preservation of the lithological boundaries around the cappings on hills (*e.g.* Figure 6b) and limited migration along watercourses into adjacent hornfels.

Enclaves are relatively uncommon throughout the batholith. There are a few microgranular magmatic enclaves in the equigranular cordierite granite, proximal to the southern boundary, but hornfels xenoliths and schistose to gneissic xenoliths are rare.

Structures within the granite

The morphologies of lineaments, creeks and outcrops differ greatly between the granite, the Violet Town Volcanics, the Paleozoic country rocks and the Cenozoic alluvium and colluvium. The patterns in the granite owe much to the orientations and densities of joints and small fractures (Figure 7a, b); brittle faults that show evidence of brecciation are rarely seen at the surface, and those that do occur are less than 1 m wide. The only area of more common (although

Figure 6. Sheet-like features in the Strathbogie batholith. (a) A thin capping of aplite along the ridge top with coarse-grained granite (partly covered by moss and lichen) in the foreground. Between these two rock types is a small grassy perched paddock reflecting weathered rock with groundwater emerging along the contact. (b) Small knoll capped with aplite surrounded by weathered coarse-grained granite with some outcrop and float in the foreground. (c) Aplite (foreground) capping poorly outcropping coarse-grained granite. The aplite is co-planar with several other visible aplite patches for 200 m distance. (d) Small knolls of aplite overlying poorly outcropping coarse-grained granite. (e) Knoll of aplite on the ridge line overlying dominantly coarse-grained, weathered granite. (f) One of many perched paddocks that characterise parts of the Strathbogie Ranges. To the right is a tree covered, rocky slope of aplite that is non-arable, and there is further rocky ground on the far left. Much of the mid-ground is a grassy field on weathered coarse-grained granite. (g) View looking east across the Gooram valley (350 m AMSL) to Mt Wombat (810 m AMSL) on the skyline. Halfway up the Mt Wombat 'massif' is a horizontal grassy strip, being the perched paddock of over 5 km^2 of Kelvin View (500 m AMSL). (h) Reverse view to (g) looking from Mt Wombat to the west and overlooking the green perched paddock of Kelvin View. In the background, clouds fill the Gooram valley.

Figure 7. Structural features in the Strathbogie batholith. (a, b) Examples of the fracture zones exposed within the Strathbogie granites, at Rocky Ned Creek and Rokeby Falls, respectively. (c) Hillside of granite tors and outcrops dominated by multiple joint orientations on Mt Rose, south of Avenel. (d, e) Near-vertical jointing in granite striking north–south on Rokeby and Mt Wombat, respectively. (f) Joints of millimetric width infilled with tourmaline.

still minor) deformation is along the Broken River valley, south of Swanpool. The most abundant breccia and north–south-trending quartz veining in the granite are in a few hectares on Morella Hill, near the headwaters of Castle Creek, on the northward extension of the Terip section.

There are three main joint sets in the granite, including a prominent near-horizontal set that produces pavements, and two steeply dipping and orthogonal joint sets that guide the formation of tors (Figure 7). A lineament analysis (Phillips & Clemens, 2013, figure 3) has been subdivided into domains and illustrates the strong north–south-trending pattern across the northeastern Tallarook and northwest Highlands plateaux and the Gooram valley. There is a 010° trend in both the eastern Seven Creeks and Mt Samaria plateaux. There are also three corridors with well-developed 080° trends: one extending 50 km along the Brankeet section boundary of the batholith, one for almost 40 km trending west from Strathbogie town and a shorter corridor solely in the Violet Town Volcanics. Within the eastern part of these volcanic rocks, a 010° trend dominates and is the same trend as in the adjacent eastern Seven Creeks plateau. A 330° trend of lineaments in the western part of the Violet Town Volcanics is not matched in the adjacent granite. Major faults parallel to the 080° trend have not been recognised in the contact aureole adjacent to the Brankeet section. The Gobur corner coincides with intersecting north–south and 080° corridors.

Paleozoic rocks intruded by the Strathbogie batholith

At the eastern end of the southern boundary, the Glen Creek inlier exposes minor Cambrian silicic and mafic volcanic rocks, along with chert, mudstone and andesite up to 200 m thick, for 500 m adjacent to the granite (Sandl, 1989). The Cambrian rocks are fault-bounded against the younger Paleozoic metasedimentary rocks, and the inlier coincides with a 500 m offset of the southern boundary of the granite.

The younger metasedimentary rocks along the southern boundary were deposited from the late Silurian to Early Devonian as shale, black shale, siltstone, sandstone, lithic sandstone (quartz-rich greywacke), rare conglomerate and calcareous rocks (Figure 8). Nine distinct lithostratigraphic units abut the southern boundary. From oldest to youngest, these are: Cambrian 'greenstone,' the Sinclair Valley Sandstone, Whitelaw Siltstone, Humevale Siltstone, Broadford Formation (dominantly sandstone), Eildon Sandstone, Wilson Creek Shale, Norton Gully Sandstone and the Montys Hut Formation of dominantly siltstone (Australian Stratigraphic Units Database [http://www.ga.gov.au/data-pubs/datastandards/stratigraphic-units]; VandenBerg *et al*., 2000, figure 2.106). Black shale is a component of the Wilson Creek Shale, which abuts the granite in several places along the Larnoo and Brankeet sections. The Norton Gully Sandstone is a distinctive lithic sandstone with subordinate conglomerate that occurs from Bonnie Doon to Tallangallook, against the granite for several kilometres around Gobur, along the full Terip section, and as far south as Mt Concord. The Norton Gully Sandstone also spans the southward extension of the Gooram valley.

The Paleozoic sedimentary rocks were deformed in the Tabberabberan Orogeny of 385–380 Ma, *i.e.* Middle Devonian (VandenBerg, 2003) involving east–west shortening to produce upright curvilinear north-northwest-trending folds (Edwards *et al*., 1997; VandenBerg *et al*., 2006). These folds become north–south adjacent to the southern

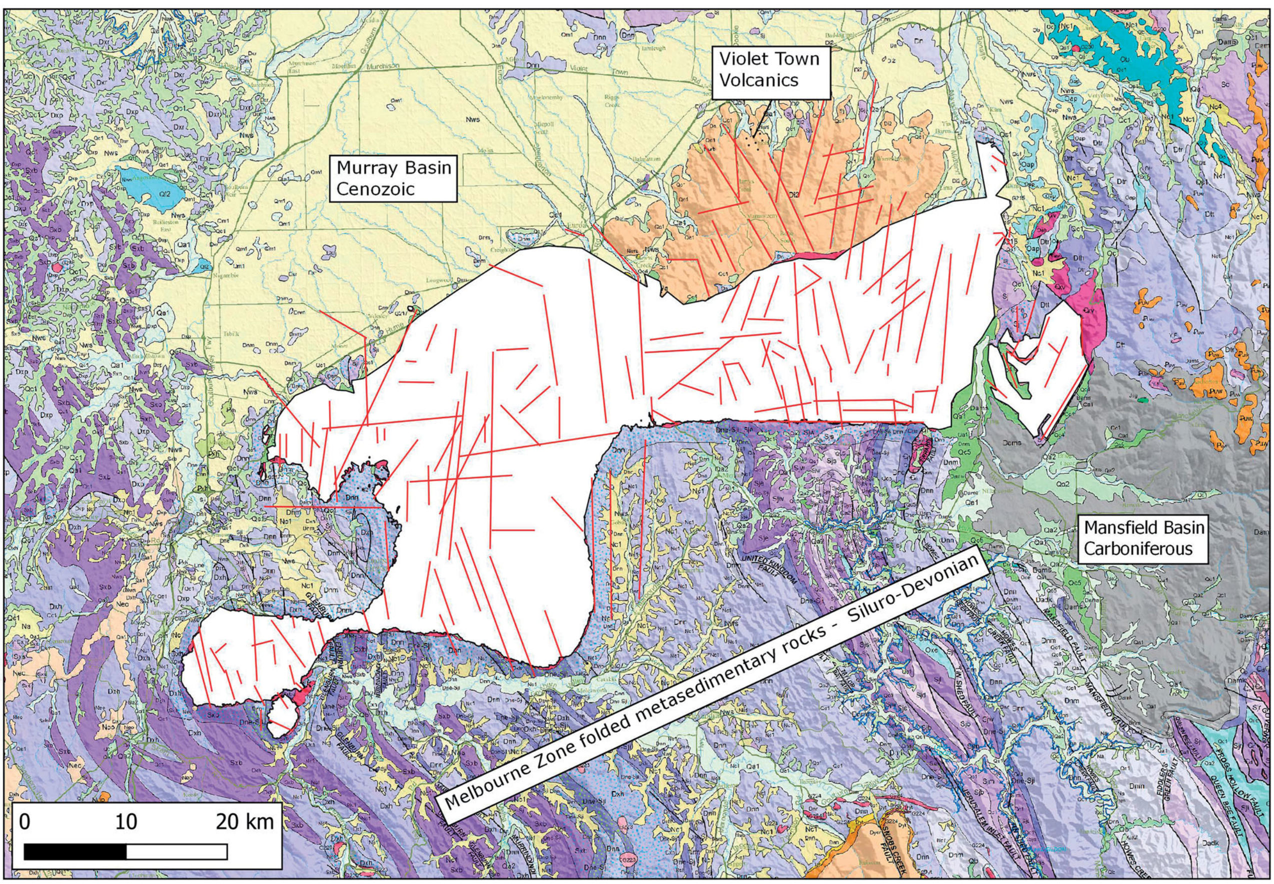

Figure 8. Paleozoic geology around the Strathbogie batholith and lineament analysis within the granite and the Violet Town Volcanics. Older metasedimentary rocks are in the darker purple, whereas the younger Paleozoic rocks are in the lighter mauve colours. In both the east and southwest of the batholith, the strikes of lineaments mimic some of the lithological boundaries and folds in the Silurian–Devonian wall-rock succession. The curvilinear nature of the rock units in the far southwest is due to refolding as also recorded to the northwest (see Gray & Mortimer, 1996). Source: seamless geology of Geoscience Victoria and current mapping of the batholith boundary; there are small areas of mismatch but at this scale there is reasonable overall agreement.

boundary of the batholith, and north of the batholith are re-orientated by local north–south shortening yielding east–west-orientated fold axes (Gray & Mortimer, 1996, 1997; Morand *et al*., 1997). In the far west and far east of the southern boundary of the batholith, broad anticlinal axes have juxtaposed the older formations against the granite (Figure 8). The clastic rocks were regionally metamorphosed to greenschist facies with only local very weak cleavage. Shale units have chlorite–muscovite mineral assemblages that lack biotite, and the metasedimentary sequence contains many auriferous quartz veins. Globally, the temperature inferred for auriferous quartz veins is 300–350 °C (Ridley & Diamond, 2000).

Older metasedimentary units against the southern boundary demarcate the positions of anticlinal zones (the southern Tallarook plateau, near northwest of Ghin Ghin and south-southwest of Aestor, and Tallangallook), and the younger units mark synclinal zones (Terip section and Gooram valley). There is some correlation between the strikes of the metasedimentary rocks in the contact aureole and the trends of lineaments in the granite suggesting that the axial-planar structures in the former have influenced jointing in the granite (Figure 8). The strike of the metasedimentary units in the contact aureole varies from 330° in the west to 010° in the east, and these orientations are replicated in the lineaments within the granite—330° in the southern Tallarook, southern Highlands and western Seven Creeks plateaux, and 010° in the eastern Seven Creeks plateau.

The contact aureole has been mapped in detail between Tallangallook and Bonnie Doon, where it extends almost 3 km outward from the southern boundary (Phillips & Wall, 1980). The outward progression is:

- cordierite–K-feldspar zone (100 m wide and mostly known from drill cores),
- cordierite–muscovite zone (1 km),
- biotite zone (up to 1.5 km), and
- spotted slate (up to 800 m wide); spotted slate has also been noted 5–10 km from the granite, but not mapped systematically.

The Upper Devonian Violet Town Volcanics are also contact-metamorphosed, producing recrystallised textures where adjacent to the batholith on its north (Clemens, 1981; Clemens & Wall, 1984; White, 1954). The pyroclastic rocks juxtaposed against the granite indicate that the granite was high-level and never beneath much sedimentary cover, *i.e.* $\leq$2 km (Phillips *et al*., 1981). Devonian volcanic rocks are not present along the southern boundary of the batholith.

Southern boundary of the Strathbogie batholith

Several features make the 2000 km^2 Strathbogie batholith well suited for the application of detailed field mapping to constrain its 3D geometry and mode of emplacement. If all the irregularities are accounted for, there is over 200 km of granite boundary exposed along the south and southwest of the batholith, and there is topographic relief of several 100 m. The batholith exhibits contrasting gross shapes, from the approximately circular granite of the Tallarook plateau and the elliptical Kerrisdale pluton (both in the southwest) to the straight, north–south and east–west boundaries in the centre and east. The granite boundaries of the Tallarook plateau and Kerrisdale pluton have been mapped in detail (Phillips, 2017), and these granite bodies are the size and shape of many plutons globally.

The southern boundary of the Strathbogie batholith consists of orthogonal linear sections that are readily visible on satellite imagery as well as topographic and geological maps, and indeed on the ground. The three linear sections are 20–30 km long but not coincident with any orthogonal vertical fault sets exposed at the surface, which could explain the distinctive geometry. A more unusual aspect is that the linear sections are orientated north–south and east–west, which is oblique to the regional trends of fold axes, faults and lithological boundaries in the mid-Paleozoic meta-turbidite succession. However, close to the granite boundary, these structures tend to be orthogonal.

The boundary of the Strathbogie batholith has been the focus of research projects since the early 1970s, despite it lacking the quality of exposures provided by alpine terrains or mining operations. Early mapping revealed some local orthogonal boundaries, on a scale of 10–100 m, that replicated the 20 km scale of the complete southern boundary, and the batholith showed other interesting features such as a contact aureole up to 3 km wide and common magmatic cordierite (Clemens & Wall, 1981; Phillips & Wall, 1980; Phillips *et al*., 1981). Examples of different boundary geometries were noted at the time, including some steep contacts but also granite below hornfels and granite above hornfels. From 2001, mapping of the batholith boundary was extended to the embayment east of Seymour and again revealed a variety of geometric relationships between granite and hornfels (Hergt *et al*., 2002; Jay, 2017; Phillips *et al*., 2002). A pilot study delineated the boundary of the granite for 60 km around the Tallarook plateau on the southwestern end of the batholith (Phillips, 2017). At each of 1500 waypoints, the boundary between granite and hornfels was constrained to within 20 m and generally within 2–10 m. Despite the main granite at Tallarook appearing lobate to circular in plan view on many maps, the detailed mapping shows that it is bounded by numerous linear intervals of several hundreds of metres each, and not by curved intervals. The Tallarook boundary has numerous flat and steep intervals from which a step-and-stair geometry of the contact was inferred. For the flat intervals, the contact could be classified as either the roof or the floor of the granite, and the granite thickness here was inferred to be $\leq$350 m, but nowhere could it be demonstrated to be $>$1 km. It was concluded that vertical fault sets were an unlikely explanation for the many orthogonal corners along the boundary. The circular shape of the granite on the Tallarook plateau contrasts with the overall shape of the whole Strathbogie batholith, so it was uncertain at the time of the pilot project how many of the Tallarook conclusions could be scaled up for the whole batholith.

Field mapping methods for the southern boundary

The terrain in central Victoria is very dissimilar to the vertical faces common in the Andes or Himalayas. Instead, the larger slopes of the Strathbogie region rarely exceed 500 m of vertical relief or gradients of 30%.

The southern boundary of the batholith is exposed for over 100 km where its position has been delineated by field mapping and constrained to better than 20 m laterally, over much of its length. Compared with the use of air photos, the accuracy and speed of mapping in this type of terrain have been revolutionised by the advent of GPS for recording position and of GIS for manipulating and analysing spatial data. GPS allows direct recording of features of the boundary, on the scale of 10 m or less, and demonstrates the existence of many right-angle jogs, and numerous straight intervals (both flat and steep; Figure 9). At many locations, the boundary can be constrained to within 2–5 m, but even where it is 10–20 m, the position is recorded and included as valuable information. In general, better results were obtained from forest rather than farmland, owing to better outcrop and less ground disturbance.

The value of this field mapping comes when the accurate position of the southern boundary is combined with contour maps and the 790 m of relief along the boundary, and existing mapping. Maps of the granite boundary around the Tallarook plateau, Kerrisdale pluton and the Seymour section have been published (Phillips *et al.*, 2002; Phillips, 2017) and now provide a total of 250 km of mapped boundary (Table 1). Each of the four main areas has at least a few 100 m of elevation difference along the boundary.

All the detailed maps of the southern boundary, such as in the supplemental data, have minor shortcomings. The least accurate GPS co-ordinate is elevation, and there can be a small discrepancy with published 10 m contours. A potential shortcoming of this style of mapping would be that any parallel but lower sheets of granite could be overlooked on steep slopes, and this was partially addressed by making several traverses within hornfels.

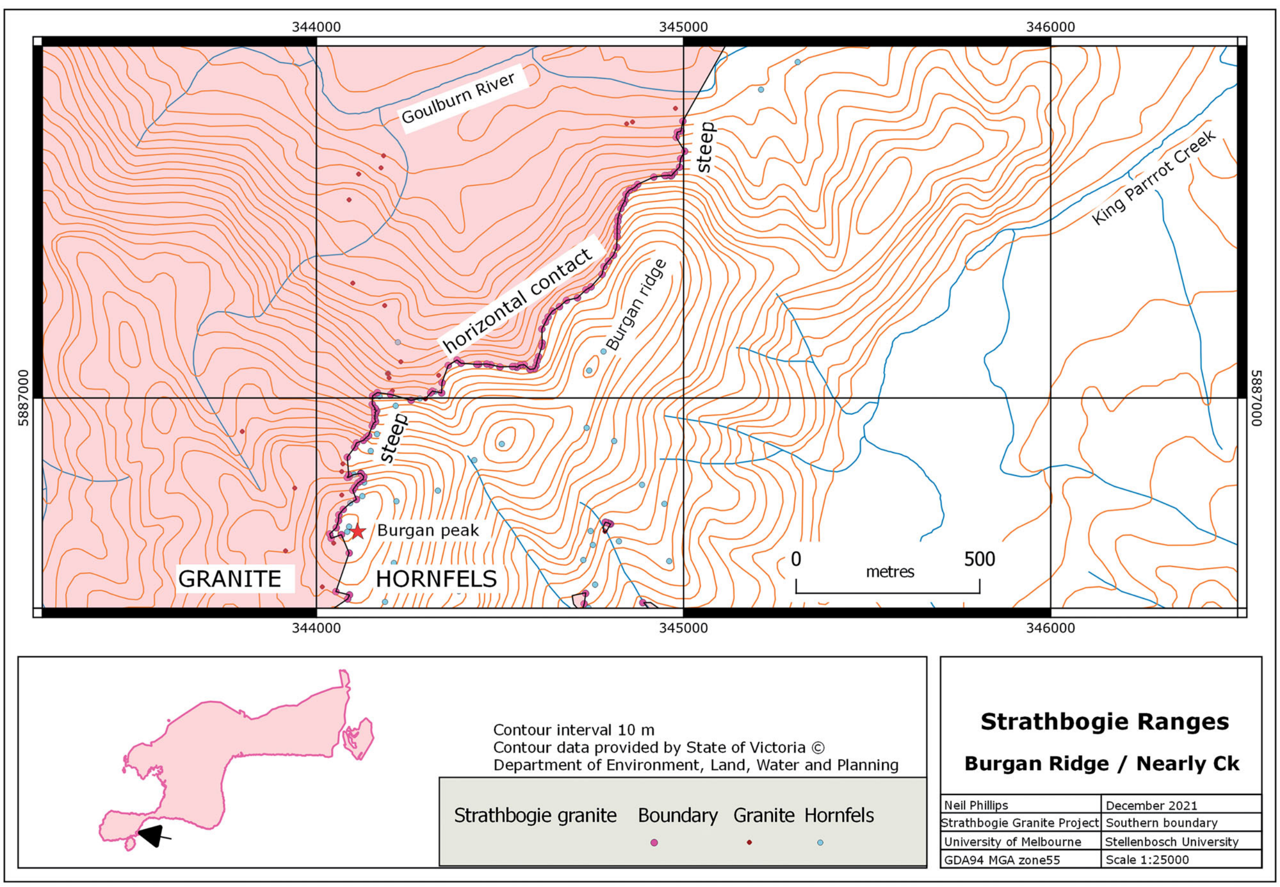

Figure 9. Batholith boundary on the eastern side of the Tallarook plateau. The boundary is more accurately defined than the diameter of the purple boundary dots. Some intervals are strongly oblique to contours and the contact is inferred to be steep. Other intervals are parallel to contours even mimicking each creek indentation, and these are inferred to reflect horizontal contacts. This detail of fieldwork is necessary to understand the 3D geometry of the granite contacts. This is the Nearly Creek section of Phillips (2017, figure 9).

Table 1. Density of field data along the boundary of the Strathbogie batholith.

Component of boundary	Length (km)	Waypoints	Elevation of boundary (m AMSL) Maximum	Minimum	Comments
Seymour	76	100	550	200	Additional GPS tracks
Kerrisdale	15	290	620	210	9 km^2 of granite
Tallarook	50	1200	790	170	88 km^2 of granite
Southern boundary	110	2200	940	150	

The mapping of the boundary in areas with difficult terrain and vegetation was dependent upon GPS technologies, and this was much superior to the initial use of a pace-and-compass approach. Access and visibility were assisted by the harvesting of commercial pine plantations and forest fires (planned and accidental). Areas including Burgan Ridge, Greenslopes, Hell Hole and Glen Creeks stand out as difficult, and their mapping was facilitated by GPS locating. The Munsra screen of hornfels separating the main granite of the Tallarook plateau from the Kerrisdale pluton was mapped following a controlled burn and the Mt Hickey accidental fire of late 2015. Overall, the mapping included private properties, which relied upon liaison with approximately 100 landowners, including long-term farmers, tree changers (*i.e.* those who moved from urban areas for lifestyle considerations) and absentee owners. The requirements of prior permission meant that mapping by progressing from one end of the boundary to the other was not feasible. What became clear from well-exposed sites was that the orientation of the local boundary could vary dramatically, even within a single outcrop; the use of longer intervals and multiple waypoints overcame this local effect by reflecting the larger-scale boundary position.

Processing of the boundary maps is illustrated for the Tallarook plateau (Phillips, 2017). Here, the waypoints are grouped into intervals of tens of metres either parallel or at a high angle to contours. An illustrative example is the Nearly Creek section, immediately across the Goulburn River from the *Greenslopes* map sheet where contour-parallel and contour-oblique intervals together define a step-and-stair geometry for the boundary and show it to be the roof of the granite. Not all the contour-parallel intervals of the boundary are individually definitive of the orientation of the contact, but several are and permit the interpretation of these flat parts of the boundary to mean that the granite–hornfels contact is near-horizontal (Figures 9 and 10).

Government Survey maps covering parts of the Strathbogie batholith have used a combination of previous information, the interpretation of air photos, airborne radiometric and magnetic data, and field observations (Edwards *et al.*, 1997; Edwards, 2005, figure 30; McDonald, 1997; VandenBerg *et al.*, 2006). The batholith geometry, as depicted on these maps, is certainly adequate for regional geology but can be in error by 500 m. Reasons for the discrepancies include influences of slope, vegetation, scree and soil. Consequences of the hundreds of metres of discrepancy include the inability to recognise the finer details of the contact, including the local orthogonal jogs, and this then leads to interpolations yielding straight or smoothly curved boundary lines and hence to an interpretation that the contact is near-vertical (Figure 11). White (1954, p 8) was correct in expressing a reservation about the linear appearance of the boundary on maps, *e.g.* in the Brankeet section, but attributed this to a lack of outcrop.

Nature of the southern boundary of granite

At the scale of the Strathbogie Ranges, the boundary broadly follows the topography and the margins of the four plateaux. These plateaux are cut by the Goulburn and Broken rivers, and continuity across the former is interpolated with confidence. Continuity of the granite across the Broken River appears likely but has not been confirmed through mapping. In detail, the boundary varies from being on the plateaux and set back from the scarp, to being on the scarp that links plateau and lower country, to being at the foot of the scarp.

The three main sections of the southern boundary have slight differences, and none are completely straight. The Larnoo section is slightly arcuate, trending from 090° to 120°. The Terip section varies from 340° to 030°. The Brankeet section is quite linear, trending 090° for most of its length. In greater detail, all three sections have minor irregularities illustrated by the more detailed 1:25 000 maps of the southern boundary overlain on contours (see the 12 supplemental data map sheets labelled from a to l, from west to east). The extent to which each map sheet covers part of the boundary is indicated on Figure 4. Where possible, the roof, side (wall) and floor of granite sheets are identified (Figures 12 and 13). The whole north–south-orientated Terip section is presented on a single map of 1:250 000 scale.

Greenslopes map sheet

This is the westernmost of the 12 map sheets covering the southern boundary and is a continuation of the boundary mapping already published for the Tallarook plateau (Phillips, 2017). From Nearly Creek and Burgan Ridge on the Tallarook plateau (see Phillips, 2017, figure 9), the boundary continues across the Goulburn River (148 m AMSL) near Greenslopes homestead (the watercourses flowing southward join the Goulburn River just south of the map sheet).

From Greenslopes homestead, heading northeast, the boundary rises toward Mt Eaglehawk (530 m) and, in doing

Figure 10. Boundaries of the Strathbogie batholith (red arrows) against metasedimentary hornfels (light blue arrows). (a) View south along the boundary as it descends this gully for nearly 300 m vertically from Mt Concord; hornfels *in situ* on the left and as scree in the gully. Granite is on the right. (b) Looking along a near-horizontal contact from hornfels in the foreground toward the floor of the granite upstream—Ruoak area on North Creek. (c) Hornfels in the foreground with a granite tor behind—Nearly Creek at the base of Burgan Ridge. (d) Hornfels on the right overlying the roof of the granite in the Watchbox Creek catchment. The purple arrow marks the contact, which dips at a gentle angle to the right. (e) Boundary that can be mapped accurately to within a few metres—on the northwest of the Tallarook Plateau. (f) View from Knight Rock to the southwest toward Mt Concord showing the full extent of the Terip section (i.e. Black Range) between the two right-angle bends in the boundary at Mt Concord and Gobur. (g) Two right-angle bends of the boundary in an open paddock with granite tors. There is widespread hornfels in the otherwise bare grassy areas. Two boundary corners are shown in purple. (h) Complex example of multiple right-angle bends and intrusions of micro-dykes of granite in hornfels from southwest of Mt Hickey.

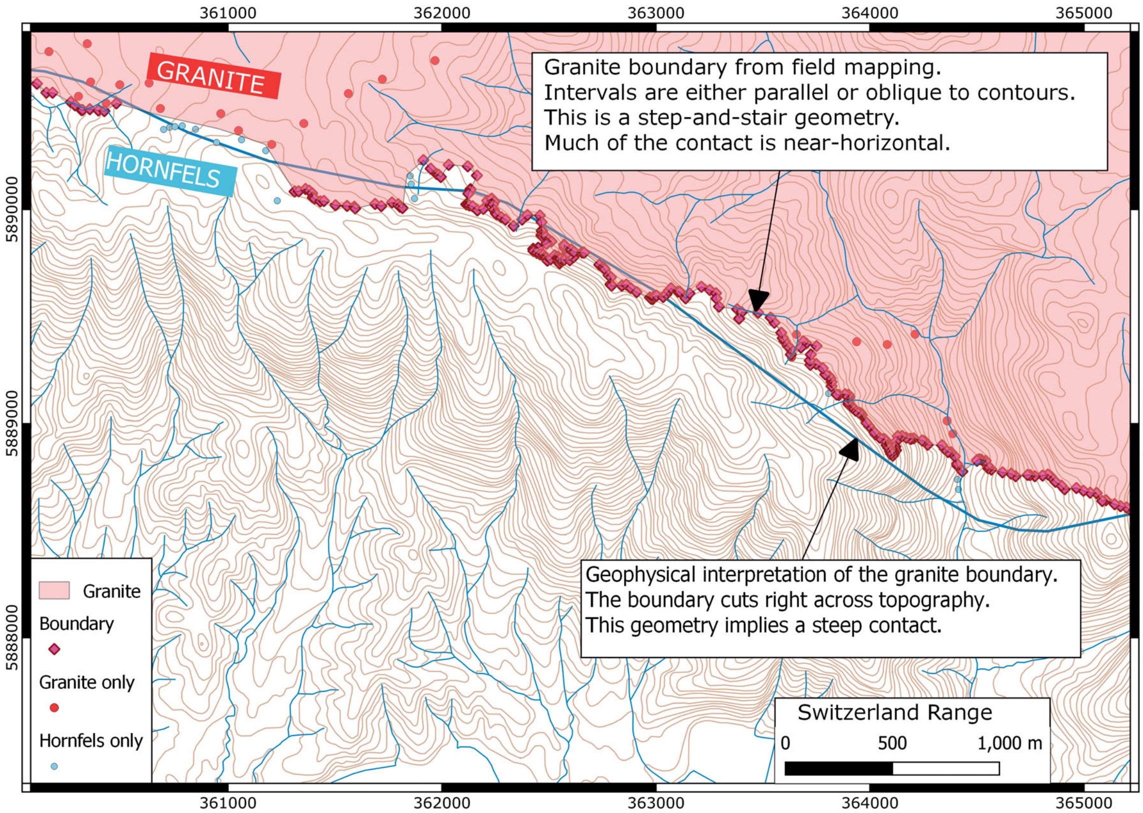

Figure 11. Comparison of maps of the granite boundary showing the publicly available geophysical interpretation (thin blue line) and the boundary determined by the detailed field mapping (red line, see Switzerland Range supplemental data map sheet). The geophysical boundary is a good approximation to the batholith margin and the two lines are mostly within 500 m of one another. However, the two methods lead to quite different interpretations of the contact geometry. A vertical granite contact is one reasonable interpretation of the geophysical boundary, but the lack of accuracy of that boundary means that many other interpretations are also possible.

so, is mostly strongly oblique to the contours, but with some intervals of 10–100 m where the boundary is parallel to contours and the contact likely to be near-horizontal. Where the Wilson Creek Shale is in the contact aureole around Eaglehawk Creek, there is a change in trend in the boundary, from northeast to east, as it steps down to 300 m AMSL and cannot be located for 600 m across Larnoo swamp.

For most of the Greenslopes map sheet, the flat intervals reflect the local roof of the granite, and this leads to the contact aureole being at a slightly higher elevation than the adjacent granite plateau. A significant exception is where the boundary crosses Eaglehawk Creek; it is the floor of the granite that forms the boundary at around 300 m elevation, and there is surrounding granite up to 450–500 m elevation.

The arcuate shape of the boundary, rising northeast and then east from Greenslopes, is not easily explained as a steeply dipping fault. The preferred explanation involves offsets on multiple small horizontal steps, especially north of Mt Eaglehawk, in the same way that the boundary climbs away from the south side of the Goulburn River on Burgan Ridge (Figure 9). This pattern means that the course of the Goulburn River has exploited the extreme low point in the batholith roof—no doubt a major reason for the position of the river.

Ghin Ghin map sheet

The granite boundary on the Ghin Ghin map sheet is mostly on the plateau, except for some creek valleys, including Stony Creek near Mt Broughton. An anticlinal axis in the metasedimentary rocks juxtaposes Wilson Creek Shale against granite from 2 to 3 km east of Larnoo hill (south of Aestor).

There is a mix of intervals where the boundary is flat and others where it is orthogonal to contours. In some places the boundary is straight as it crosses valleys, and in others it is flat at valleys and approximately mirrors contours. A feature of this section is the presence of numerous waterfalls at the boundary, exposing multiple examples of granite structurally above hornfels (Easton, 2015).

Switzerland Range map sheet

From Mt Broughton (655 m), the boundary trends 110°, first across the plateau and then along the northern slope of the hornfels ridge that forms the Switzerland Range. This is an unusual situation for the southern boundary, being north of the hornfels scarp and at a significantly lower altitude. There are several intervals of 200–400 m where the boundary is parallel to contours and others where the boundary and contours are orthogonal as it steps down to

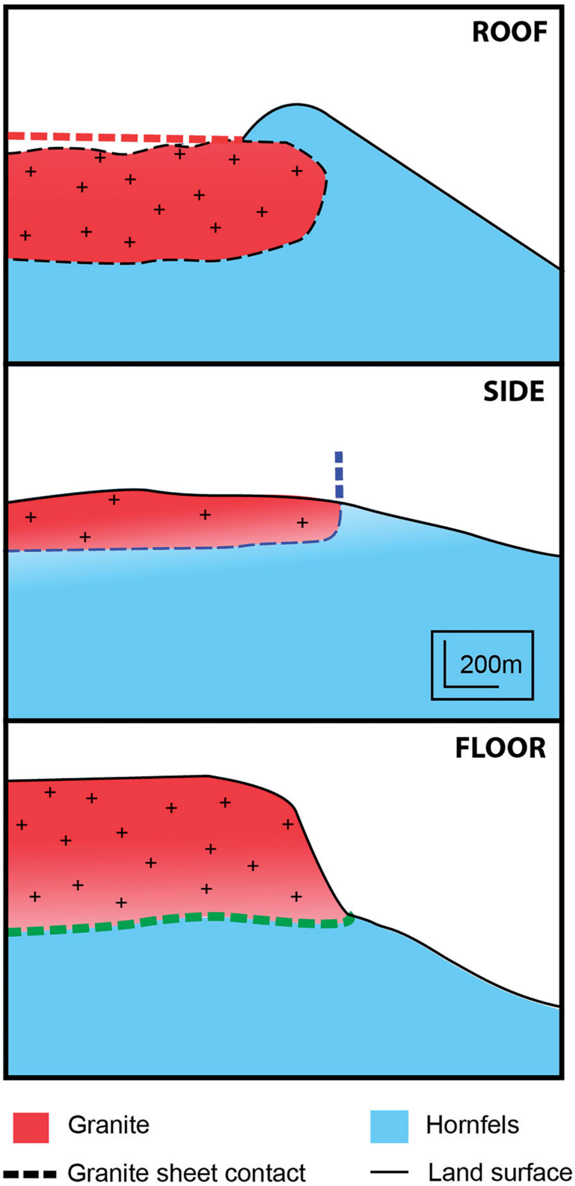

Figure 12. Three different geometric arrangements of the batholith contact. During mapping, the roof and floor both reveal flat boundaries that are parallel to contours, but with granite below, and above, hornfels, respectively. The side (wall) of a sheet yields a boundary that is quite oblique to contours. All three situations can be found over the full length of the southern boundary of the Strathbogie batholith.

the east. The boundary is colinear across Jack Creek (230 m) except for a minor deviation downstream.

Jack Creek map sheet

From just west of Jack Creek to east of Nar Darak, the Wilson Creek Shale is the dominant unit adjacent to the granite. The Goulburn River floodplain is within a few hundred metres of the granite.

The boundary maintains the same 110° trend, colinear with the Switzerland Range map sheet, despite crossing several creeks and ridges with 350 m of relief. The boundary is orthogonal to contours on the steep slopes, and there are intervals in some valleys and across the plateau where the boundary is flat.

Mt Concord map sheet

This is a particularly important map sheet in that it defines the major orthogonal bend in the southern boundary between the Larnoo and Terip sections and can be seen on satellite images (Figures 2 and 3). The topography along the boundary comprises a gently rising valley northeast of Nar Darak (200 m AMSL) and then a 300 m scarp rising to Mt Concord (649 m AMSL). This contrast in topography coincides with geology, *i.e.* Wilson Creek Shale along the gently rising valley, and sandstone on the scarp. From Nar Darak, the trend of the boundary swings anti-clockwise from the Larnoo section as it rises to Mt Concord and then follows an 030° trend, remaining on the plateau for several kilometres.

The Mt Concord corner coincides with a change in rock type in the contact aureole, a change from exposure of the granite floor to the granite roof and a major change in boundary trend.

Terip section and map sheet

The terrain and required style of mapping are different along the Terip section because the drainage is mostly internal across the Highlands plateau towards Hughes Creek. The mapping is at 1:250 000 scale, orientated north–south and overlaps with Mt Concord and Watchbox map sheets. Throughout the Terip section, mapping is less definitive than elsewhere on the southern boundary because the land has a low relief and is lacking in outcrop, and so has been cultivated and requires semi-quantitative float mapping of the boundary for considerable lengths.

For 6 km north from Mt Concord, the boundary trends 030° then shifts to 340° for 8 km, and then 010° for another 6 km into Gobur corner near Morella Hill. The boundary for much of this section is on the plateau west of the scarp and the ground rises in the hornfels to form a rim around the plateau that is 10–100 m above the granite. The main inflexion from 030° to 340° coincides with a valley along which the boundary trends down, then across parallel to contours and then up again to plateau level. The interval that is parallel to contours is inferred to reflect the contact being near-horizontal, and, as granite is above hornfels on this hillside, this contact is the local floor of the granite sheet.

Watchbox map sheet

The Watchbox area is the western end of the 090°-trending Brankeet section. Much of the boundary is on the plateau where it is north of and downslope from the top of the scarp. Watchbox Creek forms the eastern side of the

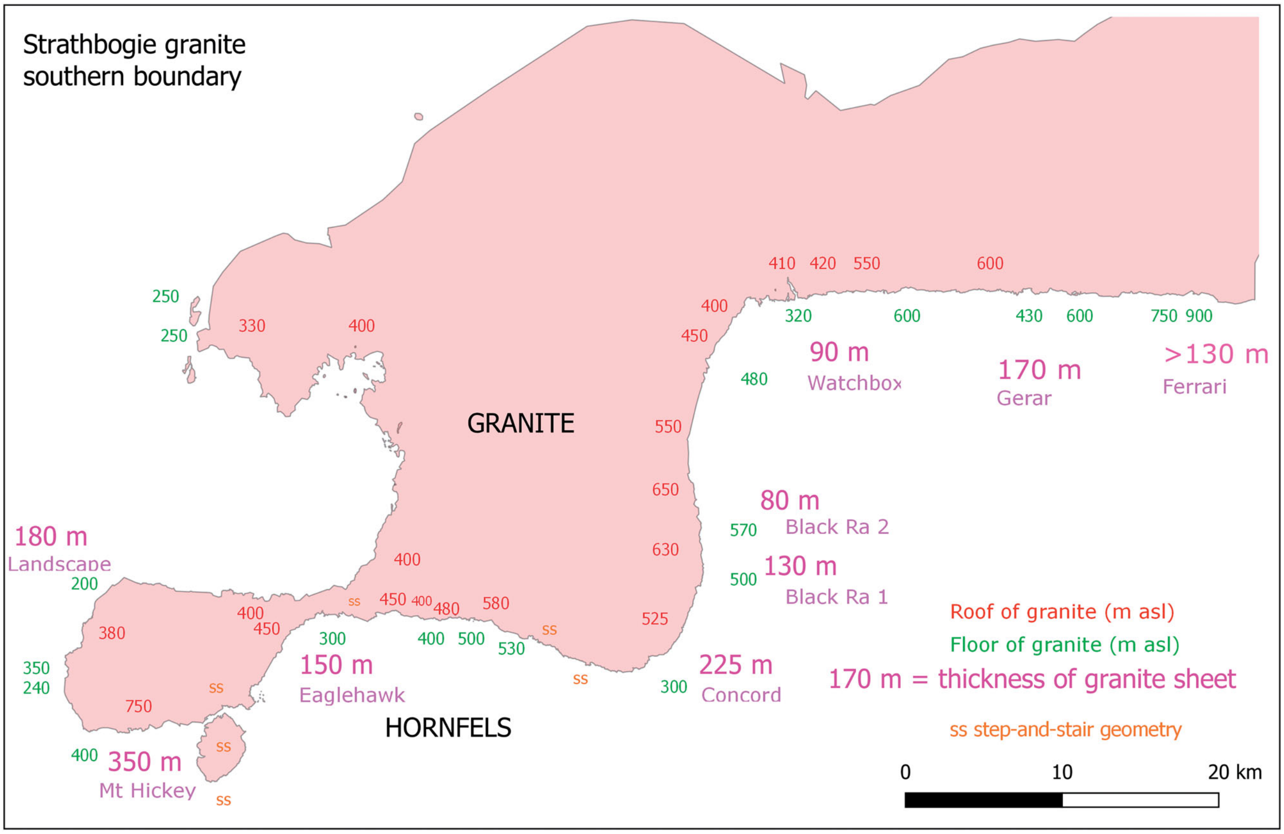

Figure 13. Map of the southern boundary and Tallarook plateau showing nine localities at which the thickness of the batholith can be constrained (Table 2). The elevation of the roof is calculated at 21 segments (red) based on multiple intervals where the contact is near-horizontal. The elevation of the floor is similarly calculated for 20 segments (green). Nine localities are then used to estimate the difference between roof and floor (purple), and this varies from 80 to 350 m. Segments along the granite boundary showing six locations of *step-and-stair* geometry (orange) along the granite boundary that are not suitable for thickness estimates. Between the 280 flat intervals that make up these segments, there are 300 steep intervals (not shown). For the 80 km width of this map, all roof and floor segments are between 150 and 1050 m AMSL.

Gooram valley and is joined by Seven Creeks, and together they drain much of the Seven Creeks plateau.

Around Gobur and Morella Hill, there are several pronounced north–south-orientated features that parallel the Terip section of the boundary and Gooram valley. These include creeks flowing south on the hornfels, those flowing north on the granite and two lines of hornfels hills, including the main Terip-section scarp, *i.e.* Black Range. A few kilometres removed is the cliff line of Garden Range, within the granite. The more general trend in the metasedimentary rocks is oblique to the north–south trend and close to 350°. Quartz veins, which are generally rare in the batholith away from its boundary, form north–south-trending parallel sets for 10 km along Gooram valley and extending across the granite from Gobur corner.

Watchbox Creek is one of the few watercourses that start in hornfels and flow north into and then across the granite. Along Watchbox Creek, the boundary between granite and hornfels is quite unusual in that it deviates 1.5 km north of the main 30 km long Brankeet section. The hornfels pieces along Watchbox Creek are fresh, angular and are interpreted as being within a few metres of their origin, rather than having been transported any distance along the shallow-gradient watercourses. Determining the position of this boundary took account of the quartz-vein trends (which suggest that some hornfels is in place), bedding trends in the hornfels, highly angular blocks of hornfels of up several kilograms and a lack of mixing of hornfels and granite clasts in the soil. In places, the hornfels extends 10–20 m above the valley floors. All these features suggest that the hornfels had been exposed by the downward erosion of Watchbox Creek through the granite floor. An east–west dyke across Watchbox Creek acts as a nick point that slows further downcutting into the hornfels.

In the south, hornfels overlies granite, and the granite has textures and dykes indicating that the granite roof lies at 410 m AMSL. The granite boundary along Watchbox

Table 2. Estimated thicknesses of the Strathbogie batholith.

Location	Map sheet	Floor (m AMSL)	Roof (m AMSL)	Thickness (m)
Landscape	Phillips (2017)	200	380	180
Mt Hickey	Phillips (2017)	400	750	350
Eaglehawk	Greenslopes	300	450	150
Concord	Mt Concord	300	525	225
Black Ra 1	Terip	500	630	130
Black Ra 2	Terip	570	650	80
Watchbox	Watchbox	320	410	90
Gerar	Ruoak	430	600	170
Ferrari	Glen Creek	900	Over 1030	Over 130

Creek descends northward to 320 m AMSL and is interpreted as the floor of the granite sheet; the implied gradient of the granite floor would be 2°N. Two minor creeks, parallel to and immediately west of Watchbox Creek, illustrate the same boundary relationships but on a smaller scale; although their outcrop is imperfect, they are also interpreted as exposing the floor of the thin granite sheet.

Enderlee map sheet

The trend of the boundary on this map sheet is 090°, with numerous offsets of tens of metres to 200 m, marked by sharp changes of direction. From Enderlee eastward, the boundary is parallel to, but 200 m north of, a hornfels ridge line, and flat intervals of the boundary have hornfels on higher ground, indicating the granite roof. There is a significant step-up of the boundary from Enderlee eastward, mirrored by the rise to Knight Rock but not obviously reflected in the contact aureole. Farther east, the boundary is relatively linear and incised by several creeks. Various flat intervals reflect near-horizontal contacts with hornfels either above or beneath granite.

Ruoak map sheet

The trend of the boundary on this map sheet is 090°, first marked by a creek in the west, then with a 2 km-long interval over which the boundary is flat on the side of a hornfels ridge and easy to see across open paddocks. In the open paddocks along the side of the ridge, the boundary is flat, the contact inferred to be near-horizontal, and hornfels lies above granite. Going east, the boundary descends almost 200 m to North Creek. It then becomes flat again, where it is incised by the creek, and it bends 300 m upstream to remain at a constant elevation with hornfels downstream and granite forming a 200 m-high hillside to the north. Here, the contact is inferred to be near-horizontal with the granite above hornfels. Overall, the west of this map sheet is characterised by a boundary following linear valleys, the central part by the granite roof overlain by a hornfels ridge and the east by hornfels overlain by the granite floor.

Dry Creek map sheet

The boundary also trends 090° on this map sheet with 350 m of relief along the boundary. Some intervals are steep, whereas others are flat and follow contours, although with a strong influence of creek valleys. Nineteenth-century gold mining disturbed the vegetation and distribution of rock float, especially along Brankeet Creek, Dry Creek, Hell Hole Creek, and Glen Creek (the latter two on map sheets farther east). Locally, the granite comprises multiple sheets near the contact with hornfels. The interpretation is that the Dry Creek map sheet contains both steep-dipping and near-horizontal intervals of the contact, with the latter mostly representing the granite floor, with fewer examples of the granite roof.

Hell Hole map sheet

From Tallangallook, the boundary trends 090° for 2 km and is essentially flat and remains near 700–750 m AMSL, despite being on a steep hillside with 250 m of granite exposed above and 250 m of hornfels below. This interval is interpreted as a horizontal contact with the granite floor on hornfels. There is a small step-up of the boundary to 900 m AMSL, and it remains near this level for 1 km to Ferrari saddle, and this is also interpreted as a horizontal contact and the granite floor.

The contact-metamorphic aureole has been mapped in detail here and is up to 3 km wide, with cordierite hornfels adjacent to the granite. This is a low-strain environment in which original sedimentary bedding remains discernible in the hornfels, based on the sedimentary structures and the variable cordierite, biotite and quartz abundances reflecting more clay-rich and more silty layers.

Immediately north of Hell Hole Creek, the floor of the granite is 700–750 m AMSL, and above this, it is all granite to the summit of Golden Mountain (1030 m AMSL). This is one of the thickest (demonstrable) parts of the batholith, approximating 300 m.

Glen Creek map sheet

Mt Strathbogie (1038 m AMSL) is the highest point on the granite and is 1 km north of Ferrari saddle. This saddle is the highest elevation along the boundary (940 m AMSL), which descends to 500 m AMSL by Glen Creek.

The boundary from Ferrari saddle trends 090° with 500 m of southward offset where Glen Creek follows the arc of the boundary. This offset coincides with the only juxtaposition of Cambrian rocks against the Strathbogie batholith (Sandl, 1989). The offset may also reflect a moderate outward dip of the granite beneath hornfels and bounding faults on the east and west of the Cambrian package.

Interpretation of the granite–hornfels contact

The mapping allows identification of intervals over which the boundary is parallel to contours and others where it is at a high angle to contours (Figure 9). Unless a hillside is parallel to the strike of a steep contact, contour-parallel intervals on an undulating surface imply that the two-dimensional granite–hornfels contact is horizontal. Along the southern boundary, and around the Tallarook plateau and the Kerrisdale pluton, there are 280 contour-parallel intervals of tens of metres to several kilometres length, and the lengths of the intervals do, in part, reflect the outcrop quality. Some other horizontal intervals reflect local irregularities, such as tongues of granite that are tens of metres or shorter and are not used further in the analysis of roof and floor. Additional information has been gleaned from published mapping of the Seymour section and northwest margin of the batholith near Avenel (Phillips *et al*., 2002).

A plutonic contact that is horizontal may mean granite overlies wall rock (floor), or the granite is overlain by wall rock (roof; Figure 12). Along the southern boundary including the Tallarook plateau and Kerrisdale, the supplemental data map sheets show approximately 170 intervals that reflect the roof of the granite, and 110 that reflect the floor, and these are interspersed with 300 intervals that are contour-oblique (moderate to steep-dipping contact). The vertical displacement on the steep intervals is mostly a few tens of metres and rarely exceeds 100 m.

Three areas have a *step-and-stair* geometry in which many small, horizontal intervals are offset by steep intervals (Figure 13):

- three examples involving the Kerrisdale pluton vicinity, involving both its floor and roof, and the adjacent Burgan Ridge to Munsra screen (stepping up 400 m in 4 km),
- the west side of Larnoo swamp, and
- Jack Creek, with the roof to the west and the floor to the east (two examples).

These *step-and-stair* intervals produce a local gradient of the contact around 1 in 10 along these parts of the southern boundary.

Most of the horizontal intervals can be grouped into 20 segments of *floor* and 21 of *roof*, with an elevation associated with each segment. Plotting these 41 segments on a map of the southern boundary provides a remarkably consistent pattern of roof and floor (Figure 13). These segments can be used to constrain the local thickness of the granite and the attitude of the granite roof along the length of the southern boundary. Combined with published data from the Seymour section and Avenel area, the attitude of the roof, orthogonal to the southern boundary, is also constrained.

The floor of the granite lies between 200 m AMSL in the west and 900 m AMSL in the east, and so slopes gently upward over the 80 km towards the east, and to the southeast (Figure 13). The roof of the granite has been removed by erosion in the far east but is at least 1030 m AMSL at Mt Strathbogie. The roof elevation is generally lower around the Goulburn River near Greenslopes and the far northwest at Avenel. In general, the roof, along much of the southern boundary, is close to horizontal, *i.e.* with gradients of 1 in 100 or less:

- along the Brankeet section, it varies 150 m in 15 km,
- along the Terip section, it varies 200 m in 20 km,
- along the Larnoo section, it varies 200 m in 15 km, and
- from Samaria to Tallarook, the roof varies less than 1000 m in 100 km.

This overall horizontal disposition exists, despite the more local 1-in-10 gradients where there are *step-and-stair* climbs of 100 m or more.

A north–south section provides an indication of the roof attitude orthogonal to the southern boundary; from Enderlee (500 m) to Mt Wheeler (560 m, alternatively called Mt Cecilia), the upper parts of the granite are essentially horizontal over 10 km.

The thickness of the granite near the southern boundary can be estimated using proximal floor and roof measurements (Figure 13). A thickness of 350 m can be demonstrated in the far southwest, but otherwise lesser thicknesses are implied (Table 2). In addition to these brackets of roof and floor, there is likely to be 330 m thickness from the granite floor above Hell Hole Creek (700 m AMSL) to the summit of Golden Mountain (1030 m AMSL; which itself is still some unknown distance below the roof).

These estimates are compatible with much of the present plateau surfaces being close to the original roof of the batholith, except where the plateau has been incised by modern drainage. This interpretation is supported by the distribution of vugs, pegmatite and tourmaline across the plateau—all features found towards the roof of granite sheets. This distribution makes it unlikely that there has been a kilometre of granite eroded from above the current plateaux.

These estimates do not constrain the thickness of the granite in the centre of the batholith but models of steeply plunging pipes and very thick granite bodies receive no support from the geometry of the southern boundary.

The overall pattern differs for each section—Larnoo (mostly roof), Terip (roof), Brankeet (floor), Tallarook plateau (floor to the northwest, roof to the southeast), Kerrisdale pluton (floor to the southeast, roof to the northwest). Additionally, the Seymour section of Zintara to Mittagong (roof) and Avenel (floor) can be similarly interpreted by including previous mapping.

Discussion

The data presented above raise the three issues of granite emplacement, global comparisons and the reasons for the scarcity of previous reports of roofs, floors and the pizza-like geometries. There is a considerable literature on the sill-like geometries of igneous intrusions and their emplacement mechanisms, and the majority involve mafic magmas that intruded incompletely lithified sedimentary rocks (*e.g.* Du Toit, 1920; Schofield *et al*., 2012). In flat-lying sedimentary basins, *step-and-stair* geometries have been well documented by Francis (1982) and Eide *et al*. (2017) and explained by Malthe-Sørenssen *et al*. (2004); and see also early reports from the Henry Mountains in Utah USA (Gilbert, 1877). Further studies infer a sheet-like geometry of granitic rocks that have been intruded into consolidated rock sequences (Miller & Paterson, 2001; Miller *et al*., 2011).

Mechanisms and controls of magma emplacement

The Strathbogie granitic rocks were emplaced soon after the Tabberabberan Orogeny, during which the Paleozoic succession had been folded, metamorphosed to greenschist facies and subsequently exhumed. Sharply cross-cutting relationships against the regionally folded bedded sequence suggest that the granitic magma flow was not strongly controlled by bedding, except on a local outcrop scale, and that the form of the batholith is better described as a sheet rather than a sill (since it is not layer-parallel). The granite had little overburden when emplaced; there was some metasedimentary hornfels and several hundreds of metres of the subaerially erupted welded ignimbrite of the Violet Town Volcanics (Clemens & Wall, 1984).

For this batholith, considerations for the controls on the mechanisms of emplacement include: (1) its shallow emplacement level, (2) intrusion into folded, but brittle wall rocks that were exhumed from moderate crustal depths, (3) the late- to post-tectonic setting, and (4) the presence of multiple, compositionally distinct, sub-horizontal granitic sheets within the batholith.

The overall sheet-like geometry of the batholith and the internally sheeted or layered structure suggest that Strathbogie batholith was assembled through multiple emplaced magma batches. The sheet-like geometry further indicates that the granites propagated laterally as magma-filled fractures. Magma propagation in fractures that are jacked open by the internal magma pressure and fracture propagation critically depends on stresses concentrated along the tips of the fractures (*e.g.* Bartley *et al*., 2006; Emerman *et al*., 1986). The shallow emplacement depth and post-tectonic setting of the batholith also suggest that regional differential stresses had little influence on the emplacement of the granitic magmas. Instead, on a regional and local scale, the straight sections bounding the Strathbogie batholith are parallel to regionally prominent joint sets and master joints (Figure 8). The joint sets represent anisotropies and, at shallow crustal levels, open as fractures across which magma-filled cracks cannot propagate. The close relationship between the straight sections of the southern granite margin and the orientation and presence of joint sets suggests that propagation of the sub-horizontal granite magma sheet(s) was arrested by the prominent joint sets or master joints (Figure 8). The prominent east–west Brankeet section, along the southern granite contacts, corresponds to ac-joints (hinge-normal), whereas the northerly trending Terip section is parallel to bc-joints (strike-parallel) and the axial-planar foliations in the folded wallrock. Moreover, joint sets and lower tensile strengths across the joint systems may have facilitated roof uplift along the pre-existing anisotropies. The opportunistic magma used even the most subtle features and slightest variations of those parameters.

There is no indication that the Strathbogie batholith has the form of a laccolith (roof arched up), since we can demonstrate a near-horizontal roof with local *step-and-stair* geometry in the west. A lopolith (saucer-shaped) overall pattern of intrusion is possible and could be consistent with the constituent plutons passing downward into feeder structures. However, the existing data along the boundaries suggest that the batholith must be thin and sheet-like over much of its outcrop area. Although this interpretation differs from previous *pipe-like* interpretations (Figure 1a), it is compatible with the interpretation for the nearby Mt Disappointment pluton, 20 km to the south of Tallarook, that used a network of ground-based anisotropy of magnetic susceptibility measurements to determine magma flow patterns and a nested laccolith geometry (Clemens & Benn, 2010).

Strathbogie batholith in a global context

Pipe shapes appear to be well established for some igneous bodies, such as some small felsic plutons and kimberlite intrusions. The 3D pipe shape can be confirmed where there are mining activities such as for Cu–Au or diamonds. However, the pipe interpretation has probably become a default choice for many deposits in economic geology in which multiple interpretations may be possible particularly where there are limited data on which to base any interpretation.

The sheet-like nature of the Strathbogie batholith is common globally and, for example, reported from granitic intrusions in the alpine terrains of the Himalaya and Karakorum mountains, and the Torres del Paine granite in southern Chile. Rock exposure in the Himalaya strongly contrasts with central Victoria, but the Himalayan exposures provide clear illustrations of several of the features being interpreted for the Strathbogie batholith. In his book, based on a career of fieldwork studying the Himalaya, Karakorum and Tibet, Searle (2013) summarised two large areas of granite as being I-type to the north, and S-type to the south, which included the highest peaks. The latter contain garnet, muscovite, cordierite and quartz-tourmaline stars (suns) from Manaslu (Searle, 2013, figure 9.12c), which appear indistinguishable from those in the Strathbogie granitic rocks (Phillips & Clemens, 2013, figure 7). Cordierite is widespread in S-type granitic rocks of the Himalaya, including those from Nanga Parbat in the west to Makalu some 1500 km to the east. Granite sheets are a feature of the Greater Himalayan sequence from Manaslu to Everest to Kangchenjunga—a 350 km distance that includes six of the world's ten highest peaks. The sheet on the face of Kangchenjunga is up to 3 km in vertical extent, but the others are much thinner and discontinuous (Searle, 2013).

The Torres del Paine batholith in southern Chile is interpreted as a post-deformational, 20 km by 10 km laccolith that is very well exposed in 2–3 km-high mountains (Altenberger *et al*., 2003; Michael, 1991). Intruded into sandy to shaly turbidites at around 12 Ma, the batholith is up to 2000 m thick and comprises a basal gabbro and

Figure 14. Torres del Paine in southern Chile. The summits of the two main peaks and the two smaller peaks in the foreground are dark-coloured metasedimentary hornfels. The main face of each of these peaks is a sheet of granite (light grey). Photo by Julian Vearncombe with permission.

dominant biotite granite. The roof of the granite is overlain by pelitic hornfels (Figure 14), and despite a consistent shallow dip of the intrusion for several kilometres laterally, the upper boundary displays numerous steeply dipping offsets of tens of metres, producing a step-and-stair geometry.

A contrast to the examples described here from Torres del Paine is found in the economic geology literature that depicts many granitic bodies as steeply plunging pipes with associated larger magma chambers lying at greater depth. This idea, of pipes emanating from magma chambers, is widespread in the Cu–Au porphyry literature, for example, but extends to other ore-deposit types in igneous rocks (*e.g.* Corbett & Leach, 1998; Sillitoe, 2021). The geometry of some small, pipe-like bodies can be demonstrated by drilling and mining of these deposits. However, the linkage of the host plutons to major deeper source batholiths appears problematic and not demonstrated (Figure 15). It is interesting to speculate as to the influence of economic geology and the way its literature depicts orebodies as pipes above enormous chambers of magma because, in doing so, there would appear to be a rift with the thinking of igneous petrologists who doubt the enormous chambers of molten rock (Brown, 2013; Clemens, 2012; Clemens *et al.*, 2021; Cruden, 1998; Lundstrom & Glazner, 2016). It may be that the traditional genetic model for Cu–Au porphyry deposits, which is based on the extraction of large amounts of Cu and Au from felsic magmas, has led to either an acceptance of, or requirement for, enormous parent reservoirs for which there is limited definitive evidence.

Why are granitic sheets uncommon in the literature on southeastern Australia?

If sheet-like granitic intrusions are evident in widely spaced parts of the Himalaya, in Chile, and elsewhere (*e.g.* Cruden, 1998), why are granite sheets, including their floors, so rarely identified in other areas such as the Lachlan Orogen of southeastern Australia? Answers to this question may include reasons given in the following paragraphs.

It is possible that similar boundary features are present elsewhere, but the granites have not been studied. This lack of attention to the details of batholith boundaries is inconsistent with the fact that granitic rocks comprise approximately 40% of southeast Australia and have been the subject of some classic granite studies by Bruce Chappell and Allan White (*e.g.* White *et al.*, 1974). Furthermore, there have been two major contributions on the regional igneous petrology and geochemistry of the Lachlan Orogen in Victoria in the recent literature. A major summary addresses the Paleozoic igneous rocks of Victoria (Rossiter, 2003), and a long-term project involves the systematic documentation of granitic batholiths and silicic volcanic complexes throughout central Victoria (Clemens, 2018, 2019; Clemens & Benn, 2010; Clemens & Bezuidenhout, 2014; Clemens & Birch, 2012; Clemens & Phillips, 2014; Clemens & Wall, 1984; Clemens *et al.*, 2011, 2017; Clemens, Mass *et al.*, 2016; Clemens *et al.*, 2016; Phillips *et al.*, 1981; Phillips & Clemens, 2013; Regmi *et al.*, 2016; Wallis & Clemens, 2018). Two possible reasons for the lack of focus on the batholith boundaries are the previous unavailability of appropriate mapping technologies, and a perceived unattractiveness of regional mapping projects in granitic terrains, by commercial, government and academic organisations.

The application of new technologies has been a major part in the present study. The small-scale orthogonal boundaries were first identified in 1973, using pace-and-compass mapping in thick vegetation on a steep hillside with generalised contours, and were initially interpreted as reflecting orthogonal vertical faults. The advent of GPS made it possible to map in such areas by focussing on the geological boundary rather than navigation, recording positions by GPS waypoints and thus greatly improving the speed and accuracy of mapping.

Regional mapping projects within the batholiths of Victoria are unattractive for both universities and geological surveys. In universities, there are perceptions that such mapping is either redundant with results already established or logistically difficult to fund or execute, or that they provide fewer clear-cut pathways to prestigious publication than igneous petrology and geochemistry. Consequently, relevant batholith boundary data may be scattered through many honours projects with nobody tasked with their synthesis. The lack of gold in Victorian granitic rocks makes it more difficult for a geological survey to justify and fund long-term studies of batholiths, although there have been some important peripheral geophysical studies in areas where auriferous rocks neighbour granitic batholiths (*e.g.* Cayley *et al.*, 2008). Mostly however, airborne gravity and seismic surveys have been specifically designed to avoid batholiths, including the Strathbogie batholith.

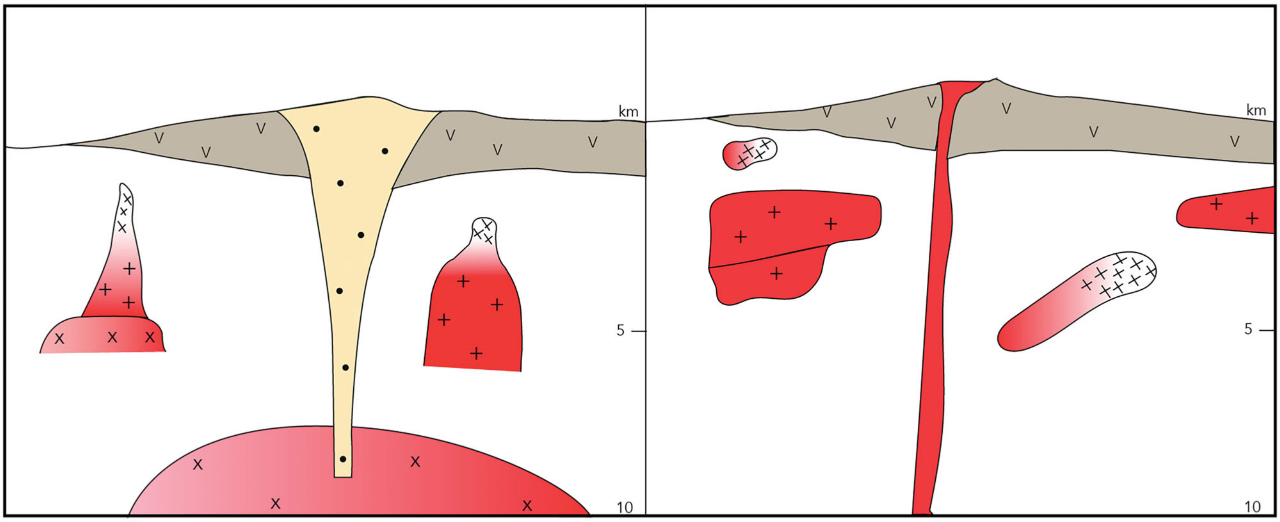

Figure 15. (left) Shapes of intrusions interpreted as the sources and host rocks for various types of Cu–Au porphyry deposits modified from multiple publications including Corbett and Leach (1998), Perkins *et al.* (2016) and Sillitoe (2021). The host rocks solidified from magma before being hydraulically fractured by the mineralising event, hence the host rock pre-dates the mineralising event (Skarmeta, 2021) and cannot be the source of fluid or metals (Phillips & Vearncombe, 2021). Commonly, there is uncertainty in making definitive links between these deposits and their ultimate source. (right) An alternative representation with plutons that are sheet-like, with limited depth, an absence of huge batholiths at depth and mineralised veins of uncertain origin that have been localised in favourable host rocks based on rheological contrasts.

Much of the boundary of the Strathbogie batholith traverses private land involving 100 individual properties for which permission for access is required. Exposures are generally better on this land, but less visited by geologists than the more easily accessible roads. This may be a common situation in other areas in which granitic rocks underlie agricultural land, and public roads tend to avoid critical outcrops.

The positioning of the roof and floor of the Strathbogie batholith between 150 and 900 m AMSL, in a region of modest hills to 1.5 km elevation, is important. Were the position of the batholith 1–2 km lower or higher, there may have been neither roof nor floor exposed (or preserved) for field mapping. Some similar relationships of straight boundaries and *step-and-stair* geometry are suggested on regional geology maps (*e.g.* in northern Portugal and the Mt Buffalo Granite in central Victoria) but must remain speculative until detailed mapping has been carried out.

Weathering, including paleo-weathering, conditions are likely to have contributed to the adequate exposures for mapping between Tallarook, Barjarg and Benalla. In general, the granite and the hornfels are better exposed proximal to their boundary rather than distal. Along the boundary, the mix of hornfels forming the main ridge in some places, and granite forming the ridge in others, probably reflects a fine balance between chemical and mechanical erosion by weathering and fluvial action that differentially affected hornfels and granite. In a colder paleoclimate, frost cracking would have been a significant process of mechanical erosion, but chemical weathering may have been less pronounced.

The influence of economic geology, and especially traditional Cu–Au porphyry descriptive models, has led to pipe-like intrusions connected to enormous reservoirs of magma as being almost the default interpretation in research projects and regional mapping despite definitive evidence for the 3D geometry being incomplete at best.

Summary and conclusions

Field mapping of the Strathbogie batholith in central Victoria has been greatly facilitated by using GPS and GIS techniques and by gaining access to considerable tracts of private property, facilitated through personal liaison with local communities. The margin of the granite against hornfels is constrained by 3800 waypoints that embrace the southern boundary (110 km), the Tallarook plateau (50 km), the Kerrisdale pluton (15 km) and the Seymour section (76 km). The boundary has been mapped with an accuracy of better than ±20 m, and mostly 2–5 m. This detail has allowed identification of intervals over which the boundary is parallel to contours, and others where the boundary is strongly oblique to contours. These contrasting relationships are interpreted as near-horizontal and steeply dipping contacts, respectively, and in places combine to produce a *step-and-stair* geometry.

Where the contact is interpreted as near horizontal, some situations reflect the batholith roof and others the floor, and both are exposed at various positions along the 250 km of mapped boundary. Nowhere can it be shown that the granite is as much as 1 km thick, and it is mostly just a few hundreds of metres thick. An aspect ratio of approximately 300:1 is implied. Except in incised valleys, the land surfaces of the plateaux today are close to the original roof of the batholith, and the roof itself is close to horizontal over its full 100 km (east–west) and 20 km (north–south) extents.

The interpretation of the Strathbogie batholith as a pizza-like sheet contrasts with the previous pipe-like geometry based on geophysical surveys (*e.g.* Edwards *et al.*, 1997). Globally, granitic intrusions have been depicted as steeply plunging *pipes*, but there is incontrovertible evidence from areas of alpine exposures and in mining operations that many intrusions are more the shape of a *pizza*, with limited depth extent, except for relatively small feeder systems (Vigneresse, 1988). Globally, the *step-and-stair* geometry is known from well-exposed intrusive bodies, including in open-pit mines and some mountain ranges, but rarely has it been demonstrated for the whole length of a major batholith.

In hindsight, once the Strathbogie boundary had been accurately mapped and positioned over a digital elevation model, much of the 3D geometry became evident. Overlaying a less accurate granite boundary, based on geophysics, on a contour map would imply a boundary that cuts right across topography and thus would probably lead to an interpretation of a near-vertical contact. This alone might be justification for taking a closer look at such boundaries, on foot.

Acknowledgements

Colleagues from University of Melbourne (Professor Janet Hergt, Caitlin Jay) and CSIRO (Drs Katy Evans and Kim Ely) played important roles in mapping and understanding the Kerrisdale pluton and the Seymour section, respectively. The boundary crosses 100 private properties, and access from the landowners is gratefully recognised. Leon Costermans, Arthur Day, Gowanvale farm, Ian Herbert, Martin Hughes, Greg and Gen Johnstone, Nat Phillips and Warambie Pastoral Co of Gordon and Gail Davis were generous with their provision of support in the field, accommodation, advice and logistic assistance. Julian Vearncombe convened the Granite 2017@Benalla International Symposium and shared many ideas during the planning of field trips and the conference itself. Community meetings, field trips including the Riparian Walks series (led by Alastair Tame) and the Highlands Ramblers (Andrew Shaw, Peg Lade) were invaluable as forums to test ideas and see more of the batholith. The late Dr Vic Wall is acknowledged for his important contributions during the early stage of this granite and contact aureole research. Roberto Weinberg and Ian Withnall are thanked for their very helpful suggestions to improve the manuscript. The maps were compiled for the Granite 2017@Benalla International Symposium, Tallarook Geology guide, community valorisation and Strathbogie guidebooks and are reproduced here with permission from Phillipsgold Pty Ltd. The maps have relied on data from the Geoscience Australia, the Victorian Government and a NASA image, and advice from Grant Boxer. The contribution of data and ongoing advice from Martin Hughes have been especially appreciated.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Twelve map sheets covering the 100 km of the southern boundary of the Strathbogie batholith are included as supplemental data. These maps include the raw waypoints highlighting granite, hornfels and both (*i.e.* the boundary).

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