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Inferring a deep-crustal source terrane from a high-level granitic pluton: the Strathbogie Batholith, Australia

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Abstract

The Strathbogie Igneous Complex is comprised of the ignimbritic rocks of the Violet Town Volcanics and the granitic rocks of the Strathbogie batholith. It is Late Devonian in age and postorogenic-extensional in tectonic setting. The batholith was constructed from peraluminous, metasediment-derived magmas emplaced as several internally heterogeneous plutons. Chemical variation in the magmas was largely inherited from the protolith rather than having been produced by differentiation (crystal-liquid separation) or magma mixing. The Strathbogie magmas formed during a granulite-facies metamorphic event that caused partial melting of the rocks of the Proterozoic Selwyn Block, which forms the basement in this region. The chemistry of the Strathbogie batholith, the Violet Town Volcanics and various other felsic complexes of similar age, implies that the Selwyn Block here originally consisted of andesite, dacite, greywacke and pelite, probably deposited in a back-arc extensional setting. The sedimentary components of this protolith may have been deposited in a basin that was extending and deepening with time, so that the sediments contained progressively higher ratios of clay to volcanic materials. Much later, in the Late Devonian, extensional tectonics allowed the emplacement of mantle magmas into the deep and middle crust, causing the low-pressure granulite-facies metamorphic event that was responsible for the production of the crustal components in the granitic magmas of Central Victoria.

Introduction and regional geology

The Tasman Fold Belt in Eastern Australia contains Palaeozoic, mainly sedimentary sequences intruded by numerous granitic bodies. In the south of the Belt, in the Melbourne Zone of Central Victoria (Birch and VandenBerg 2003), the Late Devonian granitic rocks intrude Ordovician to Middle Devonian, folded, low-grade metasedimentary rocks. This widespread, postorogenic magmatism was associated with rifting, the formation of nonmarine basins and a small amount of mafic to intermediate volcanism (e.g. Clemens and Birch 2012, Soesoo 2000) Here, both felsic volcanic and plutonic rocks commonly contain igneous-textured microgranular enclaves (ME) that appear to represent hybridised, mantle-derived magmas that mingled with the much larger volumes of felsic host magmas (e.g. Elburg and Nicholls 1995; Elburg 1996a, b, c; Clemens and Bezuidenhout 2014). We use the terms 'igneous microgranular enclave' or 'ME' to denote igneous-textured enclaves of magmatic origin and the term 'xenolith' to denote other accidental rock fragments included in the magmas.

In the Melbourne Zone the Palaeozoic metasedimentary sequence is 4 to 10 km thick. Geophysical evidence has shown that beneath the Melbourne Zone lies the Selwyn Block, a mainly Proterozoic, continental, exotic terrane, 20 to 25 km thick but with almost no surface expression (Cayley et al. 2002b; Cayley 2011). Chemical and isotopic work has shown that the crustal components of the Late Devonian, felsic, magmatic rocks cannot have been derived from the Palaeozoic metasedimentary sequences and are therefore inferred to have originated through partial melting of the Selwyn Block (see e.g. Wyborn and Chappell 1979, Phillips et al. 1981, Clemens 2003, Clemens et al. 2011a and Clemens and Birch 2012). The Selwyn Block is thought to be dominated by Proterozoic metasedimentary and metavolcanic rocks, overlain by a layer of Cambrian metavolcanic rocks (Cayley et al. 2002a). Thus, if these interpretations are correct, the Late Devonian granitic and felsic volcanic rocks represent a valuable if indirect window into the unexposed Selwyn Block. This study combines field-based data, geophysical constraints, petrography, geochemistry, geothermometry and barometry and experimental petrology provide more specific information on the lithological character of the Selwyn Block, the *P*-*T*-fluid conditions at the time of felsic magma genesis and the likely tectonic setting in which the rocks of the Selwyn Block originally formed.

The Strathbogie batholith

The east-west elongated Strathbogie batholith is the largest of the Late Devonian felsic intrusions in the Melbourne Zone. It forms the plutonic portion of the Strathbogie Igneous Complex, which encompasses the batholith, the adjacent Violet Town Volcanics and some minor intrusive bodies (Clemens and Wall 1984). Using SHRIMP U-Pb analyses of zircons, the batholith has been dated at 374 ± 2 Ma (Bierlein et al. 2001) and 366 ± 3 Ma (Kemp et al. 2008). The date of Kemp et al. is preferred here because it is fully consistent with the geological field evidence batholith intrudes the Violet Town ignimbrites (373 ± 3 Ma, Kemp et al. 2008; 379 ± 8 Ma, Elburg 1996a; 373 ± 7 Ma, Clemens and Wall, 1984). The zircon SHRIMP date of 366 Ma is also consistent with the Rb-Sr dates of 365 and 366 Ma (Richards and Singleton 2001, Rossiter 2001). Finally, when plotted with 2σ instead of 1σ errors, the Bierlein et al. (2001) data define a single zircon population at 366 ± 6 Ma (Kemp et al. 2008, Prof. Dirk Frei of Stellenbosch University, pers. comm. 2014).

The Siluro-Devonian metasediments intruded by the batholith contain lower greenschist facies mineral assemblages (Phillips and Wall 1980). Thus, since these rocks were regionally metamorphosed and folded in the Middle Devonian, there was a period of uplift and erosion of several kilometres before the Strathbogie Igneous Complex was emplaced. The Strathbogie batholith is overwhelmingly S-type in character, apart from two tiny hornblende-bearing I-type plutons (Phillips et al. 1981, Phillips and Clemens 2013). The granitic rocks contain no obvious foliations or lineations, apart from some magmatic flow structures delineated by alignment of the K-feldspar phenocrysts.

Phillips et al. (1981) studied the general geology and petrology of the batholith, introducing the concept of a large S-type batholith with widespread occurrence of relatively abundant magmatic cordierite, with some magmatic garnet. The origin of the chemical variations in the batholith was not well constrained. However, based on their small chemical database, they formulated a preliminary differentiation model. Linking to the experimentally determined phase relations of Clemens and Wall (1981), Phillips et al. (1981) also placed constraints on the *P* and *T* of magma genesis (≥ 400 MPa and ≥ 800 °C) and the likely initial H_2O contents of the magmas (~ 4 wt%). Based also on chemical arguments, the experiments of Clemens and Wall (1981) and the presence of some high-grade gneissic xenoliths, Phillips et al. (1981) concluded that the source rocks for the Strathbogie magmas lay beneath the exposed Palaeozoic rocks and that, although sedimentary, were not dominated by metapelites. They also inferred that, to reach the temperatures required for crustal melting, it was probable that heat was advected into the deep crust by mantle-derived magmas.

Since the late 1970s a mass of remotely sensed data has become available, we have had joint mapping projects (with Drs Kim Ely and Katy Evans of CSIRO and Prof. Janet Hergt of University of Melbourne) and subsequently recorded more detailed field observations at over 1000 locations throughout the 2000-km^2 batholith. A much broader chemical database has become available, through D. G. Cownley (written communication 2001) and the late Prof. B. W. Chappell (who kindly made his unpublished data available to Cownley). We have augmented this with 38 new whole-rock analyses (21 plutonic rocks, 14 ME and 3 metasedimentary xenoliths), with Sm-Nd and Rb-Sr isotope analyses for 5 plutonic rocks, 5 ME and 2 xenoliths. These data enable us to produce a superior model for the origins of the chemical variations in the different parts of the batholith, including the ME. Also, conclusions based on the experimental data of Clemens and Wall (1981) need to be reappraised because improved models for the H_2O contents of the experimental melts have become available (see Holtz et al. 2001). We now have a clearer idea of what rock types are likely to have been present in the source region for the Strathbogie magmas, and hence of the probable tectonic setting in which the rocks of the Selwyn Block were formed.

The batholith contains five S-type plutons (Fig. 1). From west to east these are – Kerrisdale, Dabyminga, Mt Wombat, Lima and Lightning Ridge plutons. The two tiny plutons of I-type Tallangallook Hornblende Microgranite have not been individually dated, though they appear to intrude their immediately surrounding S-type granitic rocks (Phillips and Clemens 2013).

Geophysical Information

The digital terrain model, the airborne radiometric (K, Th, U) surveys and the Bouger gravity anomalies provide data important in defining the map areas occupied by the various plutons (Phillips and Clemens 2013). The following is a very brief summary of the important points, in the petrogenetic context.

The northwestern sector of the batholith is dominated by the K signal, consistent with the highly felsic and K-feldspar-rich character of the rocks in this area of the Mount Wombat pluton (Fig. 2a and b). The eastern part of the batholith appears to have a higher U response. The Th image indicates areas of lower Th in the far southwest, northwest and far east. The first two of these Th lows coincide with U lows, but the far east is an area of low Th with high U suggesting some decoupling of these elements. Also, there are some arcuate to circular features apparent in the image, especially in the southwestern area of the Mount Wombat, Dabyminga and Kerrisdale plutons. We interpret these as probable magma feeder zones. The chemical characteristics of individual rock samples and the overall picture from the radiometrics do not exactly match. Each area within the batholith is heterogeneous and, with the small numbers of analysed samples, the radiometric image provides the most reliable indicator of overall chemical characteristics.

Petrography and mineral chemistry of the Strathbogie granitic rocks and their igneous microgranular enclaves

The gallery of photomicrographs in Electronic Appendix 1 illustrates some of the mineralogical and textural features of the plutonic rocks and their ME. Further descriptions, particularly of the garnet and cordierite varieties can be found in Phillips et al. (1981), whereas Phillips and Clemens (2013) presented photographs of and data on the mesoscopic textures. Many of the S-type Strathbogie rocks are porphyritic with potassic alkali feldspar phenocrysts, and the groundmasses of the rocks are equigranular to seriate. Orthopyroxene itself is not present in the Strathbogie granitic rocks, but biotite-quartz pseudomorphs of this mineral (Electronic Appendix 1, Fig. EA1.1) are relatively widespread, in low abundance, in thin sections, especially of samples from the Mount Wombat and Lima plutons. Cordierite is very widespread in outcrop and its size and abundance were systematically recorded by Phillips and Clemens (2013). As pointed out by Phillips et al. (1981), cordierite is the mafic mineral that typifies this batholith.

Kerrisdale pluton

This pluton is a circular, non-magnetic, very low-K/Th/U pluton on the southwestern end of the batholith (McDonald 1997). The main rock type is a medium-grained, mainly porphyritic biotite-cordierite granodiorite with irregularly scattered K-feldspar phenocrysts.

Dabyminga pluton

The Dabyminga pluton is more felsic than the Kerrisdale, being dominated by medium-grained, biotite-phyric monzogranite to syenogranite. Biotite dominates over cordierite, and the rocks have abundant K-feldspar phenocrysts. Compared to most of the batholith, the Dabyminga pluton is low in K, U and especially Th (Fig. 2) and the circular haloes around the

Dabyminga and Kerrisdale plutons (Meyers 2002), suggest subsurface laccolithic shapes similar that of Mt Disappointment (Clemens and Benn 2010).

Mount Wombat pluton

Comprising the bulk of the batholith, the Mount Wombat pluton is quite variable, with rock types ranging from porphyritic micromonzogranite to aplitic-textured alkali feldspar microgranite. Electronic Appendix 1, Figs EA1.2 and 1.3 illustrate some of the wide variation in microscopic fabric in the Mount Wombat rocks. Large euhedral to subhedral quartz and numerous ~ 5 cm K-feldspar phenocrysts characterise the more mafic rocks in the Mount Wombat pluton. Cordierite dominates over biotite, and garnet (including its biotite-cordierite pseudomorphs) is most abundant in this pluton, which also contains many examples of subhorizontal layering. Complex, layered, aplitic to pegmatitic units are present in a number of localities, especially on the northwestern edge, where Phillips and Clemens (2013) identified the pluton roof zone. This pluton contains the highest concentrations of enclaves of all kinds, with metasedimentary hornfels xenoliths, igneous-textured ME and schistose to gneissose xenoliths being the most abundant. However, even here, the enclaves make up less than 0.1% of the overall rock volume.

Lima pluton

In this pluton, the main rock type is porphyritic microgranite to micromonzogranite with relatively high K and U but low Th. As in the Mount Wombat pluton, magmatic cordierite dominates over biotite but garnet is scarce and enclaves uncommon. In one locality there are anhedral, subsolidus cordierite growths around 1 to 2 cm across, with ‘bleached’ haloes in which biotite is absent. These are texturally similar to tourmaline-quartz growths in the roof zones of the Mount Wombat pluton and are interpreted as products of localised, late hydrothermal activity. Electronic Appendix 1, Fig. EA1.4 illustrates the typical microgranitic fabric of the rocks in the Lima pluton.

Lightning Ridge pluton

The north-south-elongate Lightning Ridge pluton shares a similar radiometric signature with the surrounding Lima pluton and also contains few enclaves. In contrast to the other plutons, however, the Lightning Ridge rocks contain anhedral quartz that rarely reaches grain sizes comparable to the quartz in the rest of the S-type rocks of the batholith outside of the Kerrisdale pluton. The Lightning Ridge rocks are very leucocratic (modal ferromagnesian mineral content (M) < 5) and dominated by aphyric medium-grained syenogranite and less abundant monzogranite with low cordierite and biotite contents and widespread but minor tourmaline. In thin section the Lightning Ridge rocks contain small amounts of muscovite, inferred on textural grounds to be of late-magmatic origin, as well as about 2 modal % of anhedral, interstitial tourmaline (schorlite), which probably formed close to the solidus (Electronic Appendix 1, Fig. EA1.5).

Tallangallook hornblende microgranite

A small I-type pluton (≤ 200 m in extent) was identified by Phillips et al. (1981), and a second, similar body was discovered about 7 km to the northwest (Phillips and Clemens 2013). The rock is a sparsely porphyritic hornblende microgranite with small quartz and plagioclase phenocrysts in a groundmass of anhedral quartz and alkali feldspar, subhedral plagioclase, minor euhedral green hornblende, lesser olive-brown biotite and accessory ilmenite, magnetite, titanite, apatite and zircon. Electronic Appendix 1, Figs EA1.6 and 1.7 illustrate the microscopic textural features in these I-type rocks.

Xenoliths and Igneous-textured Microgranular Enclaves

Table 1 provides an overview of the various kinds of rock enclaves (ME and xenoliths) in the Mount Wombat pluton. A common type is sub-angular xenoliths of local country-rock hornfels. There are also rare, irregular to rounded or jagged, mainly metapelitic gneissic enclaves with upper amphibolite- to possibly lower granulite-facies mineral assemblages. The mineralogy and textures of these enclaves were described by Phillips et al. (1981). They are inferred to be xenoliths of the mid-crustal equivalents of the Palaeozoic metasedimentary rocks of the Melbourne Zone, sampled by Strathbogie magma as it ascended. However, the most common type of enclave in the batholith is the igneous-textured ME, the textures (grain sizes and inter-grain relationships) of which vary. The chemical and modal variations of the ME correlate poorly with the textural varieties because the textures reflect local cooling rates, rather than magma compositions.

The ME range from monzogranitic (~ 10%) through granodioritic (~ 70%) to tonalitic (~ 20%). The most common type is poikilitic with anhedral quartz (and, in some cases, K-feldspar) enclosing tiny red-brown biotite platelets, plagioclase laths (sometimes in radial clusters), thin ilmenite plates and acicular to prismatic apatite. Orthopyroxene is not present but a single sample contains abundant biotite-quartz pseudomorphs after original pyroxene. Electronic Appendix 1, Fig. EA1.8 shows a typical example of the texture of these ME.

The second most abundant textural variety among the ME is microgranitic, with anhedral quartz intergrown with stubby euhedral, oscillatory-zoned plagioclase with subhedral red-brown biotite partly enclosed by the quartz and partly interstitial to quartz and plagioclase grains (Electronic Appendix 1, Figs EA1.9 and 1.10). Anhedral and interstitial garnet (Electronic Appendix 1, Fig. EA1.11) and subhedral cordierite both occur rarely. A small proportion of these microgranitic-textured enclaves are sparsely porphyritic, the main phenocryst mineral being euhedral plagioclase tablets and glomerocrysts. Quartz phenocrysts are very rare. The major accessory minerals are ilmenite platelets and long acicular apatite crystals, although zircon is present in some, along with very rare tourmaline. Some of these enclaves exhibit a degree of recrystallisation in the form of finely scalloped grain boundaries. The microgranitic ME contain stubby prismatic apatite instead of the acicular type found in the other textural types, suggesting slower cooling rates.

A third, rare type of ME contains poikilitic to interstitial quartz, colourless columnar ortho- and clino-amphibole intergrown with anhedral, shred-like, red-brown biotite and accessory ilmenite and acicular apatite (Electronic Appendix 1, Figs EA1.12, 13, 14 and 15). The ratio of amphibole to biotite varies, with some examples containing no amphibole (e.g. sample SB1812, shown in Electronic Appendix 1, Fig. EA1.12). The textures in these enclaves suggest that the biotite replaced earlier amphibole and that the mineralogical varieties represent different stages in this process, most probably related to reaction between the enclave and the enclosing granitic magmas. In all examples of this variety of enclave, the ilmenite platelets are large (average 0.8 mm) and very thin, and some exhibit dendritic growth habits (Electronic Appendix 1, Figs EA1.12, 14 and 15). Some examples of this variety also contain rare, large, rounded plagioclase polycrystals with feeble zoning (Electronic Appendix 1, Fig. EA1.13), inferred to be either primacrysts (earliest-formed crystals in the magma) or xenocrysts. The amphibole-bearing and biotite-rich ME with this set of textural and mineralogical features are more mafic than the dominant varieties.

Irrespective of their particular variety, the textures of all the ME signify cooling at rates much faster than those experienced by the host granitic magmas. Some also contain miarolitic cavities (e.g. sample SB1810 in Electronic Appendix 1, Fig. EA1.16), implying that the ME magmas cooled rapidly at very shallow plutonic levels (see e.g. Kumar 2010, Vernon 2014). The ME were sought out and sampled, as they potentially hold valuable information about the genesis of the Strathbogie magmas. For a recent general examination of the microstructures of

ME in granitic rocks from southeastern Australia and their interpretation, the reader is referred to Vernon (2014).

Chemistry of the Strathbogie granitic rocks and their igneous microgranular enclaves

Data Provenance

The major-oxide and trace-element data are derived from a number of sources. All the data have been compiled and presented in Tables EA2.1, 2.2 and 2.4 (Electronic Appendix 2), where they are grouped according to which pluton they come from. To rationalise the sample numbering systems used in the various data sources, we allocated a universal set to all samples for which analytical data are available. Electronic Appendix 3 provides a table showing our allocated sample numbers and the corresponding original sample numbers given in the various data sources. Some samples have more than one original number because they were catalogued in various collections.

Table EA2.1 presents the whole-rock major oxide and O isotope data, Table EA2.2 most trace elements and Table EA2.3 the REE concentrations. Phillips et al. (1981) published major-element analyses for 21 S-type granitic rocks and 2 from the Tallangallook hornblende microgranite, analysed by XRF at Monash University. Thirteen additional S-type samples were collected and analysed by us, along with one sample from the second pluton of Tallangallook hornblende microgranite and 14 ME from the Mount Wombat pluton. All these were analysed for major and trace elements in the Central Analytical Facility at the University of Stellenbosch, using XRF on fused beads for the major elements and LA-ICP-MS on polished sections through the XRF beads for the trace elements. Selected samples were analysed for Rb, Sr, Sm and Nd concentrations by solution ICP-MS using a quadrupole mass spectrometer, and were also analysed for their Sr and Nd isotope ratios, in AEON Labs at the University of Cape Town. Two BSc honours theses from Melbourne University contain further XRF analyses. That of Bannister (2003) contributed 6 analyses (all nearly identical within analytical error) from other parts of the first-recognised pluton of the Tallangallook hornblende microgranite. The mean of these is presented here as ‘sample’ SB1507. The thesis of Cownley (2001) provided 8 further analyses, mainly from a small, very leucocratic, highly differentiated portion of the Mt Wombat pluton, close to the roof of the batholith. An additional 27 analyses come from the unpublished dataset of the late Prof. B. W Chappell, and were also included in the thesis of Cownley (2001). These were analysed by XRF at the Australian National University. Two analyses were taken from Gray (1990) and one from Richards and Singleton (1981). Prof. W. Compston at the Australian National University carried out TIMS Sr isotope analyses of samples SB1003, SB1005, SB1006, SB1010, SB1017, SB1020 and SB1024. Dr J. R. O’Neil kindly analysed the same samples, and SB1016, for oxygen isotopes, at the United States Geological Survey at Menlo Park, California. All calculated radiogenic isotope parameters have been referred to a magmatic age of 366 ± 3 Ma. In this paper, we refer to several calculated chemical parameters: FM = FeO^T+MnO+MgO in wt%, Mg# = 100 × mol. Mg/(Mg+Fe) and ASI = mol. $Al_2O_3/(CaO+Na_2O+K_2O)$.

General Observations

All the analysed rocks (both S- and I-type) belong to the high-K series (Fig. 3d). Na_2O, K_2O (Fig. 3c, d) and U generally increase with SiO_2, whereas the rest of the oxides and trace elements decrease. The largest mass of felsic plutonic rocks, the Mount Wombat pluton, exhibits a much greater range of composition than the other plutons. It has SiO_2 ranging from 70.2 to 77.6 wt%, whereas the rest of the analysed rocks have SiO_2 between 70.9 and 74.5 wt%. Thus, it seems that only the Mount Wombat pluton contains the most siliceous (potentially differentiated) rocks.

Compared to the S-type samples with similar SiO_2 contents, the I-type Tallangallook hornblende micrograndites have high Na_2O, low TiO_2, FM and P_2O_5 and, being metaluminous, they have low ASI (Figs 3a, b, c, e and f). Among the S-types, the Dabyminga and Kerrisdale plutons appear to have relatively low K_2O contents and K_2O/Na_2O ratios, and higher Sr contents than the Mount Wombat and Lima plutons (Fig. 4a). The samples from the Dabyminga and Kerrisdale plutons also have relatively elevated Th and Ce contents (Fig. 4b, c). Note, however, that the radiometric image in Fig. 2 suggests that the Dabyminga pluton, as a whole, contains relatively low Th. The analysed rocks from the Lightning Ridge pluton are distinguished from the other S-types in having relatively high P_2O_5 contents and high ASI values.

Under equilibrium conditions, U should partition strongly into zircon. However, there is a lack of correlation between Zr and U in the rocks (Fig. 4e), and the U contents appear to increase with SiO_2 content (Fig. 5c), suggesting that a significant proportion of the U remained in the residual melts as crystallisation proceeded. As discussed by Bea et al. (2007) a credible explanation for lack of equilibrium between accessory minerals and the host magma is that the processes of partial melt extraction, magma ascent, emplacement and cooling were rapid, on a time scale of $\leq 10^3$ yr. As inferred by Bea et al., such short timescales suggest that the melting events were driven by short-duration advection of mantle heat, through the medium of mafic magmas, and not by the much slower increase in intracrustal radioactive heat in a thickened crust.

Strong negative correlations between SiO_2 and Ba, Sr and Cr suggest that the concentrations of these elements may be related to magmatic processes that progressively either concentrated or depleted the magmas in feldspars and ilmenite (Fig. 4a, Fig. 5a, b). ASI shows essentially no correlation with either SiO_2 (Fig. 3f) or FM, which suggests that peraluminous minerals (mainly cordierite, lesser biotite and trace garnet) are not uniformly enriched and depleted in the rocks. This inference is borne out by the field observation that the less aluminous biotite is concentrated in the more mafic rocks and the cordierite in the more felsic rocks, with their mutual effects on ASI roughly balancing. This further suggests that the melt in the more siliceous magmas was also more aluminous, favouring the right-hand sides of equilibria such as:

Bt + Qz + high-Al melt = Crd + Kfs + lower-Al melt.

Among the S-type rocks, initial $^{87}Sr/^{86}Sr$ is highly variable (0.708 to 0.714, Table 2) and, taking the batholith as a whole, this parameter shows no correlation with SiO_2 (Fig. 6a). However, among the rocks of the Mount Wombat pluton the initial Sr ratio is positively correlated with ASI (R^2 = 0.614, Figs 6b and 7). This relationship suggests that the Mount Wombat magmas may have been derived through partial melting of a metasedimentary protolith that originally had internal variations in the amounts of clay in the fine fraction (e.g. through variations in clay contents of the greywackes and the ratio of psammitic to pelitic beds in the package). There is no apparent mixing trend in the initial $^{87}Sr/^{86}Sr$ vs 1000/Sr diagram (Fig 6c), which suggests incremental addition of magma fractions without significant interaction between individual magma pulses. Whole-rock $\delta^{18}O$ values of the S-types vary from +9.6 to +11.6‰ (Table EA2.1, Electronic Appendix 2), within the range expected for magmas derived from metasedimentary protoliths. There are no significant correlations between this parameter and either SiO_2 or initial $^{87}Sr/^{86}Sr$. If the relatively low value (9.6) for sample SB1024 is excluded, there is a slight positive correlation between ASI and $\delta^{18}O$, as might be expected if the more aluminous magmas were derived from protolith rocks with higher original clay contents. The I-type Tallangallook hornblende microgranite (sample SB1016) has a relatively low $\delta^{18}O$ of 9.4, which is still high enough to be more typical of an

S-type rock, perhaps indicating O exchange with the vast volume of enveloping S-type magma. The εNd_T values for the S-type rocks (Table 3) vary from -6.6 to -1.0, with those for the Kerrisdale (and possibly the Dabyminga) pluton being systematically lower than the Mount Wombat and Lima plutons (Fig. 6d). The I-type Tallangallook hornblende microgranite has far more primitive initial Sr and Nd isotope ratios than the S-types, with initial $^{87}Sr/^{86}Sr$ = 0.70632 and εNd_T = +0.6. Most Central Victorian I-type granitic rocks have more evolved Nd isotopes, with εNd_T generally between -2 and -4. The Tallangallook hornblende microgranite is also metaluminous, in contrast to a majority of Central Victorian I-type rocks, which are mildly peraluminous (Clemens et al. 2011, Chappell et al. 2012). Taken together, these characteristics suggest a possible juvenile mantle connection for the Tallangallook magma. These I-type rocks are most likely the products of differentiation of a more mafic parent magma that was present, at depth, at the same time as the crustally derived Strathbogie magmas.

The Woods Point Dyke Swarm (WPDS) has approximately the same age as the batholith, individual dykes having been dated at 378 to 372 Ma (Richards and Singleton 1981, Bierlein et al. 2001, Foster et al. 1998). The Swarm lies 50 km to the south where a bend in the trend of the Swarm makes the dykes trend directly toward Tallangallook. The vast majority of the Woods Point dykes are ultramafic to mafic. However, there are reported to be some granophyres and rhyolites, interpreted as the end products of high degrees of differentiation of the mafic magmas (Junner 1920, Hills 1952, Green et al. 1982). The only published analysis of a felsic Woods Point dyke, that we are aware of, appears in the MSc thesis of Green (1973). This sample (numbered 194) is an extremely silicic, oxidised and ferroan rock (SiO_2 = 76.89%, Mg# = 6.61) that is also highly peraluminous (ASI = 2.06) with K_2O/Na_2O of 1.36 (medium-K, in contrast to the high-K character of the Tallangallook I-types). These characteristics contrast strongly with those of the Tallangallook hornblende microgranites (see earlier). Published compilations of analyses of fresh samples of the Woods Point Dykes (e.g. Jowitt et al. 2012) show that they are mantle-derived and that the most evolved rocks are no more silicic than quartz diorite; the apparently felsic rocks are all actually strongly hydrothermally altered mafic rocks (Dr P. Jackson, Morning Star Gold, written comm. 2014). On this basis, it is uncertain whether rocks related to the WPDS occur within the batholith, but we revisit this question later.

Igneous microgranular enclaves (ME)

The ME in the Mount Wombat pluton are mainly granodioritic, with some tonalites and a single analysed monzogranite (sample SB1822). Their Mg#s are rather low, even for the most mafic of the ME samples, ranging from about 30 to 40, with a single enclave (with the lowest SiO_2 content of 59.88 wt%) having a value of 48. Unlike their host rocks, which fall in the high-K field, the ME range from being high-K series at the low-SiO_2 end to medium-K at the high-SiO_2 end of their compositional range – essentially opposite to what might be expected if the ME and host magmas formed parts of a mixing trend (Fig. 8c). The one exception to this general trend is the monzogranitic ME sample SB1822, which falls in the high-K field and might have a different origin to the rest.

When plotted with their Mount Wombat host rocks on Harker diagrams (e.g. Figs 6 and 8), the ME do not form linear mixing arrays with the host series. Their variation is generally more scattered than that of the host granitic rocks, though there is a suggestion of rough linearity in their internal variations (e.g. for TiO_2, Na_2O, K_2O and Ce in Fig. 8). For some oxides and trace elements, the ME form trends parallel to but offset from those defined by the host-rock points (e.g. TiO_2 and Na_2O in Fig. 8). Other oxides and trace elements actually form trends in the opposite sense to those defined by the host rocks (e.g. K_2O and Ce in Fig. 8). The ME are notably richer in TiO_2, FM, Na_2O and Ce (e.g. Fig 8a, b, f), and they are generally *more peraluminous* than the host rocks (Fig. 8d). The ME are also poorer in K_2O than their hosts (Fig. 8c) and their variations in Ba, Sr and Zr are scattered and unrelated to trends shown by the host-rock samples (e.g. Fig 8e). As noted above, the Ce variation in the ME is in the opposite sense to that in the host rocks (Fig. 8f). The K_2O variation among the ME is most unusual, with the more mafic samples having higher K_2O contents (Fig. 8c). This feature could be interpreted as indicating diffusive reaction with the host granitic magmas, with K transferred from the hosts to the enclaves to allow growth of abundant biotite. However, the biotite in the ME forms part of the igneous quench texture and there are only very rare examples of biotite-rich selvages surrounding such enclaves. Thus, this chemical characteristic is likely to have a deeper and earlier origin. The chondrite-normalised rare-earth-element (REE) spectra of the Strathbogie granitic rocks are practically identical with those of the ME from the Mount Wombat pluton (Fig. 9), with the exception that some of the ME samples have more negative Eu anomalies than any of the host rocks. There are two groups of Mount Wombat host granitic rocks. One group has much lower total REE contents and far deeper negative Eu anomalies (Fig. 9a). Although we have little evidence of differentiation by crystal fractionation affecting the bulk of the batholith, there is good evidence that this process occurred locally (see later). All the low-REE rocks have SiO_2 contents > 76 wt%, and we therefore interpret these patterns to reflect high degrees of fractionation of REE-bearing accessory minerals (e.g. zircon, apatite and monazite), probably as inclusions in biotite that was separated from the liquid, along with early-crystallised plagioclase feldspar.

It has been hypothesised that igneous-textured ME in granitic rocks are derived from basaltic parent magmas that underwent hybridisation with the enclosing felsic magmas. We have already demonstrated that such a model is untenable for the ME of the Mount Wombat pluton, since they do not appear to form mixing trends with their host-rock series, and because they display some chemical trends that run contrary to those defined by the host rocks. Vernon (2014) pointed out that any mixing between mantle-derived magma and granitic magma is most likely to have occurred near the source and that the quench textures in ME make it unlikely that significant mixing occurred with the host magmas at emplacement levels. These views are strengthened by the features of Fig 8d (ASI v FM) and Fig. 10, in which ASI and TiO_2 are plotted against FM for the granitic rocks of the Mount Wombat pluton, the ME and medium-K calcalkaline basaltic rocks. If a putative parent magma for the ME were basaltic, and we adopt a mixing model for the production of the present compositions of the ME, that basaltic magma must have been extremely hybridised by some highly aluminous, high-Ti material, that cannot have been a magma. Figure 10 also shows the points for the mafic to intermediate rocks of the Mt Buller-Mt Stirling complex at the eastern edge of the Melbourne Zone (Soesoo 2000). For similar reasons, it is equally clear that such magmas are unlikely to have been the progenitors of the ME. From the isotope characteristics of the enclaves (Tables 2 and 3) it is apparent that they bear strong resemblances to their Mount Wombat host rocks. They have initial $^{87}Sr/^{86}Sr$ between 0.710 and 0.712 with εNd_T in the range of -5.4 to -2.9. Thus, any model must take account of this similarity and the lack of similarity with the expected characteristics of mantle-derived magmas of this era (positive εNd_T and initial $^{87}Sr/^{86}Sr$ around 0.704). A possible alternative model is explored briefly in the discussion section.

Are the Violet Town Volcanics and the Strathbogie batholith comagmatic?

The Sr and Nd isotope characteristics of the Violet Town Volcanics (Elburg 1996b) are similar to those of Strathbogie granites from the Mount Wombat pluton, and the Volcanics are dated at 373 ± 3 Ma, older than the 366 ± 3 Ma date for the Mount Wombat pluton (Kemp et al. 2008), consistent with the geological constraints. For the most part, the main series is rhyodacitic and far more mafic than the Strathbogie rocks, although there is a group of VTV rocks with similar SiO_2 contents (around 72 to 73 wt%, Fig. 11). The VTV mostly have subtly lower K_2O and ASI (Fig. 11a) than the Strathbogie rocks. Likewise, at the same SiO_2 content, although the VTV have similar Sr concentrations (Fig. 11b) they define a separate trend on the Ba variation diagram (Fig. 11c). The VTV have generally lower SiO_2 than the Strathbogie S-type rocks and their initial $^{87}Sr/^{86}Sr$ ratios extend to somewhat less radiogenic values. Also, the VTV and the Strathbogie batholith display contrasting trends in their Hf and O isotope covariations suggesting that the two are not co-magmatic (Kemp et al. 2008).

Nevertheless, the VTV and the Strathbogie magmas are clearly related, in space, time and general magma chemistry. The contrasts between the two mean that the VTV, though not comagmatic with the Strathbogie, probably represent products of partial melting of the less aluminous, metagreywacke-dominated part of a package of metasedimentary rocks in the Selwyn Block, whereas the Strathbogie magmas were derived through partial melting of a more aluminous part of the same package, still mainly metagreywackes but containing a higher proportion of metapelitic layers. Indeed, even within the Mount Wombat pluton, this kind of variation is evident; the rocks with higher ASI values also have higher initial $^{87}Sr/^{86}Sr$ (Fig. 7).

Experimental constraints on the formation of the magmas of the Mount Wombat pluton

Results of crystallisation experiments on the most mafic rock sampled from the Mount Wombat pluton – sample 889 (here renumbered SB1024) were published by Clemens and Wall (1981). Clemens and Wall presented three isobaric temperature-$X^{Fl}H_2O$ diagrams (for 100, 200 and 500 MPa, i.e. 1, 2 and 5 kb) and derived a *P-T* phase diagram for this magma at a constant 4 wt% H_2O in the melt. Using these plots and the petrographic evidence for the order of crystallisation of the magmatic minerals, Clemens and Wall concluded that the magma originated at a pressure of at least 400 MPa (i.e. deeper than 10 km), at a temperature near 850 °C, and that the magma initially contained 3 to 4 wt% H_2O. The chemistry of the S-type rocks in the Strathbogie batholith, their experimentally demonstrated lack of equilibrium with an Al_2SiO_5 polymorph, the character of the near-liquidus mineral assemblage (Grt-Opx-Pl-Qz) and the markedly H_2O-undersaturated nature of the melts were used to infer that the Strathbogie granitic magmas were formed by granulite-facies, fluid-absent, partial melting reactions that involved biotite breakdown in mildly aluminous metasedimentary protoliths (e.g. metagreywackes).

Clemens and Birch (2012) pointed out that the isopleths for melt H_2O content published by Clemens and Wall (1981) are significantly in error, due to the use of a model (Burnham 1979a, b) that overestimated the melt H_2O contents. Thus, the primary T-XH_2O plots have been redrafted using the Holtz et al. (2001) model for the relationship between $X^{Fl}H_2O$ and melt H_2O content (Electronic Appendix 4, Figs EA4.1, 4.2 and 4.3). Using the method detailed by Clemens and Birch (2012), it is possible to calculate P-T pseudosections for constant H_2O contents in the system (Fig. 12). These can then be used to revise the estimates of both early and late crystallisation conditions. From the data of Clemens and Wall (1981), it appears that the near-liquidus mineral assemblage in the rocks of the Mount Wombat pluton is similar to that in the adjacent and related Violet Town Volcanics – quartz-plagioclase-orthopyroxene-garnet. This could only be satisfied in sample SB1024 if the near-liquidus melt H_2O content were less than 4 wt% since (see Fig. 12), at this H_2O content, quartz is not a near-liquidus mineral (Fig. 12c). Furthermore, since plagioclase is a near-solidus mineral at 3 wt% H_2O, the initial melt H_2O content must have been nearer 2 wt%, quite low for a granitic magma, and in agreement with the inferred high-T character of the Strathbogie magmas (e.g. Clemens and Wall, 1981). From the pseudosection for 2 wt% H_2O (Fig. 12b), it is apparent that the near-liquidus mineral assemblage requires early crystallisation of the magma at some pressure between about 350 and 600 MPa. At lower pressures, garnet is not a near-liquidus mineral and is replaced by cordierite and orthopyroxene and, at higher pressures, orthopyroxene is not stable. If early crystallisation began at some pressure between 400 and 500 MPa, in the orthopyroxene field, the magma temperature would have been between about 850 and 900 °C, with initial magma temperature possibly even higher, depending on how much crystalline, peritectic material was entrained from the protolith.

On an adiabatic magma ascent path (with cooling of only a few degrees per 100 MPa of decompression), early-formed (or residual, peritectic) garnet would become unstable at about 350 MPa, possibly becoming resorbed into the melt with its ferromagnesian components reprecipitated as orthopyroxene. At about 250 MPa any surviving garnet would begin to react with the magma to produce orthopyroxene and cordierite. Cooling and crystallisation at near-emplacement levels, at pressures ≤ 100 MPa would cause orthopyroxene to be replaced by biotite and the re-appearance of garnet, relatively close to the solidus, with the last major mineral to appear being K-feldspar. As pointed out by Clemens and Wall (1981), there would still have been around 40% liquid left at this stage, allowing growth of the alkali feldspar phenocrysts and flow of the magma. All these predictions are fully consistent with the petrographic and field observations of Phillips et al. (1981) and Phillips and Clemens (2013). The predicted mineral assemblage at the solidus would be – Qz-Pl-Kfs-Bt-Crd-Grt, as observed in the rocks. The early-formed garnet crystals in rock SB1024 (889) are armoured by overgrowths of cordierite and biotite; some garnet has survived as large corroded remnants. The near-solidus garnet is found as tiny anhedral grains of spessartine-enriched almandine in the groundmasses of some porphyritic micrograpites – noted by Phillips and Clemens (2013) but not systematically recorded.

In summary, we can revise the Clemens and Wall (1981) estimate of initial melt H_2O content down to something less than 3 wt%, with initial crystallisation at a pressure between

350 and 600 MPa. The crustal depth to the top of the Selwyn Block (the likely magma source) at the time of magma genesis could not have been much greater than the present depth of around 15 km (Gibson et al. 1981, Cayley et al. 2002b) because the subaerially erupted Late Devonian volcanic successions remain largely intact. This implies a minimum pressure of 400 MPa. Initial magma temperature would have been > 850 °C and possibly > 900 °C. The Clemens and Wall (1981) conclusion that the magmas were formed under granulite-facies metamorphic conditions remains valid, although the temperatures are likely to have been considerably higher than originally proposed. This confirms the high crustal geothermal gradient necessary – a minimum of around 28 °C/km and possibly even > 50 °C/km. In a crust with only 35 km thickness, this necessitates an extracrustal heat source, as also previously envisioned.

Chemical evolution of the main granitic magmas

Most current models that seek to explain chemical diversity among groups of granitic rocks rely either on the concept of differentiation from a parent magma (e.g. by crystal fractionation or restite unmixing), assimilation of country rocks, or mixing between mafic and felsic end-members. A further model (peritectic assemblage entrainment or PAE) has been proposed more recently (Stevens et al. 2007; Clemens and Stevens 2012). The PAE process is fundamentally different to the restite-unmixing model of Chappell et al. (1987) in that PAE is not a differentiation mechanism. PAE operates at the magma source, and the model postulates that, although various mechanisms can be responsible for some of the observed chemical variations, these are generally subordinate to primary, source-derived variations that are preserved throughout magma segregation, ascent, emplacement and crystallisation. These source-derived variations are ascribed to entrainment of differing proportions (up to about 20% of the magma volume) of small crystals (typically of mafic minerals and plagioclase) that are solid products of the partial melting reactions that formed the magmas. The magmas so formed are not related to each other by separation of crystals from liquid, and Clemens et al. (2010) present evidence that granitic magmas rarely differentiate (by crystal-liquid separation) on any large scale, at their emplacement levels. As pointed out by Pitcher (1997), the idea that granitic magmas 'image' their protoliths has spurred granite research since the 1960s and Chappell et al. (1987) championed this concept with reference to the restite-unmixing hypothesis. As noted by Wall et al. (1987), all magmas must image their sources in some way, though the source of the signal may not always be readily apparent or simple to read (Clemens et al. 2010).

From the scattered chemical trends, lack of mixing trends and isotopic heterogeneity, we can discount evolution of the magmas of the Strathbogie batholith by fractionation of magmatic crystals from a common parent magma, unmixing of restite, or magma mixing. There is no sign of assimilation of emplacement-level wall rocks (which form some subangular hornfels xenoliths) and, as mentioned earlier, the chemistry of the magmas also suggests that their generation, ascent and emplacement was probably too rapid to permit significant chemical interaction with wall rocks at depth. Furthermore, the presence of ME has evidently had negligible effects on the chemistry of their host magmas. There are no magma-mixing trends here, either in the elemental or isotopic variation diagrams. Rather, the scatter in the variation diagrams suggests that the batholith and its component plutons were formed by numerous additions (pulses) of magmas with slightly differing source-related characteristics, but all derived from a metasediment-dominated protolith. These magma additions, the compositions of which were governed mainly by the amounts of entrained peritectic material in them, agglomerated to form the batholith, and only a small amount of crystal fractionation then modified their compositions. This is not to deny the existence of highly differentiated rocks, such as the layered aplitic to pegmatitic bodies with high boron concentrations that typify the roof zones in the batholith. Such features suggest that these zones were formed by the upward flux of volatile-rich residual melts, extracted from the underlying Mount Wombat magmas. However, the Mount Wombat pluton contains widespread small amounts of tourmaline (around 0.5%), indicating a generally high B content. Approximate mass-balance calculations suggest that the B in the highly differentiated rocks was probably scavenged from only a few hundreds of metres of the underlying source magmas, as they crystallised.

Plots of Ba versus Pb concentrations in S-type granitic rocks have been used to distinguish between those magmas produced by relatively low-temperature partial melting involving muscovite breakdown and those formed by higher-temperature reactions involving biotite breakdown (Finger and Schiller 2012). These authors also used this diagram to distinguish between data distributions caused through differentiation by crystal fractionation (trends parallel to the dividing line) or due to some other process (scatter orthogonal to this line). A Pb-Ba plot for the Strathbogie plutonic rocks (Fig. 13) shows that, as expected, all but two of the Strathbogie rocks plot in the high-temperature field. There is evidently some variation that could be interpreted as crystal fractionation but much of the variation defines a scatter of points roughly orthogonal to the dividing line (toward much higher Ba concentrations). In a given group of genetically related granitic rocks, higher Ba concentrations can be linked with increasing melting proportion in the protolith and consequent increased proportions of entrained peritectic crystals (Clemens 2014). Following the logic presented by Clemens (2014) we interpret the high Ba to indicate that the Strathbogie magmas were the products of relatively high degrees of partial melting of their protolith and that this would imply efficient entrainment of peritectic crystals into the rising magmas. Thus we suggest that the magmas of the batholith gained the bulk of their compositional variability through PAE but that a degree of differentiation by crystal fractionation also occurred, principally to create the very felsic, layered rocks with high tourmaline concentrations, found on plateau tops in the northwest of the batholith and inferred to represent near-roof zones (see e.g. Fig. 4F of Phillips and Clemens 2013).

Discussion, conclusions and implications

The Late Devonian, mainly S-type Strathbogie batholith is comprised of several plutons, delineated through the work of Phillips and Clemens (2013). There is much similarity in the chemistry across S-type portions of the batholith but the Dabyminga and especially the Kerrisdale plutons are characterised by higher Ba, Sr, LREE contents and lower εNd_T than the rest of the batholith. The two tiny I-type plutons of Tallangallook hornblende microgranite are also distinctive in their low TiO_2, FeO^T, MgO, P_2O_5, ASI and initial $^{87}Sr/^{86}Sr$, and high Na_2O, Nb, Zr, Th, LREE and εNd_T. The chemistry of these I-types suggests that they are the products of differentiation of a more mafic parent magma that contained a significant, juvenile, mantle-derived component. This contrasts with most of the voluminous I-type rocks in the region, which contain dominant crustal components. The Sr and Nd isotope characteristics of the mafic rocks in the WPDS (Soesoo 2000) overlap with the values reported here for the Tallangallook hornblende microgranite. Thus, although we have no felsic Woods Point rocks to compare directly with the Tallangallook hornblende microgranite, we cannot rule out the possibility that these small intrusions represent the products of fractionation of a mafic magma similar to the main components of the WPDS.

The rhyolitic ignimbrites of the Violet Town Volcanics, intruded and metamorphosed by the Mount Wombat pluton, are only slightly older than the batholith, though the exact age difference is unconstrained, and may be very small. The two sets of magmas are clearly related in space, time and general chemistry. The differences (higher magma temperatures, lower SiO_2, K_2O and ASI, higher FM contents, less radiogenic Sr and differing trend in the

Ba-SiO_2 plot for the VTV) suggest that the protolith for the Volcanics contained a higher ratio of metagreywacke to metapelite than the protolith for the batholith, and that the melting temperature was higher when/where the volcanic magmas were produced. Thus we speculate that the older volcanic magmas were derived from deeper in the Selwyn Block and that the melting front progressed upward through a sequence of rocks in which metapelites became more abundant toward higher structural levels. If we assume that this may represent a single original sedimentary package, such a transition might signify a deepening of the basin, perhaps through widening by extension. Such a setting would take both the Proterozoic arc and the adjacent continent further from the site of deposition, with progressive lessening of the medium to coarse sediment fraction. Given the abundance I-type granitic rocks in the Melbourne Zone, this suggests a source terrane with dacitic to andesitic components, as well as metagreywacke and minor metapelite (e.g. Clemens et al. 2011b). This inferred package of rock types suggests that this part of the Selwyn block had a strong volcanic arc connection, possibly as a continental back-arc basin.

The high-T, markedly H_2O-undersaturated S-type magmas that formed the bulk of the batholith were derived through fluid-absent partial melting of a metagreywacke-dominated metasedimentary package, most probably located in the Proterozoic Selwyn Block, which forms the basement in this part of southeastern Australia. The depth of melting was between 15 and 23 km, at temperatures of at least 850 and probably 900 °C or more. This thermal event signals granulite-facies metamorphism in the Late Devonian middle crust, perhaps at depths as shallow as 15 km. Given the high implied geothermal gradient, this necessitates the introduction of heat from the mantle, most likely in the form of sheets of intraplated mafic magmas (e.g. Petford and Gallagher 2001). In Central Victoria at this time, the development of terrestrial, red-bed basins floored by bimodal volcanic sequences (see e.g. Cas et al. 2003) suggests a post-orogenic extensional tectonic setting for these mantle and crustal melting events, as for example in the Basin and Range Province of the Southwestern United States.

One consequence of the high T of this partial melting event is that biotite was completely or almost completely eliminated from the protolith by the melting reactions. Since biotite is the main reservoir of Ba in the probable protolith rocks, the near-complete liberation of this element into the melt phase may partially explain why felsic magmatic rocks with elevated Ba contents typify Central Victoria. It has been suggested that this characteristic reflects Ba-rich protoliths (e.g. Rossiter and Gray 2008). However, because this feature is present in both the S- and I-type rocks, which will have different types of protoliths, we favour the main influence being the particularly high T of the deep crust in Central Victoria, at this time.

The chemical variations within the batholith appear to be dominated by features inherited from the protolith, carried in the form of primary variations in melt composition and the contents of entrained accessory and peritectic mineral grains. Differentiation of the Mount Wombat pluton is evident in the occurrence of aplitic to pegmatitic, layered, leucocratic rocks in thin zones that are inferred to have been near the pluton roof. However, we infer that the process involved fractionation of only the upper few hundreds of metres of the magma, controlled by the upward flux of interstitial, volatile-enriched residual silicate liquids. We speculate that this set of processes may have been driven by filter pressing of the crystal-liquid mush beneath subsiding, detached roof blocks.

In many respects the ME in the Mount Wombat pluton appear to be similar to those recently studied in the I-type Lysterfield Granodiorite (Clemens and Bezuidenhout 2014), which lies 200 km to the south. As in the Lysterfield Granodiorite, the Strathbogie ME do not form mixing trends with their host rocks. They appear to have formed through rapid crystallisation (chilling) of more mafic magmas that have slightly less evolved εNd_T values than their host rocks. The fact that the Strathbogie ME are highly peraluminous suggests that, despite being fine-grained, they may not represent the compositions of their original magmas. Instead of representing simply the chilled enclave magmas, the mineralogy and chemistry of these enclaves probably reflect the occurrence of a cumulate process. Accumulation of aluminous magmatic biotite (with its accessory inclusions), with minor garnet and/or cordierite would explain the high ASI values (1.16 to 1.46) of the ME, as well as the elevated TiO_2, Nb, Zr and P_2O_5, lower K_2O and high initial $^{87}Sr/^{86}Sr$ (similar to the granitic host rocks). As with the ME in the Lysterfield Granodiorite, the Strathbogie ME most probably originated as magmas derived from the enriched subcontinental mantle, heavily hybridised by near-source interaction with crustal melts. These hybrid magmas accompanied, and perhaps preceded, the more voluminous granitic magmas that inflated the batholith. The physical model presented by Clemens and Bezuidenhout (2014) suggests that the enclave magmas were chilled against the cool, emplacement-level rocks, as a pre-batholithic sheet-like intrusion. The influx of the vastly more voluminous granitic magmas then disrupted the initial sheet, incorporating pieces of it into the main magmas, to become the enclaves that we observe. The probable cumulate-like character of at least some of these magma globules could have arisen through the expulsion of interstitial felsic liquid at the magma emplacement level. This is the quench-cumulate model of Phillips et al. (1981) Clemens and Wall (1984) and Donaire et al. (2005). The presence of what appear to be large host-derived crystals in some ME, as well as microscopic flow fabrics suggest that the still plastic globules of enclave magma were rolled and kneaded, like dough, during flow of the host magmas.

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Figure Captions

Fig. 1 Simplified geological map of the Strathbogie batholith showing its component plutons (Phillips and Clemens 2013) and the locations of some prominent towns. The inset shows the location of the batholith within the continent of Australia. Note that the Palaeozoic rocks intruded by the batholith include Cambrian to Middle Devonian, low-grade metasedimentary rocks of the Melbourne Zone as well as the silicic ignimbrites of the Violet Town Volcanics. These pre-batholith rocks are not differentiated on this map, and are all coloured white. More detailed maps of the context of the Strathbogie batholith are presented in Phillips and Clemens (2013)

Fig. 2 Radiometric images of the Strathbogie batholith derived from airborne gamma-ray spectroscopy. The outline of the Strathbogie batholith is in blue, the pluton outlines are in thin black lines and also on Fig. 1 – **a** Map of thorium distribution showing three areas of the batholith with lower Th, i.e. the far SW, NW near Avenel, and east, **b** Map of uranium distribution showing two parts of the batholith with lower U, i.e. the far SW and the NW near Avenel, but with particularly high U in the east

Fig. 3 Harker variation diagrams illustrating chemical features of the rocks of the Strathbogie batholith – **a** TiO_2, **b** FM (FeO^T+MnO+MgO), **c** Na_2O, **d** K_2O, **e** P_2O_5, **f** ASI (mol. Al_2O_3/[CaO+Na_2O+K_2O]). Colour coding for data points in this and subsequent chemical figures: Mount Wombat pluton – green dots, Lima pluton – yellow dots with black rims (sample SB1818 indicated by a thick black rim), Lightning Ridge pluton – purple dots, Tallangallook hornblende microgranite plutons – blue dots, Dabyminga pluton – red dots, Kerrisdale pluton – orange dots with black rims, small black dots – igneous-textured microgranular enclaves in the Mount Wombat pluton, black triangles – Violet Town Volcanics

Fig. 4 Diagrams illustrating variations among some trace elements in the rocks of the Strathbogie batholith. **a** Sr, **b** Th, **c** Ce, **d** U v. Ce, **e** U v. Zr, **f** Th v. Ce. Colour coding as in Fig. 3

Fig. 5 Variations in **a** Ba, **b** Cr, **c** U with SiO_2 content for the rocks of the Strathbogie batholith. Colour coding as in Fig. 3.

Fig. 6 Initial Sr isotope ratios for the Strathbogie samples, plotted against **a** SiO_2 and **b** ASI, and plots for **c** Sr isotope mixing and **d** Sr-Nd isotope correlation, with values for bulk Earth plotted as thick lines. Colour coding as in Fig. 3, with the addition, in **c**, of a black cross for the high-grade metasedimentary xenolith sample SB1806. Calculated 2σ error bars are shown for the isotope parameters but note that some errors are smaller than the sizes of the symbols

Fig. 7 Plot of initial Sr isotope ratio against ASI for rocks of the Mount Wombat pluton, showing a positive correlation with a correlation coefficient (R^2) of 0.614. Calculated 2σ error bars are shown for the initial Sr isotope ratios. This plot suggests that the Mount Wombat magmas had metasedimentary source rocks that varied in their original clay and Rb contents

Fig. 8 Variation diagrams showing the relationships between the compositions of the rocks of the Mount Wombat pluton (green dots) and their igneous microgranular enclaves (smaller black dots). Points for medium-K calcalkaline basaltic rocks (data from www.earthchem.org) are shown as reddish-brown squares

Fig. 9 Chondrite-normalised rare-earth-element spectra for **a** the rocks of the Mount Wombat pluton and **b** the igneous microgranular enclaves. Note that there are two distinct groups of Mount Wombat rocks, those with normal and those with low ΣREE and deep Eu anomalies. See text for further discussion

Fig. 10 Plots of **a** ASI (mol. $Al_2O_3/(CaO+Na_2O+K_2O)$) and **b** TiO_2 against FM ($FeO^T+MnO+MgO$) for the rocks of Mount Wombat pluton (with linear trend illustrated) and its igneous microgranular enclaves, with colour coding as in Fig. 3, but with the addition of reddish-brown squares representing points for medium-K calcalkaline basalts (data from www.earthchem.org) and points for the mafic to intermediate rocks of the Mt Buller–Mt Stirling complex are shown as mauve squares. See text for further discussion

Fig. 11 Plots illustrating chemical differences between the rocks of the Violet Town Volcanics (VTV) and those of the S-type rocks of the Strathbogie batholith. **a** ASI, **b** Sr, **c** Ba. Colour coding as in Fig. 3, with the addition of black triangles for the VTV

Fig. 12 Calculated, experimentally based, *P-T* pseudosections for Strathbogie granite SB1024 with **a** 2 wt%, **b** 3 wt% and **c** 4 wt% H_2O in the system, with mineral saturation boundaries colour coded (Qz – yellow, Kfs – blue, Pl – green, Bt – dark brown, Crd – purple, orthopyroxene – orange-brown, garnet – red). Orthopyroxene and cordierite are stable at conditions between the two curves for these minerals. In all other cases, the mineral is stable on the low-*T* side of its saturation boundary. Note that 1 kb = 100 MPa. See text for further explanation and discussion

Fig. 13 Pb-Ba plot, after Finger and Schiller (2012), showing the dividing line between low-*T* S-type granitic magmas formed by muscovite breakdown reactions and high-*T* S-type magmas formed by biotite breakdown. Note that variation parallel to the line is interpreted as reflecting crystal fractionation and that perpendicular to the line as some other, unspecified process. See the text for further discussion

Table 1 Petrography of rock inclusions hosted by the granitic rocks of the Mount Wombat pluton

Inclusion type	Variety	Texture	Major minerals	Notes
igneous microgranular enclaves with igneous textures	micropoikilitic, biotite-rich	small euhedral Bt and Pl enclosed by larger anhedral Qz or Qz+Kfs	Qz+Bt+Pl±Kfs Bt+Qz pseudomorphs after Opx	most abundant igneous type Bt is red-brown in colour rarely have Bt-enriched selvages
	microgranitic	fine-grained but subidiomorphic-granular texture	Qz+Pl+Bt rare Crd and/or Grt	next most abundant igneous type Bt is red-brown in colour rarely porphyritic in Pl
	micropoikilitic, amphibole-rich	small Oamp, CAmp prisms and Bt shreds enclosed by larger anhedral to interstitial Qz	Qz+Oamp+Camp+Bt	rarest and most mafic type of igneous enclave Bt is red-brown Rarely porphyritic in Pl

country-rock hornfels xenoliths	metasedimentary rocks ranging from metapelitic to metapsammitic	very fine-grained hornfelsic (polygonal grains)	variable but the dominant pelitic type have Qz+Kfs+Bt+Crd	reasonably common but subordinate to the igneous enclaves similar to the highest-grade hornfelses in the contact aureole
high-grade regional metamorphic xenoliths	metapelitic migmatitic gneisses	foliated gneissose with quartzofeldspathic layers with igneous textures	Qz+Pl+Kfs+Bt+Crd+Sil trace zincian Hc Crd+Hc probably pseudomorph Grt	similar abundance to the hornfels types upper amphibolite- to granulite-facies xenoliths of Melbourne-Zone metasedimentary rocks
	metapelitic schists	foliated schistose	Qz+Pl+Bt±Ms±Crd	rarest type upper greenschist- to lower amphibolite-facies xenoliths of Melbourne-Zone metasedimentary rocks

Table 2 Whole-rock Rb-Sr isotope data for Strathbogie batholith samples

Sample No.	Pluton	Rb (ppm)	$2\sigma_m$	Sr (ppm)	$2\sigma_m$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ	$^{87}Sr/^{86}Sr$ at 366±3 Ma	2σ
SB1003	MW	225	0.2	98	1.6	6.67	0.74751	18	0.71334	35
SB1005	MW	258	0.2	44	1.6	17.12	0.80138	14	0.71365	122
SB1006	MW	223	0.2	80	1.6	8.10	0.75256	4	0.71106	39
SB1010	MW	168	0.2	148	1.6	3.29	0.72612	24	0.70926	27
SB1020	MW	234	0.2	93	1.6	7.31	0.74874	12	0.71129	36
SB1024	MW	209	0.2	115	1.6	5.27	0.73777	10	0.71074	25
SB1025	MW	184	1.9	93	1.0	5.74	0.737809	11	0.70838	27
SB1601*	MW	225	0.2	96	1.6	6.81	0.74682	5	0.71193	33
SB1801	MW	200	2.1	109	0.7	5.33	0.741018	17	0.71373	24
SB1802	MW	215	3.1	97	0.2	6.44	0.745201	19	0.71222	29
SB1803	MW	198	0.6	124	0.2	4.63	0.732182	16	0.70846	19
SB1901†	MW	248		98					0.71154	
SB1701‡	L	238	0.2	60	1.6	11.55	0.7715	5	0.71233	88

SB1017	L	317	0.2	56	1.6	16.52	0.79573	22	0.71106	98
SB1830	K	161	1.4	183	1.9	2.55	0.723037	15	0.70997	12
SB1831	K	155	1.2	177	1.8	2.54	0.722924	16	0.70991	11
SB1832	K	146	1.8	163	1.4	2.60	0.724498	18	0.71119	13
SB1602*	K	163	0.2	178	1.6	2.65	0.72338	1	0.70986	12
SB1833	D	184	1.5	123	0.5	4.34	0.731312	14	0.70908	19
SB1816	T	179	0.7	154	1.0	3.37	0.723585	12	0.70632	14
SB1808	ME	140	2.1	144	1.9	2.82	0.725914	16	0.71147	15
SB1809	ME	362	3.6	96	0.7	10.97	0.765894	25	0.70964	49
SB1814	ME	167	1.6	131	1.3	3.70	0.730680	13	0.71172	18
SB1822	ME	238	1.6	87	1.2	7.95	0.751616	15	0.71087	38
SB1827	ME	274	1.9	68	0.7	11.73	0.771649	10	0.71153	52
SB1829	ME	226	3.2	141	1.0	4.65	0.735317	15	0.71149	22
SB1806	X	257	3.4	84	0.8	8.90	0.765544	13	0.71990	41

pluton abbreviations: MW = Mount Wombat, D = Dabyminga, K = Kerrisdale, L = Lima, LR = Lightning Ridge, T = Tallangallook hornblende microgranite (I-type), ME = igneous microgranular enclave from the MW pluton, X = high-grade metasedimentary xenolith
* sample from Gray (1990), † sample from Richards and Singleton (1981), ‡ sample from Kemp et al. (2008). For samples with $2\sigma_m$ values of 0.2 and 1.6 for Rb and Sr respectively, these are assumed values.

Table 3 Whole-rock Sm-Nd isotope data for Strathbogie batholith samples

Sample No.	Pluton	Sm (ppm)	$2\sigma_m$	Nd (ppm)	$2\sigma_m$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2σ	εNd_{366}	2σ*	T_{DM2} Ga†
SB1025	MW	7.94	0.01	37.9	0.3	0.126706	0.512234	11	-4.6	0.2	1.83
SB1801	MW	9.16	0.21	44.3	0.5	0.124952	0.512164	8	-5.9	0.2	1.86
SB1802	MW	6.25	0.04	28.2	0.8	0.133975	0.512193	10	-5.8	0.2	1.70
SB1803	MW	4.18	0.19	20.1	0.2	0.125587	0.512299	14	-3.3	0.2	1.84
SB1825	MW	1.75	0.03	4.98	0.2	0.212197	0.512396	9	-5.5	0.2	0.39
SB1818	L	6.21	0.13	26.8	0.6	0.139878	0.512449	10	-1.0	0.2	1.60
SB1821	L	2.84	0.06	9.47	0.1	0.181496	0.512352	9	-4.9	0.2	0.91
SB1817	LR	1.26	0.02	3.28	0.1	0.231526	0.512572	8	-2.9	0.2	0.06
SB1839	LR	1.12	0.02	2.72	1.1	0.247769	0.512552	30	-4.1	0.2	-
SB1830	K	7.66	0.10	38.3	0.3	0.120803	0.512143	10	-6.1	0.2	1.93
SB1831	K	7.20	0.11	36.2	0.7	0.120213	0.512139	11	-6.2	0.2	1.94
SB1832	K	8.14	0.17	41.1	0.4	0.119763	0.512115	11	-6.6	0.2	1.94
SB1833	D	5.84	0.03	28.0	0.9	0.125994	0.512199	11	-5.3	0.2	1.84
SB1816	T	6.85	0.13	38.5	0.4	0.107663	0.512453	9	+0.6	0.2	2.15
SB1808	ME	9.58	0.14	39.7	0.4	0.145764	0.512368	11	-2.9	0.2	1.51
SB1809	ME	6.76	0.07	28.8	1.0	0.142175	0.512332	8	-3.4	0.2	1.57
SB1814	ME	7.84	0.13	32.6	0.7	0.145566	0.512321	11	-3.8	0.2	1.51

SB1822	ME	12.00	0.14	56.4	0.5	0.128167	0.512273	9	-3.9	0.2	1.80
SB1827	ME	9.98	0.10	46.3	0.5	0.130187	0.512203	9	-5.4	0.2	1.77
SB1829	ME	9.48	0.18	44.0	0.4	0.130260	0.512227	9	-4.9	0.2	1.77
SB1806	X	7.77	0.13	42.3	0.2	0.111005	0.511810	11	-12.2	0.2	2.09

pluton abbreviations: MW = Mount Wombat, D = Dabyminga, K = Kerrisdale, L = Lima, LR = Lightning Ridge, T = Tallangallook hornblende microgranite (I-type), ME = igneous microgranular enclave from the MW pluton, X = high-grade metasedimentary xenolith

* assumed typical value

† two-stage depleted mantle model age