Magmatic systems of the Paleoproterozoic St Peter Suite, western Gawler Craton: insights from reconnaissance mapping

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Introduction

The St Peter Suite in the southwestern Gawler Craton has been identified as an unusual set of magmatic rocks, with a distinct geochemistry to other Proterozoic magmatic suites of the region (Swain et al. 2008; Wade 2012). Isotopically, the St Peter Suite is relatively juvenile and represents an addition of mantle material into the crust of the Gawler Craton. The relative enrichments in large ion lithophile elements (e.g. Rb, K, Sr) and depletions in Ta, Nb and Ti have led some authors to propose that the St Peter Suite may have formed in response to subduction zone processes in a late Paleoproterozoic magmatic arc (Ferris, Schwartz and Heithersay 2002; Swain et al. 2008). In this case, this has implications for models of assembly and evolution of Proterozoic Australia and for the mineral potential of the Gawler Craton.

Previous geochronology suggests the St Peter Suite formed over the interval 1647–1604 Ma (Swain et al. 2008; Symington et al. 2014), which means this magmatic event predates the major magmatic and mineralising event of the Gawler Craton; that of the Gawler Range Volcanics, Hiltaba Suite and iron oxide – copper–gold systems of the eastern Gawler Craton (Reid et al. 2013; Skirrow et al. 2007). By understanding the causes and setting of the St Peter Suite there is potential to better understand the context for the early Mesoproterozoic events of the Gawler Craton. Indeed, the possibility exists that the geodynamic drivers behind the formation of the St Peter Suite may have in some way primed the crust of the Gawler Craton for the subsequent magmatic and mineralisation event.

If the St Peter Suite did form in a subduction-related magmatic arc, then these rocks themselves may have considerable mineral potential. Magmatic arcs are the site of extensive mineralisation in the Phanerozoic earth; copper–gold porphyry systems in the Andes, British Columbia and New Guinea for example, and Lachlan Fold Belt deposits such as gold at Cadia within the Macquarie Arc. Numerous studies (e.g. Audétat and Pettke 2006; Halter, Heinrich and Pettke 2005; Seedorff et al. 2005; Steinberger et al. 2013) have found that the interaction of felsic and mafic magmas is an important process in the magmatic and metallogenic evolution of these systems. Firstly, the mafic magma, which represents a mantle contribution, can provide sulfur and metals (Hattori and Keith 2001; Maughan et al. 2002). Secondly, the injection of the hotter mafic magma into a relatively cool, crystal-rich felsic magma chamber can promote evacuation of the magma chamber and eruption, and also increase fluid flow (Murphy et al. 2000; Pallister, Hoblitt and Reyes 1992). Consequently, understanding the magmatic evolution and depth of exhumation of the St Peter Suite will provide new insights into mineral exploration models for the western Gawler Craton.

The purpose of this article is to present some preliminary observations from recent field investigations of the coastal exposures of the St Peter Suite, between Slade Point (south of Streaky Bay) to west of Point James (west of Ceduna; Fig. 1). As these coastal outcrops are the largest onshore surface exposures of the St Peter Suite they provide a window into what rock types and geological processes might be expected to be found in the inland regions beneath sedimentary cover. The field observations and interpretations indicate that the interaction of mafic and felsic magmas was common throughout the St Peter Suite. Magma mingling is when two or more magmas interact,

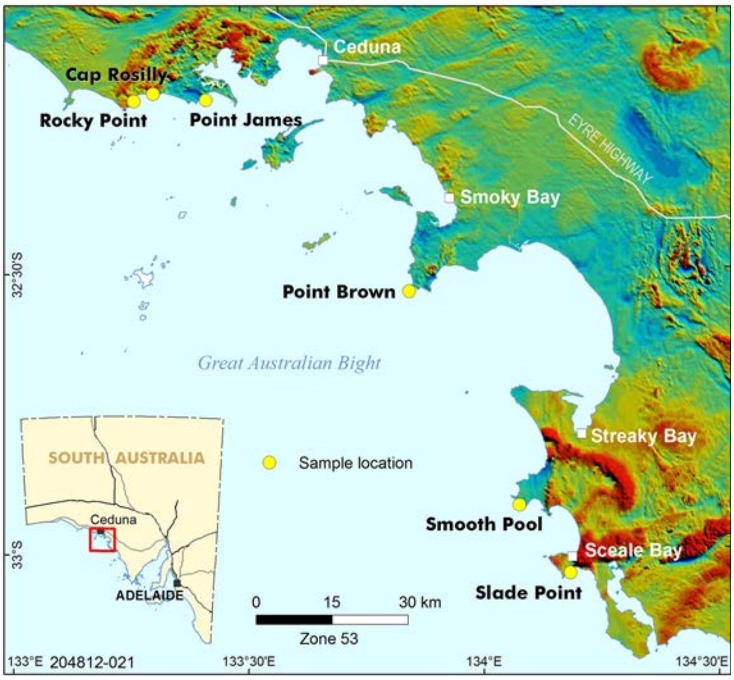

Figure 1 Location map showing the three areas of outcrop described in this article, shown on state total magnetic intensity image.

yet both magmas retain some characteristic of the original composition. This process results in a series of characteristic features, such as synplutonic dykes and mafic enclaves. Magma mixing is when two or more magmas more completely interact to form a hybrid composition that is intermediate between the end-members. It has also been demonstrated at Rocky Point (to the west of the study area) that the injection of later magma batches can lead to the remobilisation of interstitial liquid, and partial melting of the earlier phases resulting in more differentiated felsic magmas and greater compositional diversity in the St Peter Suite (Symington et al. 2014). Although these rock associations have previously been recognised (e.g. Berry and Flint 1988; Chalmers 2009; Flint 1987; Flint, Rankin and Fanning 1990; Rankin and Flint 1991), the reinvestigation of these outcrops has allowed us to selectively sample the main lithological units for geochronology, and to determine their geochemical and isotopic characteristics. The geochronology has been completed and the report is forthcoming (Reid et al. in prep.). The results of this mapping, and the geochemical and isotopic studies that are underway, should help us further understand the petrological evolution and metallogenic potential of the St Peter Suite, and the Gawler Craton as a whole.

Field observations

The outcrops visited are considered to represent three different styles of magmatic system:

1. a magma transfer zone where various felsic and mafic magmas interacted
2. a felsic magma chamber with minor comagmatic mafic magmas
3. a mafic magma chamber.

1. Magma transfer zone

The coastal platform at Smooth Pool, Point Westall (Fig. 1), is composed of various granitic rocks that have a broad north-striking layering defined by complex compositional and textural variation.

One felsic phase is a medium-grained, pale blue to grey monzogranite, with small wispy biotite lenses (<1 mm wide and 1 cm long) and locally developed schlieric layering that define a north-striking magmatic-state flow foliation and a parallel, variable, moderately developed solid-state foliation defined by quartz ribbons. The monzogranite is intruded by medium- to coarse-grained, pale pink to cream granite, which also contains small wispy biotite lenses (<1 mm wide and 1 cm long) that define a foliation aligned parallel to the foliations in the monzogranite. The granite forms sheets that are subparallel to the foliation in the monzogranite. However, the granite sheets are irregular and locally cut the foliation in the monzogranite at a low angle, with some granite sheets also bifurcating (Fig. 2a). The monzogranite often has a concentration of biotite along the contacts. The concordancy of the north-striking layering, magmatic flow foliation and the solid-state foliation suggests that the strain started while the granitic rocks were still magmatic and continued until after they had crystallised. The relationships also suggest that the granite intruded after development of the foliation in the monzogranite, but under the same stress field, hence the alignment of the sheets and development of the foliation in both phases.

The interlayered granite and monzogranite both contain abundant melanocratic, fine- to medium-grained mafic enclaves. The finer grained enclaves are darker and equigranular, whereas the medium-grained ones are more speckled and inequigranular. In several places the enclaves are particularly concentrated within 5 m wide, north-striking layers that dip steeply to the west. These enclaves range in size up to 1 m long, are very elongate with aspect ratios of >20:1, and are aligned parallel to the layering (i.e. parallel to the magmatic foliation; Fig. 2b). There are also abundant parallel mafic schlieren, which are likely more attenuated enclaves. The enclave-rich layers are interpreted to represent conduits where contemporaneous mafic and felsic magmas flowed and mingled (c.f. Collins et al. 2000).

2 (a) *View to the north of subparallel blue-grey monzogranite (under the hammer) and cream coloured granite sheets that are locally at a low angle to each other. (Photo 415010)*

2 (b) *Plan view of a granite layer rich in elongate, aligned mafic enclaves. (Photo 415011)*

2 (c) *Plan view of a melt-filled sinistral shear band offsetting a large enclave (dark layer). (Photo 415012)*

Figure 2 Field photographs of St Peter Suite from Smooth Pool. The hammer head points to the north in all photographs.

One of the layers rich in elongate, aligned enclaves is offset by a melt-filled shear band that has an apparently sinistral sense of shear. This shear also offsets one of the larger enclaves (Fig. 2c). This suggests that the layered granites and concordant enclave-rich zones were overprinted by sinistral shear bands before the rocks had completely crystallised. It is unclear whether the shear is part of a broader sinistral shear zone (i.e. simple shear), or if dextral kinematic indicators are also present, which would suggest that the area was undergoing pure shear during magma injection.

2. Felsic magma chamber

The outcrops at Point Brown (Fig. 1) are predominantly composed of relatively homogenous medium- to coarse-grained, equigranular to porphyritic granite to granodiorite. These rocks are generally massive, but locally contain a magmatic foliation defined by aligned feldspar phenocrysts and mafic schlieren. Evidence exists for magma interaction, including dispersed rounded, equant to elongate, medium-grained mafic enclaves and mafic schlieren.

Several comagmatic phases are recognised at the northern part of Point Brown. The main phase is a coarse-grained, creamy coloured, locally feldspar porphyritic granite that contains common, dispersed elongate mafic enclaves. The granite contains fine-grained basalt, which forms a series of roughly north-striking, thin, often discontinuous, sinuous sheets that often have lobate contacts with the host. Some of the sheets are composite, comprising relatively homogeneous basalts and grey, medium-grained, feldspar porphyritic granodiorite. In the composite sheets, the basalt forms elongate, rounded enclaves within the granodiorite, although the basalt also forms sheets that intrude the granodiorite. In one case (Fig. 3a) a composite sheet bifurcates, with the western branch dominated by the grey rock with discrete, elongate basaltic enclaves, whereas the eastern branch is dominated by basalt with a screen of granodiorite preserved along one wall. These observations indicate that these three phases have mutually crosscutting relations and are comagmatic. This also suggests that the granodiorite may represent local mixing and hybridisation of the basalt with the host granite, with the feldspar phenocrysts derived from the crystal-rich granite magma. The three magmas would then have mingled to form the composite dykes and enclaves.

The mafic sheets are often connected to larger, irregular bodies (Fig. 3b), indicating that the magma was locally ponding. The boundary between the basalt and the host granite is often characterised by a thin zone of grey, medium-grained granodiorite that has a sharper contact with the basalt and sharp

3 (a) View to the north of a sinuous composite synplutonic dyke intruding the granite. The composite dyke is composed of a grey, medium-grained, feldspar porphyritic granodiorite, which contains a dark-grey to black basalt that forms a continuous layer on the right side of the dyke and elongate, rounded enclaves within the granodiorite to the right. (Photo 415013)

3 (b) View to the south of a large, irregular body where the grey granodiorite and dark-grey to black basalt is ponding. (Photo 415014)

3 (c) Plan view of the contact between the basalt and the host granite, showing the thin zone of grey granodiorite that has a relatively sharp contact with the basalt, and a more gradational contact with the granite. (Photo 415015)

3 (d) View to the north of a network of mafic enclave-rich grey granodioritic sheets. Note that the enclaves are elongate, parallel and north-striking, regardless of the orientation of the host sheet. (Photo 415016)

Figure 3 Field photographs from Point Brown. The hammer head points to the north in all photographs.

to gradational contacts with the granite (Fig. 3c). The granodiorite also extends into the basalt body to form irregular, lobate, curviplanar vein networks that isolate round basalt enclaves (Fig. 3b).

The host granite has a north-striking foliation defined by biotite lenses and lamellae, and parallel, attenuated mafic enclaves, whereas the basalt contains a parallel foliation defined by drawn out and attenuated veins and feldspar alignment. At one location there is an irregular network of mafic enclave-rich sheets, where the enclaves are elongate, parallel and north-striking, regardless of the orientation of the sheet (Fig. 3d).

Overall, the outcrops at Point Brown are interpreted to represent a felsic magma chamber where the magmas have resided and crystallised to form thick cumulate piles. There is evidence for contemporaneous mafic magmatism, most notably the dispersed mafic enclaves and schlieren that represent mingling of the two end-members, and the mixing within the conduit. However, the continuity of the synplutonic mafic dykes suggests that the crystal mush was thick and relatively coherent with little convection or externally induced flow during the injection of the mafic magma. Furthermore, there is no evidence at these outcrops for the deposition of enclave swarms on the floor of a magma chamber, which would represent the lateral movement and dispersal of the synmagmatic mafic magmas along the boundary between the crystal-rich mush and the overlying crystal-poorer magma (e.g. Wiebe and Collins 1998). The presence of a uniform, north-striking magmatic-state foliation in the area suggests that the magmas were under pure shear conditions as they crystallised. It is unclear, however, whether this strain influenced the orientation of the comagmatic mafic sheets, or whether the orientation was solely the result of the magma ascent.

3. Mafic magma chamber

At Cap Rosilly (Fig. 1), a package of mafic, ultramafic and felsic rocks are exposed along a 500 m long coastal outcrop. The mafic rocks are the dominant rock type in this area, with only minor amounts of ultramafic and felsic rocks observed. In this respect, these rocks stand in marked contrast to the dominantly felsic rock systems observed elsewhere in the St Peter Suite, where the mafic rocks are a minor phase that are generally represented by discrete synplutonic mafic dykes or microgranular enclaves. The mafic rocks at Cap Rosilly are generally coarse grained and range from equigranular gabbros, to inequigranular quartz diorites that have common elongate amphiboles in a grey groundmass of feldspar and minor quartz.

Towards the eastern part of the outcrop, the mafic rocks contain coarse to very coarse pyroxene-rich cumulate layers that often have asymmetric modal mineral proportions (Fig. 4a), and locally developed cross-beds (Fig. 4b). In places, the cumulate layering has been eroded with the scours filled with more of the layered mafic–ultramafic rocks (Fig. 4b). The coarse-grained mafic–ultramafic rocks are locally cut at a moderate- to high-angle by fine- to medium-grained dykes that are up to 0.5 m wide

4 (a) Fine-scale cumulate layering in the gabbro. The rock is cut by a network of centimetre-scale felsic veins. (Photo 415017)

4 (b) Cross-beds in the cumulate rock have been eroded, with the scours filled with layered mafic-ultramafic rock. (Photo 415018)

4 (c) Composite mafic dyke cutting the cumulate layering at a moderate angle. (Photo 415019)

4 (d) Diorite enclaves within a more leucocratic groundmass of quartz diorite. (Photo 415020)

4 (e) Magmatic breccia with angular, sharp-edged blocks of massive diorite in a groundmass of massive, leucocratic tonalitic material. (Photo 415021)

4 (f) Strongly flattened fine- to medium-grained mafic enclaves in a pale brown foliated granite. (Photo 415022)

Figure 4 Field photographs from Cap Rosilly.

(Fig. 4c). These dykes have an internal layering, aligned subparallel to the boundaries, which likely represents composite features with multiple episodes of magma migration.

The western portion of the Cap Rosilly section is predominantly composed of relatively massive diorite to quartz diorite, with minor pyroxenite and felsic rocks. This area includes zones where common ovoidal aggregations of mesocratic, quartz-poor diorite form enclaves within a more leucocratic quartz diorite groundmass (Fig. 4d). This is suggestive of the mingling of a more mafic magma with a quartz-bearing, intermediate, possibly hybrid magma. Locally, the rocks contain 2–5 m wide zones where angular, sharp edged blocks of the massive diorite are hosted in a groundmass of massive, leucocratic tonalitic material (i.e. plagioclase–quartz–hornblende–biotite; Fig. 4e). The blocks are randomly oriented and there is jigsaw fit between some of the pieces. This texture suggests that some of the mafic magma was semi-solid and able to fracture when the felsic magma was injected, forming a magmatic breccia. Brecciation may be the result of either seismic deformation of a mafic magma chamber with late-stage magmatic fluids moving into the low-pressure zone (i.e. external stresses), or it may be the result of increased magma pressure within the crystallising mafic body (i.e. internal stresses). The diorite also preserves patches of very coarse grained quartz–plagioclase (± K-feldspar ± phlogopite) that appear to have crystallised as late stage more felsic minerals in the diorite.

Near the western end of Cap Rosilly is a relatively large body of massive pyroxenite and cumulate plagioclase–pyroxene diorite, comprising equant, subhedral, poikiolitic pyroxenes, up to 6 cm across, in a groundmass of coarse-grained amphibole and minor feldspar. This area is interpreted to represent a large piece of ultramafic cumulate material in the chamber.

The westernmost exposures comprise pale brown, coarse-grained, biotite-rich foliated granite that contains abundant fine- to medium-grained mafic enclaves, up to 50 cm long. The enclaves are generally rounded and range from elongate to less commonly equant. In some places the enclaves are intensely flattened within a narrow zone, grading out to more equant shapes (Fig. 4f), suggesting locally greater strain and flow attenuation of the enclaves.

The Cap Rosilly locality coincides with a magnetic high on the regional total magnetic intensity image (Fig. 1). There are other magnetic highs in the vicinity of Cap Rosilly that have similar trend and magnitude, suggesting that the exposed mafic rocks represent part of a larger mafic complex. No drillholes are reported to have intersected these magnetic anomalies and therefore they remain untested.

Discussion

Magmatic processes of the St Peter Suite

Taken together the observations presented here confirm that the St Peter Suite is a bimodal magmatic system, with abundant interaction between coexisting mafic and felsic magmas. Three types of magma interaction can be recognised in the outcrops of the St Peter Suite.

Mixing and mingling of mafic and felsic magmas within the magma transfer zones resulted in the heterogeneous, sheeted, hybridised rocks at Smooth Pool. The mixing of mafic and felsic magmas occurs in conduits (e.g. Fig. 2b) through the development of, and the progressive migration of, thermal boundary layers between the hotter mafic magma and the relatively cooler felsic magma. The mechanical erosion at the thermal boundary layer by the flow of hot mafic magma causes the fine-scale mingling of felsic magma into the mafic material (Collins et al. 2000). Such feeder structures would have connected to magma chambers at higher crustal levels, thereby influencing the compositional evolution of the pluton. Magma transfer zones are regions of high rates of magma flux, resulting in the mixing of different magmas of different compositions and the possibility of changes in the flow regime; processes that can facilitate reductions in sulfide miscibility with the melt and hence the formation of massive sulfide deposits (e.g. Arndt, Lesher and Czamanske 2005).

Based on the reconnaissance-scale mapping it is unclear whether the layering at Smooth Pool represents the accumulation and movement of magma within a shear zone, or if it formed under pure shear conditions. In the first instance, magmas can intersect and be entrained along an active shear zone, which would form a site of relatively low pressure. Successive magma batches would be entrained within the shear walls, forming the parallel sheets (e.g. Pawley, Collins and Van Kranendonk 2002). In the second instance, magma movement may have simply been driven by buoyant ascent within a conduit, without displacement of the wall rocks. This could either happen if the magma rose through a dilational opening, or if the magma pressure was high enough at the crustal depth to 'jack' open the wall rocks. Further mapping would be needed in this area to test these hypotheses, which would provide insights into the structural regime of the mid-crust during St Peter Suite magmatism. Whatever the driving force, it is likely that the layered magmas ascended through these zones to be emplaced at higher crustal levels.

A less dynamic setting is preserved at Point Brown where relatively minor mafic magmas have formed synplutonic dykes that intruded the crystal-rich mush at the bottom of the felsic magma chamber (Fig. 3a). The mafic magmas are initially able to intrude the crystal-rich mush near the margins of the felsic pluton as a relatively coherent dyke, as the host will have a high crystal fraction near the margin that forms a thermal boundary (Collins et al. 2000). The mafic magma will be undercooled due to the temperature contrast with relatively cooler felsic magma, forming either quenched blocks that are able to 'break' and form more angular blocks or crystal aggregates that are able to flow and attenuate. The ability of the magma to intrude the crystal mush is enhanced by the locally high fluid pressure, which will result in transient brittle behaviour of the mush. Alternatively, transient brittle failure of a semi-solid granitic magma chamber can be facilitated by changes in the regional stress field within the seismogenic zone (Collins et al. 2000). Nonetheless, the behaviour of the magma will change as the crystal fraction varies within the mush. As the mafic magma intrudes parts of the pluton that have a lower crystal fraction, i.e. likely to be away from the margin and towards the centre of the crystallising body, the intruding magma will segment into trails of mafic enclaves. The movement of the mafic magma through the mush will allow local interaction with individual crystals being plucked from the host and incorporated into the magma, and local hybridisation as the mafic magma mixes with the interstitial melt in the mush to form thin rinds of intermediate compositions. Ultimately, however, magma mixing is relatively inefficient in these more static processes and will have a minor effect on magna composition.

The rocks at Cap Rosilly represent a mafic magma chamber where several aspects of chamber evolution can be recognised. The rocks at the eastern part of Cap Rosilly are interpreted to represent a magma chamber where mafic magma was ponding and crystallising to form the cumulate rocks. The cyclic layering suggests that the chamber was periodically being recharged with fresh pulses. The erosion and truncation of the layering in the previously settled gabbroic cumulate (e.g. Fig. 4b) suggests there was traction flow of the new magma pulses along the floor of the chamber, at the interface between the crystal-rich mush at the floor and the liquid-dominated part of the chamber. These dykes would represent relatively late magma pulses that intruded up through the crystal-rich mush to be emplaced at higher levels, likely replenishing the magma chamber.

In contrast, the mafic rocks at the western parts of the exposure are more massive, with less evidence for the magmatic layering. Furthermore, these rocks preserve more evidence for interaction with contemporaneous felsic magmas, ranging from mafic-dominated to the east where the more felsic compositions form a minor groundmass to angular mafic blocks (e.g. Fig. 4d), to felsic dominated to the west where minor rounded enclaves are preserved within the granite (e.g. Fig. 4f). It is unclear whether this transition from east to west represents progression towards the margin of the mafic magma chamber, or if it is a site where a pulse of felsic magma intruded the crystallising chamber.

Comments on exploration significance

Of importance to exploration models in this region will be determining the emplacement levels of the different granitic and mafic portions of the St Peter Suite. For example, in other terranes such as the Andean Cu systems, it is the upper crustal parts of the magma systems and host rocks that preserve porphyry Cu deposits, with evidence for quartz-pyrophyllite or argillic alteration indicative of this crustal level (Sillitoe 2010). However, due to the dominance of feeder systems and crustal cumulates, it appears that the rocks exposed at the current erosion level would be deeper than the crustal levels that typically host porphyry Cu–Au deposits. Nevertheless, the presence of deformation within the magma transfer zone could indicate that the St Peter Suite was likely emplaced, in part, into a contractional tectonic setting. The coincidence of contractional tectonics and arc magmatism are two features of Phanerozoic Cu–Au porphyry systems (Sillitoe 2010). The presence of a mafic magma chamber with cumulate textures in the exposed St Peter Suite may give some indication that the suite has potential for magmatic Ni–Cu sulfide mineralisation (e.g. Arndt, Lesher and Czamanske 2005).

Conclusion

The field observations presented here have outlined three main lithological associations within the exposed St Peter Suite. The presence of both felsic and mafic magma chambers, along with zones of magma transfer shows the complexity present within the suite. Subsequent investigations are underway into the petrological and isotopic evolution of the St Peter Suite that will provide further information towards improving our understanding of this rock suite, its mineral potential, and its place in the geological evolution of South Australia.

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We found mapping and description of the St Peter Suite on the STREAKY BAY and NUYTS 1:250,000 map sheets produced by R Flint and L Rankin to be helpful in our understanding of the geology of the St Peter Suite. We'd also like to thank Claire Wade and Richard Flint for their thorough reviews.

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FURTHER INFORMATION

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