Relationships between magmatism and deformation in northern Yorke Peninsula and southeastern Proterozoic Australia

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ABSTRACT
The ca 1600–1580 Ma time interval is recognised as a significant period of magmatism, deformation and mineralisation throughout eastern Proterozoic Australia. Within the northern Yorke Peninsula in South Australia, this period was associated with the emplacement of multiple phases of the Tickera Granite, an intensely foliated quartz alkali-feldspar syenite, a leucotonalite and an alkali-feldspar granite. These granites belong to the broader Hiltaba Suite that was emplaced at shallow crustal levels throughout the Gawler Craton. Geochemical and isotopic analysis suggests these granite phases were derived from a heterogeneous source region. The syenite and alkali-feldspar granite were derived from similar source regions, likely the underlying ca 1850 Ma Donington Suite and/or the ca 1750 Ma Wallaroo Group metasediments with some contamination from an Archean basement. The leucotonalite is sourced from a similar but more mafic/lower crustal source. Phases of the Tickera Granite were emplaced synchronously with deformation that resulted in development of a prominent northeast-trending structural grain throughout the Yorke Peninsula region. This fabric is associated with composite events resulting from folding, shearing and faulting within the region. The intense deformation and intrusion of granites within this period resulted in mineralisation throughout the region, as seen in Wheal Hughes and Poona mines. The Yorke Peninsula shares a common geological history with the Curnamona Province, which was deformed during the ca 1600–1585 Ma Olarian Orogeny, and resulted in development of early isoclinal and recumbent folds overprinted by an upright fold generation, a dominant northeast-trending structural grain, mineralisation, and spatially and temporally related intrusions. This suggests correlation of parts of the Gawler Craton with the Curnamona Province, and that the Olarian Orogeny also affected the southeastern Gawler Craton.

Introduction
The ca 1600–1580 Ma time slice is a recognised period of low- to high-grade metamorphism associated with intense crustal orogenesis and emplacement of major mineral deposits within eastern Proterozoic Australia, which includes the Gawler Craton and Curnamona Province of South Australia (e.g. Betts, Giles, Lister, & Frick, 2002; Collins & Shaw, 1995; Forbes, Betts, Giles, & Weinberg, 2008; Forbes et al., 2012; Stewart & Betts, 2010; Figure 1a, b). Within the Gawler Craton, this period was also associated with bimodal magmatism that included the ca 1592 Ma Gawler Range Volcanics (Fanning, Flint, Parker, Ludwig, & Blissett, 1988) and emplacement of the ca 1595–1575 Ma Hiltaba Suite granites (e.g. Conor, 1995; Creaser & Cooper, 1993; Fanning, Reid, & Teale, 2007; Flint et al., 1993) to shallow crustal levels (e.g. Daly, Fanning, & Fairclough, 1998; Stewart & Foden, 2003). Hiltaba Suite granites are widely distributed across the Gawler Craton, vary across the A-, I- and S-type range, and have characteristic chemical signatures (such as high Th, low CaO, MnO and Sr concentrations at a given SiO₂ level, and evolved Sm–Nd isotope signatures) depending on the region (Hand, Reid, & Jagodzinski, 2007; Stewart & Foden, 2003).

Granites in the northern Yorke Peninsula in the southern Gawler Craton (Figure 1c) are suggested to be part of the Hiltaba Suite, and include the deformed Tickera Granite (1598 ± 7 Ma, 1575 ± 7 Ma; Conor, 1995) and undeformed Arthurton Granite (1583 ± 7 Ma; Creaser & Cooper, 1993; Jack, 1917). These granites intrude metasediments and metavolcanics of the ca 1750 Ma Wallaroo Group (Cowley, Conor, & Zang, 2003). Magmatic crystallisation ages derived from the Tickera Granite range from ca 1598 to 1575 Ma, suggesting a prolonged period of emplacement. The timing of emplacement of the Tickera Granite is also synchronous with deformation, metamorphism and metasomatism that is suggested to have affected the Wallaro Group at ca 1600–1575 Ma (Conor et al., 2010). However, the timing relationships
Figure 1. (a) Map of Australia showing the area of Proterozoic Australia affected by tectonothermal activity and magmatism during the ca 1600–1580 Ma time slice. (b) Simplified geological map of the Gawler Craton showing the distribution of Hiltaba Suite plutons, the Donington Suite the Gawler Range Volcanics and geological domains after Stewart and Foden (2003). (c) Solid geology map of the Yorke Peninsula displaying the distributions of the Arthurtown and Tickera Granites, modified after Conor et al. (2010). Mapping and sample locations of Point Riley, and sample locations of Black Rock and Wallaroo North Beach are shown.
Regional geology of the Gawler Craton

The Gawler Craton preserves a complex geological history spanning from the Archean to the early Mesoproterozoic. Mesoarchean granitoids of the Cooyerdoo Granite were emplaced between ca 3200 and 3150 Ma, and are recognised as the oldest known units within the Gawler Craton (Fraser, McAvaney, Neumann, Szpunar, & Reid, 2010; Jagodzinski, Reid, & Farrell, 2011; Reid & Hand, 2012). Felsic magmatism was associated with emplacement of the ca 2823 Ma Coolanie Gneiss (Fraser & Neumann, 2010), and was followed by a period of basin development, bimodal magmatism and sedimentation during the Neoarchean to early Paleoproterozoic, forming the Sleaford Complex and the Mulgathing Complex in the southern and central western Gawler Craton, respectively. Basin development was terminated as the Archean part of the Gawler Craton was deformed and metamorphosed during the ca 2480–2420 Ma Sleafordian Orogeny (Daly & Fanning, 1993; Daly et al., 1998; Reid & Hand, 2012). Magmatic events and widespread sedimentation proceeded until the onset of rift-basin formation (Szpunar, Hand, Barovich, Belousova, & Jagodzinski, 2011). Basin development was interrupted at ca 1850 Ma with emplacement of the Donington Suite across much of the eastern Gawler Craton during compressional deformation associated with the Cornian Orogeny (Reid, Hand, Jagodzinski, Kelsey, & Pearson, 2008). Subsequent bimodal magmatism and deposition of sedimentary packages occurred, which included the Wallaroo Group (1760–1740 Ma; Cowley et al., 2003). The Gawler Craton underwent another tectono thermal event during the ca 1730–1690 Ma Kimban Orogeny (Dutch, Hand, & Kinny, 2008; Ferris, Schwarz, & Heithersay, 2002; Hand et al., 2007; Hoek & Schaefer, 1998), which was associated with the intrusion of the ca 1745–1700 Ma Peter Pan Supersuite (e.g. Wade & McAvaney, 2017). The Kimban Orogeny was followed by juvenile mantle input, resulting in widespread crustal melting and a period of intense magmatism, which included the ca 1640–1608 Ma St Peter Suite, ca 1592 Ma Gawler Range Volcanics and the ca 1595–1575 Ma Hiltaba Suite (Creaser & Cooper, 1993; Daly et al., 1998; Fanning et al., 1988; Reid & Hand, 2012; Swain, Barovich, Hand, Ferris, & Schwarz, 2008; Symington et al., 2014; Teasedale, 1997). The Gawler Range Volcanics and Hiltaba Suite represent bimodal magmatism that occurred between 1595 and 1575 Ma, during a period of regional deformation (e.g. Conor, 1995; Creaser & Cooper, 1993; Fanning et al., 2007; Flint et al., 1993). The Hiltaba Suite is suggested to have been generated from mafic underplating associated with lithospheric attenuation, and melting of the overlying continental crust (Flint et al., 1993; Zang, Fanning, Purvis, Raymond, & Both, 2007). Geochemical variations within the Hiltaba Suite granites across the Gawler Craton are suggested to be due to derivation from a depleted mantle source that mixed with various crustal components, at different melting and emplacement conditions (Stewart & Foden, 2003). Further deformation across the Gawler Craton occurred during the ca 1570–1540 Ma Kararan Orogeny and ca 1470–1450 Coorabie Orogeny (Hand et al., 2007).

Regional geology of the Yorke Peninsula

The Yorke Peninsula is part of the Moonta Domain in the southeastern Gawler Craton, South Australia (Figure 1b, c). The area comprises upper Paleoproterozoic metasediments and metavolcanics of the ca 1750 Ma Wallaroo Group (Cowley et al., 2003), which extends northward from Yorke Peninsula, below the Stuart Shelf and along much of the Olympic Domain (Figure 1b; Conor et al., 2010). The Wallaroo Group preserves evidence of metamorphism and multiple folding events, where the metamorphic grade varies from upper greenschist in the northern Yorke Peninsula to amphibolite facies in the southern part (Conor et al., 2010).

Fine-grained psammites, siltstones, calc-silicates, albites, quartzites and iron-rich sediments of the Wandearah Formation dominate the Wallaroo Group. These metasediments are interlayered with bimodal A-type volcanics of the Weetula Formation, which were subsequently cut by intrusives associated with the Matta Formation (Conor, 1995; Cowley et al., 2003). Within the Wallaroo Group, two phases of deformation are locally preserved at Wallaroo North Beach. The earlier phase involved generation of isoclinal folds with limbs extending up to several kilometres in length. The timing of this deformation event has been suggested to be related to the ca 1730–1690 Ma Kimban Orogeny (e.g. Conor et al., 2010), however this is equivocal (e.g. Conor, 2016). The later deformation phase involved refolding of the isoclinal folds by open upright folds. This late folding is suggested to be associated with deformation during ca 1600–1580 Ma time period based on preservation of amphibole-rich calcisilicate alteration within the axial plane of the open upright folds. Alteration and mineralisation within the region has been linked to the intrusion of Hiltaba Suite equivalents during this period (Conor, 1995; Conor et al., 2010).
On Yorke Peninsula, the Hiltaba Suite is represented by both felsic and mafic components. The mafic component of the Hiltaba Suite is represented by the Curramulka Gabbro-norite (e.g. Conor, 1995, 2016; Cooper, Mortimer, Rosier, & Uppill, 1985; Fanning et al., 1988), which facilitated melting of the lower crust to form its felsic component (Zang et al., 2007). Jack (1917) has differentiated bodies of the felsic component into the deformed Tickera Granite and undeformed Arthunton Granite. The Tickera Granite, located in the northern Yorke Peninsula (Figure 1c) is the largest single body exposed on Yorke Peninsula. Point Riley on the western Yorke Peninsula preserves a well-exposed shore platform of multiple phases of the Tickera Granite and has been used to suggest that the granite was intruded into a tectonic regime in which shearing was prominent. Conversely, the Arthunton Granite to the south is suggested to post-date local deformation (Conor, 1995; Conor et al., 2010; Wurst, 1994).

Methodology

The Point Riley shore platform was mapped in detail to show the distribution and intrusive relationships of granite phases and preserved structural fabrics (Figure 2).

Twelve samples were collected in situ from Point Riley. These samples were spatially distributed across the mapping area and as fresh as possible (Figure 2). Two additional samples representing the southern and northern extents of the Tickera Granite were collected; 2.87 km southeast of Point Riley at Wallaroo North Beach (sample 2149822) and 7.87 km northeast of Point Riley at Black Rock (sample 2149823). The samples were used for a combination of petrography, whole-rock geochemistry and Sm–Nd isotopic analysis (Table 1).

Eight samples were selected for petrographic analysis (Table 1). All samples were sawn at the University of Adelaide and prepared by Thin Section Australia. Petrographic analysis was undertaken using standard transmitted and reflected light microscopy to assess mineralogy and textural relationships.

Twelve samples were used for whole-rock geochemical analysis (Table 1), which was undertaken at ALS Global using standard preparation methods (<https://www.alsglobal.com/analys/downloads>). Major elements were analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) and trace elements were analysed by inductively coupled plasma mass spectrometry (ICP-MS).

Eight samples were analysed at the University of Adelaide for Sm–Nd isotope geochemistry: six from Point Riley, one from Wallaroo North Beach and one from Black Rock (Table 1). Samples from Point Riley were selected to represent each of the granite phases observed, based on their spatial distribution and trace- and rare earth-element (REE) geochemistry. Samples collected from Wallaroo North Beach and Black Rock were analysed to provide a broader understanding of the Sm–Nd isotopic composition of the Tickera Granite across the northern Yorke Peninsula. Sm–Nd analysis was undertaken following the method of Wade, Barovich, and Hand (2006) using a Finnigan MAT262 and MAT261 thermal ionisation mass spectrometer at the University of Adelaide. The $^{146}$Nd/$^{144}$Nd ratio was normalised to 0.721903, and Nd blanks were corrected for 200 pg and Sm for 150 pg.

Observations and results

Field observations

The Point Riley area (Figures 1b, c and 2a, b) preserves well-exposed shore platforms of the Tickera Granite. Four phases of granite were recognised and are divided based on colour, grain size, composition and deformation style. Granite phases show minor variance in mineral abundances across shore platforms. The four phases were then classified as granite nodules, a quartz alkali-feldspar syenite, a leucotonalite and an alkali-feldspar granite.

Granite nodules

Resistant oval granite nodules are preserved throughout a brown-red syenite (quartz–alkali-feldspar syenite; Figures 3 and 4a, b). The nodules protrude from the surrounding syenite, are up to 30 cm length, and comprise medium-grained K-feldspar (50–60 vol%; 1–4 mm), quartz (20–30 vol%; 1–4 mm), biotite and amphibole (10–15 vol% mafics; 1–2 mm) and minor plagioclase (<5 vol%; 1 mm; Figure 3a). This

| Sample | Rock type  | Easting | Northing | Geochemistry | Petrography | Sm–Nd |
|--------|------------|---------|----------|--------------|------------|-------|
| 2147273| Nodule     | 740562  | 6248547  | ✓            | ✓          | ✓     |
| 2147279| Nodule     | 740683  | 6248565  | ✓            | ✓          | ✓     |
| 2147276| Syenite    | 740613  | 6248533  | ✓            | ✓          | ✓     |
| 2147280| Syenite    | 740688  | 6248588  | ✓            | ✓          | ✓     |
| 2147281| Syenite    | 740684  | 6248588  | ✓            | ✓          | ✓     |
| 2147277| Leucotonalite| 740561 | 6248524  | ✓            | ✓          | ✓     |
| 2147275| Leucotonalite| 740600 | 6248550  | ✓            | ✓          | ✓     |
| 2147276| Leucotonalite| 740636 | 6248576  | ✓            | ✓          | ✓     |
| 2147271| Alkali-feldspar granite | 740547 | 6248550  | ✓            | ✓          | ✓     |
| 2147274| Alkali-feldspar granite | 740586 | 6248542  | ✓            | ✓          | ✓     |
| 2147278| Alkali-feldspar granite | 740642 | 6248566  | ✓            | ✓          | ✓     |
| 2147282| Alkali-feldspar granite | 740661 | 6248574  | ✓            | ✓          | ✓     |
| 2149823| Alkali-feldspar granite (Black Rock) | 745828 | 6254438  | ✓            | ✓          | ✓     |
| 2149822| Alkali-feldspar granite (North Beach) | 742546 | 6246420  | ✓            | ✓          | ✓     |

Eastings and northings are in GDA94, MGA Zone 53.
composition classifies the nodules as an alkali-feldspar granite. Mineral grains vary from rounded (K-feldspar and quartz) to sub-rounded (amphibole) and elongated within a well-developed, northeast-trending foliation that dips steeply to the northwest. This foliation is also preserved in the surrounding syenite.

**Quartz-alkali-feldspar syenite**

The dominant phase in the mapping area is a brown-red syenite that is recessively weathered, forms the bulk of the rock platform and shares similar mineralogy to the granite nodules (Figures 2, 3 and 4a–d). Mineral grains are sub-rounded to rounded, vary in size from medium- to coarse-grained and
comprise K-feldspar (60–70 vol%; 1–7 mm), quartz (10–20 vol%; 1–4 mm), biotite and amphibole (~10 vol% mafics; 1–2 mm), and small quantities of plagioclase (<5 vol%; 1 mm). This composition classifies this phase as a quartz–alkali-feldspar syenite, herein simplified to ‘syenite,’ and has previously been referred to as a foliated quartz monzonite (Wurst, 1994). Hematite alteration is evident in this phase through its red/orange colour.

The syenite preserves a well-developed, pervasive foliation (Figures 2b, c and 4a–d) defined by consistently orientated and elongated K-feldspar and quartz crystals. The foliation is northeast-trending and steeply northwest or southeast dipping. A locally well-developed cleavage is also preserved in the syenite, particularly close to the contact boundaries with the leucotonalite and alkali-feldspar granite phases, within which the cleavage is a dominant feature. The cleavage is discontinuous, northwest-trending and moderately to steeply northeast dipping.

Enclaves of undeformed syenite are locally preserved within the intensely foliated syenite in the northwestern part of the study area (Figure 2b). Metasedimentary xenoliths of the Wallaroo Group are also preserved within the same local area and range in size from 20 cm to 1 m and comprise fine-grained metapelites (Figure 2b). Quartz and K-feldspar veins that are 5–30 cm thick cross-cut this phase throughout the study area.

**Leucotonalite**

A white leucotonalite forms prominent, blocky exposures throughout the study area (Figures 2a, b and 4d–g). Mineral grains are sub-rounded and medium-grained, and comprise plagioclase (50–60 vol%; 1–4 mm), quartz (30–45 vol%; 1–3 mm) and minor mafics (<5 vol%; 1 mm), which classifies this phase as a leucotonalite.

Two distinct cleavages are evident in the leucotonalite (Figures 2b, d and 4d, e). The first is a locally well-developed, 5–30 cm spaced, northeast-trending and moderately to steeply northwest-dipping cleavage. The second cleavage is a moderate to well-developed northwest-trending cleavage and dips steeply to the northeast. This cleavage is 10–100 cm spaced and is evident throughout the whole mapping area. A poorly developed northeast-trending mineral foliation is
Figure 4. Representative photos of granite phases and contact relationships observed at Point Riley. (a) Granitic nodules within the foliated syenite. Nodules can be seen to protrude from the hosting syenite. (b) Granitic nodule within the intensely foliated syenite. The recessive nature and the intense northeast-trending foliation can be seen in the syenite. Photo taken looking north. (c) Contact boundary between foliated syenite (left) and alkali-feldspar granite (right) showing a localised northeast-trending cleavage. Photo taken looking southwest. (d) Leucotonalite apophyses intruding into the surrounding foliated syenite. (e) Two cleavages in the leucotonalite. Photo taken looking northwest. (f) Contact metasomatic boundary between the leucotonalite and alkali-feldspar granite. Northeast to the top of photo. (g) Raft of leucotonalite within the alkali-feldspar granite dyke. Photo taken looking northwest. (h) Metasomatism between the leucotonalite and alkali-feldspar granite phases. Photo taken looking northwest. (i) Possible miarolitic cavities in the alkali-feldspar granite. Photo taken looking southeast. (j) Alkali-feldspar granite intruding through the syenite. Photo taken looking southeast. Location of photos shown in Figure 2b.
preserved in the same orientation as the northeast-trending cleavage and is defined by the alignment and elongation of quartz crystals.

**Alkali-feldspar granite**
A red granite intrudes all phases as a sheeted dyke and is exposed at both high and low reliefs across the study area (Figures 2 and 4c, g, i–j). This phase was also observed at Black Rock and Wallaroo North Beach (Figure 1c). This granite comprises coarse, sub-rounded grains of K-feldspar (40–70 vol%; 1–12 mm), quartz (10–35 vol%; 1–10 mm), amphibole and biotite (5–25 vol% mafics; 1–6 mm) and minor amounts of plagioclase (<5 vol%; 1–2 mm). This composition classifies the granite as an alkali-feldspar granite, and has previously been referred to as a quartz monzonite (Wurst, 1994). Within the high relief outcrops of the alkali-feldspar granite, cavities ranging in size from 3 to 5 mm are preserved (Figures 2b and 4h). Hematite alteration is also evident by the red colouration of the granite.

Two cleavages are preserved within the alkali-feldspar granite (Figures 2b, e and 4c). A northeast-trending cleavage is locally preserved along the margins of the alkali-feldspar granite within 50 cm of the contact boundary with the intensely foliated syenite, and steeply dips to the northwest and southeast. The second cleavage is a locally preserved, northwest-trending, 5–30 cm spaced, moderately to steeply northeast- or southwest-dipping cleavage that is continuous into the other granite phases.

**Contact relationships**
The contact boundaries between the intensely foliated syenite, leucotonalite and alkali-feldspar granite are sharp in most cases (Figure 4c, d). The leucotonalite locally intrudes the foliated syenite as metre-scale fingers along the foliation plane of the enclosing syenite phase. The fingers are 20–30 cm wide and up to 3 m in length (Figure 2). In the centre of the map area, small 5–10 cm long apophyses of the leucotonalite intrude the foliated syenite (Figures 2b and 4d).

Evidence of contact metasomatism between the alkali-feldspar granite and leucotonalite is locally preserved (Figures 2b and 4f). The contact metasomatic boundary ranges in thickness from 5–20 cm, and is manifest by a colour difference between the two phases, where the leucotonalite gradually becomes redder in colour. In the northeastern section of the study area, evidence of metasomatism between the alkali-feldspar granite dyke and leucotonalite is also evident (Figures 2b and 4h); contact boundaries are highly irregular and commonly unclear. Iron staining on the surface of the leucotonalite is also a prominent feature in this part of the study area. Approximately 2 m east of the contact metasomatic boundary, a raft of leucotonalite is preserved within the alkali-feldspar granite dyke, which itself is surrounded by the leucotonalite (Figures 2b and 4g). The leucotonalite raft is rounded, approximately 1 x 2 m in size.

**Petrography**

**Granite nodules**
The granite nodules primarily comprise K-feldspar, quartz, magnetite, biotite and plagioclase. The majority of the feldspars show evidence of significant sericite alteration and hematite staining. Few microcline and perthitic textures are seen in K-feldspar. Biotite is subhedral while magnetite is euhedral, and are both fine-grained and randomly distributed throughout the granite. Hematite-filled veins also cross-cut all minerals (Figure 5a).

**Intensely foliated alkali-feldspar syenite**
The syenite comprises K-feldspar, quartz, biotite, magnetite, plagioclase and minor amphibole. Microcline and microperthite feldspars are evident within this phase. Evidence of sericite alteration is also seen along with hematite staining. Biotite is euhedral and along with K-feldspar is aligned within the dominant foliation preserved in the granite. Localised brecciation shows a stockwork of hematite veining that is predominantly developed around altered feldspars and within quartz grains (Figure 5b).

**Leucotonalite**
The leucotonalite dominantly comprises plagioclase and quartz, with minor magnetite. Plagioclase is significantly sericite altered. A weak foliation defined by quartz crystals is preserved, and thin hematite veins occasionally cross-cut quartz and plagioclase (Figure 5c).

**Alkali-feldspar granite**
The alkali-feldspar granite generally comprises medium to coarse-grained K-feldspar and quartz, with minor plagioclase, magnetite and biotite. Minor microcline is observed. Sericite and hematite alteration of feldspars is preserved (Figure 5d). Minor perthitic exsolution is also observed. At Wallaroo North Beach, a local prominent foliation in the alkali-feldspar granite is defined by quartz and significantly sericite altered and brecciated feldspars (Figure 5e). At Black Rock, the alkali-feldspar granite also contains amphibole, with higher modal proportion of biotite and more intense sericite alteration (Figure 5f). Minor hematite is commonly preserved and is present in thin veins.

**Geochemistry**

**Major elements**
Major-element geochemical results for the nodules, syenite, leucotonalite and alkali-feldspar granites are displayed in Figure 6 and Table 2. The SiO₂ content of the Tickera Granite ranges from 69.9–79.2 wt%. The nodules have an SiO₂ content of 71.1 and 73.4 wt%, the syenite ranges from 69.9–71.1 wt%, while the leucotonalite clusters around 77 wt%. The alkali-feldspar granite shows the widest variation in SiO₂ content of 70–79 wt% (Figure 6). Al₂O₃ and P₂O₅ display a general negative trend with increasing SiO₂ content for all samples; however, a steep positive trend is observed in Al₂O₃ in the syenite.
Figure 5. Representative plane polarised photomicrographs of Tickera Granite phases at Point Riley. (a) Granitic nodule illustrating sericitised feldspar, with biotite and magnetite localised around the edges. (b) Syenite displaying a stockwork of hematite-filled veins and altered feldspar. Sample 2147281. (c) Leucotonalite displaying sericitised plagioclase, quartz, minor magnetite and thin hematite-filled veins. Slight foliation defined by quartz. Sample 2147277. (d) Alkali-feldspar granite displaying hematite stained feldspar, quartz, hematite veins and microcline. (e) North Beach alkali-feldspar granite (2149822) displaying foliation defined by brecciated, altered feldspars and quartz. (f) Black Rock alkali-feldspar granite (2149823) displaying abundance of biotite and amphibole, sericitised feldspars and minor magnetite. Mineral abbreviations: ser-alt feld, sericite-altered feldspar; bi, biotite; mt, magnetite; hem, hematite; ser-alt plag, sericite-altered plagioclase; qtz, quartz; mc, microcline; amph, amphibole.
samples (Figure 6a, b). The MgO, TiO₂, and Fe₂O₃ contents have steep negative trends at lower SiO₂ contents, which then become shallower with higher SiO₂ content (Figure 6c–e). Variable CaO and Na₂O content is evident with the nodules, syenite and alkali-feldspar granite phases, where the alkali-feldspar granite displays the lowest content for both (Figure 6f). The leuco-}

| Sample | Unit | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MnO | MgO | CaO | Na₂O | Total |
|--------|------|------|------|-------|-------|-----|-----|-----|------|-------|
| Syenite | 69.90 | 0.47 | 14.00 | 4.19 | 0.19 | 0.58 | 0.57 | 0.57 | 4.03 | 90.21 |
| Nodule | 70.80 | 0.48 | 14.35 | 4.69 | 0.20 | 0.51 | 0.85 | 0.85 | 4.11 | 90.91 |
| LOI    | 4.03  | 0.33 | 13.60 | 2.67 | 0.11 | 0.34 | 0.99 | 1.08 | 0.97 | 0.96 |

Trace and REE geochemical results are displayed in Figure 7 and Table 2. A positive correlation is evident in Th with increasing SiO₂ content, while a negative trend is observed
Figure 6. Major-element variation diagrams for samples from Point Riley. Sample location shown in Figure 2. Data from the Moonta (Creaser, 1989; Giles, 1980; Wurst, 1994), Olympic (Creaser, 1989; OZCHEM; SARIG), Wilgena (Stewart & Foden, 2003; SARIG) and Nuyts (Stewart & Foden, 2003; SARIG) domains are also shown for comparison.
for Sc, Zr and Ba (Figure 7a–d). Ce, La and Sr display a slight negative trend for the nodules and alkali-feldspar granite; however, no clear trend is seen in the other phases (Figure 7e–g).

Primitive mantle-normalised multi-element trace-element plots show well-defined patterns for each of the granite phases, and are characterised by positive anomalies in Rb, Th and Ta, and negative anomalies in Ba, Nb, P and Ti (Figure 8). There is a slight variance in the Zr content where all but three alkali-feldspar granite samples have a positive anomaly (Figure 8). Similarly, Pb shows a positive anomaly in all samples except one from each of the orange and alkali-feldspar granite phases that have slight negative anomalies.

Chondrite-normalised REE diagrams are presented in Figure 9. All samples show moderately steep REE patterns owing to relative enrichment in light REE (LREE), with moderate negative Eu anomalies (Eu/Eu" = 0.49–0.88; Figure 9; Table 2). The nodules display the highest REE enrichment, followed by the alkali-feldspar granite and syenite, then the leucotonalite (Figure 9). One sample from both the syenite and

Figure 7. Trace-element variation diagrams for samples from Point Riley. Sample locations shown in Figure 2. Data from the Moonta (Creaser, 1989; Giles, 1980; Wurst, 1994), Olympic (Creaser, 1989; OZCHEM; SARIG), Wilgena (Stewart & Foden, 2003; SARIG) and Nuyts (Stewart & Foden, 2003; SARIG) domains are also shown for comparison.
leucotonalite granite phases are relatively depleted in REE, have an overall flatter REE pattern and positive Eu anomalies when compared to other samples (Eu/Eu$^+$ = 1.08 and 1.28). This leucotonalite sample is mainly depleted in LREE, whereas the syenite sample displays depletion in few major elements, trace elements and all REE compared with samples within the same phase. REE fractionation (La/Yb)$_N$ plotted against Eu/Eu$^+$ (Figure 10) illustrates higher degrees of fractionation in the nodules, syenite and alkali-feldspar granite compared with the leucotonalite. The leucotonalite has consistently higher Eu values compared with the other granite phases and a broader range.

**Sm–Nd isotope analysis**

Sm–Nd isotope results for two intensely foliated syenites, one nodule, two leucotonalites and three alkali-feldspar granite samples are given in Table 3 and Figure 11. Initial $\varepsilon_{Nd(t)}$ values
were calculated at 1590, 1585 and 1580 Ma for the syenite, leucotonalite and alkali-feldspar granite phases, respectively, based on the known age of the Tickera Granite (ca 1598–1575 Ma; Conor, 1995) and interpreted relative timing of emplacement of the granite phases. $\varepsilon_{\text{Nd}(i)}$ values for the syenite and nodule are well grouped and range from −6.73 to −3.55. The leucotonalite and alkali-feldspar granite phases have broad $\varepsilon_{\text{Nd}(i)}$ values ranging from −9.78 to −2.42 and from −13.81 to −5.13, respectively. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios range between 0.1294 and 0.1390 for the syenite and nodules, 0.1296 and 0.1561 for the leucotonalite, and 0.1098 and 0.1663 for the alkali-feldspar granite. $T_{\text{DM}}$ values for the syenite and nodule range from 2804 to 2601 Ma, from 2771 to 2383 Ma for the leucotonalite and from 3079 to 2433 Ma for the alkali-feldspar granites (Table 3).

Discussion

Relative timing of emplacement of granitic phases

Granitic nodules, similar in appearance to those observed at Point Riley, have previously been described as granitic ‘corestones,’ which are spherical masses surrounded by weathered rock of the same composition (Hirata, Chen, & Chigira, 2016; Twidale & Vidal Romani, 2005). Corestones form as a result of chemical and physical weathering in hard uniform rocks with
well-developed joint patterns over an extended period of time. Joint patterns are not observed within the sample area but the northeast-trending foliation and northwest-trending cleavage present in the syenite could be acting as zones of weakness for weathering. The granitic nodules observed at Point Riley have similar mineralogy and deformation fabrics to their host, the syenite. However, they differ in degrees of relief and in chemistry, specifically REE, which can be attributed to physical and chemical weathering over an extended period (Figures 4a, b and 9; Table 2). The morphology of the nodules, which are distinctly located within the syenite, suggests that the nodules are corestones and are, therefore, the same phase as the syenite.

Contact relationships are commonly used to infer relative timing of emplacement of granitic phases. An example includes apophyses of the leucotonalite penetrating into the syenite (Figures 2b and 4d), indicating that the syenite was emplaced before the leucotonalite. Metasomatic alteration of the leucotonalite associated with emplacement of the alkali-feldspar granite is evident in the study area (Figures 2b and 4f–h). A raft of the leucotonalite is preserved within the alkali-feldspar granite and displays metasomatised boundaries (Figures 2b and 4g). This raft may be an independent enclave of leucotonalite within the alkali-feldspar granite, or it may be a horizontal section through a roof pendant. The syenite and alkali-feldspar granite have mostly sharp contacts. However, metasomatism in the northwestern corner of the study area is evident between the two phases, suggesting that metasomatism was coincident with the emplacement of the alkali-feldspar granite. The relative overprinting relationships suggest the intensely foliated syenite and nodules are the same phase and are the oldest granites exposed in the Point Riley area. These were intruded by the leucotonalite, and then the youngest phase, the alkali-feldspar granite.

### Petrogenesis of Point Riley granites

Geochemical data can be used to model the source and evolution of magmas, and determine whether a suite of granites have been derived from a single source, which has melted at different conditions, or have incorporated variable crustal/mantle components (Hertogen & Mareels, 2016; Winter, 2010). At Point Riley, the syenite and leucotonalite have a restricted range of SiO₂ content, whereas the alkali-feldspar

| Sample no. | Granite phase                | Age (Ma) | Sm (ppm) | Nd (ppm) | Sm/Nd/₁⁴³Nd | Nd/₁⁴⁴Nd | 2SE  | εNd(0) | εNd(i) | TDM (Ma) |
|------------|------------------------------|----------|----------|----------|-------------|---------|------|--------|--------|----------|
| 2147273    | Nodule                       | 1590     | 14.3     | 62.1     | 0.1390      | 0.511855 | 0.000002 | -15.27 | -3.55  | 2601     |
| 2147276    | Syenite                      | 1590     | 3.7      | 16.9     | 0.1315      | 0.511614 | 0.000001 | -19.98 | -6.73  | 2804     |
| 2147281    | Syenite                      | 1590     | 0.5      | 2.4      | 0.1294      | 0.511667 | 0.000011 | -18.94 | -5.25  | 2641     |
| 2147272    | Leucotonalite                | 1585     | 4.6      | 21.3     | 0.1296      | 0.511816 | 0.000001 | -16.04 | -2.42  | 2383     |
| 2147277    | Leucotonalite                | 1585     | 1.1      | 4.3      | 0.1561      | 0.511716 | 0.000003 | -17.98 | -9.78  | 2771     |
| 2147282    | Alkali-feldspar granite      | 1580     | 2.34     | 13.4     | 0.1098      | 0.511466 | 0.000002 | -22.85 | -5.29  | 2439     |
| 2149822    | Alkali-feldspar granite (North Beach) | 1580 | 0.8 | 2.9 | 0.1663 | 0.511619 | 0.000003 | -19.89 | -13.81 | 3079     |
| 2149823    | Alkali-feldspar granite (Black Rock) | 1580 | 15.5 | 84.7 | 0.1105 | 0.511482 | 0.000002 | -22.56 | -5.13  | 2433     |

₁⁴⁷Sm/₁⁴⁴Nd CHUR T = 0 = 0.1966; ₁⁴⁷Sm/₁⁴⁴Nd DM T = 0 = 0.2145; ₁⁴⁴Nd/₁⁴⁴Nd CHUR T = 0 = 0.512638; ₁⁴⁴Nd/₁⁴⁴Nd DM T = 0 = 0.513150 (Goldstein, Onions, & Hamilton, 1984).
granite has the broadest SiO₂ range, which overlaps with that of the syenite and leucotonalite (Figures 6 and 7). The variable SiO₂ content between the granite phases suggests they could be derived from different sources.

The syenite and alkali-feldspar granite phases are depleted in Ca and Na; however, the leucotonalite is enriched as a result of the high modal proportion of plagioclase in this phase, indicating it was derived from a more Ca–Na-rich magma (Figure 6f, g). Additionally, the syenite and alkali-feldspar granites are predominantly K-feldspar rich, as they were derived from a K₂O-rich magma, and also affected by metasomatism. The leucotonalite preserves relatively low Fe₂O₃ and variable Al₂O₃ contents (Figure 6a, e), which are likely a result of distinctive differences in mineralogy and alteration as the leucotonalite contains negligible amounts of K-feldspar or hematite alteration, unlike the other granite phases. Based on these differences in mineralogy and geochemistry, it is inferred that the leucotonalite is derived from a different source region to the syenite and alkali-feldspar granite phases or is from the same source, which has been melted under different conditions.

Enriched LREE content in granites is considered indicative of higher degrees of crustal contamination, melting and emplacement conditions. Overall, the nodules, syenite and alkali-feldspar granite phases exhibit similar REE patterns showing enriched LREE contents and high LREE/HREE ratios (Table 2; Figure 10). This supports the conclusion that these phases are from a similar crustal source region, although comparatively different REE patterns within the granite phases indicate the incorporation of variable sources (Figure 10). The leucotonalite preserves a significantly different REE pattern showing relatively lower LREE/HREE ratios compared with the other granite phases, suggesting the incorporation of a more mafic/mantle source.

One leucotonalite and one syenite sample (samples 2147277 and 2147281, respectively) display relatively flat to positive Eu anomalies and relatively low LREE/HREE ratios (Figure 10), suggesting the incorporation of a more mafic material or that they have been derived from a source that was characterised by positive Eu anomalies (Winter, 2010). These two samples are also close to the area where a high degree of metasomatism is observed, which could have affected the overall chemistry of the samples. Alternatively, the remainder of the samples are characterised by negative Eu anomalies, suggesting a crustal source and the fractionation of plagioclase during formation (Winter, 2010). Two alkali-feldspar granites and one nodule display high degrees of plagioclase fractionation but relatively low LREE/HREE ratios (Figure 10), which also implies incorporation of more mafic or lower crustal material into these phases. These interpretations suggest the granite phases do not solely have an evolved crustal source; rather a more variable source including amalgamation of a lower crustal and/or mafic/mantle material, or from the same source that has melted at different conditions to produce different plagioclase vs orthoclase feldspar ratios.

Sm–Nd isotopes can be used to determine the source region of magmas and the relative contribution of crustal vs mantle material (e.g. DePaolo, Perry, & Baldridge, 1992). The ƐNd(i) values for the samples analysed in this study cover a
broad range from –13.81 to –2.44 (Figure 11). Previously published $\varepsilon_{\text{Nd}}(t)$ values for samples of the Tickera Granite, which were taken from the same pluton in the Moonta region (Creaser, 1989; Giles, 1980; Wurst, 1994), show similar values despite having an older inferred crystallisation age (Figure 11). Overall, the phases of Tickera Granite in the Moonta region show increasingly negative $\varepsilon_{\text{Nd}}(t)$ values over the inferred timing of crystallisation. This is likely due to the assimilation and fractional crystallisation of the surrounding wall rock as the magma ascends and evolves. One sample of the leucotonalite has a more juvenile $\varepsilon_{\text{Nd}}(t)$ value (–2.42: 2147272) than the other granite phases, indicating some input from a more mafic source or mantle material. Overall, the mineralogy, geochemical and isotopic data for the Tickera Granite suggest that the nodules, syenite and alkali-feldspar granite phases are from a similar source, and the leucotonalite is from a different, more mafic source region.

Possible sources for the Tickera Granite in the Moonta Domain includes the underlying Wallaroo Group, Donington Suite, migmatitic gneisses of the Corny Point Paragneiss and the underlying Archean basement (Zang & Fanning, 2001; Zang et al., 2007). The variable REE content of the Tickera Granite phases suggests input from a crustal source of variable nature, e.g. metasediments/metasedimentary source, or a variable mixture of two or more sources. The Wallaroo Group is metasedimentary in composition and therefore has the potential to produce a melt with a variable REE content (and therefore $\varepsilon_{\text{Nd}}$ values). Metasedimentary xenoliths are also preserved within the syenite, supporting the suggestion that Wallaroo Group rocks were incorporated into this granite phase. There are currently no $\varepsilon_{\text{Nd}}$ data available for the Wallaroo Group, so it is difficult to assess the potential input. Similarly, the Donington Suite comprises igneous rocks of mafic to felsic composition, which also has the potential to produce variable REE content and $\varepsilon_{\text{Nd}}$ values. The $\varepsilon_{\text{Nd}}$ values for the Donington Suite partially overlap with the Point Riley samples (Figure 11), and are generally relatively juvenile, so it is unlikely to be the sole source of the Tickera Granite. The $\varepsilon_{\text{Nd}}$ values of Archean basement (the Mesaoarchean Cooyerdoo Granite and Neoarchean Sleaford Complex) range from approximately –24 to –8 at 1600–1560 Ma (Fraser et al., 2010; Swain et al., 2005; Turner, Foden, Sandiford, & Bruce, 1993; Figure 11) and are significantly more evolved than the majority of the samples analysed in this study (Figure 11).

Based on the available $\varepsilon_{\text{Nd}}$ and REE data, it is suggested that the Tickera Granite may be derived from the Donington Suite and/or Wallaroo Group with some input from the mantle, and a more mafic or lower crustal source, which could potentially be the underlying Archean basement.

**Comparison with the broader Hiltaba Suite**

The Tickera Granite is generally inferred to be part of the ca 1595–1575 Ma Hiltaba Suite granites (e.g. Conor, 1995; Conor et al., 2010). Comparison of whole-rock geochemical data for samples of the Tickera Granite collected in this study with published data from other Hiltaba-aged granites of the Moonta Domain shows similar trends (Figure 1b). Major- and trace-element data generally overlap, except for a cluster of samples for the Moonta Domain that are lower in SiO$_2$, but elevated in P$_2$O$_5$, MgO and TiO$_2$ (Figure 6b–d), and Sc, Zr, Ce and La (Figure 7b, e, f). These differences are likely a result of the variation of different Hiltaba-aged granite phases in the Moonta region.

Comparison of the Tickera Granite samples from this study with the broader Hiltaba Suite granites from the Olympic, Wilgena and Nuyts domains (Figure 1b) shows that the data define similar linear trends for most major- and trace elements. Differences in chemistry of Hiltaba Suite granites between domains have previously been studied by Stewart and Foden (2003). The Moonta Domain is considered to preserve elevated Th concentrations, and depleted CaO, Sr and MnO concentrations compared with the rest of the suite. The samples used in this study generally support this interpretation however, only half of the Point Riley and Moonta samples display elevated Th, CaO and Sr concentrations compared with the rest of the Hiltaba Suite. The leucotonalite mapped at Point Riley has elevated Na$_2$O and depleted K$_2$O concentrations compared with other data from the Tickera Granite and broader Hiltaba Suite, apart from three or four samples from the Moonta Domain and three samples from the Wilgena Domain (Figure 6k), which is attributed to this phase being plagioclase rich. In general, the plagioclase-rich nature of the leucotonalite contrasts with the typically K-feldspar-rich nature of the Hiltaba Suite (e.g. Daly et al., 1998; Stewart & Foden, 2003). Data in this study have also shown that the leucotonalite is from a different source to the other phases observed at Point Riley. Comparison of $\varepsilon_{\text{Nd}}$ signatures of the Tickera Granite samples of this study with the broader Hiltaba Suite granites shows that the data are broadly comparable (Figure 11).

Overlapping geochronological ages, in conjunction with similar major, trace-element and isotopic data between the Tickera Granite and the majority of the Hiltaba Suite, support the notion that the Tickera Granite is part of the broader Hiltaba Suite. However, it is noted that there are localised phases within the Moonta Domain (including the Tickera Granite) and Wilgena Domain that suggest they were derived from a different source region compared with the broader Hiltaba Suite. This is supported by Stewart and Foden (2003) who suggested that the Hiltaba Suite is a combination of mantle and crustal material, with the crustal component being less than 30%, and variations related to different amounts of compositions of mantle and crustal endmembers.

**Structural fabrics and deformation style within Yorke Peninsula**

A strongly developed northeast-trending structural grain across Yorke Peninsula is obvious from aeromagnetic imagery north of Curramulka, where long-limbed, upright, tight to isoclinal folds with northeast-trending fold axial planes have been described, and suggests northwest–southeast-directed shortening (Conor, 2016, figure 4). Deformation on northern
Yorke Peninsula has been attributed to different structural events resulting in folding, shearing and the development of conjugate and other faults (Figures 1c; Arcaro, 2000; Conor, 2002, 2016; Conor et al., 2010; Parker et al., 1993; Wurst, 1994; Zang, 2006). Reworking of faults and sheared zones, such as those visible at Point Riley and the Wheal Hughes and the Poona mines, indicates that the northeast-trending fabric is related to composite structures, and has facilitated mineralisation in the region that is broadly coincident with the intrusion of the Hiltaba Suite granites (Conor et al., 2010). Few studies have been carried out to compare the timing of structural fabrics preserved within the Tickera Granite to the surrounding metasediments of the Wallaroo Group, or to constrain the timing of deformation in northern Yorke Peninsula (e.g. Arcaro, 2000; Conor et al., 2010; Wurst, 1994).

Depth of emplacement and timing of deformation

Structures preserved within granite phases such as miarolitic cavities, foliations and cleavages can be indicative of depth of emplacement (Petford, 2003; Winter, 2010). Miarolitic cavities, known to develop during uplift as pockets of gas expand within a magma, are present in the alkali-feldspar granite (Figures 2b and 4i; Petford, 2003). Therefore, it is suggested that the alkali-feldspar granite may have been emplaced during a period of late uplift. Similarly, at higher metamorphic grades, foliations develop, while cleavages form at lower metamorphic grades, assuming no variations in geothermal gradients (Winter, 2010). The northeast-trending foliations preserved predominantly in the syenite and poorly in the leucotonalite suggest these granite phases were emplaced deeper in the crust compared with alkali-feldspar granite. The alkali-feldspar granite bears a local northeast-trending cleavage, supporting the interpretation that it was emplaced at a shallower crustal level. This same northeast-trending cleavage is also prominent in the leucotonalite, suggesting that variations in the intensity of development of the cleavage relate to variation in rheology between the granite phases and were possibly influenced by the earlier foliation when developing higher in the crust.

From limited exposures and drill core, it would appear that the Tickera Granite is generally not deformed; however, the coastal strip from North Beach to Tickera, which includes Point Riley, exposes a zone of high strain (Conor, 2016, plate 38; Conor et al., 2010; Wurst, 1994). Development of Type 3 fold interference patterns implies that the axial trace of the earlier fold generation was sub-parallel to the axial trace of the overprinting fold generation, and that the axial plane of the folds were at a high angle (Ramsay, 1962). The mechanism for development of recumbent folds with a northeast-trending axial trace is consistent with northeast–southeast-directed shortening. Critically, the axial fracture cleavage of the later upright folds focusses a calc-silicate alteration assemblage, which, being similar to that observed around granite stocks, suggests that some fold deformation was broadly coincident with the introduction of the Hiltaba Suite (Conor et al., 2010). The axial trace of the folds observed at Wallaroo North Beach and on aeromagnetic imagery is in the same orientation as the dominant northeast-trending foliations and cleavage in the granite phases at Point Riley, suggesting the structures are the result of the same deformation event.

Examples from diamond drill core of alteration assemblages having invaded the axial regions of folds and intensely foliated zones are indicative of the broadly coeval relationship of deformation and the intrusion of the Hiltaba Suite (Conor et al., 2010). The same structural relationship can be observed in the case of mineralisation, e.g. the Moonta and Wallaroo mines, and the Hillside Prospect (Conor et al., 2010). Viewed
from a regional perspective, the timing of deformation, metamorphism and mineralisation seen in the Yorke Peninsula shows a very similar history to other regions in southern Proterozoic Australia during the ca 1600–1580 Ma time slice, particularly the Curnamona Province (e.g. Conor, 2016; Conor et al., 2010; Forbes et al., 2008, 2012; Hand et al., 2007; Page et al., 2005; Figure 12).

**Relationships with the eastern Gawler Craton and the Curnamona Province**

The late Paleo to early Mesoproterozoic marked a significant period of metamorphism, deformation, magmatism and mineralisation within eastern Proterozoic Australia (e.g. Betts et al., 2002; Collins & Shaw, 1995; Forbes et al., 2008, 2012; Giles & Nutman, 2002; Hand et al., 2007; Stewart & Betts, 2010). Within southern Proterozoic Australia, this event is unnamed, but is recognised within the Gawler Craton (e.g. Cutts, Hand, & Kelsey, 2011; Forbes et al., 2011, 2012; Hand et al., 2007; Morrissey, Hand, Raimondo, & Kelsey, 2014; Szpunar, Wade, Hand, & Barovich, 2007), and is identified as the ca 1600–1585 Ma Olarian Orogeny within the Curnamona Province (e.g. Connor, 2016; Connor et al., 2010; Forbes et al., 2008; Page et al., 2005; Figure 12). It was during this period that mineralisation and related alteration was imposed upon both the eastern Gawler Craton and western Curnamona Province. Correlation between the southeastern and northern Gawler Craton and the Curnamona Province has previously been suggested (e.g. Hand, Reid, Jagodzinski, Kelsey, & Pearson, 2008; Preiss, 2012; Szpunar et al., 2007); however, detail of any direct comparison on deformation regimes within the Yorke Peninsula during the 1600–1580 Ma time period is limited.

Within the northern Gawler Craton, the metamorphic regime at ca 1600–1580 Ma is well defined (e.g. Cutts et al., 2002; Collins & Shaw, 1995; Forbes et al., 2008, 2012; Giles & Nutman, 2002; Hand et al., 2007; Stewart & Betts, 2010), but the deformational regime is not. Deformation within the Mount Woods Inlier in the northeastern Gawler Craton (Figure 1b) may have resulted in development of isoclinal folds during the Kimban Orogeny (Betts, Hand, & Kelsey, 2011; Forbes et al., 2011, 2012; Morrissey et al., 2014; Szpunar et al., 2007), or leading up to/synchronous with emplacement of the ca 1584 Ma Balta Granite Suite (O’Sullivan, 2010). Subsequent deformation involved the uplift and exhumation of the Mount Woods Inlier along the Southern Overthrust, which was initiated at ca 1592–1582 Ma (Forbes et al., 2012). Although the timing of the early isoclinal folding event in the Mount Woods Inlier is conjectural, it shares similarities to the
early deformation history observed in the Yorke Peninsula. However, later generation of open upright folds similar to that observed in the Yorke Peninsula has not been recognised in the Mount Woods Inlier. Overall, the lack of constraint on the Proterozoic deformational regime of the Gawler Craton makes correlation with the deformation history of the Yorke Peninsula difficult.

The geological history of the Curnamona Province (Figure 1b) at 1600–1580 Ma is better constrained and shows a similar history to the Yorke Peninsula. Early isoclinal, recumbent (nappe) folds are interpreted to have developed during northwest-directed thrusting. The early folds were overprinted by northeast-trending, open, upright folds during upper amphibolite to granulite-facies metamorphism as a result of northwest–southwest-directed shortening and are associated with magnetite-bearing calcsilicate alteration (Forbes, Betts, & Lister, 2004; Forbes, Betts, Weinberg, & Buick, 2005; Forbes, Giles, Betts, Weinberg, & Kinny, 2007; Hobbs, Archibald, Etheridge, & Wall, 1984; Marjoribanks, Rutland, Glen, & Laing, 1980; Page et al., 2005). In the northern Broken Hill Inlier, overprinting of the fold generations led to the development of Type 2 and Type 3 fold interference patterns. The generation of open upright folds is also responsible for the dominant north–south-structural grain throughout the Broken Hill Block. Granites intruded the Curnamona Province synchronously with, and immediately following, the deformation events and include the ca 1600–1570 Ma Ninnerie Supersuite (Page et al., 2005; Wade, 2011), which was emplaced during the generation of the later upright folds (Gibson, Peljo, & Chamberlain, 2004). Granites of the Ninnerie Supersuite are suggested to be temporal equivalents of the 1595–1575 Ma Hiltaba Suite (Conor, 2016; Conor et al., 2010; Hand et al., 2008), although of different composition.

From a regional perspective, the timing and history of deformation, alteration and mineralisation evident in the southeastern Gawler Craton are strikingly similar to the Curnamona Province to the east. Both regions have nappe-scale isoclinal folds overprinted by northeast-trending upright folds that are associated with magnetite-bearing calcsilicate alteration, and a northeast-trending structural grain across the region. Additionally, the timing of granite intrusion associated with these deformation events and mineralisation is similar between the regions, as the Ninnerie Supersuite is considered to be an equivalent of the Hiltaba Suite. These newly recognised correlations between the Yorke Peninsula, the Curnamona Province and, in part, the Mount Woods Inlier show the common influence of intense deformation, metamorphism, alteration and mineralisation at the ca 1600–1580 Ma time slice and directly confirm that the footprint of the system extends to the southern Gawler Craton.

Conclusions

The Tickera Granite is part of the broader Hiltaba Suite and comprises three phases; an early intensely foliated syenite that was intruded by a leucotonalite and a later alkali-feldspar granite. These localised phases differ compositionally, geochemically and isotopically, suggesting a heterogeneous source region. The leucotonalite originated from a similar source but with the incorporation of mafic/mantle material. Derivation of the Tickera Granite is likely from the Donington Suite and/or Wallaro Granite, with minor contamination from the underlying Archean basement.

The intrusion of the Tickera Granite and dominant northeast-trending structural grain seen is associated with mineralisation throughout the region. Structural fabrics observed in the granite phases at Point Riley are attributed to different structural events resulting in folding, shearing and faults, stemming from southeast–northwest compressional stress applied over a long period of time. Deformation preceded the intrusion of the Tickera Granite, but also continued through and after emplacement.

The Yorke Peninsula shares a very similar deformational and magmatic history to the ca 1600–1585 Ma Olarian Orogeny in the Curnamona Province and has been correlated with that event.

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References

ALS Database. Retrieved from https://www.alsglobal.com/myals/downloads
Arcaro, H. D. (2000). Structure of the Proterozoic assemblages of Point Riley and North Beach: Tectonic environment of formation. BSc (Hons.) thesis, unpublished. Clayton Vic: Monash University.
Belpiero, A., Flint, R., & Freeman, H. (2007). Prominent Hill: A hematite-dominated, iron oxide copper–gold system. Economic Geology, 102, 1499–1510.
Bendall, B. (1994). Metamorphic and geochronological constraints on the Kimban Orogeny, southern Eyre Peninsula; unpublished Bsc (Hons) thesis, Adelaide: University of Adelaide.
Betts, P. G., Giles, D., Foden, J., Schaefer, B. F., Mark, G., Pankhurst, M. J., … Hills, Q. G. (2009). Mesoproterozoic plume modified orogenesis in eastern Precambrian Australia. Tectonics, 28, 1–28, doi: 10.1029/2008TC002325
Betts, P. G., Giles, D., Lister, G. S., & Frick, L. R. (2002). Evolution of the Australian lithosphere. Australian Journal of Earth Sciences, 49(4), 661–695
Betts, P. G., Valenta, R. K., & Finlay, J. (2003). Evolution of the Mount Woods Inlier, northern Gawler Craton, Southern Australia: An integrated structural and aeromagnetic analysis. Tectonophysics, 366, 83–111.
Budd, A., & Skirrow, R. (2007). The Nature and Origin of Gold Deposits of the Tarcoola Goldfield and Implications for the Central Gawler Gold Province, South Australia. Economic Geology, 102(8), 1541–1563.
Collins, W. J., & Shaw, R. D. (1995). Geochronological constraints on orogenic events in the Arunta Inlier: A review. Precambrian Research, 71(1–4), 315–346.
Conor, C. H. H. (1995). Moonta–Wallaroo Region – An interpretation of the geology of the Maitland and Wallaroo 1:100 000 sheet areas. Open file Envelope 8886. Adelaide SA: Department of Primary Industries and Resources South Australia.
Conor, C. H. H. (2002). The Palaeo–Mesoproterozoic geology of northern Yorke Peninsula, South Australia: Hiltaba Suite-related alteration and mineralisation of the Moonta–Wallaroo Cu–Au District. Report Book 2002/007. Geological Field Guidebook, Geological Survey of South Australia.

Conor, C. H. H. (2016). Geological Field Excursion Guide — IOCGs – Where it all began: The Moonta–Wallaroo region of the eastern Gawler Craton. Report Book 2016/00009. Adelaide SA: Department of State Development, South Australia; and Geological Society of Australia, South Australian Division.

Conor, C., Raymond, A. L., Baker, T., Teale, G., Say, P., & Lowe, G. (2010). Alteration and Mineralisation in the Moonta–Wallaroo Copper–Gold Mining Field Region, Olympic Domain, South Australia. Hydothermal Iron Oxide Copper–Gold and Related Deposits, 3, 147–170.

Cooper, J. A., Mortimer, G. E., Rosier, C. M., & Uppill, R. K. (1985). Gawler Range magmatism—further isotopic age data. Australian Journal of Earth Sciences, 32, 115–123

Cowley, W. M., Conor, C., & Zang, W. L. (2003). New and revised Proterozoic stratigraphic units on northern Yorke Peninsula. MESA Journal, 29, 46–58

Creaser, R. A. (1989). The geology and petrology of middle Proterozoic felsic magmatism of the Stuart Shelf, South Australia. Unpublished PhD thesis. Melbourne, Vic: LaTrobe University.

Creaser, R. A., & Cooper, J. A. (1993). U–Pb Geochronology of Middle Proterozoic Felsic Magmatism Surround the Olympic Dam Cu–U–Au–Ag and Moonta Cu–Au–Ag deposits, South Australia. Economic Geology, 88, 186–197

Cutts, K. A., Hand, M., & Kelsey, D. E. (2011). Evidence for early Mesoproterozoic (ca. 1590 Ma) ultrahigh-temperature metamorphism in southern Australia. Lithos, 124, 1–16.

Daly, S. J., & Fanning, C. M. (1993). Archaean. In J. F. Drexel, W. V. Preiss, & Cutts, K. A., Hand, M., & Kelsey, D. E. (2011). Evidence for early Mesoproterozoic evolution of the Gawler Craton, South Australia. Bulletin 54.

Daly, S. J., Fanning, C. M., & Fairclough, M. C. (1998). Tectonic evolution and exploration potential of the Gawler craton, South Australia. AGSO Journal of Australian Geology and Geophysics, 17, 145–168.

Dentith, M. (Ed.) (2003). Geophysical signatures of South Australian mineral deposits. Nedlands, WA: Centre for Global Metallogeny, The University of Western Australia, Australian Society of Exploration Geophysicists, Primary Industries & Resources South Australia.

DePaolo, D., Perry, F., & Baldridge, W. (1992). Crustal versus mantle sources of granitic magmas: A two-parameter model based on Nd isotopic setting of prograde metamorphism: An example from the northeastern Gawler Craton, South Australia. Precambrian Research, 185, 65–85.

Dutch, R., Hand, M., & Kinny, P. D. (2008). High-grade Paleoproterozoic reworking in the southeastern Gawler Craton, South Australia. Australian Journal of Earth Sciences, 55, 1063–1081.

Fanning, C. M. (1993). Ion-microprobe U–Pb zircon dating of the Mount Woods Inlier, Preliminary Results (Unpublished). Research School of Earth Sciences, Australian National University, 8 pp.

Fanning, C. M. (1997). Geochronological synthesis of southern Australia: Part II, The Gawler Craton. Department of Primary Industries and Resources, Adelaide, South Australia (pp. 24–76). ENV 08918 (unpublished).

Fanning, C. M., Flint, R. B., Parker, A. J., Ludwig, K. R., & Blissett, A. H. (1998). Refined Proterozoic evolution of the Gawler Craton, South Australia, through U–Pb zircon geochronology. Precambrian Research, 40(141), 363–386.

Fanning, C. M., Reid, A., & Teale, G. (2007). A geochronological framework for the Gawler Craton, South Australia. Adelaide, SA: Geological Survey, Bulletin 55.

Ferris, G. M., Schwarz, M. P., & Heithersay, P. (2002). The geological framework, distribution and controls of Fe-oxide and related alteration, and Cu–Au mineralisation in the Gawler craton, South Australia. Part I: Geological and tectonic framework. In T. M. Porter (Ed.), Hydothermal iron oxide copper–gold and related deposits: A global perspective, 2 (pp. 9–31): Adelaide, SA: Porter GeoConsultancy Publishing.

Finlay, J. (1993). Structural interpretation of the Mount Woods Inlier. Honours Thesis (unpub.), Clayton Vic: Monash University.

Flint, R. B., Blissett, A. H., Conor, C. H. H., Cowley, W. M., Cross, K. C., Creaser, R. A., Daly, S. J., Krieg, G. W., Major, R. B., Teale, G. S., & Parker, A. J. (1993). Mesoproterozoic. In J. F. Drexel, W. V. Preiss, & A. J. Parker (Eds.), The Geology of South Australia: Volume I, The Precambrian (pp. 166–169). Adelaide, SA: South Australia Geological Survey, Bulletin 54.

Forbes, C. J., & Betts, P. G. (2004). Development of Type 2 fold interference patterns in the Broken Hill Block: Implications for strain partitioning across a detachment during the Oligo-Miocene. Australian Journal of Earth Sciences, 51, 173–188.

Forbes, C. J., Betts, P. G., & Lister, G. S. (2004). Synchronous development of Type 2 and Type 3 fold interference patterns: Evidence for recumbent shear folds in the Allendale Area, Broken Hill, NSW, Australia. Journal of Structural Geology, 26, 113–126

Forbes, C. J., Betts, P. G., Giles, D., & Weinberg, R. (2008). Reinterpretation of the tectonic context of high-temperature metamorphism in the Broken Hill Block, NSW, and implications on the Palaeo- to Mesoproterozoic evolution. Precambrian Research, 166, 338–349.

Forbes, C. J., Giles, D., Betts, P. G., Weinberg, R., & Kinny, P. (2007). Dating prograde amphibolite and granulate facies metamorphism in the Broken Hill Block, NSW, using in situ monazite U–Pb SHRIMP analysis. Journal of Geology, 115, 691–705.

Forbes, C. J., Giles, D., Hand, M., Betts, P. G., Suzuki, K., Chalmers, N., & Dutch, R. (2011). Using P–T paths to interpret the tectonothermal setting of prograde metamorphism: An example from the northeastern Gawler Craton, South Australia. Precambrian Research, 185, 65–85.

Forbes, C. J., Giles, D., Jourdan, F., Sato, K., Omori, S., & Bunch, M. (2012). Cooling and exhumation history of the northeastern Gawler Craton, South Australia. Precambrian Research, 200–203, 209–238.

Forbes, C. J., Betts, P. G., Weinberg, R., & Buick, I. S. (2005). Metamorphism and high temperature shear zones in the Broken Hill Block, NSW, Australia. Journal of Metamorphic Geology, 23, 745–770.

Fraser, G., McAvaney, S., Neumann, N., Szpunar, M., & Reid, A. (2010). Discovery of early Mesoproterozoic crust in the eastern Gawler Craton. South Australia: Precambrian Research, 179, 1–21.

Fraser, G. L., & Neumann, N. (2010). New SHRIMP U–Pb zircon ages from the Gawler Craton and Curnamona Province, South Australia, 2008–2010. Canberra, ACT: Geoscience Australia, Record 2010/16.

Gibson, G. M., Peljo, M., & Chamberlain, T. (2004). Evidence and timing of crustal extension versus shortening in the early tectonothermal evolution of a Proterozoic continental rift sequence at Broken Hill, Australia. Tectonics, 23, TCS012. doi:10.1029/2003TC001552

Giles, C. W. (1980). A comparative study of Archaean and Proterozoic felsic volcanic associations in southern Australia. PhD thesis, University of Adelaide.

Giles, D., & Nutman, A. P. (2002). SHRIMP U–Pb monazite dating of 1600–1580 Ma amphibolite facies metamorphism in the southeastern Mt Isa Block, Australia. Australian Journal of Earth Sciences, 49, 455–465.

Goldstein, S. L., Onions, R. K., & Hamilton, P. J. (1984). A Sm–Nd isotopic study of atmospheric dusts and particulates from major river systems. Earth and Planetary Science Letters, 70(2), 221–236.

Hand, M., Reid, A., & Jagodzinski, E. (2007). Tectonic Framework and Evolution of the Gawler Craton, Southern Australia. Economic Geology, 102, 1377–1395.

Hand, M., Reid, A., Jagodzinski, E., Kelsey, D., & Pearson, N. (2008). Paleoproterozoic orogenesis in the southeastern Gawler Craton, South Australia. Australian Journal of Earth Sciences, 55(4), 449–471. doi: 10.1080/08120090801888954

Hertogen, J., & Mareels, J. (2016). SimMush: A procedure for modeling of the geochemical evolution of silicic magmas and granitic rocks. Geochimica et Cosmochimica Acta, 185, 498–527. https://doi.org/10.1016/j.gca.2016.04.044
Implications for Cu–Au mineralisation in the “Copper Triangle” of South Australia. Bsc (Hons) thesis, unpublished. Adelaide SA: University of Adelaide.

Zang, W. L. (2006). *Maitland Special, South Australia, Map Sheets SI53-12 and portion SI53-16, Geological Atlas 1:250 000 Series, Explanatory Notes*. Adelaide, SA: Geological Survey of South Australia.

Zang, W., & Fanning, C. M. (2001). Age of the Kimban Orogeny revealed – U–Pb dates on the Corny Point Paragneiss, Yorke Peninsula, South Australia. *MESA Journal*, 23, 28–33

Zang, W., Fanning, C. M., Purvis, A. C., Raymond, O. L., & Both, R. A. (2007). Early Mesoproterozoic bimodal plutonism in the southeastern Gawler Craton. *South Australia: Australian Journal of Earth Sciences*, 54, 661–674.