Multiple intrusions and remelting-remobilization events in a magmatic arc: The St. Peter Suite, South Australia

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ABSTRACT

Granitoids with juvenile signatures are common in arc environments and contribute to growth of the continental crust. Thermo-mechanical models of arcs suggest that intermittent intrusion of magma batches leads to magma hybridization, remelting, and remobilization of earlier intrusive rocks driven by fluctuations in temperature and water fluxing. While there are numerous examples in the literature of multiple intrusions and magma hybridization, field examples of remelting and remobilization of earlier intrusive rocks within an arc are rare. Here, we investigate the evolution of magmatic rocks of the Paleoproterozoic St. Peter Suite, emplaced along the SW margin of the Gawler craton, South Australia, a typical calc-alkaline arc suite. Magmatic rocks recording multiple intrusions and multiple magma interactions have undergone in situ remelting and remobilization forming migmatites.

Laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U–Pb zircon dating yielded crystallization ages of 1647 ± 12 Ma for a tonalitic gneiss representing the oldest intrusive suite, and 1604 ± 12 Ma for a leucogranite representing the younger suite rather than postdating it, as expected. We interpret these results to indicate that crystallization of the younger suite and the second anatectic event occurred in the time encompassed by the error of these young ages. Leucosomes from both anatectic phases lack anhydrous peritectic phases and are interpreted to represent low-temperature anatexis resulting from water fluxing.

Combined, these results suggest that a protracted and complex intrusive history can be made significantly more complex by anatexis, giving rise to evolved magmas after older ones, erasing earlier intrusive relationships, and establishing new ones. Rocks of the St. Peter Suite record many of the key processes expected in arcs, including the prediction that early intrusive arc rocks remelt to form younger and more fractionated magmas.

INTRODUCTION

Arc magmatism above subduction zones is the main process in the formation of continental crust (Taylor and McLennan, 1985). Understanding arc processes is therefore critical in comprehending the evolution of the continental crust (e.g., Annen et al., 2006). Despite considerable research on the subject, a clear picture of the evolution of magmas in arcs has not yet emerged. Of particular interest, and shrouded in controversy, is the process underlying the origin of intermediate to silicic magmas from mantle-derived mafic magmas.

Magmatic arcs are complex environments with a multitude of processes at play, driven by high and variable magma and aqueous fluid fluxes and fluctuations in temperature (T) and pressure (P). Primary magmas are thought to be basaltic to magnesian andesitic in composition and tend to pond at the base of the crust, where they undergo hybridization through mixing with crust-derived partial melts or assimilation of solid crust, and then undergo a period of storage and homogenization (MASH; Hildreth and Moorbath, 1988), forming more-evolved magmas that are emplaced higher in the crust.

Most composite granitoid plutons are thought to grow through episodic emplacement of multiple magma batches rather than as large molten bodies (e.g., Coleman et al., 2004; Matzel et al., 2006; Miller et al., 2011). Zircon geochronology, thermal modeling, and a lack of geophysical evidence for large magma chambers with >20% melt suggest that large magma bodies can remain in hypersolvus “mush” state over time periods of hundreds of thousands to several million years as a result of incremental addition of new magmas (e.g., Annen et al., 2006; Matzel et al., 2006; Miller et al., 2007).

The evolved compositions of plutonic and volcanic rocks emplaced above subduction zones result from the processing of primary magmas within the crust. Crustal processing models emphasize fractional crystallization of mantle-derived magmas (Bachmann and Bergerg, 2004) and anatexis of crustal material (Pettit and Gallagher, 2001) to explain the origin of evolved magmas. Numerical models of the thermal effect of multiple intrusions of basalt into arcs indicate that such hot zones can produce significant volumes of crustal melt (Annen and Sparks, 2002; Huppert and Sparks, 2003).
1988). Given fluctuations in thermal conditions and fluid fluxes in the interior of arcs, the remelting of magmatic rocks intruded early during the arc-building history is expected to be a typical process (Davidson et al., 2007; Weinberg and Dunlap, 2000; White et al., 2011). It is thus surprising that a survey of the literature reveals little in the form of direct field evidence of remelting of arc intrusive rocks.

Geochemical studies of the Izu-Bonin volcanic arc in Japan (Tamura and Tatsumi, 2002) and the Costa Rican volcanic front (Vogel et al., 2007) suggest that rhyolitic volcanic rocks probably originated from remelting and remobilization of mantle-derived, calc-alkaline magmas deeper in the arc. Similarly, geochemical modeling of island-arc granitoids emplaced in the Norwegian Caledonides suggests they originated from anatectic of a mantle-derived, mafic source rock at the base of the crust with various water activities (Hansen et al., 2002).

Another indirect line of evidence for remobilization of early intrusive rocks during arc building has been suggested for the Ladakh Arc in NW India, an island arc that became extinct when India collided with Asia and part of the much longer Gangdese or Transhimalaya arc. Here, a spread of zircon ages between ca. 70 and 45 Ma in individual samples suggests that magmas crystallized significantly and were remobilized to form new magmas, perhaps several times during this 25 m.y. period (Weinberg and Dunlap, 2000; White et al., 2011). This was interpreted as recording a multistage remelting of arc rocks to produce fractionated magmas, preserving the original juvenile isotopic composition. This process explains the outcrops of migmatic diorites linked to the generation of hornblende-tonalites to hornblende-granites documented in this arc (Weinberg and Dunlap, 2000).

This paper focuses on the St. Peter Suite, a suite of calc-alkaline magmatic rocks exposed along the coast of South Australia (Fig. 1), representing a magmatic arc emplaced between 1622 ± 6 Ma and 1608 ± 5 Ma (Swain et al., 2008). In common with many arcs, exposures record multiple intrusive pulses and magma hybridization. Interestingly, these exposures record evidence of remelting and remobilization of intrusive rocks. We investigate the origin and evolution of the St. Peter Suite at Rocky Point and Point Brown (Fig. 1) using structural geology, geochronology, and geochemistry.

This paper starts with a regional geology overview, followed by a detailed description of the field relationships at Rocky Point. We divide the rocks into two suites of different ages. We then document two deformation events and coeval anatexes, followed by a description of U-Pb dating results of zircon and titanite, which constrain the timing of magmatism, anatexis, and deformation events. We present geochemical and isotopic data for both suites and finish with a discussion of the implication of the findings, with particular focus on the process of remobilization of arc rocks through remelting.

REGIONAL GEOLOGY

The St. Peter Suite is part of the Gawler craton, which is a large (~800 km by 1000 km) crustal province on the southern margin of Australia (Fig. 1A). It is made up of a sheared, irregularly shaped, dominantly metasedimentary Archean nucleus, surrounded by Proterozoic orogenic and plutonic rocks. A late Archean phase and a late Paleoproterozoic–early Mesoproterozoic tectonic phase dominate its evolution. The St. Peter Suite is an I-type sequence representing a magmatic arc with ages in the literature between 1622 ± 6 Ma and 1608 ± 5 Ma emplaced in the SW margin of the Gawler craton (Fig. 1B; Hand et al., 2007; Swain et al., 2008). The A-type Hiltaba Suite and the related extrusion of the Gawler Range volcanics (Fig. 1) followed the cessation of the St. Peter Suite magmatism and coincided with widespread high-temperature metamorphism and deformation (1595–1575 Ma; Daly et al., 1998; Hand et al., 2007). Tholeiitic gabbros intruding the St. Peter Suite at St. Peter Island have been interpreted as part of the Hiltaba Suite (Chalmers, 2009).
The St. Peter Suite is composed of variably intermingled gabbro, diorite, tonalite, granodiorite, and granite (Chalmers, 2009; Flint et al., 1990; Hand et al., 2007; Swain et al., 2008). Geophysical interpretation, core samples, and geochronology suggest that this suite forms a shear zone–bounded, triangular block that extends ~25,000 km² under sedimentary cover (Swain et al., 2008). Its magmatic rocks are calc-alkaline, enriched in large ion lithophile elements (LILEs) and light rare earth elements (LREEs) and depleted in high field strength elements (HFSEs), similar to modern-day arc rocks (Swain and depleted in high field strength elements (HFSEs), similar to modern-day arc rocks (Swain et al., 2008). The St. Peter Suite rocks 145 km east of Rocky Point has revealed a polydeformational history characterized by three compressional events (D1–D3), followed by two extensional events (D4–D5; Stewart and Betts, 2010).

RESULTS

Rock Types and Intrusive Relationships

Detailed geological mapping was conducted on a 3 km stretch of coastal outcrop at Rocky Point (Figs. 1C and 2). This area records two phases of magmatism, deformation, and anatexis. The older magmatic phase was named here Rocky Point Suite, and the younger, Charra Suite. The Rocky Point Suite is characterized by a tonalitic intrusion with mafic dikes and irregular intrusions of mafic magmas, disrupted to varying degrees, indicating a protracted magmatic history. The Charra Suite intrudes the Rocky Point Suite, is less deformed, and is characterized by a dominant pink leucogranite and a suite of comagmatic intrusive rocks. This section first describes the lithologies of each suite and their relationships, summarized in Table 1, followed by a description of their deformation and anatexis.

Rocky Point Suite

The general appearance of outcrops of Rocky Point Suite is of a heterogeneous, foliated package composed of a host tonalite (Table 1) with numerous schlieren, enclaves, and dikes, and with multiple crosscutting relationships and varied contact features (Figs. 3A–3B). Dikes and enclaves are comprised of several phases of tonalite, diorite, and white leucogranite, intruded at different times and interacting with the surroundings in different ways (Fig. 4). Early dikes were disaggregated into narrow, long enclaves and millimeter-wide schlieren, parallel to a dominant foliation (Fig. 3A). Later dikes were disaggregated into pillows or angular blocks, or form continuous, up to 150-m-long, 1–2-m-wide dikes with irregular margins against the tonalite, or are broken up into semicontinuous blocks along discrete centimeter-wide magmatic shear zones (Fig. 4) with up to 5 m of offset. In general, contact relationships suggest that the tonalite host was not fully solidified during most of the intrusive history of this suite.

All Rocky Point Suite lithologies contain millimeter- to 10-cm-wide leucosomes weathering to a pink or yellow surface. Leucosomes range from patchy (Figs. 3C and 3E) to stromatic or banded (Fig. 3F) and are characterized by fuzzy, irregular margins against the host and relatively rare rims of melanosome, and may include hornblende porphyroblasts when within or in the vicinity of dioritic rocks (Fig. 3E). Leucosomes are especially voluminous within the more biotite-rich lithologies, such as the host tonalitic gneiss, and are interpreted as being produced in situ by anatexis of Rocky Point Suite protoliths.

Figure 2. Geological map of Rocky Point divided into three areas (divisions into these areas are simply for presentation of purposes with no specific geological significance). Lower-hemisphere equal-area stereonets display poles to dominant foliation for each area. Points A–C mark localities referred to in text.
Charra Suite

The Charra Suite intrudes the Rocky Point Suite and commonly forms large bodies consisting of various intrusive rocks with irregular, complex margins against one another (Fig. 3D), and locally including Rocky Point Suite xenoliths (Figs. 5A–5B). The main contact between the two suites, exposed in area one (Fig. 2), has Rocky Point Suite enclave-rich tonalitic gneiss intruded by Charra Suite granodiorite. The two rock types are similar in appearance, but the younger granodiorite has a less intense foliation and fewer and smaller mafic enclaves and schlieren. The differences between the two are particularly clear when Rocky Point Suite tonalitic gneiss xenoliths are found within the Charra Suite granodiorite (Figs. 5A–5B).

The Charra Suite consists of a dominant pink leucogranite, as well as granodiorite, tonalite, and diorites (Table 1). The pink leucogranite intrudes as centimeter- to meter-scale dikes into Rocky Point Suite tonalites and diorites and forms also a homogeneous, 800-m-long outcrop (Fig. 2). This homogeneous body gives way to areas of complex intrusive relationships with other mafic rocks in regions tens of meters across, commonly with cupulate-lobate contacts indicative of interaction between magmas. Tonalite forms a body with a number of E-W–trending, meter-wide tonalitic sheets with varying proportions of diorite enclaves and strongly foliated, angular Rocky Point Suite migmatic tonalite xenoliths up to several meters in length (area three, Fig. 2). Diorite enclaves have sharp to fuzzy margins and are typically highly elongated or sigma-shaped with a long axis parallel to the dominant foliation and an asymmetry indicative of dextral shearing (Fig. 5C). The sheeted tonalite contains a faint E-W foliation defined by a preferred grain orientation. Solid-state deformation is nearly absent, evidenced only by weak internal deformation of quartz grains (Fig. 6). Weak solid-state deformation suggests dextral shearing of enclaves in the magmatic state (Paterson et al., 1989). Similar to the Rocky Point Suite, Charra Suite rocks also have millimeter- to centimeter-wide leucosomes interpreted to indicate anatectic because of their diffuse contacts with the surrounding rock.

Table 1. Rock Units and Their Petrography, Occurrence, and Evidence of Relative Timing Listed from Older to Younger

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Petrography</th>
<th>Occurrence</th>
<th>Rock relationship</th>
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<tbody>
<tr>
<td>Rocky Point Suite</td>
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<tr>
<td>(a) Enclave-rich tonalitic gneiss</td>
<td>~50% Pl, 30% recrystallized Qtz, 15% Bt, 5% Kfs, accessory opaques, Chl, Ap, Zrn, Hem.</td>
<td>&gt;100 m scale. Including rounded to angular centimeter-scale enclaves.</td>
<td>Intruded and disaggregated by mafic tonalite and diorite dikes (lithologies b and c; Fig. 3B) and white leucogranite (lithology d). Contains numerous mafic enclaves in different stages of disaggregation (Fig. 3A). Intruded and sometimes disaggregated by Charra Suite. Partially melted forming metatexites or diatexites.</td>
</tr>
<tr>
<td>(b) Mafic tonalite dikes</td>
<td>~62% Pl, 20% recrystallized Qtz, 15% Bt, 3% microcline, accessory opaques, Ap, Tln, Hem.</td>
<td>Centimeter- to meter-wide dikes variably disaggregated into schlieren, enclaves or lenses.</td>
<td>Intrude and are disaggregated by it (Figs. 3A–3B). Truncated by porphyritic diorite dikes (lithology c; Fig. 3B).</td>
</tr>
<tr>
<td>(c) Porphyritic diorite dikes</td>
<td>~45% Bt, 40% Pl, 4% Hbl, accessory opaques, Ap, Chl.</td>
<td>Dikes tens of centimeters to meter wide.</td>
<td>Truncate mafic tonalite dikes (lithology b; Fig. 3B). Dike margins are irregular in places. Lobate margins with white leucogranite (lithology d; Fig. 3C).</td>
</tr>
<tr>
<td>(d) White leucogranite</td>
<td>~45% microcline, 30% recrystallized Qtz, 22% Pl, accessory Bt, opaques, Hem, Tln.</td>
<td>Meter-scale bodies.</td>
<td>Irregular contacts with porphyritic diorite. Contains rounded xenoliths of tonalitic gneiss (lithology a; Fig. 3C).</td>
</tr>
<tr>
<td>(e) D, anatectic leucotonalite/leucogranite</td>
<td>~45% microcline, 25% Qtz, 18% sericitized Pl, 4% Bt, 3% opaques.</td>
<td>Millimeter- to centimeter-wide leucosomes. Forms a large (100s of meters) diatexite body (area three).</td>
<td>Lobate margins and interfingering with pink leucogranite (lithology i). Contains anatectic tonalite schollen (lithology a) and diorite enclaves.</td>
</tr>
<tr>
<td>Charra Suite</td>
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<tr>
<td>(g) Granodiorite/tonalite</td>
<td>~40%–50% anhedral to tabular Pl, 25%–40% recrystallized Qtz, 10% Bt, accessory opaques, Ap, Zrn, Hem, Ms.</td>
<td>&gt;100-m-scale irregular body (in contact with Rocky Point Suite), centimeter- to meter-scale bodies, and &gt;100-m-scale sheeted intrusion.</td>
<td>Disaggregates Rocky Point Suite. Interfingering and lobate-cuspatite margins with pink leucogranite and diorite (lithologies i and f, respectively) (Fig. 3D). Intruded by composite dikes (lithology j).</td>
</tr>
<tr>
<td>(h) Diorite</td>
<td>~48%–60% sericitized Pl, 25% Bt, 10%–20% poikilitic Hbl, accessory Qtz, opaques, Ap.</td>
<td>Bodies up to hundreds of meters or enclaves within pink leucogranite with cuspatelobate margins. Also as a set of irregular (comagmatic) dikes.</td>
<td>Lobate margins against tonalite (lithology g). Intruded by pink leucogranite (lithology i), although irregular margins suggest comagmatism.</td>
</tr>
<tr>
<td>(i) Pink leucogranite</td>
<td>~45% Kfs, 45% Qtz, 8% Pl, 2% Bt, accessory opaques, Tln, Chl, Zrn, Hem.</td>
<td>&gt;100-m-scale body or centimeter- to meter-scale sheets or dikes oriented mostly parallel to it.</td>
<td>Intrudes all Rocky Point Suite lithologies (Fig. 3D) and enclave-poor granite (lithology f). Irregular margins against Charra Suite lithologies.</td>
</tr>
<tr>
<td>(j) Composite dikes</td>
<td>Pl, Bt, Hbl, Qtz.</td>
<td>30–50-cm-wide dikes striking ~060.</td>
<td>Intrudes pink leucogranite (i) and granodiorite (lithology g).</td>
</tr>
<tr>
<td>Late anatectic rocks and dikes</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(k) Pegmatite/aplite</td>
<td>Qtz, Kfs, Pl.</td>
<td>Forms centimeter-scale veins and a meter-scale aplite body.</td>
<td>Intrudes all other units.</td>
</tr>
<tr>
<td>(l) Anatectic leucotonalite/leucogranite</td>
<td>~40%–50% sericitized Pl, 30%–40% recrystallized Qtz, 10% microcline, minor Bt, poikilitic Hbl, accessory opaques, Ap, Chl, Tln, Hem, Zrn.</td>
<td>Millimeter- to centimeter-scale in situ leucosomes with diffuse margins. Forms matrix to diatexites within large shear zones. Leucosomes linked continuously with long anastomosing leucogranitic sheets, interpreted as extraction channels.</td>
<td>All intrusive units (Fig. 3F).</td>
</tr>
</tbody>
</table>

Note: Mineral abbreviations from Kretz, 1983.
Structural Evolution and Anatexis

All lithologies at Rocky Point record magmatic flow responsible for the dominant, broadly E-W magmatic foliation and banding. This was followed by two deformation phases, both associated with migmatization that affected all major rock types and gave rise to in situ or in source leucosomes that vary in morphology from patch leucosomes to diatexite bodies and irregular leucogranitic sheets (Figs. 3B, 3C, 3E, and 3F). Migmatite terminology used here is from Sawyer (2008).

Symmagmatic Layering and Foliation

The earliest structure is a pervasive steeply dipping foliation most strongly developed in the older, more mica-rich Rocky Point Suite lithologies, and also present in Charra Suite rocks. This foliation is magmatic (Sm) and is parallel to banding originated from multiple dike intrusions (Fig. 4) and dike disaggregation to form elongated enclaves and mafic schlieren (Figs. 3A–3B and 5C). The strike of Sm varies across the area between NNW-SSE and NNE-SSW (dominantly E-W; Fig. 2). Generally, magmatic foliation and banding do not record asymmetries indicative of simple shear flow. However, locally there are well-developed σ-shaped enclaves indicative of dextral shearing during magma emplacement (Fig. 5C).

Sm is defined by the alignment of magmatic minerals such as biotite, hornblende, or less commonly euhedral plagioclase laths. Quartz is typically irregular and retains its primary shape, commonly unoriented with lobate margins and lacking strong internal deformation (Fig. 6A). There is a solid-state overprint in more intensely deformed rocks where quartz is partly recrystallized via grain boundary migration, suggesting deformation at temperatures of 500–700 °C (Stipp et al., 2002). Chessboard extinction in some quartz grains suggests deformation by a combination of basal (a) and prism (c) slip at temperatures above 630 °C (Fig. 6B; Stipp et al., 2002). Quartz deformation suggests continued deformation into solid-state conditions.

Anatexis and first deformation phase (D₁).

The first anatectic event affected rocks of the Rocky Point Suite and gave rise to metatexites, rocks that preserve their original continuity, and diatexites, rocks that flowed en masse, as magma. The dominant foliation in these migmatites (S₁) is parallel to the original magmatic foliation. Leucosomes have diffuse margins against the surroundings. The best example of this kind of migmatite is an ~200-m-thick body of diatexite in the south of area three (Fig. 2). The diatexite matrix covers between ~40% and >95% of this area and grades into meter-scale areas of metatexite and contains centimeter- to meter-scale metatexite tonalitic rafts, diorite enclaves, and schlieren. The tonalite rafts contain leucosomes that merge with the matrix of the surrounding host, suggesting the Rocky Point Suite tonalitic gneiss is the main protolith to the diatexite. Flow banding in the diatexite, defined by schlieren and the long dimensions of rafts, is oriented parallel to S₁. Sinistral shearing on E-W planes is characteristic of D₁ and is indicated in horizontal outcrops by leucosomes and schlieren defining sigmoidal foliation patterns, by σ-clasts, and by asymmetric strain shadows around centimeter- to meter-scale rigid blocks or rafts in magma (Fig. 5D).

The morphology of metatexites varies depending on the composition of the host rock and intensity of anisotropies. Stromatic (banded) metatexites are more common in lithologies with a strong foliation, such as the Rocky Point Suite tonalitic gneiss. Leucosomes typically form high-aspect-ratio veins that are less than 3 cm thick, have diffuse margins with...
Figure 4. Different styles of interaction between mafic dikes and surrounding tonalitic magma ordered according to increased disaggregation (top to bottom) and style (brittle on left, ductile on right).  

(A) Dike broken down into regular squares separated by healed magmatic fractures. Scale: ~3 m from left to right. This can be followed for 100 m. Dike intruded while surrounding was still in a magmatic state and rapidly cooled.  

(B) Discontinuous dike broken up by back-veining of surrounding felsic magma.  

(C) Diorite dike broken up into small angular blocks in surrounding magma, which preserves flow banding surrounding the cluster of mafic blocks.  

(D) Mafic dike with irregular margin indicative of contemporaneous flow as magmas. Unlike A, this dike interacted with the tonalite magma before solidifying.  

(E) More extensive ductile disaggregation of a diorite dike in tonalite magma. Necking of the mafic dike, close to lens cap, relates to a D2 shear zone overprinting the S2 trend of the dike.  

(F) Final product of physical hybridization of the tonalite magma by diorite intrusions. All photographs are from Rocky Point Suite rocks except for E.
Multiple intrusions and remelting in a magmatic arc

The host rock, and are subparallel with $S_1$. These sometimes have biotite-rich melanosomes, indicating that they are in situ. The volume of leucosomes is up to 50% where stromatic metatexites are dominant, suggesting protracted melting and crystallization so as not to destroy rock coherence.

$F_1$ folds are uncommon, and, where found, they are isoclinal (Figs. 5A–5B) or pytgmatic with an axial plane subparallel to $S_1$. In a few places, migmatite xenoliths with strong stromatic layering, including isoclinal folded leucosomes, are truncated by the host Charra Suite rocks (Figs. 5A–5B). This is interpreted to represent blocks of Rocky Point Suite that have undergone this first anatectic event pre-dating Charra Suite magmatism. This contrasts with the second phase of anatexis, which affects both suites.

**Anatexis and second deformation phase ($D_2$)**. The dominant E-W foliation ($S_n \parallel S_1$) is overprinted by folds and a conjugate pair of strike-slip shear zones filled with leucosomes at high angle to $S_1$, and defining $D_2$. Shear zones are vertical and can be found as individual planes, sets of neatly spaced planes with a single shear sense (dextral or sinistral; Fig. 7), or in conjugate pairs with a very small angle in between them, one on each limb of folds (Fig. 7C). Folds are typically small-scale, isolated folds (rather than fold trains), tens of centimeters to meters in wavelength (e.g., Fig. 7C). $D_2$ shear zones deflect the surrounding foliation and lack visible lineations, and therefore only apparent strike-slip shear sense was determined on horizontal

![Figure 5](image1.png)

Figure 5. (A) Strong foliation within banded Rocky Point Suite migmatite xenolith within Charra Suite granodiorite. Note isoclinal $F_1$ folds with an axial plane subparallel to $S_1$. A leucosome is hosted within a $D_2$ dextral shear zone crossing the photograph diagonally and crossing the boundary between xenolith and host. (B) An interpretive overlay of A. Dashed-dotted line indicates $F_1$ axial plane, and dashed line indicates the $D_2$ shear zone with leucosome. (C) Sigma-shaped diorite enclaves within sheeted tonalite of the Charra Suite (CS). Asymmetry of enclaves indicates synmagmatic dextral shearing. (D) Sinistral shearing in diatexite of the Rocky Point Suite (RPS) indicated by the asymmetry of flow around the dark schollen forming a small duplex, stepping to the left. Inset shows interpretation of features and orientation of the main shear plan. All photographs are from subhorizontal rock platforms.

![Figure 6](image2.png)

Figure 6. Photomicrographs in cross polarized light. (A) Anhedral quartz (Qtz) grain with lobate margins in Charra Suite pink leucogranite lacking evidence of solid-state deformation. (B) Chessboard extinction in amoeboidal quartz grain in Charra Suite pink leucogranite indicative of high-temperature solid-state deformation. Kfs—K-feldspar.
planes. Given that the shear zones and deflected foliations are both vertical, the apparent strike-slip shear sense reflects a true horizontal motion component, but a vertical component could not be determined.

In places, continuous leucosomes cross the boundaries between xenoliths of Rocky Point Suite and Charra Suite host (Fig. 8). This contrasts with leucosomes related to the early anatectic event that predated Charra Suite magmatism (Figs. 5A–5B). Figure 8 shows examples of a common type of D₃ leucosome, which are oriented broadly NNE-SSW, parallel to the axial planar orientation, and in contrast to those in Figure 7, lack evidence of shearing.

Second-generation folds (F₂) have a NNE-SSW–striking axial plane (average strike 018°), approximately bisecting the small (24°) acute angle between the shear zone pair (Fig. 9A). The geometric relationship between shear zones and folds (Fig. 7C) and the small angle between sinistral and dextral shear zones suggest that they represent slip planes subparallel to the axial planar foliation. These melt-lubricated planes accommodated slip on fold limbs, facilitating folding (Fig. 9B; Weinberg et al., 2013; Weinberg and Mark, 2008).

**Syn-D₂ anatexis and melt extraction channels.** Syn-D₂ anatexis is best preserved in area one (Fig. 2) and formed metatexites and local diatexites in both Rocky Point Suite and Charra Suite lithologies. Leucosomes are typically leucogranitic to leucotonalitic, compositionally similar to D₁ leucosomes. They may truncate preexisting igneous layering (Figs. 10 and 11) or may be directly and continuously linked with leucosomes parallel to S₁ || S₂ (Fig. 10). In this case, leucosomes rotate into and merge with leucosomes in D₂ orientations (Fig. 9B), suggesting that lithological contacts and anisotropy related to the early foliation played a role during melting.

Leucosomes in D₂ structures tend to link up and form long anastomosing leucogranitic sheets trending NNE-SSW (Fig. 12). These are the most striking feature of D₂ anatexis. They are distributed throughout areas one and three (Fig. 2), where they vary in width from 1 to 50 cm, and are up to 45 m long (Fig. 12), spaced by 5 m on average over 100 m of outcrop. The granitic rock in these sheets may be composed of dirty diatexite, or clean or layered leucogranite. They may be composed of sections associated with shearing and sections without obvious shearing and typically parallel to the axial plane foliation of folds. They have diffuse to sharp margins and typically lack accompanying melanosomes. Magma in the sheets truncated, dragged, folded, and transposed S₁ (Fig. 10) toward the NNE, including preexisting mafic dikes that may be disrupted into centimeter- to meter-scale enclaves inside the sheets and may even be folded isoclinally (Fig. 11). Interestingly, these sheets may be discontinuous, locally disappearing along strike into the tonalitic host, only to reappear 1 or 2 m further along (Fig. 12). We interpret these NNE-trending sheets to mark localized, high-strain magma extraction channels, developed by the linking of leucosomes in D₂ structures that removed layer-parallel magma and dragged, folded, and transposed magmatic banding.

Leucosomes formed during both anatectic events are mineralogically similar, predominantly pink to gray, biotite-bearing leucogranites to leucotonalites only rarely rimmed by a melanosome. Hornblende-bearing leucosomes are common in diorite (Figs. 3C and 3E) or in

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**Figure 7.** Quartz-diorite dikes that underwent partial melting and were disrupted by D₃ shearing and folding associated with leucosomes. (A) Several-meters-wide dike disrupted by sinistral shear zones with leucosomes. (B) Detail showing leucosomes organized so as to accommodate shearing along dike margin. (C) Leucosomes define shear planes accommodating opposite movement on opposite limbs of a fold.
its immediate vicinity in felsic protoliths. Peritectic hornblende combined with the lack of anhydrous peritectic minerals suggest water-fluxed melting for both events (Brown, 2013; Weinberg and Hasalová, 2014).

**Geochronology**

In order to constrain the temporal evolution of key magmatic intrusions and deformation events, we dated zircons and titanite from six samples (results are summarized in Fig. 13; Tables DR1–DR5). Laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb dating of zircon grains was conducted on four samples in order to determine the timing of Rocky Point Suite and Charra Suite magmatism and to constrain the timing of D₃. Sensitive high-resolution ion microprobe (SHRIMP) U-Pb dating was conducted on titanite grains from a syn-D₃ anatectic tonalite and on zircon grains from Point Brown (Fig. 1). Sample coordinates are given in Tables DR1–DR5 (see footnote 1).

**Methodology**

All samples were crushed and milled, and minerals were separated using heavy liquids (density 2.96 and 3.30 g/cm³) and the Franz magnetic separator. Zircons were mounted onto epoxy resin, sectioned in half, and polished. Cathodoluminescence (CL) images using a scanning electron microscope (SEM) were prepared for all zircons (e.g., Figs. 14A–14C) and used to determine internal zoning within grains and choose suitable spots for laser analysis. U-Pb zircon dating was carried out at the School of Geosciences, Monash University, using a Thermo X-series 2 quadrupole ICP-MS coupled with a New Wave 213 nm, Nd:YAG laser. The zircons were sampled in a mixed He/Ar atmosphere (He/Ar ~4/1) with the laser operating at a repetition rate of 5 Hz, 40 μm spot size, and ~12 mJ cm⁻² of laser energy at the sample. Instrumental mass bias, drift, and downhole fractionation were taken into account by analyzing the 91500 standard zircon every hour throughout the analytical session (Jackson et al., 2004) to correct results for instrumental drift. Forty-eight analyses of the zircon standard GJ (Jackson et al., 2004) were conducted for quality-control purposes. The results yielded an average ²⁰⁷Pb/²⁰⁶Pb ratio of 0.0601 (% relative standard deviation [RSD] = 1.35%), an average ²⁰⁶Pb/²³⁸U ratio of 0.0973 (%RSD = 3.11%), an average ²⁰⁷Pb/²³⁸U ratio of 0.8066 (%RSD = 3.98%), an average ²⁰⁸Pb/²³²Th ratio of 0.0341 (%RSD = 19.06%), a ²⁰⁷Pb/²⁰⁶Pb mean weighted average age of 611 ± 13 Ma (mean square of weighted deviations [MSWD] = 0.34) and a mean weighted average age of ²⁰⁶Pb/²³⁸U age of 601 ± 4 Ma (MSWD = 5.6).

Data obtained from these experiments were processed using the GLITTER software (Jackson et al., 2004). Uncertainties for ratios and ages of individual analyses are given at the 1σ level; no common Pb corrections were applied. U-Pb concordia plots, probability density diagrams, and mean weighted average ²⁰⁷Pb/²⁰⁶Pb ages were calculated using Isoplot/Ex version 4 (Ludwig, 2003). Concordia plots (Figs. 15 and 16) and tables include only the filtered data used to determine the final ages (Tables DR1–DR5 [see footnote 1]).

U-Pb dating was also undertaken using the SHRIMP–Reverse Geometry (RG) at the Research School of Earth Sciences, The Australian National University. Zircon and titanite grains were handpicked under a binocular microscope from clean mineral separates and mounted...
onto double-sided tape together with grains of the zircon standard Temora 2 and the titanite standard BLR-1. Backscatter electron (BSE; Fig. 14D) imaging by SEM was done on the titanites to select areas to be analyzed.

The standard analytical protocols described by Williams (1998) were used. A mass-filtered primary O beam was focused onto the target grains producing a spot size appropriate for the target—in the case of the current samples, this was ~25 μm in diameter. The surface was rastered for 2.5 min before analysis in order to clean the surface of any contamination. Data acquisition for zircons was done by repeatedly stepping through the masses 90Zr, 16O ("reference mass 200") as the reference mass.

The data were reduced in a manner similar to that described by Williams (1998, and references therein), using the SQUID I Excel Macro of Ludwig (2001). The reference zircon Temora 2 (416.8 ± 1.3 Ma; Black et al., 2004) was the primary U-Pb geochronology calibration standard, with standard zircon SL13 (U concentration of 204 ppm; Claoué-Long, 1995) used to calibrate the U, Pb, and Th concentrations for the session. The reference titanite BLR-1 (1050.5 ± 0.9 Ma, 2σ; Aleinikoff et al., 2007) was the primary U-Pb geochronology calibration standard for the titanite and the reference used to calibrate the U, Th, and Pb concentrations for the session (U concentration of 250 ppm; Aleinikoff et al., 2007). The decay constants recommended by the International Union of Geological Sciences (IUGS) Subcommission on Geochronology (Steiger and Jäger, 1977) were used in the age calculations.

Uncertainties given for individual U-Pb analyses (ratios and ages) are at the 1σ level; however, uncertainties in the calculated weighted mean ages are reported as 2σ confidence limits and include the uncertainties in the standard calibrations where appropriate. For the age calculations, corrections for common Pb were made using the measured 204Pb and the relevant common Pb compositions from the model of Stacey and Kramers (1975). Concordia plots, regressions, and any weighted mean age calculations were carried out using Isoplot/Ex 3.0 (Ludwig, 2003) and where relevant include the error in the standard calibration.

LA-ICP-MS U-Pb Zircon Dating

Zircons from all four samples analyzed had similar morphologies. They were honeycolored, ranged from 40 to 200 μm in length, mostly euhedral, and showed concentric oscillatory zoning indicative of igneous crystallization (Figs. 14A–14C; Corfu et al., 2003). However, zircons with needle shape, more equant, and with a distinct core with a homogeneous rim were also present. Where rims and cores were >40 μm in width, they were analyzed separately to determine age differences. There was, however, no systematic relationship between zircon morphology or zoning and age. Zircons with >90% concordancy were considered concordant and used to determine a mean weighted average 207Pb/206Pb age. However for sample RP1–7, zircons with >85% concordancy were used in order to obtain a statistically meaningful mean weighted average 207Pb/206Pb age. Discordant zircons displayed a Pb-loss trend that plotted toward the origin, a common Pb trend, or a combination of the two.

Rocky Point Suite tonalite gneiss—Sample RP1–6 (from point A, Fig. 2). This sample is from an in situ anatectic leucotonalite from within the tonalite gneiss and sampled within meters of RP1–6. Fifty-one spots from 49 zircons were analyzed. Concordant points cluster between the 207Pb/206Pb ages of 1550 Ma and 1702 Ma. Fifteen zircons had >85% concordancy and yielded a mean weighted average 207Pb/206Pb age of 1647 ± 12 Ma (MSWD = 1.13; Fig. 15B; Table DR1 [see footnote 1]).

Syn-D1, leucosome—Sample RP3-L2 (from point C, Fig. 2). This is also a syn-D1 in situ leucosome from within the tonalite gneiss. Thirty-seven spots from 32 zircons were analyzed. Concordant zircons cluster between 1600 and 1690 Ma, with a Pb-loss trend toward the origin. Thirty-one zircons that had >90% concordancy yielded a mean weighted average 207Pb/206Pb age of 1649 ± 18 Ma (MSWD = 2.7; Fig. DR1; Table DR2 [see footnote 1]). The two leucosome samples collected from within the Rocky Point Suite yielded zircon ages similar to that of the Rocky Point Suite tonalite protolith.

Charra Suite pink leucogranite—Sample RP3–5-1 (sampled at point B, Fig. 2). This is the lithology described in Table 1(i) and one of the latest intrusions comprising the Charra Suite. Seventy-eight spots from 72 zircons were analyzed. The concordant results cluster between 207Pb/206Pb ages of 1535 and 1701 Ma, mostly Rubay, and showed a Pb-loss trend toward the origin. The average of these results was 1649 ± 18 Ma (MSWD = 2.7; Fig. DR1; Table DR2 [see footnote 1]).
Figure 10. D$_2$ leucosome networks forming channels, crosscutting, disrupting, and transposing preexisting magmatic banding and S$_1$ foliation. In all examples, channels trend between N-S and N30E. (A) Leucosome network cuts across mafic dike and isolates and displaces a mafic block. Leucosomes, well-defined within the mafic dike, become diffuse in surrounding tonalite. (B) Similar to A: notice development of an ill-defined antiform, and deformation of newly formed mafic enclaves disrupted from mafic body. Leucosomes give rise to a granitic dike (top central part of photograph). (C) Ill-defined granitic channels sharply truncating mafic blocks in tonalite. (D) A 20-cm-wide channel dragging and transposing magmatic layering in surrounding rocks. (E) A 2-m-wide band where mafic dike is disrupted by leucosomes (white horizontal lines). Disrupted mafic enclaves are in some cases stretched, rotated, and physically disaggregated, giving rise to dark patches in the felsic rock (white horizontal line is scale, 2 m long).
while discordant zircons produce a strong Pb-loss trend toward the origin. Forty-eight zircons were >90% concordant and yielded a 207Pb/206Pb age of 1604 ± 12 Ma (MSWD = 0.75; Fig. 15C; Table DR3 [see footnote 1]).

SHRIMP U-Pb Zircon and Titanite Dating
Syn-D, leucosome—Sample RP1–7. Because zircons from this sample yielded the same age as the protolith, we proceeded to analyze titanite, in an attempt to determine the time of anatexis of the Rocky Point Suite. Titanites are light brown and range in length from 200 to 400 μm. They are mostly euhedral with a rhomboidal or rounded cross section, although many grains were broken. Most grains have irregular internal zoning manifest as light and dark areas on the BSE image (Fig. 14D), while oscillatory zoning is rare. No systematic age differences were identified between different areas. The results cluster on the concordia between 1580 and 1620 Ma (Fig. 16), with four discordant points defining a Pb-loss trend toward the origin. The concordia age is 1604.6 ± 6.9 Ma (MSWD = 0.83; Fig. 16), while the mean weighted 207Pb/206Pb age is 1599.7 ± 8.1 Ma (MSWD = 0.22; Fig. 16; Table DR4 [see footnote 1]). This age dif-
Multiple intrusions and remelting in a magmatic arc

fers from the zircon age of the same sample and coincides with the zircon age of Charra Suite sample RP3–5-1.

Point Brown Sample PB4–2hy. This is a medium-grained biotite-hornblende granite containing K-feldspar and plagioclase phenocrysts, and diorite enclaves. Twenty-nine points from 24 zircons were analyzed. Zircons are honey-colored, euhedral, and show concentric oscillatory zoning. Results yield a strong Pb-loss trend that plots toward the origin with an upper intercept of 1625 ± 7 Ma (MSWD = 0.56, probability of fit = 0.97; Fig. DR2, Table DR5 [see footnote 1]). The mean weighted average 207Pb/206Pb age is 1622 ± 5 Ma (MSWD = 0.56).

In summary, three of the four samples dated using LA-ICP-MS yielded ages centered around 1645 Ma (Fig. 13). The Charra Suite pink leucogranite (RP3–5–1) yielded a much younger age of 1604 ± 12 Ma, which coincides within error with the SHRIMP titanite 1605 ± 7 Ma age of the leucosome sampled from within the Rocky Point Suite tonalitic gneiss (RP1–7). Dating suggests that crystallization of the Charra Suite and the second anatexis that remelted both suites occurred within the ~25 m.y. period afforded by the 1σ uncertainties of these two young ages. The Point Brown granite (PB4–2hy) yielded an age of 1622 ± 5 Ma, in between these two groupings. These results suggest that the St. Peter Suite magmatism may have lasted longer than existing constraints (1622 ± 6 Ma and 1608 ± 5 Ma in Swain et al., 2008).

Geochemistry

Major and Trace Elements

Sixteen St. Peter Suite samples from Rocky Point and Point Brown were crushed and analyzed for major and trace elements. Major elements were analyzed using X-ray fluorescence at James Cook University. Trace elements were analyzed at Monash University, School of Geosciences, using a Thermo Finnigan X Series II, quadrupole ICP-MS. Results are given in the GSA Data Repository Tables DR6 and DR7 (see footnote 1). Samples from Rocky Point and Point Brown have some differences in major- and trace-element compositions, such as enrichment in Cs and Rb and a negative Eu anomaly for Point Brown samples (Fig. 17).

Rocky Point and Point Brown samples are metaluminous and cover a range of compositions.
Figure 15. Results from laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb dating of zircons. Tera-Wasserburg concordia diagram and 207Pb/206Pb age probability density plot (insets) are shown for: (A) Rocky Point Suite (RPS) tonalitic gneiss (RP1-6) for analyses with >90% concordancy; (B) syn-D2 leucosome derived from analyses with >85% concordancy; (C) pink leucogranite from Charra Suite (CS) (RP3-5-1). Error ellipses and mean weighted average 207Pb/206Pb ages for all samples are 1σ. MSWD—mean square of weighted deviates.

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**Sm-Nd Isotope Geochemistry**

Sm-Nd isotopic analyses were undertaken on three Rocky Point samples and four Point Brown samples (samples vary in composition from gabbro to leucogranite; Table 2). Rocky Point samples were crushed and analyzed using a Thermo Fisher Scientific Triton multicolonctor mass spectrometer at the Research School of Earth Science, The Australian National University. In each analytical session, the unknowns were analyzed together with the La Jolla Nd standard (146Nd/144Nd = 0.721963) and/or the in-house Ames nNd-1 Nd standard. Unknowns were adjusted to the nominal 146Nd/144Nd value of 0.511860 for La Jolla. Epsilon Nd (εNd) values are reported relative to a chondritic uniform reservoir (CHUR) composition of 0.512638.

Sm-Nd isotopic analyses of Point Brown samples were conducted at the University of Melbourne, following procedures described by Maas et al. (2005). Instrumental mass bias was corrected by normalizing to 146Nd/144Nd = 0.201255 (Vance and Thirlwall, 2002), and data are reported relative to the accepted standards La Jolla and SRM987. Internal precision for 146Nd/144Nd is ±0.0000012 (±2 standard deviations [σ]), while external precision (2σ reproducibility) is ±0.0000020 (±2σ). External precision for 143Nd/144Nd is ±0.2%.

Rocky Point samples yielded initial 143Nd/144Nd and εNd ranging from 0.51058 to 0.51063 and +0.65 to +1.8, respectively (Table 2). Point Brown samples yielded broadly similar results with initial 143Nd/144Nd and εNd ranging from 0.51058 to 0.51063 and +0.65 to +1.8, respectively.

The εNd values fall within the range found for the broader St. Peter Suite (between –2.9 and +3.7, for 17 samples; Chalmers, 2009; Swain et al., 2008), but they are considerably lower than those recorded for the St. Peter Island tholeiitic gabbro (εNd = +2.65 to +6.27, four samples; Fig. 18; Chalmers, 2009). Figure 18 shows that the initial εNd values of St. Peter Suite rocks overlap with the εNd values expected for the mantle at that time (εNd = +1.8; calculated after Zindler and Hart, 1986). The εNd values are much higher than the local basement thought to be composed of 48.4–78.8 wt% SiO2 and 0.54–10.1 wt% MgO. Most samples define a calc-alkaline trend on the Na2O + K2O (A), FeO + Fe2O3, and MgO (M) (AFM) diagram, except for two samples that plot within the tholeiite field (Kuno, 1968) close to a late tholeiitic A-type gabbro cropping out at St. Peter Island (Fig. 1; Chalmers, 2009).

The chondrite-normalized rare earth element (REE) plot (Fig. 17) shows similar character-istics as the broader St. Peter Suite (Chalmers, 2009; Swain et al., 2008) with LREE enrichment (La/Yb = 3.6–45; Fig. 17A). Trace-element patterns normalized by primitive mantle are characterized by high LILE/HFSE (Ba/Nb = 6.3–75.9) and high LILE/LREE (Ba/La = 1.5–8.5), which is typical of calc-alkaline magmas. Figure 17B indicates that the multiple processes involved in the evolution of these magmatic rocks lead to formation of rocks approaching upper-crustal composition.
Multiple intrusions and remelting in a magmatic arc

Figure 16. Results from sensitive high-resolution ion microprobe (SHRIMP) U-Pb dating of titanites from syn-D₂ anatectic leucoxenitaitalite (RP1–7) in Wetherill concordia diagram for concordant analyses with four discordant points removed (ages in Ma). The white ellipse represents the concordia age and associated error. Inset is a $^{207}$Pb/$^{206}$Pb age probability density plot. Error ellipses and mean weighted average $^{207}$Pb/$^{206}$Pb age are 1σ (MSWD = 0.83).

Multiple intrusions and remelting in a magmatic arc

The two calc-alkaline magmatic suites at Rocky Point record a protracted history of magmatism, each characterized by broadly comagmatic intrusions. Both have a dominant E-W magmatic foliation, $S_m$, parallel to magmatic banding, suggesting similar emplacement controls. Dikes of tonalite and diorite intrude the main Rocky Point Suite tonalite at different stages of its crystallization, and record different styles of liquid-liquid or liquid-mush interaction with various degrees of hybridization (Barbarin and Didier, 1992). Features vary from nearly complete disaggregation and hybridization of early intrusions, to dikes with well-preserved, sharp, cuspatelobate margins against host tonalite with back-veining, or to dikes disrupted into sharp, angular blocks (Fig. 4). Planar, straight, and continuous contacts are relatively rare, suggesting that most magmas intruded into a suprasolidus host tonalite. The younger Charra Suite intruded and locally disaggregated the Rocky Point Suite tonalite (Figs. 5A–5B and 8) and is characterized by either diorite or pink leucogranite intruding granodiorites and tonalites at various stages of crystallization, giving rise to similar relationships as described for the older Rocky Point Suite (Figs. 3D and 4E).

The fact that most contacts are characterized by comagmatic relationships suggests that rocks of each magmatic suite remained at suprasolidus conditions for the duration of their intrusive history (Matzel et al., 2006). The large variety of lithologies, and the multiple intrusions, typically as dikes and sheets (from centimeters to 100 m wide), suggest that this region may have represented a major magma passageway from the mantle to the upper crust.

Deformation and Anatexis

Magmatic foliation, $S_m$, was overprinted by the first deformation event, D₁, responsible for sinistral movement during anatexis parallel to $S_m$. This deformation may also have been responsible for the weak solid-state overprint recorded as chessboard extinction and recrystallization of quartz in Rocky Point Suite rocks (Fig. 6B). D₂ folded the early magmatic banding and foliation and gave rise to conjugate shear zones at high angle to $S_m$ parallel to $S_c$ commonly, but not exclusively, on the limbs of the folds (Fig. 7C). Leucosomes parallel to $S_c$ are continuously linked with leucosomes and magma sheets segregated into D₂ shear zones and fold axial planar orientations (Fig. 9B). These two deformation phases described here lack direct relationship to solid-state deformation of St. Peter Suite rocks described elsewhere (Stewart and Betts, 2010).

D₂ and Extraction Channels

$D_2$ gave rise to vertical conjugate strike-slip shear zones, up to a few meters long, and metric, isolated vertical folds with sheared limbs. Shear zones and axial planar foliations (not necessarily sheared) are filled with leucosomes that link together to give rise to long magma sheets (Figs. 10–12). The presence of melt weakened the rock mass, and melt migration into low-pressure structures localized deformation and amplified local folds in a positive feedback loop (Brown and Solar, 1998). The small acute angle between conjugate shear zones (24° between their average orientations) is bisected by the axial plane of folds (Figs. 7C and 9), and is significantly smaller than the 90° predicted for ductile conjugate pairs (Mancktelow, 2002). This suggests shearing took place in planes at high angles to the maximum shortening direction (z). Melt that segregated into these planes acted as lubricants, facilitating slippage (Fig. 9B). Thus, shear zones nucleated on axial planar foliations, and their shear sense was controlled by their orientation on each fold limb.

The magma sheets formed by the linking of leucosomes in these axial planar orientations, and they are interpreted to represent extraction channel networks of anatectic magma. Interconnected leucosomes funnel toward the northeast, forming folds with closures pointing NNE, resulting from dragging along channel walls (Fig. 11). These features are interpreted to indicate a NNE-directed preferential magma migration (see Weinberg et al., 2013; Weinberg and Mark, 2008).

$D_2$ Anatexis before the End of Crystallization?

Anatexis related to $D_2$ has been assumed implicitly to have occurred after complete crystallization of Charra Suite magmas. There are alternatives, however. One is that leucosomes represent extraction of interstitial melt from a mush during crystallization of Charra Suite magmas. Another is a combination of the two processes: a crystallizing mush undergoes an increase in melt fraction due to increases in temperature or water content, facilitating melt extraction during deformation.

Conditions during Anatexis

Both anatectic events produced neosomes lacking anhydrous peritectic minerals such as garnet, sillimanite, and orthopyroxene, characteristic of water-fluxed melting. The only ferromagnesian peritectic mineral found is hornblende in leucosomes in the vicinity of dikes.
Figure 17. (A) Chondrite-normalized rare earth element (REE) plot (Sun and McDonough, 1989) showing a light (L) REE enrichment less pronounced in the tholeiitic samples. (B) Incompatible element plot normalized to upper continental crust (Taylor and McLennan, 1985) showing values close to unity except for a slight large ion lithophile element (LILE) enrichment and negative Ta-Nb anomaly, a typical arc signature.
Multiple intrusions and remelting in a magmatic arc

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<th>RP2-C-1</th>
<th>RP3-5-1</th>
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Note: Initial isotope data for Rocky Point Suite (RPS) diorite, Charra Suite (CS), and Point Brown (PB) samples were recalculated at 1647 Ma, 1604 Ma, and 1622 Ma, respectively. Hbl—hornblende. See Tables DR6 and DR7 in the GSA Data Repository for major- and trace-element geochemistry for these samples (see text footnote 1).

We have thus documented that magmatic flow gave rise to banding and foliation recorded by Rocky Point Suite rocks. This flow was overprinted by the sinistral D1 deformation during the first migmatization event. This event predated intrusion of the 1604 ± 12 Ma Charra Suite, which contains xenoliths of Rocky Point Suite migmatites (Fig. 5A). Charra Suite rocks record magmatic flow with a dextral simple shear component on approximately E-W planes recorded by asymmetric enclaves (Fig. 5C). The timing of D1 was constrained by titanites from leucosomes in late shear zones within Rocky Point Suite rocks (sample RP1–7). However, instead of yielding an age younger than Charra Suite, as expected, their age of 1605 ± 7 Ma coincides within error with that of crystallization of the Charra Suite. The similarity between the crystallization age of the Charra Suite sample, given by zircons, and anatexis, given by titanites, implies that crystallization of the Charra Suite and subsequent anatexis took place within the uncertainty of the two ages.

Therefore, we conclude that the Charra Suite intruded and crystallized possibly in the early part of the period between 1616 and 1592 Ma, defined by age uncertainties (1604 ± 12 Ma) and remelted in the late part of the period. An alternative interpretation is that the titanites recorded only the thermal event related to Charra Suite intrusion but did not record the younger anatetic event. The apparent ease of resetting titanite ages at high temperatures, however, argues against this alternative.

Are Dynamics and Origin of the Upper Crust

Despite extensive research, the processes by which evolved silicic magmas are generated from primary, mantle-derived magmas in arcs remain unclear. Differentiation of primary basalts (Bachmann and Bergantz, 2004) and partial melting of the crust (Petford and Gallagher, 2001) are currently recognized as the two dominant processes at play. As noted in (e.g., Fig. 3E). Experiments have shown that at least 3–4 wt% water is required to stabilize hornblende during melting at 10 kbar (Gardien et al., 2000). A number of incongruent melting reactions producing hornblende-bearing leucosomes have been proposed based on microstructural relationships. Typically, these reactions occur at P-T conditions above the water-saturated melting and below dehydration melting of biotite (Lappin and Hollister, 1980; Kenah and Hollister, 1983; McLellan, 1988; Mogk, 1992). Escudier-Viruete (1999) suggested that the presence of hornblende in leucocratic segregations with rounded inclusions of biotite, plagioclase, and quartz indicates that melting started in the presence of water according to the reaction:

\[
\text{biotite + plagioclase + quartz + water} \rightarrow \text{hornblende + melt}
\]

for rocks of dacitic composition (65 wt% SiO₂). The solidus for this reaction depends on the composition of plagioclase and the Mg⁰ of the rock, as well as the availability of water, and for common intermediate rocks, these occur near 700 °C and 730–750 °C, between 5 and 10 kbar (Conrad et al., 1988; Naney, 1983).

In summary, D₁ was likely associated with water influx that triggered partial melting of the intrusive rocks. D₁ was typified by weak deformation that gave rise to leucosomes parallel to convergent axial planar foliations that lubricated these planes and slipped. Leucosomes in these orientations linked up to develop extension channel networks. Anatexis was estimated to have occurred by the influx of aqueous fluids at temperatures between 700 °C and 750 °C.

Temporal Evolution

Rocky Point rocks yielded two distinct age groups (Fig. 13). The first group is made up of U-Pb zircon ages from Rocky Point Suite tonalitic gneiss (RP1–6) and two syn-D₂ leucosomes from within this tonalite (RP1–7 [zircon] and RP3-L2) and yielded the following weighted ²⁰⁶Pb/²³⁸U ages (1σ errors): 1647 ± 12 Ma (MSWD = 2), 1640 ± 21 Ma (MSWD = 1.13), and 1649 ± 18 Ma (MSWD = 2.7). The second group consists of the Charra Suite pink leucogranite (RP3–5–1) LA-ICP-MS zircon age and the syn-D₂ leucosome SHRIMP titanite age (RP1–7 [titanite]). These samples yielded ages of 1604 ± 12 Ma (MSWD = 0.75) and 1605 ± 7 Ma (MSWD = 0.83), respectively.

Samples of the older age group analyzed using LA-ICP-MS show large age errors accompanied by MSWD values between one and two. Given the error for the zircon standard GJ (±13 m.y. and MSWD = 0.34) analyzed in the same session as the unknown zircons, we follow common practice and attribute this spread of data to analytical scatter and assume that the mean weighted age represents a single crystallization age, but we note the possibility that they may represent an age span centered around 1645 Ma.

We interpret the older group as representing the age of crystallization of the Rocky Point Suite tonalite (sample RP1–6). Similar syn-D₂ leucosome zircon ages (RP1–7 [zircon] and RP3–L2) are interpreted as inherited from the source (Miller et al., 2007; Williams, 1992), with no zircon ages dating D₂ anatexis. The age of the Charra Suite pink leucogranite (RP3–5–1) at 1604 ± 12 Ma constrains the crystallization age of this younger intrusion, while titanites from the syn-D₂ leucosome sampled from within the Rocky Point Suite (RP1–7 [titanite]) yield the age of the second anatexis and thus the age of D₂ deformation (1605 ± 7 Ma). The disparity in ages between zircon and titanite from sample RP1–7 is due to the fact that titanite, unlike zircon, is reactive at high temperatures and more likely to record cooling toward the end of anatexis (Frost et al., 2001; Skår and Pedersen, 2003). SHRIMP U-Pb dating of zircon from granite from Point Brown (1622 ± 5 Ma; PB4–2hy) is intermediate between the Rocky Point Suite and Charra Suite and suggests active magmatism across the St. Peter Suite between ca. 1650 and 1600 Ma.
the introductory statements, the remelting and remobilization of rocks intruded early during arc building are expected processes that have the potential to give rise to evolved magmas (see Hansen et al., 2002; Tamura and Tatsumi, 2002; Vogel et al., 2004; Weinberg and Dunlap, 2000; White et al., 2011). In this study, we have presented evidence for a protracted history of magma intrusion, mingling, remelting, and remobilization. The magmatic system has remained at temperatures above solidus for a considerable fraction of its intrusive history. We suggest that rocks at Rocky Point represent a frozen-in record of the history by multiple events of remelting and partial anatectic melts in multiple crosscutting relations. The result end is new intrusions interacting with newly generated crustal anatectic melts in multiple crosscutting relationships. Our findings support the differentiation model hypothesized by Tamura and Tatsumi (2002) and elucidate a process by which mantle-derived magmas can form rocks with upper continental crust composition.

CONCLUSION

St. Peter Point exposures at Rocky Point reveal a protracted evolution of magmatism, deformation, and anatexis. The Rocky Point Suite (1647 ± 12 Ma) is intruded by the Charra Suite (1604 ± 12 Ma), and both are made up of comingled sequences of diorite to granite. Magmatic rocks are essentially calc-alkaline with a geochemical signature indicative of an arc environment. Initial εNd values between +0.7 and +1.8 suggest magma formation by fractionation of a juvenile mantle source with some crustal contamination. Two deformation phases are recorded by these rocks. D1 was dominantly sinistral and coeval with the first anatectic event that affected the Rocky Point Suite giving rise to metatexites and diatexites. D2 affected both suites and is characterized by folding of S1 into isolated folds, associated with axial planar shear zones filled with leucosomes, indicating syn-D2 anatexis. Anatectic melt used D2 structures and developed a network of magma channels extracting magma at high angle to the early foliation. Leucosomes contemporaneous with D2 were dated at 1605 ± 7 Ma, the same age within error as the crystallization of the Charra Suite, indicating that the process of magmatic crystallization and remelting or remobilization of interstitial melt from a mush is encompassed by the uncertainty of the ages. The exposures at Rocky Point record remelting and remobilization event(s) of earlier intrusive rocks during construction of the arc, suggesting sustained conditions close to melting temperatures, with fluctuations above and below solidus driven by fluctuations in water availability and heat. This process has been suggested as significant in magmatic arcs but, surprisingly, is seldom described in the field.

ACKNOWLEDGMENTS

This work was financially supported by the Australian Research Council grant DP110102543. We thank Associate Editor Roger Gibson, Calvin Miller, and an anonymous reviewer for their comprehensive comments that helped us focus and improve this manuscript.

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