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REPORT
150

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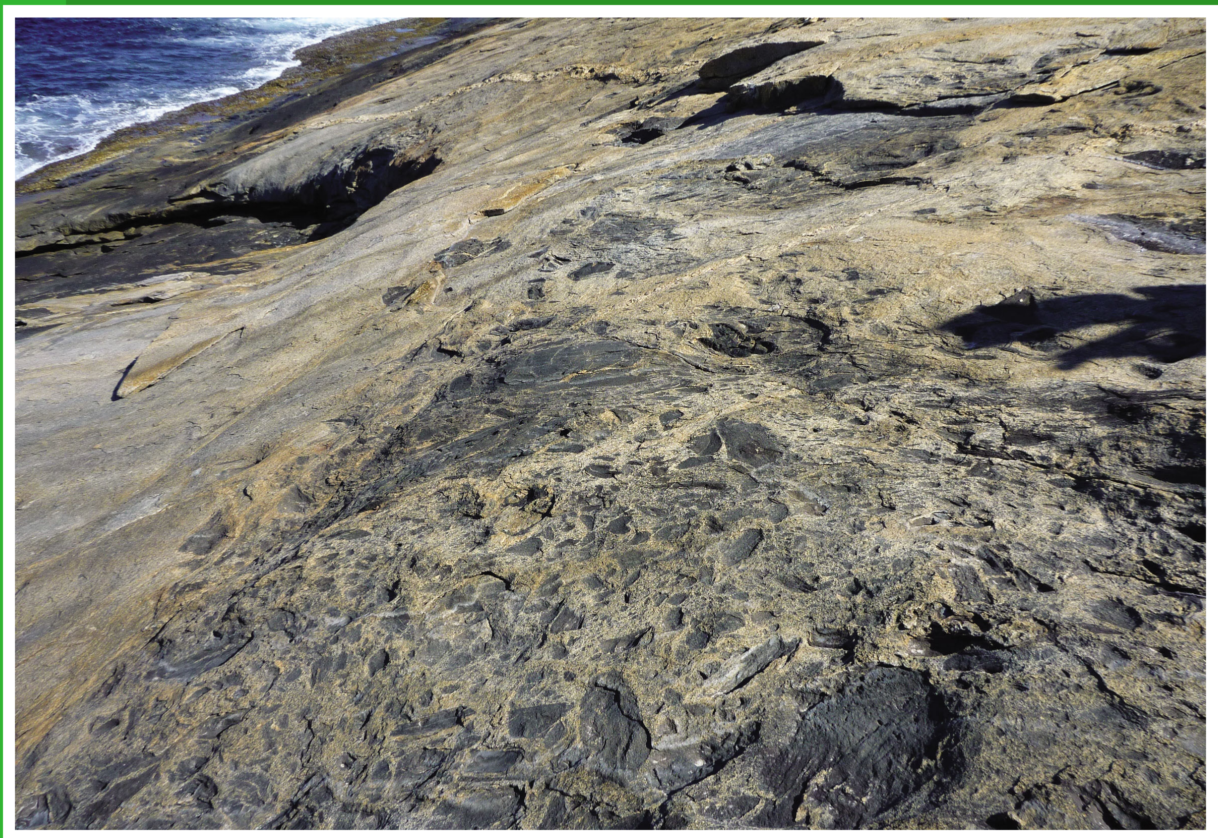

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RH Smithies, CV Spaggiari, and CL Kirkland

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Geological Survey of Western Australia

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Cover photograph: Foliated metagranite (metasyenogranite of the Gora Hill Suite – Recherche Supersuite) with sheets and veins of net-veined granite, and abundant mafic pods with foliations in random orientations, suggesting they have been rotated during intrusion. Coastal outcrops along Thomas River headland, Cape Arid National Park.

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Building the crust of the Albany–Fraser Orogen: constraints from granite geochemistry

by

RH Smithies, CV Spaggiari, and CL Kirkland

Abstract

A whole-rock geochemical dataset (156 analyses) of granites from the Albany–Fraser Orogen, of which roughly half have also been dated using U–Pb zircon geochronology, allows identification of spatial and temporal changes in granite compositions. This information constrains models for the crustal evolution of the Albany–Fraser Orogen. Twelve granite age groups are identified, spanning crustal evolution events from the Archean to the c. 1140 Ma end of the Albany–Fraser Orogeny. Throughout that period, the dominant geochemical and isotopic trend is to increasingly mask, although not destroy, the Archean heritage of the orogen through processes of crustal reworking and mantle-melt addition. The prevailing tectonic regime likely involved crustal thinning, with periodic mid-crustal melting of various, originally deep crustal, source regions. At times, this was at unusually high crustal temperatures. Granites that formed at c. 1330 Ma, near the beginning of the Albany–Fraser Orogeny, have sampled source regions belonging to the Madura Province, which lies to the southeast of the Albany–Fraser Orogen. This magmatism most likely post-dates accretion of the c. 1410 Ma Loongana arc (Madura Province) to the Albany–Fraser Orogen.

KEYWORDS: granite, crustal evolution, geochemistry, Archean, Proterozoic

Introduction

The Albany–Fraser Orogen is a component of the West Australian Craton and lies along the southern and southeastern margins of the Archean Yilgarn Craton (Fig. 1). Like other orogenic belts that surround the Yilgarn Craton, the Albany–Fraser Orogen is dominated by Paleoproterozoic to Mesoproterozoic granites formed through a complex series of events. These events involved variable recycling of a range of existing crustal components and periods of crustal refertilization through juvenile mantle input. The complex series of events means that the ensuing record of crustal evolution of these 'circum-Yilgarn' orogens is typically cryptic, and their study is further complicated by vast regions of scarce outcrop. One of the most fruitful ways of deciphering the crustal evolution of geologically complex regions is by tracing the compositional evolution of igneous rocks through time and space. Like any other field-based approach, this is obviously directly limited by the availability of suitable outcrop, or drillcores. A database of whole-rock analyses of granites from the central and east Albany–Fraser Orogen provides a wealth of information that can place critical constraints on models used to assess the tectonic evolution of the region. The dataset used here includes 156 whole-rock analyses of granites available from the WACHEM database (geochem.dmp.wa.gov.au/geochem/), including 84 samples dated by SIMS U–Pb zircon geochronology (www.dmp.wa.gov.au/geochron/), covering more than 120 000 km^2 of the central and east Albany–Fraser Orogen. Throughout this Report, the term 'granite' (senso lato) refers to all originally intrusive felsic rocks, irrespective of subsequent metamorphic or structural history. Specific reference is made to 'gneiss' and 'orthogneiss', where appropriate.

Regional setting

This section provides an overview of the geology of the Albany–Fraser Orogen, with emphasis on the nature and stratigraphic relationships of granitic magmatism during each of the recognized tectonic events that have shaped the orogen. The magma-producing tectonic events currently recognized include the 1815–1800 Ma Salmon Gums Event, the 1780–1760 Ma Ngadju Event, the 1710–1650 Ma Biranup Orogeny, and the Albany–Fraser Orogeny, which can be divided into two stages — Stage I from 1330 to 1260 Ma and Stage II from 1225 to 1140 Ma. Thus, the production of voluminous granites has persisted throughout the tectonic evolution of the region, so understanding granite sources, the nature and extent of magma types, and their role in tectonic processes is crucial to understanding how the region evolved. The majority of these granites are metamorphosed, and contain deformation-related fabrics. An overview of the Madura Province is also provided because of its significance before and during the Albany–Fraser Orogeny (Fig. 2).

Stratigraphic framework and tectonic events of the Albany–Fraser Orogen

The Albany–Fraser Orogen comprises two main tectonic units that reflect its relationship to the Yilgarn Craton — the Northern Foreland and the Kepa Kurl Booya Province (Figs 1 and 2). The Northern Foreland comprises reworked Archean Yilgarn Craton, and in general overlies the non-reworked part of the craton in various thrust sheets (Spaggiari et al., 2014c). The Kepa Kurl Booya Province (Spaggiari et al., 2009) is defined as the crystalline basement of the Albany–Fraser Orogen and includes four, fault-bound geographical and structural zones (Tropicana, Biranup, Fraser and Nornalup) that contain rocks with variable protolith ages and geological histories that are interpreted to reflect moderate to heavy modification of pre-existing Archean Yilgarn Craton crust (Spaggiari et al., 2011, 2014b; Occhipinti et al., 2014; Kirkland et al., 2014a). Three sedimentary basins are recognized: the 1815–1600 Ma Barren Basin, the 1600–1305 Ma Arid Basin, and the 1280–1215 Ma Ragged Basin (Spaggiari et al., 2014b; Waddell, 2014).

The easternmost extent of the east Albany–Fraser Orogen is defined by the east-dipping Rodona Shear Zone, which separates the orogen from the Madura Province (Figs 1 and 2; Spaggiari et al., 2012; 2014c). The eastern Nornalup Zone is separated from the Fraser Zone by the northwest-dipping Newman and Boonderoo Shear Zones, and from the eastern Biranup Zone by a wide network of southeast-dipping shear zones including the Red Island, Coramup and Heywood–Cheyne Shear Zones (Spaggiari et al., 2014c).

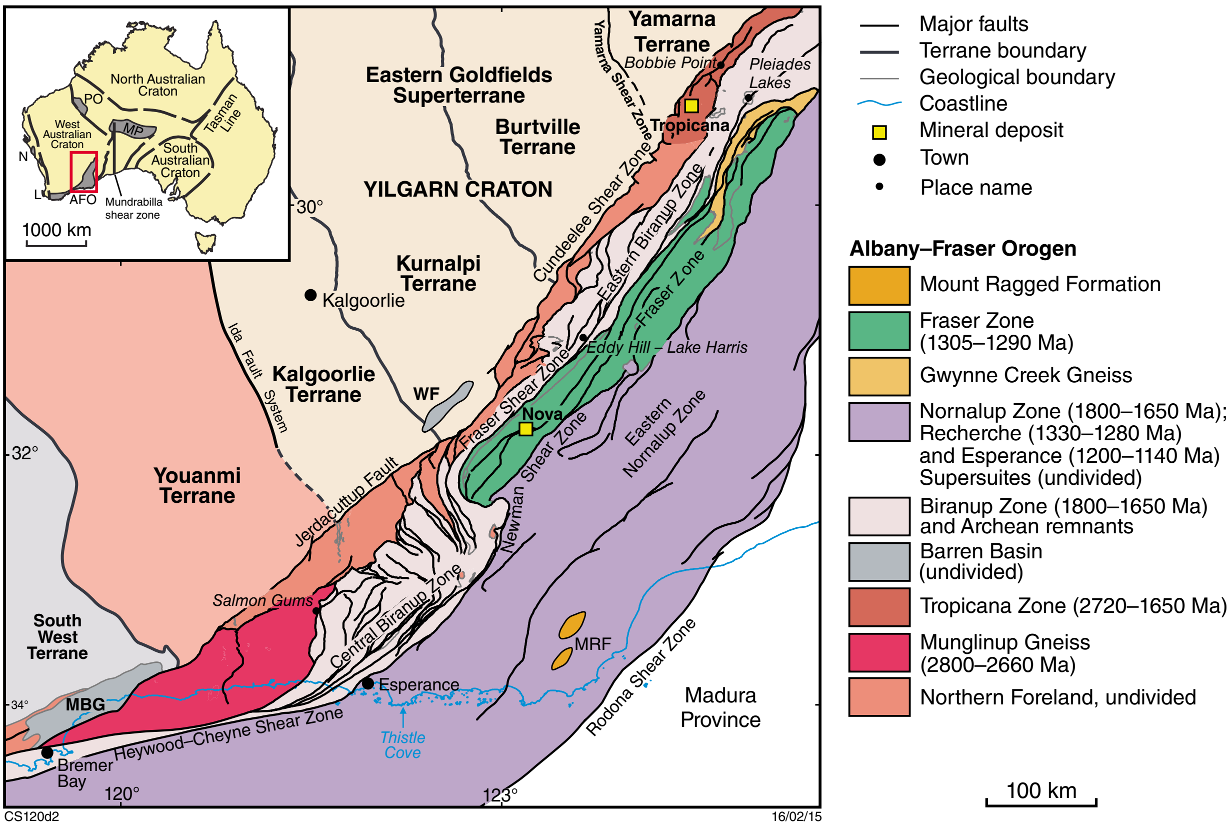


Figure 1. **Simplified, pre-Mesozoic interpreted bedrock geology of the east Albany–Fraser Orogen and tectonic subdivisions of the Yilgarn Craton (modified from Spaggiari et al., 2014a). Abbreviations used: MRF = Mount Ragged Formation; Inset PO = Paterson Orogen; MP = Musgrave Province; AFO = Albany–Fraser Orogen**

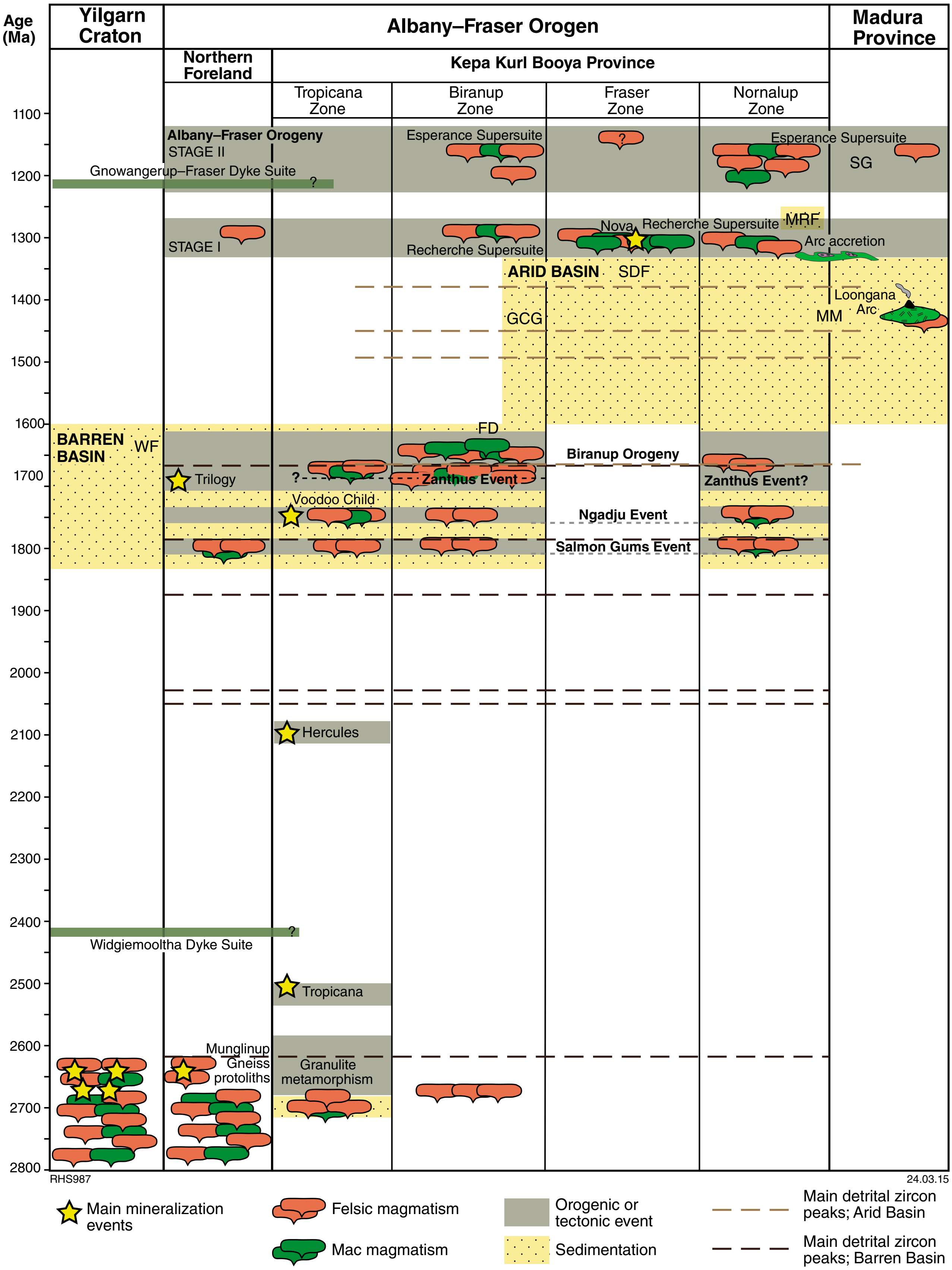


Figure 2. Time–space plot of the Albany–Fraser Orogen and Madura Province (from Spaggiari et al., 2014a). Abbreviations used: FD = Fly Dam Formation; GCG = Gwynne Creek Gneiss; MM = Malcolm Metamorphics; MRF = Mount Ragged Formation; SDF = Snowys Dam Formation; SG = Salisbury Gneiss; WF=Woodline Formation

Archean granites: Northern Foreland, Munglinup Gneiss and Tropicana Zone

The Northern Foreland consists of dominantly greenschist facies Archean gneisses and granites and remnant greenstones of the Yilgarn Craton, cut by younger dolerite dykes. The northern or northwestern limit of the Northern Foreland is defined by the presence of discontinuous and widely spaced shear zones that cut the Archean fabric, and the transition to more strongly reworked and deformed granite–greenstone (e.g. Beeson et al., 1988). This variation generally reflects higher strain conditions and higher metamorphic grade with increasing distance from the non-reworked portion of the Yilgarn Craton. Deep crustal seismic reflection data has been interpreted as showing the Northern Foreland as a series of thrusts overlying the Yilgarn Craton (Spaggiari et al., 2014c).

Rocks of the Yilgarn Craton that have been reworked at amphibolite to granulite facies are preserved in thrust sheets in the central part of the orogen, and are defined as the Munglinup Gneiss (Spaggiari et al., 2009, 2011). The Munglinup Gneiss comprises orthogneiss with protolith ages of 2720–2640 Ma interlayered with lenses of metamorphosed mafic rocks, some of which are interpreted as metamorphosed mafic dykes or sills. Minor banded metachert (jaspilite), amphibolitic schist, serpentinite, and metamorphosed ultramafic rocks are interpreted as remnants of Archean greenstone sequences. Metamorphism and deformation of the Munglinup Gneiss occurred between 1210 and 1180 Ma, during Stage II (1225–1140 Ma) of the Albany–Fraser Orogeny, although early deformation may be as old as Archean (Spaggiari et al., 2011). At least three phases of folding are recognized in the Munglinup Gneiss, overprinted locally by shears and boudins.

The Tropicana Zone (Fig. 2; Occhipinti et al., 2014) contains Archean rocks that have an affinity to the Yilgarn Craton, although their geological evolution is distinct, and cannot be readily correlated with adjacent terranes, such as the Yamarna Terrane (Occhipinti et al., 2014; Kirkland et al., 2014a; Spaggiari et al., 2014a). Differences include the presence of c. 2700 Ma granites with sanukitoid geochemistry (see below), and Archean gneisses that underwent upper amphibolite to granulite facies metamorphism over a prolonged period from c. 2718 Ma to 2554 Ma (Kirkland et al., 2014a; Doyle et al., 2014, 2015). Furthermore, the Tropicana Zone has been emplaced an unknown distance into its current position overlying the Yamarna Terrane of the Yilgarn Craton (Occhipinti et al., 2014).

Archean rocks of the Tropicana Zone include the Tropicana Gneiss and the Hercules Gneiss (Spaggiari et al., 2014a). The Tropicana Gneiss contains interlayered granitic gneiss that includes tonalitic and dioritic compositions, mafic gneiss (including metagabbro and metamorphosed ultramafic rocks), garnet gneiss, and minor metachert and meta-iron formation (see also Spaggiari et al., 2011, and Doyle et al., 2014, 2015). Locally, the Tropicana Gneiss is intruded by Paleoproterozoic granite of Biranup Zone affinity (Fig. 2). The Hercules Gneiss (Neale Project area — Atlantis and Hercules prospects) is dominated by Neoarchean granite gneiss, with the best estimate for magmatic crystallization dated at 2692 ± 16 Ma (GSWA 192523), although this interpretation is hampered by intense granulite facies overprinting (Kirkland et al., 2014a). Prolonged granulite facies zircon growth is dated at 2718–2554 Ma, and the gneissic fabric is locally crosscut by microgranite veins, dated at 1783 ± 3 Ma (GSWA 192550, Kirkland et al., 2014b), and fine- to medium-grained mafic rocks.

The Tropicana Zone shares a similar geological history to the Northern Foreland and Biranup Zone from at least 1800 Ma, with deposition of Barren Basin sediments (Lindsay Hill Formation), and intrusion of Paleoproterozoic granitic rocks such as the c. 1815 Ma Black Dragon Gneiss protoliths (Doyle et al., 2014), the c. 1763 Ma McKay Creek Metasyenogranite (associated with the Voodoo Child Formation), the c. 1710 Ma Bobbie Point Metasyenogranite, and most likely 1690–1670 Ma metagranitic and metagabbroic rocks similar to those dated in the adjacent Pleiades Lakes area of the northeastern Biranup Zone (Fig. 2; Spaggiari et al., 2011, 2014a; Occhipinti et al., 2014; Spaggiari, 2014).

Paleoproterozoic granites: Tropicana, Biranup and Nornalup Zones

The Biranup Zone is dominated by strongly deformed orthogneiss, with lesser amounts of metagabbroic and hybrid rocks that range in age from 1815 to 1625 Ma, and which flank the entire southern and southeastern margin of the Yilgarn Craton (Figs 1 and 2; Kirkland et al., 2014a). Isolated remnants of Archean granite with Yilgarn Craton affinity occur within the Biranup Zone and this, combined with the isotopic and geochemical affinities of the Paleoproterozoic intrusive rocks, indicates a direct association with the Yilgarn Craton during their emplacement (see below). The Nornalup Zone is the southern- and easternmost unit of the Albany–Fraser Orogen and also spans its entire length (Fig. 1), although much of the original basement appears to be masked by Mesoproterozoic intrusions of the Recherche and Esperance Supersuites (Fig. 2).

The Paleoproterozoic magmatic rocks intrude sedimentary rocks of the Barren Basin, which is interpreted to have formed over more than 200 million years, from c. 1815 to 1600 Ma (Fig. 2; Spaggiari et al., 2014b). The basin comprises Paleoproterozoic, dominantly quartz-rich, mature metasedimentary rocks belonging to the Stirling Range Formation, Mount Barren Group, Lindsay Hill Formation, Woodline Formation (Woodline Sub-basin), Fly Dam Formation, and unnamed occurrences of psammitic to semipelitic schist and gneiss (Spaggiari et al., 2011, 2014b). These units are interpreted to be the structural and erosional remnants of a much larger basin system that covered much of the southern and southeastern margin of the Yilgarn Craton, and evolved during extension of that margin in either a rift or back-arc tectonic setting (Spaggiari et al., 2014b).

Depositional phases relate closely to the tectonic (and magmatic) events described below. The first occurred before c. 1800 Ma with deposition of the Stirling Range Formation. This was followed at c. 1700 Ma with deposition of the Mount Barren Group, and then between 1710 and 1650 Ma by deposition of the precursors to the Coramup Gneiss, the Ponton Creek psammitic gneiss and the Big Red paragneiss, and the Lindsay Hill Formation, coincident with the Biranup Orogeny (Fig. 2). These events were in turn followed by deposition of the Woodline Formation and Fly Dam Formation, possibly in the late stages of, or shortly after, the Biranup Orogeny (Spaggiari et al., 2014b).

Although the dominant source of detritus appears to have been derived from the Yilgarn Craton hinterland, magmatic episodes associated with the Salmon Gums Event, the Ngadju Event (Fig. 2), and the Biranup Orogeny appear to have provided substantial amounts of additional detritus to the basin system (Spaggiari et al., 2014b). These interpretations are supported by Lu–Hf data (Kirkland et al., 2011a,b, 2014a). There appears to have been a close link in the timing between depositional phases and pulses of magmatism, potentially indicative of relatively rapid, cyclical uplift and erosion releasing detritus into the evolving basin system. Although not constrained, potential coeval volcanism also may have supplied detritus to the basin.

Salmon Gums Event

The oldest Paleoproterozoic granites are 1815–1800 Ma granitic gneisses that formed during the Salmon Gums Event, and which occur in both the Biranup and Nornalup Zones (Fig. 2; Spaggiari et al., 2014a). This event is also marked by the initiation of the Barren Basin (Spaggiari et al., 2014b). Metagranodiorite and metadiorite of the Black Dragon Gneiss is dated at c. 1815 Ma and occurs adjacent to the Tropicana Zone (Doyle et al., 2014a). In the central Biranup Zone, two diamond drillcores from south of Salmon Gums (Hopkinson, 2010) intersected layered, mafic and felsic granitic gneiss that yielded 1806 ± 6 Ma and 1804 ± 6 Ma zircon U–Pb dates, interpreted to reflect magmatic crystallization (GSWA sample 192502, Kirkland et al., 2014c; GSWA sample 192504, preliminary data). Migmatitic, monzogranitic gneiss containing angular mafic inclusions is exposed in the eastern Nornalup Zone, and has yielded a zircon U–Pb date of 1809 ± 8 Ma, interpreted as the age of magmatic crystallization (GSWA sample 194785, Kirkland et al., 2014d). All of these granites contain mafic enclaves.

Ngadju Event

A second phase of magmatic activity, termed the Ngadju Event, occurred at 1780–1760 Ma, coinciding with widespread sediment deposition and the formation of various sub-basins of the Barren Basin (Fig. 2; Spaggiari et al., 2014a,b). This event is recorded in the Biranup and Nornalup Zones, as well as the Tropicana Zone (Spaggiari et al., 2014b). In the central Biranup Zone, the diamond drillcores from south of Salmon Gums (Hopkinson, 2010) also intersected granitic gneiss that yielded a date of 1779 ± 7 Ma, interpreted as the magmatic crystallization age (GSWA sample 192505, Kirkland et al., 2014e). In the eastern Nornalup Zone, strongly deformed metamonzogranite in the Newman Shear Zone yielded a date of 1763 ± 11 Ma, interpreted as the magmatic crystallization age (Kirkland et al., 2012a). The similarity in magmatic ages in both the Biranup and Nornalup Zones (Fig. 2) implies that these zones shared the same Paleoproterozoic (and likely Archean) substrate, before formation of the Fraser Zone and intrusion of the Recherche Supersuite during Stage I of the Albany–Fraser Orogeny.

Biranup Orogeny

The eastern and central Biranup Zone contains widespread granitic rocks that formed during the Biranup Orogeny between 1710 Ma and 1650 Ma (Spaggiari et al., 2011; Kirkland et al., 2014a). This coincided with ongoing sedimentation and formation of the Barren Basin (Spaggiari et al., 2014b). Granitic rocks formed during the Biranup Orogeny include the c. 1710 Ma Bobbie Point Metasyenogranite in the Tropicana Zone, and the c. 1665 Ma Eddy Suite, which includes rapakivi-textured metagranodiorite mingled with metagabbro, in the eastern Biranup Zone (Spaggiari et al., 2011; Kirkland et al., 2011a,b). The youngest Biranup Zone granite is a metasyenogranite with a zircon U–Pb crystallization age of 1627 ± 4 Ma (GSWA 194736, Kirkland et al., 2010). The c. 1680 Ma Zanthus Event (Fig. 2) is a compressional phase of the Biranup Orogeny that produced folding under upper amphibolite to granulite facies conditions in Biranup Zone granitic gneiss and Barren Basin psammitic gneiss (Ponton Creek Gneiss; Kirkland et al., 2011a).

The central and eastern Biranup Zones are dominated by Paleoproterozoic gneisses that contain evidence of partial melting and migmatization, and have therefore undergone upper amphibolite to granulite facies metamorphism. Most homogeneous zircon overgrowths in these rocks indicate that high-grade metamorphism occurred during Stage II, from c. 1225 Ma to 1150 Ma, although some Stage I metamorphic dates of c. 1300 Ma occur in the Nornalup Zone (Kirkland et al., 2011a, 2014a; Spaggiari et al., 2014b).

Mesoproterozoic granites of the Albany–Fraser Orogeny

Granitic magmatism was again a major product of tectonism during the Albany–Fraser Orogeny, which is divided into two parts: Stage I (1330–1260 Ma) and Stage II (1225–1140 Ma) (Clark et al., 2000; Spaggiari et al., 2014a,b). These granites typically contain mafic enclaves, veins and pods of various sizes, providing field evidence of their association with mafic magmatism. The magmatic rocks formed during Stage I intrude sedimentary rocks of the Arid Basin, which is comprised of several successions that post-date the Biranup Orogeny, but have been affected by Stage I tectonism. These include the Malcolm Metamorphics of the eastern Nornalup Zone, the Gwynne Creek Gneiss in the northeastern part of the orogen, and the Snowys Dam Formation of the Fraser Zone (Fig. 2; Spaggiari et al., 2011; 2014b). Also included are paragneissic rocks from the western Nornalup Zone, such as those found at Whalehead Rock near Albany. Unlike the Barren Basin, the Arid Basin contains a wide range of metamorphosed lithologies including pelitic semipelitic, psammitic, calc-silicate and iron-rich metasedimentary rocks. Metamorphic grade ranges from amphibolite to granulite facies (Clark et al., 2000; Spaggiari et al., 2011; Clark et al., 2014).

Interpreted as initially being a marginal ocean basin, the Arid Basin formed after c. 1600 Ma following Paleoproterozoic rifting, and was flanked by a passive margin (the eastern Nornalup Zone ocean–continent transition). Accretion of the c. 1410 Ma Loongana oceanic arc in the Madura Province (see below) to the eastern Nornalup Zone along the Rodona Shear Zone is interpreted to have triggered crustal thickening, and the earliest phase of Stage I magmatism at c. 1330 Ma (Spaggiari et al., 2014b).

In contrast to the Barren Basin, the Arid Basin is dominated by c. 1455–1375 Ma detritus that does not correspond to any known source within the Albany–Fraser Orogen and is interpreted to be derived from the dominantly oceanic environment of the Madura Province to the east. These sediments are interpreted to have been deposited after accretion of the Loongana oceanic arc, during which the Arid Basin evolved to a foreland basin above a craton-vergent fold and thrust system (Spaggiari et al., 2014b).

Recherche Supersuite

The southeastern part of the Biranup Zone, the Fraser Zone, and much of the Nornalup Zone contain amphibolite or granulite facies granitic and gabbroic intrusions of the 1330–1280 Ma Recherche Supersuite (Nelson et al., 1995; Clark et al., 2000; Smithies et al., 2013; Kirkland et al., 2014a). A single occurrence of Recherche Supersuite granite occurs in the Northern Foreland near Bald Rock (dated at 1299 ± 14 Ma, GSWA 83690, Nelson, 1995a). The formation of these magmatic rocks coincided with Stage I of the Albany–Fraser Orogeny (Fig. 2).

Felsic rocks of the Recherche Supersuite are mostly foliated metagranites or gneisses with syenogranitic, monzogranitic and granodioritic compositions. Most of these appear to be mingled with a mafic component, generally present as enclaves of various sizes. The oldest known Recherche Supersuite granite is a biotite–hornblende monzogranite containing calc-silicate boudins from Poison Creek, dated at 1330 ± 14 Ma (GSWA 83662; Nelson, 1995b). This date provides the most robust constraint on the commencement of Stage I of the Albany–Fraser Orogeny, although it is feasible that this granite is a product of tectonism that had already commenced. Previously, Stage I was interpreted to have commenced at c. 1345 Ma (Clark et al., 2000), but this age was loosely based on two inherited zircons in a younger granite. The youngest known Recherche Supersuite granites are metamonzogranite from within the Newman Shear Zone dated at 1297 ± 8 Ma (GSWA 194711; Kirkland et al., 2012b), hornblende–biotite syenogranite gneiss dated at 1283 ± 13 Ma from the Coramup Hill Quarry, which occurs in the hanging wall of the Coramup Shear Zone (GSWA 83700A; Nelson et al., 1995c), and granitic pegmatite dated at 1283 ± 7 Ma in the Fraser Zone (GSWA 194780, Kirkland et al., 2013).

Fraser Zone

A large mass of structurally bound, dominantly gabbroic rocks define the northeasterly trending Fraser Zone, which is about 425 km long and up to 50 km wide (Fig. 1; Smithies et al., 2013). The Fraser Zone has a V-shaped cross-sectional geometry up to about 15 km depth, and is bound by the Fraser Shear Zone to the northwest, and the Boonderoo and Newman Shear Zones to the southeast (Spaggiari et al., 2014c; Brisbout et al., 2014).

The Fraser Zone contains the 1305–1290 Ma Fraser Range Metamorphics (Spaggiari et al., 2009), which comprise thin to voluminous sheets of metagabbroic rocks that range in thickness from several centimetres up to several hundred metres, interlayered with sheets of granitic gneiss, including pyroxene-bearing granitic gneiss, and hybrid magmatic rocks (Smithies et al., 2013). All are interlayered at various scales with amphibolite to granulite facies pelitic, semipelitic and psammitic gneiss, and locally calc-silicate and iron-rich metasedimentary rocks of the Snowys Dam Formation, which forms part of the Mesoproterozoic Arid Basin (Fig. 2; Spaggiari et al., 2014b).

Peak metamorphic temperatures and pressures recorded in the pelitic rocks of the Snowys Dam Formation reached about 850°C at pressures of 7–9 GPa at c. 1290 Ma, followed by a period of isobaric cooling at pressures of about 9 GPa (Clark et al., 2014). All isotopic results from the Fraser Zone indicate a short time interval for both mafic and felsic igneous crystallization, predominantly between 1305 and 1290 Ma, and essentially coeval granulite facies metamorphism (Fig. 2).

The Fraser Zone is interpreted to represent a structurally modified, middle- to deep-crustal ‘hot zone’, formed by the repeated intrusion of gabbroic magma from a mantle upwelling into quartzofeldspathic country rock, either beneath an intercontinental rift, or in a distal back-arc setting (Spaggiari et al., 2011; Smithies et al., 2013; Clark et al., 2014). Whole-rock geochemical data indicate that an oceanic-arc setting, as interpreted by Condie and Myers (1999), is unlikely because the enriched crustal component of the gabbroic rocks of the Fraser Zone is better explained by assimilation from an older, felsic basement that included a component of Archean, or reworked Archean, crust (Smithies et al., 2013). This interpretation is supported by previous and recent Nd- and Hf-isotopic data (Fletcher et al., 1991; Kirkland et al., 2011b), and the presence of Paleoproterozoic basement rocks in the eastern Nornalup Zone.

Esperance Supersuite

Widespread and voluminous granites were again produced during Stage II of the Albany–Fraser Orogeny (Myers, 1995; Kirkland et al., 2014a). These granites are particularly abundant in the eastern Nornalup Zone, and many have a distinct, locally ovoid, high magnetic signature defining a northeasterly trending belt between the Newman and Tagon Shear Zones (Spaggiari et al., 2014c). These granites are typically porphyritic, and many have a well-developed magmatic fabric. Some also contain fabrics related to post-crystallization deformation.

Only eight samples of the Esperance Supersuite in the Albany–Fraser Orogen have been dated so far, and one of the youngest appears to be the occurrence at Balladonia Rock within the eastern Nornalup Zone, which has a poorly constrained U–Pb zircon crystallization age of 1135 ± 56 Ma (GSWA 83667; Nelson et al., 1995d). The oldest is a biotite monzogranite at Mount Ridley within the Biranup Zone, which yielded a U–Pb zircon crystallization age of 1198 ± 11 Ma (GSWA 184374; Kirkland et al., 2012c).

Granites of the same age as the Esperance Supersuite are also found in the adjoining Madura Province (see below), and in the Forrest Zone of the Coompana Province to the east of the Mundrabilla Shear Zone (Spaggiari et al., 2014a). Their extent is significant and shows that magmatism at this time was not confined to the Albany–Fraser Orogen. Diamond drillcore from the Moodini prospect within the Mundrabilla Shear Zone comprises texturally variable metagranite that is mostly porphyritic, locally with a fine-grained quench texture suggesting rapid cooling. It has a high magnetic susceptibility, and overlies a discrete northerly trending magnetic high in the centre of the Mundrabilla Shear Zone. The metagranite contains a subhorizontal foliation or linear fabric with a rodded morphology, consistent with strike-slip shearing. Zircons from this metagranite have been dated at 1125 ± 7 and 1132 ± 9 Ma, interpreted as the age of magmatic crystallization of the granite (preliminary geochronology, GSWA 192565, 497.37 – 497.94 m depth interval, hole DDH MORCD 001, and GSWA 192566, 592.83 – 593.39 m depth interval, hole DDH MORCD 002, respectively). This indicates that sinistral movement on the Mundrabilla Shear Zone occurred either during emplacement of this granite, or after it.

In the Forrest Zone of the Coompana Province, the Eucla 1 petroleum well intersected a distinct ovoid feature of moderate to high magnetic intensity, interpreted as one of a series of northeasterly trending granitic intrusions that are dragged into, and cut by, sinistral movement on the Mundrabilla Shear Zone (Spaggiari et al., 2012). These magnetic intrusions have a similar signature to magnetic intrusions of the Esperance Supersuite in the eastern Nornalup Zone (Spaggiari et al., 2014c). Small rock chips from the base of the well, which are interpreted to be derived from a granitic rock, provided a date of 1140 ± 8 Ma, interpreted as the magmatic crystallization age of the granite (GSWA 194773; Kirkland et al., 2011c).

Madura Province

The Madura Province lies entirely under cover of the Cretaceous to Cenozoic Bight and Eucla Basins, and its geology is only known through geophysical data and drillcores. It is defined as the area of basement bounded by the Rodona Shear Zone to the west, and the Mundrabilla Shear Zone to the east (Spaggiari et al., 2012; 2014c). The Rodona Shear Zone (Fig. 1) is a wide, northeasterly trending, east-dipping, high strain zone that coincides with the eastern edge of the Albany–Fraser Orogen. Kinematic interpretations from aeromagnetic data indicate a period of west-directed thrusting overprinted by sinistral shearing (Spaggiari et al., 2012; 2014c). The Mundrabilla Shear Zone (Inset Fig. 1) is a prominent, north–south structure that abruptly loses its magnetic signature to the north under the Officer Basin. It is a wide, straight shear zone, which suggests it is subvertical, with drag fabrics indicative of a sinistral shear sense, at least during its more recent history (Spaggiari et al., 2012; 2014c).

Drillcores into the Madura Province contain weakly layered, medium-grained, mafic cumulate rocks, locally with peridotitic cumulate rocks, intruded by medium- to coarse-grained plagiogranite (Haig Cave Supersuite; Spaggiari et al., 2014a,b). At least five geochemically distinct mafic intrusive bodies are indicated. The mafic to ultramafic cumulate bodies are derived from low- to medium-K, tholeiitic parental magmas. Trace element variations identify two main compositional groups: Group 1 gabbro (Haig 1), derived from a depleted mantle source with little or no prior subduction enrichment, and Group 2, most likely derived from a subduction-enriched mantle source.

U–Pb zircon dating of plagiogranite and gabbro indicates the mafic and felsic components were synchronous between c. 1410 and 1400 Ma, which is consistent with observed contact relationships (Spaggiari et al., 2014b, and references therein). The plagiogranites are associated with gabbros at Loongana and at Haig. They have high Na_2O (3.1–4.8 wt%) and CaO (2.1–6.4 wt%) and very low K_2O (generally <1 wt%). Their composition is typical of felsic magmas formed in oceanic crust (e.g. Leat et al., 2006) and this is consistent with their very juvenile Hf- and Nd-isotopic compositions (ε_{Hf} values in zircon of –2.5 to +11.5, with a median of +7.8 at 1400 Ma; whole-rock ε_{Nd} of +1.3 to 1.9 at 1400 Ma — Kirkland et al., 2015). This lends strong support to a suggestion that the small amount of material so far sampled from the Madura Province most likely formed between c. 1410 and 1400 Ma in a largely oceanic realm that includes part of an oceanic arc, the Loongana oceanic arc (Spaggiari et al., 2012; 2014a,b; Smithies et al., 2014; Kirkland et al., 2015), with little contribution from continental material. The validity of these isotopic and whole-rock geochemistry interpretations, and the extent of the oceanic magmatic-arc in the Madura Province, remains to be tested.

Granite groups

The mineralogy and textural observations clearly show that most samples studied here have undergone significant deformation and recrystallization, and knowledge of the tectonic evolution of the region suggests that for many samples this may have occurred several times. Several samples of various age groups are garnet-bearing gneiss (although the rocks themselves are metaluminous or only weakly peraluminous), and several others contain a range of metamorphic assemblages. It is difficult to determine the effect that this may have had on primary geochemical compositions (i.e. composition of the original protolith), and virtually impossible for groups with low sample populations. It can be argued that coherent trends defined by specific age populations in samples collected over an orogen scale are more likely to relate to igneous processes than to metamorphic recrystallization, and loss or gain of metamorphic fluids or melts. Melting, and melt migration and accumulation, generally has a homogenizing effect on original source compositional inhomogeneities, and melt crystallization should produce systematic compositional changes. Compositional scatter about these coherent trends most likely relates to a range of competing magmatic processes, although in many cases it may also be enhanced by the loss or gain of low melt fractions related to one or several subsequent metamorphic events, especially if the granites were subjected to significant strain. Nevertheless, the aim of this Report is to identify, describe and, where possible, interpret geochemical characteristics of the granites of the Albany–Fraser Orogen, regardless of whether those characteristics relate to igneous or metamorphic processes.

Field classification, location details, and U–Pb zircon age (where available; for complete geochronological data, see http://www.dmp.wa.gov.au/geochron/) for the granites studied here are presented in Appendix 1. All geochemical data used here, together with analytical details, can be obtained from the WACHEM database (http://geochem.dmp.wa.gov.au/geochem/) and are also presented in Appendix 2. Of the 156 whole-rock granite analyses, the 84 dated samples were assigned to groups based on magmatic crystallization age. Most (70%) of the dated samples crystallized during or before the 1710–1650 Ma Biranup Orogeny, allowing more tightly defined age groups for that subset of the data. The remaining 30% of the dated samples crystallized during the 1330–1140 Ma Albany–Fraser Orogeny and have been subdivided between the Stage I (1330–1260 Ma) and Stage II (1225 –1140 Ma) age groups.

The granites were grouped according to age, recognizing coherent petrogenetic processes through time. In the case of dated samples crystallized during or before the 1710–1650 Ma Biranup Orogeny, mean ages were simply grouped into 10 Ma intervals. All undated samples have been assigned to the specific age group to which they show the closest affinity based first on their field characteristics, mineralogy, and relationships (e.g. contact relationships, structural and metamorphic history, geophysical characteristics), and subsequently on their geochemical characteristics. In no case did apparent geochemical affinity take precedence over a clear field classification. However, in several cases, samples with ambiguous field classification showed a clear geochemical affinity to a particular granite age group, and were assigned accordingly.

At least 12 granite age groups from c. 2722 to 1135 Ma are identified, each with a generally distinctive compositional range. Their geographical distribution is shown in Figure 3. Granites with ages of c. 1800 Ma are part of the Salmon Gums Event and granites with ages between 1780 and 1760 Ma are part of the Ngadju Event (Spaggiari et al., 2014a). Granites with ages between 1710 and 1650 Ma formed during the Biranup Orogeny.

Granite groups include:

1. Archean granites (Northern Foreland and Tropicana Zone)
2. Archean granites (Munglinup Gneiss)
3. Granite with crystallization ages between 1815 and 1800 Ma (c. 1800 Ma granites; Salmon Gums Event)
4. Granite with crystallization ages between 1780 and 1760 Ma (c. 1760 Ma granites; Ngadju Event)
5. Granite with crystallization ages <1750 and >1695 Ma (c. 1700 Ma granites)
6. Granite with crystallization ages between 1695 and >1685 Ma (c. 1690 Ma granites; Biranup Orogeny)
7. Granite with crystallization ages between 1685 and >1675 Ma (c. 1680 Ma granites; Biranup Orogeny)
8. Granite with crystallization ages between 1675 and >1665 Ma (c. 1670 Ma granites; Biranup Orogeny)
9. Granite with crystallization ages between 1665 and >1650 Ma (c. 1660 Ma granites; Biranup Orogeny)
10. Granites crystallized during Stage I of the Albany–Fraser Orogeny (Recherche Supersuite)
11. Granites crystallized during Stage II of the Albany–Fraser Orogeny (trace element un-enriched Truslove Suite, Esperance Supersuite)
12. Granites crystallized during Stage II of the Albany–Fraser Orogeny (trace element enriched Booanya Suite, Esperance Supersuite).

The granite groups (suites and subsuites) determined in this way show considerable overlap on many geochemical variation diagrams. The danger of the approach used here, particularly for the c. 1800 to 1660 Ma age groups, is that it creates artificial groups based on age brackets that have significant overlap within the analytical uncertainty of the age determination (typically ±10 Ma). In addition, sampling of several of these age groups (e.g. the c. 1760, 1700 and 1660 Ma granites) is geographically restricted. Nevertheless, many groups are compositionally unique (or nearly so) in at least some respects, and broad but distinct trends between consecutive age groups are likely to be significant even if a small number of individual samples of one group more likely belong to another group.

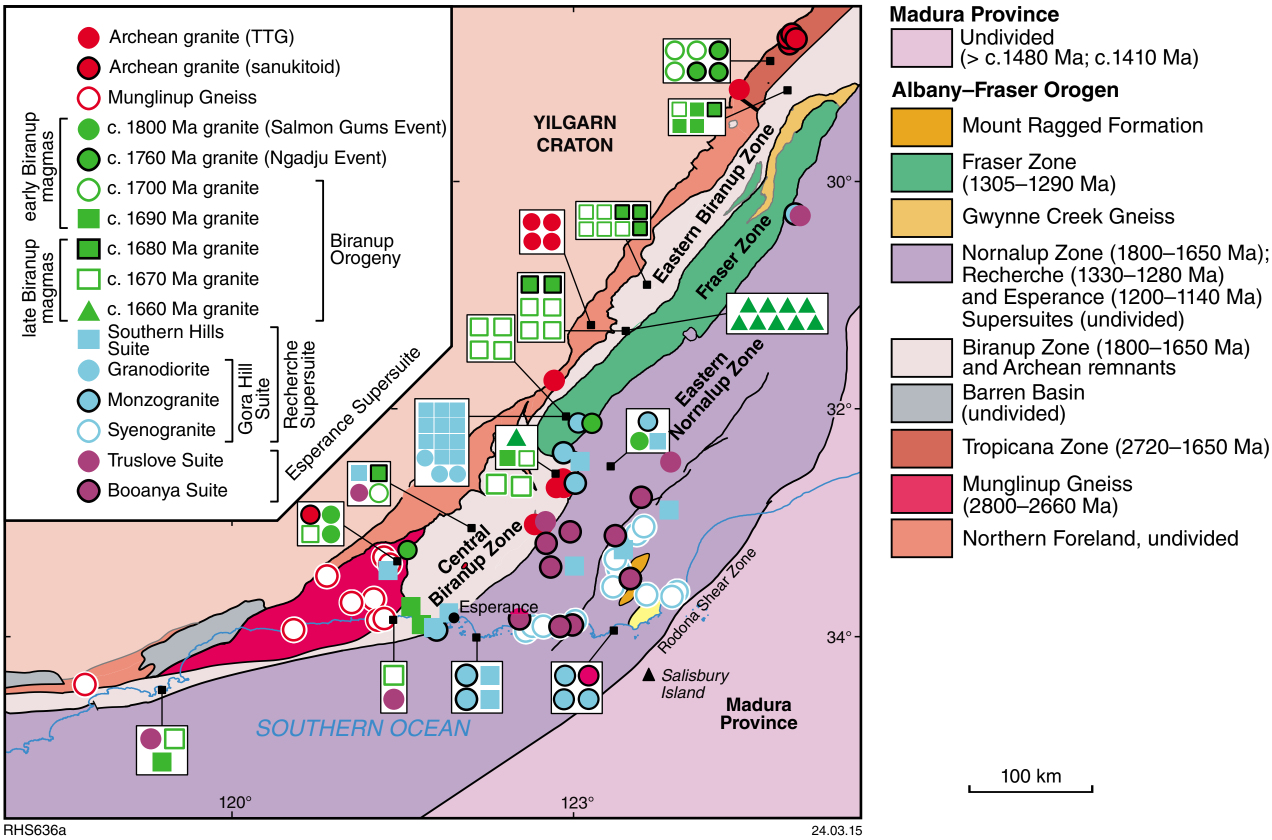


Figure 3. **Simplified, pre-Mesozoic interpreted bedrock geology of the east Albany–Fraser Orogen showing the approximate location and geographical distribution of granite samples of the various granite groups**

Composition and petrogenesis of granite magmas of the Albany–Fraser Orogen

The following section describes the granite groups in terms of their spatial distribution and geochemical characteristics. We interpret the likely petrogenesis of the granites of each group and describe geochemical trends with age, and relate these to crustal-scale processes that reflect or influenced the crustal evolution of the orogen. Pre-Mesoproterozoic granite magmatism in the Albany–Fraser Orogen is mainly represented by relatively compositionally diverse granites that have a wide age distribution, albeit with a distinct evolutionary trend. In contrast, Mesoproterozoic magmatic evolution in the Albany–Fraser Orogen can be described within a relatively narrow period (the Albany–Fraser Orogeny) that resulted in orogen-wide magmatism that can be geochemically well constrained. For this reason, the following section is divided into two discrete parts — ‘pre-Mesoproterozoic granite evolution’ and ‘Mesoproterozoic granite evolution’.

Pre-Mesoproterozoic granite evolution

Archean granites

Northern Foreland and Tropicana Zone

An Archean crystallization age for 12 of the 14 granites in this group (including metagranites and orthogneiss) has been confirmed by U–Pb dating of zircons, with ages between 2722 and 2616 Ma. Most samples are from the Northern Foreland and the Tropicana Zone, although five samples are from regions within the Biranup Zone that are remnant fragments of the Yilgarn Craton (Fig. 4). As a group, the Archean granites show most of the compositional characteristics commonly associated with sodic granites formed during the Archean, including high Na_2O, Al_2O_3, Sr and Ba concentrations, high La/Yb and Sr/Y ratios, low Y and HREE (heavy rare earth elements) concentrations, and low K_2O/Na_2O ratios (e.g. Champion and Sheraton, 1997; Champion and Smithies, 2007; Martin et al., 2005; Fig. 5). These features are typically attributed to derivation at high pressures from a mafic source (Champion and Sheraton, 1997; Martin et al.,

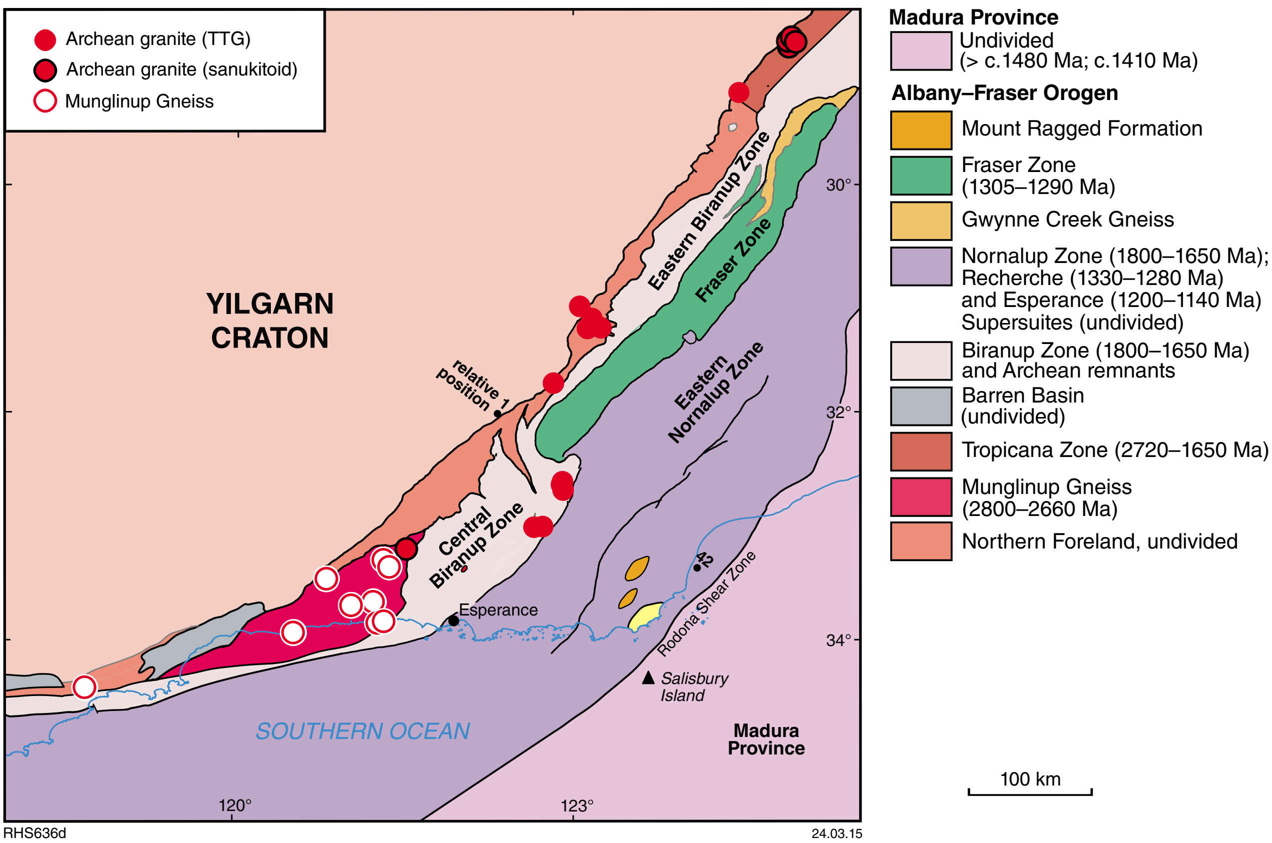


Figure 4. **Simplified, pre-Mesozoic interpreted bedrock geology of the east Albany–Fraser Orogen showing the distribution of Archean granites and Munglinup Gneiss**

2005, and references therein). The combination of these characteristics, along with typically lower TiO_2, Fe_2O_3 (or total Fe), Sc, HFSE (high field strength elements) and REE concentrations distinguishes these granites from all other populations, except for the Munglinup Gneiss (Fig. 5). A plot of La/Yb vs La provides a moderately effective discriminant of the Archean granites and distinguishes most of these granites from the majority of samples of the Munglinup Gneiss (Fig. 6).

For the Archean granites, Al_2O_3 contents >15 wt% at 70 wt% SiO_2, K_2O/Na_2O ratios generally <1.0, and Yb concentrations that remain below 0.5 ppm at SiO_2 >66 wt% reflect high-pressure (garnet-present) melting of a mafic source. Slightly higher K_2O/Na_2O (up to 1.5, with K_2O between 4.0 and 5.7 wt%) for some samples with SiO_2 >70 wt% (Fig. 5), possibly also indicates that some of these sodic granites have been reworked and low Sr and Ba concentrations in these samples suggest that this occurred at pressures low enough to stabilize feldspar (e.g. Champion and Smithies, 2007). However, one unusual characteristic of the Archean granite group from the Albany–Fraser Orogen is the extended silica range down to values as low as 60.9 wt% (Fig. 5; cf. an average of ~70 wt% for global Archean granites, e.g. Martin et al., 2005). Within this group, an absence of samples with silica contents between 62.9 and 67.1 wt% likely identifies two distinct subgroups. Whereas the higher silica subgroup closely resembles sodic granites of the Archean tonalite–trondhjemite–granodiorite (TTG) series and reworked TTG, as described above, the lower silica subgroup (8 analyses) shows characteristics of the Archean high-Mg diorite, or sanukitoid, series (e.g. Smithies and Champion, 2000; Martin et al., 2005). Most of these samples are from the Neale Project area (Hercules Gneiss, Kirkland et al., 2014a; Spaggiari, 2014) in the Tropicana Zone, although one sample is from a drillcore associated with the Salmon Gums prospect, located in the northeasternmost part of the Munglinup Gneiss (Fig. 4). The source for Archean sanukitoids is thought to form as subduction derived TTG interacts with mantle wedge peridotite (e.g. Shirey and Hanson, 1981; Smithies and Champion, 2000; Martin et al., 2005) to produce a pyroxenitic mantle capable of yielding felsic melts. These melts are characterized at about 60 wt% SiO_2, by Mg# >60 and Cr and Ni concentrations >200 and 100 ppm, respectively, coupled with high concentrations of Sr, Ba and LREE (light rare earth elements). The occurrence of sanukitoids thus might be used to indicate close proximity to an old tectonic-plate margin and their presence in the Tropicana Zone, and in the Munglinup Gneiss, might suggest that these regions include several (at least two) older plate boundaries relating to the assembly of the Yilgarn Craton.

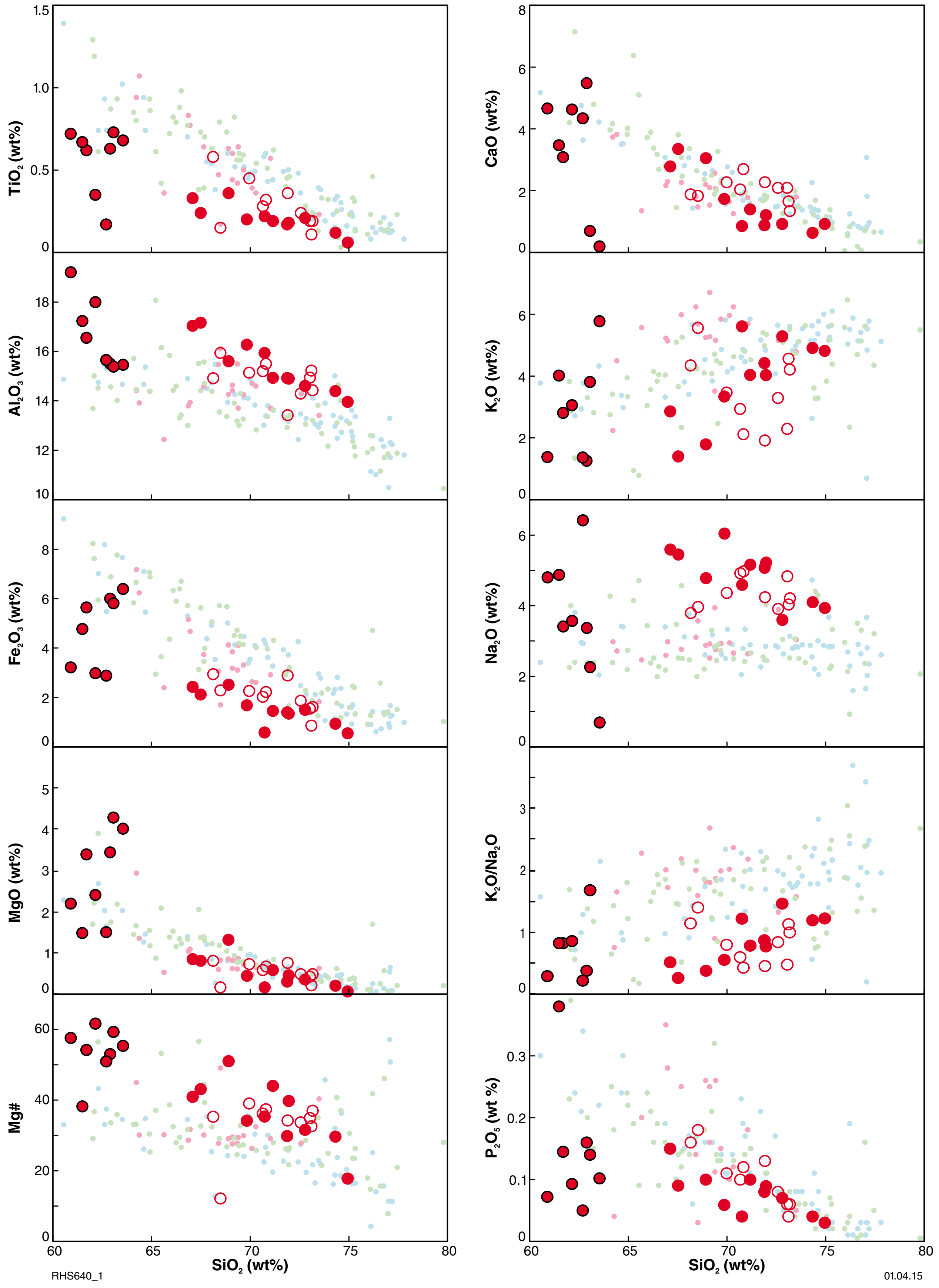
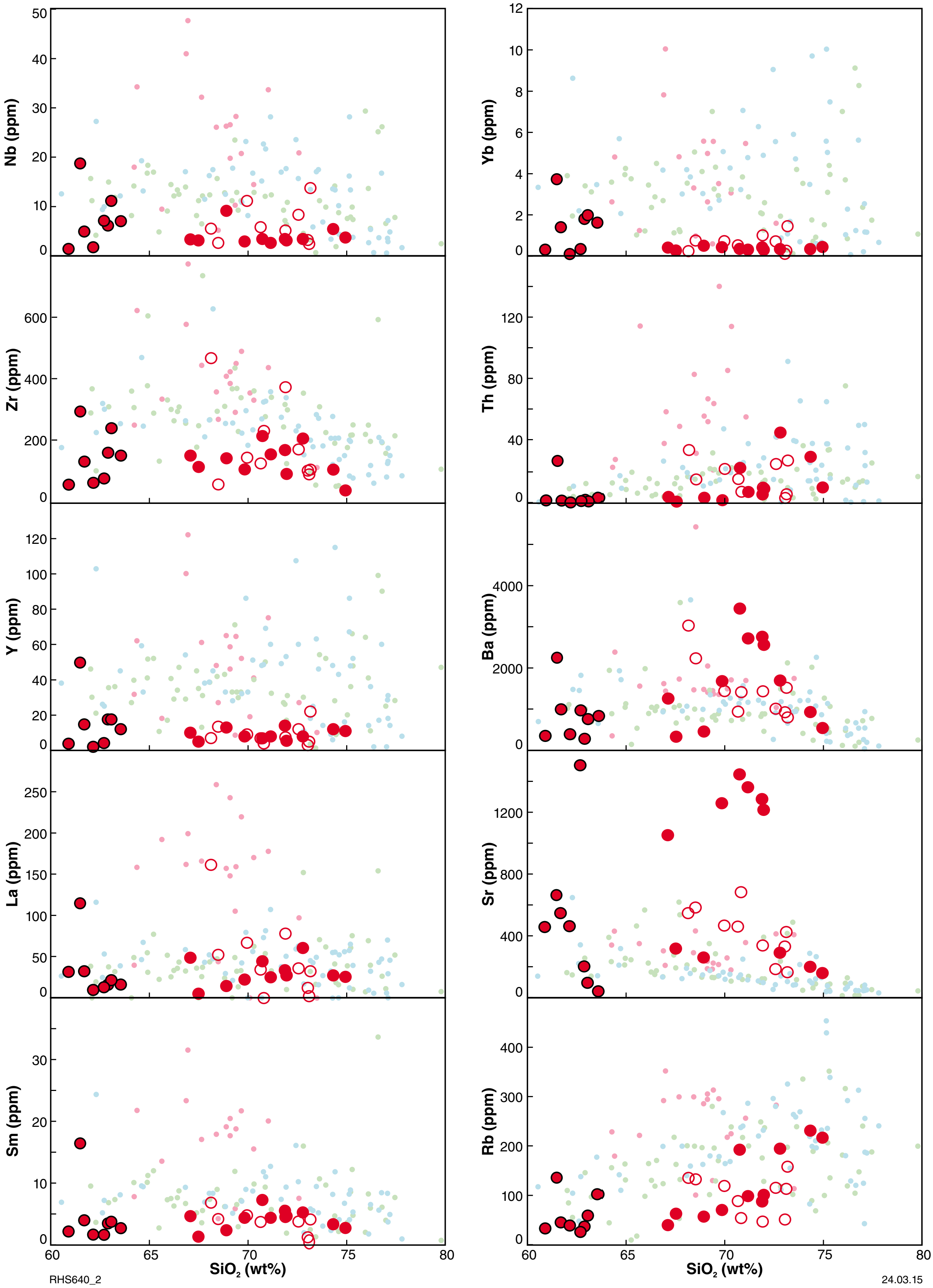


Figure 5. **Compositional variation diagrams for Archean granites and Munglinup Gneiss. Mg# = Mg number [100 x molecular ratio of Mg/(Mg+Fe) with all Fe as Fe^{2+}] (continued on pages 12 and 13)**



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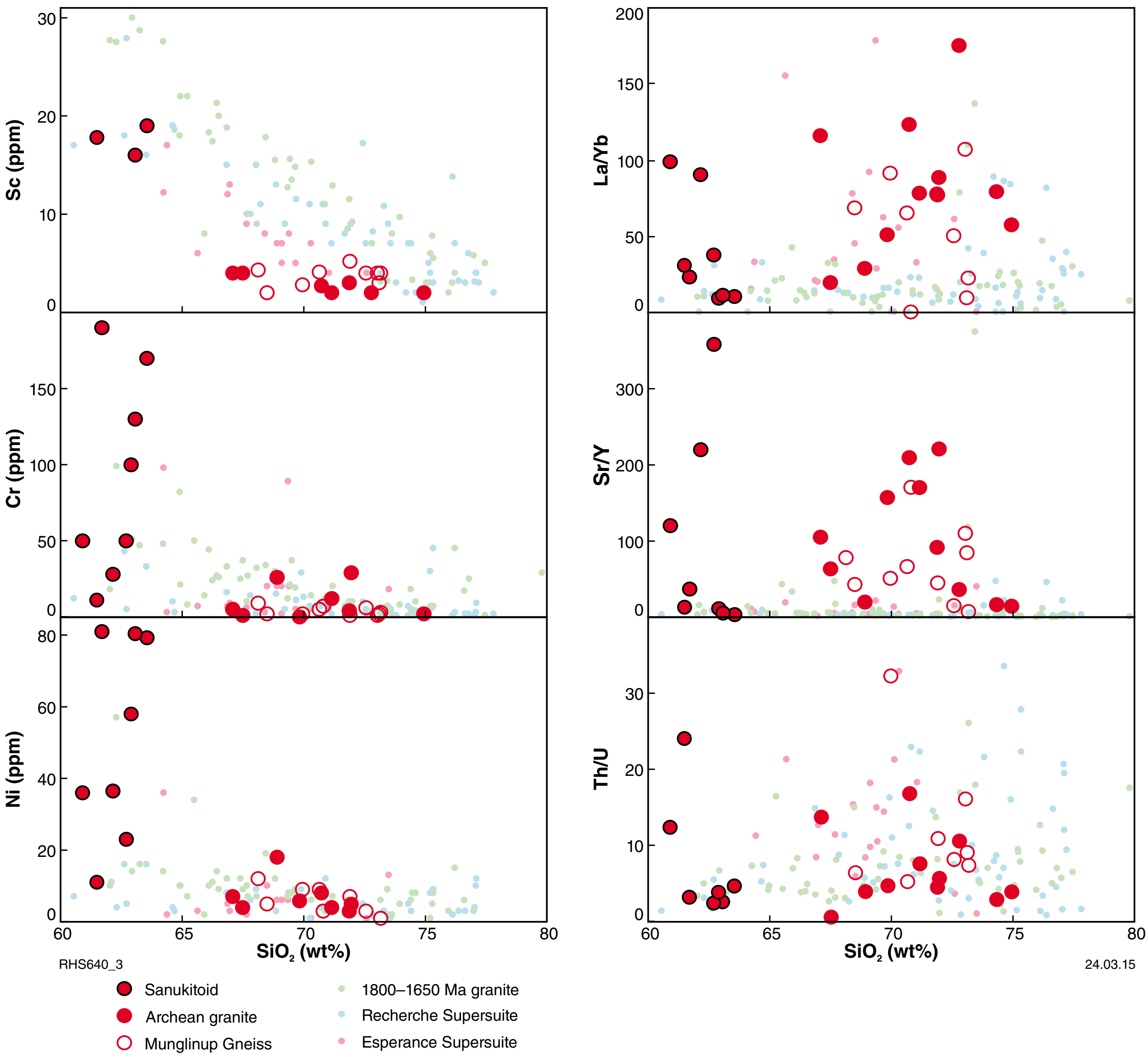


Figure 5. continued

The observation that the Archean granite group contains samples from at least two compositionally distinctive series (TTG and sanukitoid) likely explains much of the compositional scatter observed for the group. In addition, while there is no clear evidence for compositional modification during metamorphism, several of the sanukitoid samples from the Hercules Gneiss in the Tropicana Zone have anomalously low CaO and correspondingly high K_2O (Fig. 5), reflecting significant hydrothermal alteration.

Munglinup Gneiss

The Munglinup Gneiss occurs as thrust sheets within the southern part of the Northern Foreland (Spaggiari et al., 2014c). Our dataset contains 11 samples of the Munglinup Gneiss (Fig. 4), including six samples that have been dated, with protolith U–Pb crystallization ages lying between 2720 and 2640 Ma (Spaggiari et al., 2011).

All geochemical features used to characterize the Archean TTG, and to distinguish these from most other granite groups of the Albany–Fraser Orogen, are shared with the Munglinup Gneiss (Fig. 5). As indicated above, a plot of La/Yb (or La/Sm) vs La provides one of the few moderately effective geochemical means of distinguishing the two groups, with the Munglinup Gneiss having generally lower La/Yb and higher La/Sm ratios for a given La concentration (Fig. 6). In addition, Th/U ratios for the Archean granites are generally <6, close to mantle values (~2.5–4: Sun and McDonough, 1989), and are lower than most samples of the Munglinup Gneiss, which has Th/U ratios generally >6 (Fig. 5). These compositional differences are possibly consistent with removal of a very low fraction, low Th/U, fluid or partial melt from the Munglinup Gneiss, although the trends with respect to La/Yb and La/Sm ratios would likely then require metamorphic conditions that permitted minor dehydration melting of biotite, but not of hornblende (D = mineral/melt distribution coefficient; $D_{La/Yb}$ hornblende < biotite, $D_{La/Sm}$ hornblende > biotite). This is consistent with field relationships that show only limited development of partial melt (leucosomes), most likely in the upper amphibolite facies (Spaggiari et al., 2011).

Granite groups within the c. 1800–1660 Ma age range

Compositional changes in granites within this age range reflect the evolution of the Albany–Fraser Orogen crust from the c. 1800 Ma Salmon Gums Event up to the c. 1650 Ma end of the Biranup Orogeny (Fig. 2). These rocks have been sampled throughout much of the Tropicana, Biranup and Nornalup Zones, and the Northern Foreland of the Albany–Fraser Orogen (Fig. 7), although it is unclear if the geographically restricted nature of some age groups (e.g. the c. 1700 Ma granites) is real, or a reflection of poor outcrop distribution. Collectively, these granite groups show a very wide geochemical range. They are typically calc-alkalic and contain, in most groups, a high proportion of weakly peraluminous samples (ASI >1; Fig. 8), although the range is from metaluminous compositions. They can generally be distinguished from the high Na_2O, Al_2O_3, low K_2O, TiO_2 Archean granites and Munglinup Gneiss (Fig. 8), as described above, except in the case of some of the older age groups (e.g. c. 1800 Ma and c. 1760 Ma granites). Collectively, c. 1800–1660 Ma granites also have a compositional range that extensively overlaps that of the younger granite groups related to the Albany–Fraser Orogeny (Fig. 8), with very few compositional means of discriminating between these two main populations. Concentrations of Pb tend to be lower in the older granites, and at silica values below ~72 wt%, c. 1800–1660 Ma granites typically have higher Sc concentrations than the younger granites (Fig. 8).

c. 1800 Ma granites (Salmon Gums Event)

This group contains only three samples: two from the eastern Biranup Zone; the other from the eastern Nornalup Zone (Fig. 7), although granite of this age does occur at the Black Dragon prospect in the northeastern Biranup Zone (Black Dragon Gneiss, Doyle et al., 2014; Spaggiari, 2014). They cover a narrow silica range (65.2 – 67.6 wt%) and on a major element basis appear to fill the compositional gap between sodic Archean granites (TTG) and the Archean sanukitoids, although two of the c. 1800 Ma granites have the lowest K_2O concentration of all samples within the granite dataset. Trace element concentrations also closely correspond with values expected for Archean granites or Munglinup Gneiss

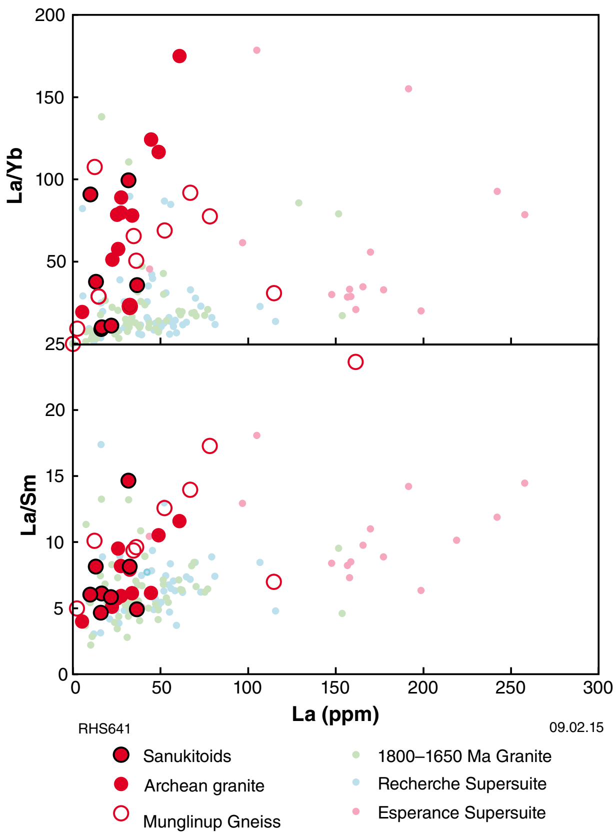


Figure 6. Compositional variation diagrams showing variations in La/Yb and La/Sm ratios vs La concentrations for Archean granites (including sanukitoids) and Munglinup Gneiss

at similar (extrapolated) silica contents for two of the three c. 1800 Ma granites; the third sample (from the Nornalup Zone) has higher HFSE and REE concentrations and lower LILE (large-ion lithophile elements) concentrations. In terms of Th/U, La/Yb and La/Sm ratios, the c. 1800 Ma granites also scatter between values expected from either Archean granites or Munglinup Gneiss (Fig. 8).

c. 1760 Ma granites (Ngadju Event)

This group contains five samples: three from the Tropicana Zone (McKay Creek and Neale prospect); and one each from the central Biranup Zone (Salmon Gums prospect) and the Nornalup Zone (Newman Shear Zone) (Fig. 7). Like the c. 1800 Ma granites, they also cover a relatively narrow silica range, although at higher silica values (70.32 – 76.1 wt%). At such high silica values, distinguishing rocks based on major element concentrations becomes problematic. However, their K_2O concentrations are lower (<3.9 wt%) than those of all other granite groups at similar silica content (with the possible exception of the Munglinup Gneiss) and high Na_2O concentrations and low K_2O/Na_2O ratios for four of the five samples (>1.0 wt%) are similar to those of the Archean granites or Munglinup Gneiss (Fig. 8). Similarly, generally high Sr and Ba concentrations and Eu/Eu* ratios and low Rb and HREE concentrations distinguish the c. 1760 Ma granites from most other granite groups, although not from Archean granites or the Munglinup Gneiss (Fig. 8).

c. 1700 Ma granites

This group is restricted to four samples, three from the Tropicana Zone and one from the eastern Biranup Zone (Fig. 7). Three of these samples are from a single area (Bobbie Point) in the Tropicana Zone, and together have a narrow range of very high silica values (75.9 – 76.8 wt%). The fourth sample occurs a considerable distance to the southwest (at Dingo Rock) and is significantly less silicic (64.9 wt% SiO_2). Because they are restricted to such high silica contents, the geochemistry of the Bobbie Point c. 1700 Ma granites is difficult to evaluate. These rocks do, however, appear depleted in CaO (and Rb, Ba and Sr, with very low Eu/Eu*) compared with all other groups (possibly reflecting alteration of feldspars) although remain more sodic than many of the younger granite groups (Fig. 8). They also have elevated concentrations of Nb and HREE (Y) compared to most other groups. The combination of elevated Na_2O and HREE is an important contrast between these rocks and the older sodic granites, which are strongly HREE-depleted. The Bobbie Point c. 1700 Ma granites are also characterized by relatively low Th/Nb, La/Sm and La/Yb ratios at their given silica contents (Fig. 8). Because of the high Nb (and Y) and low Rb concentrations, the Bobbie Point c. 1700 Ma granites plot well within the field for within-plate granite on tectonic discrimination diagrams (Fig. 9) and this is consistent with their generally alkali-calcic (cf. calc-alkalic for most of the c. 1800–1660 Ma granites) and ferroan compositions. They reflect a compositional style of magmatism very unlike the preceding sodic magmatism.

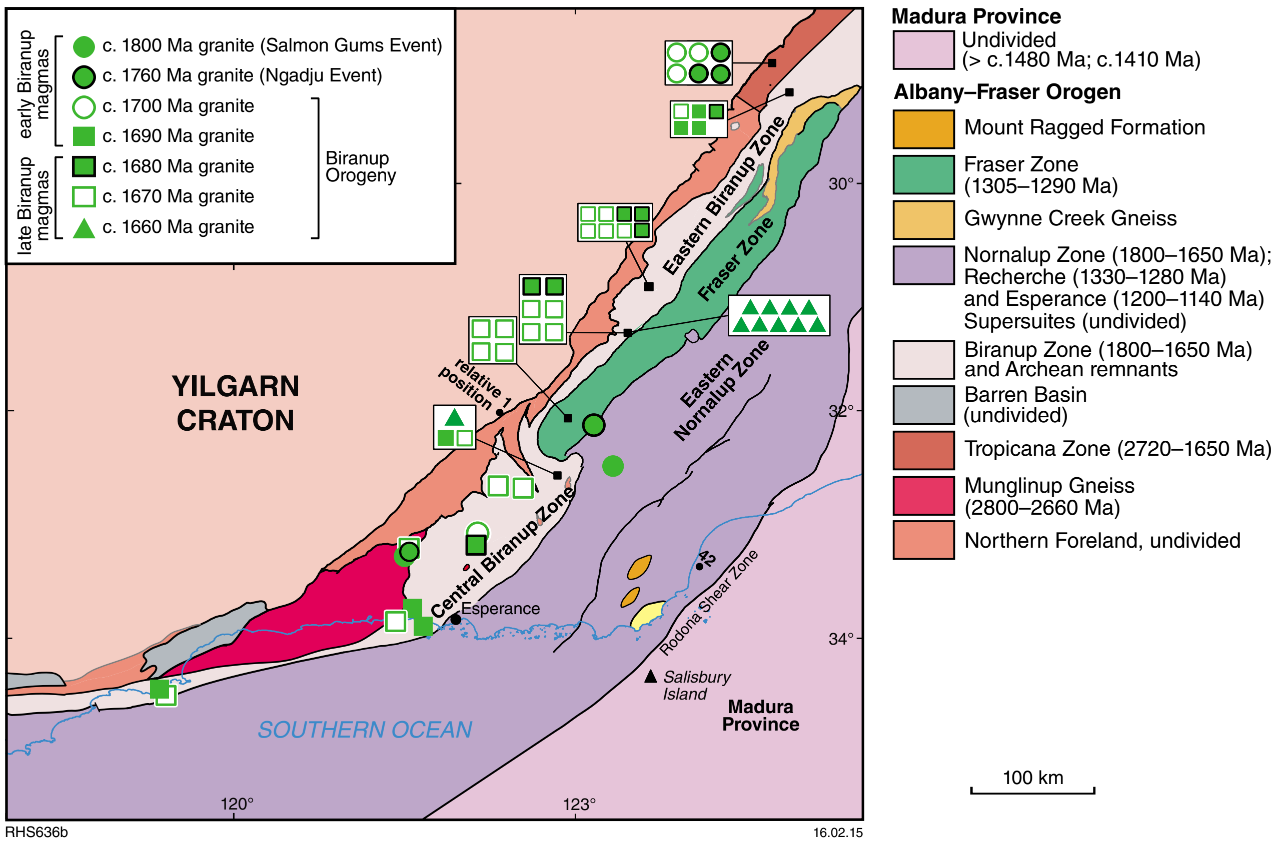


Figure 7. Simplified, pre-Mesozoic interpreted bedrock geology of the east Albany–Fraser Orogen showing the distribution of the c. 1800–1660 Ma granite groups

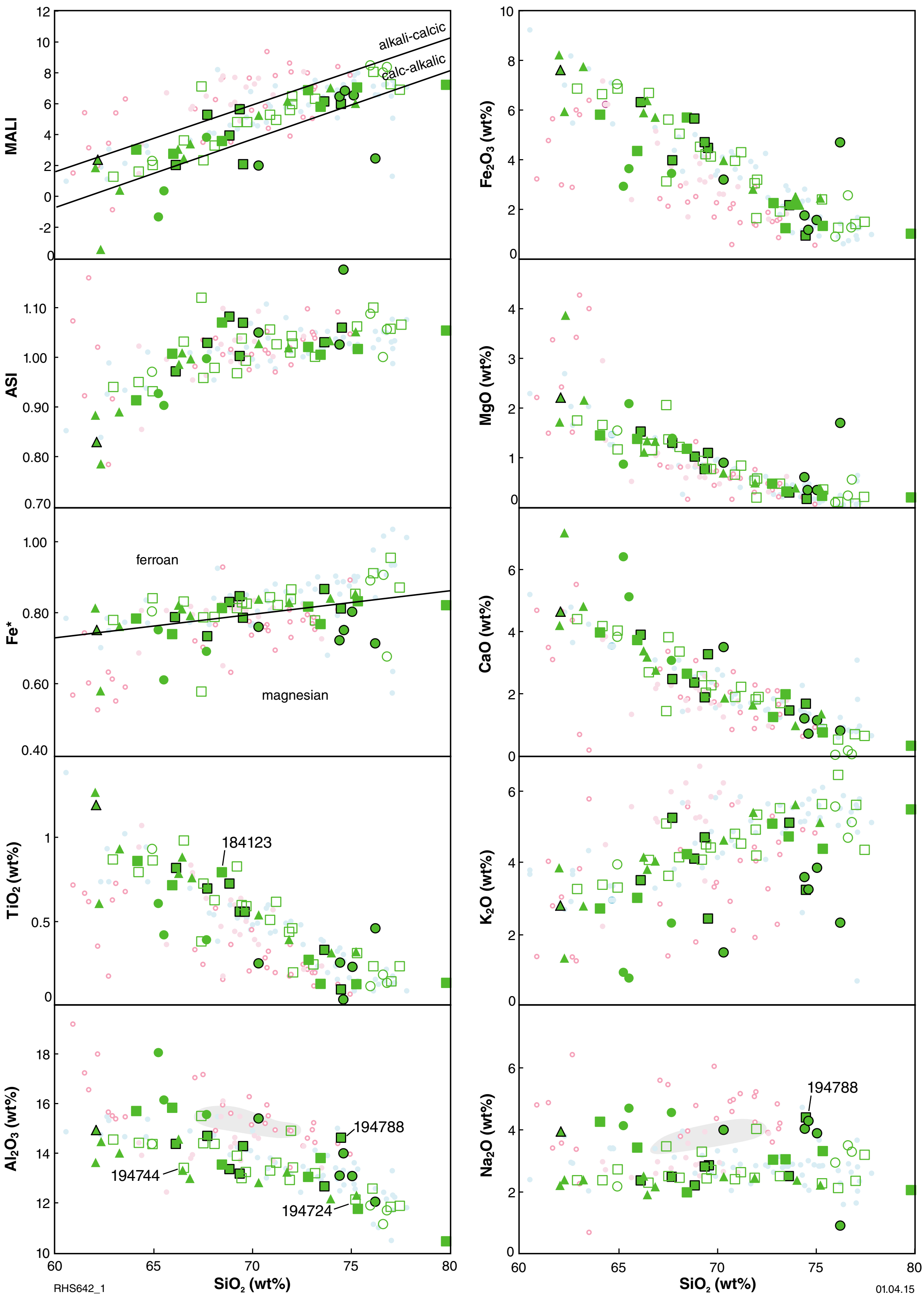
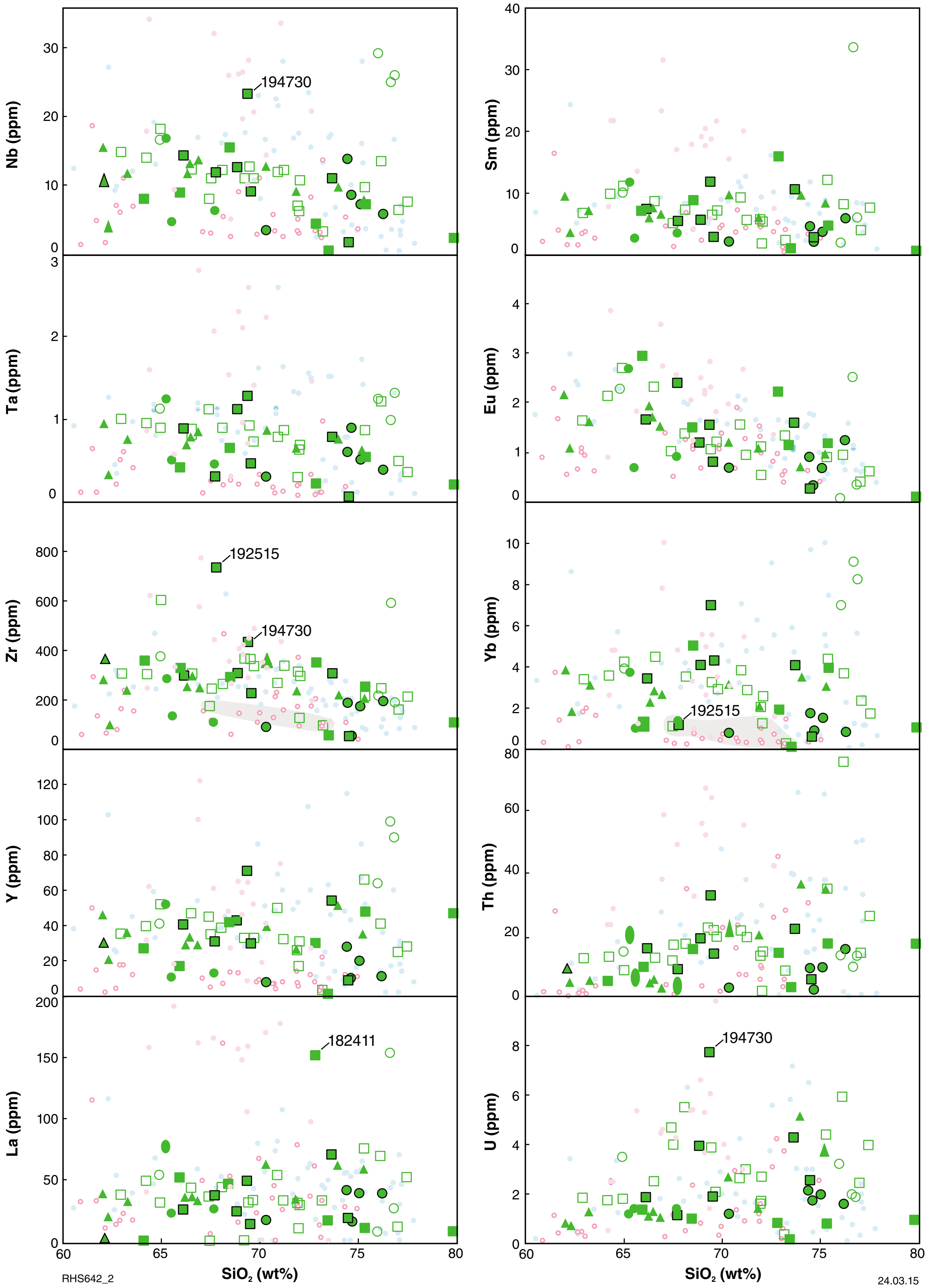


Figure 8. Compositional variation diagrams for the c. 1800–1660 Ma granite groups. MALI = modified alkali lime index ($Na_2O+K_2O–CaO$) and boundaries are after Frost et al. (2001). ASI = aluminium saturation index [= molecular ratio of Al/(Ca+Na+K)]. Fe* = Fe number [FeO/(FeO+MgO) with all Fe as Fe^{2+}], with boundaries after Frost et al. (2001). Sample numbers refer to samples specifically mentioned in the text. Field defined in some diagrams encloses specific c. 1670 Ma granites that variably display some compositional attributes of TTG (see text) (continued on pages 16–18)



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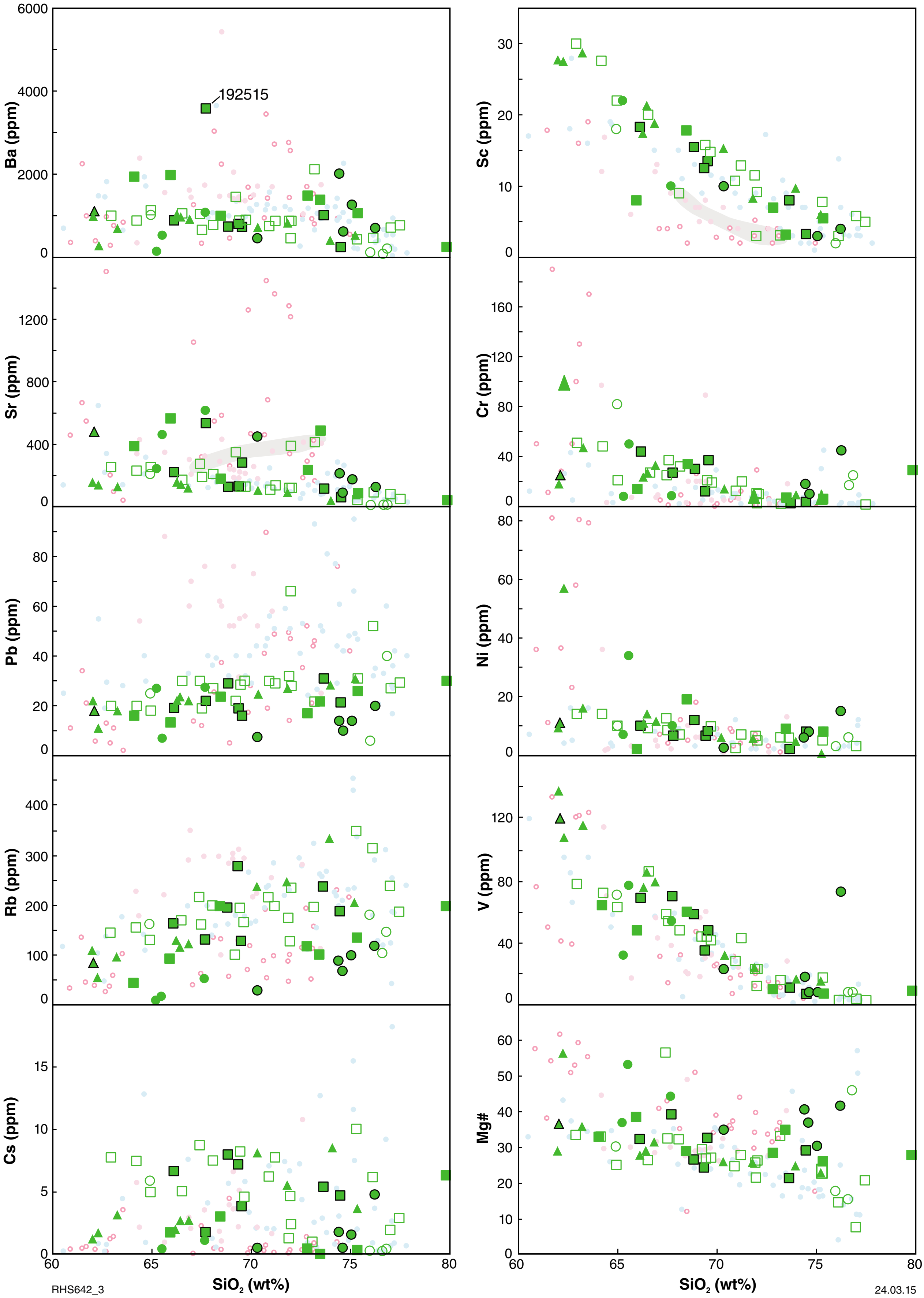

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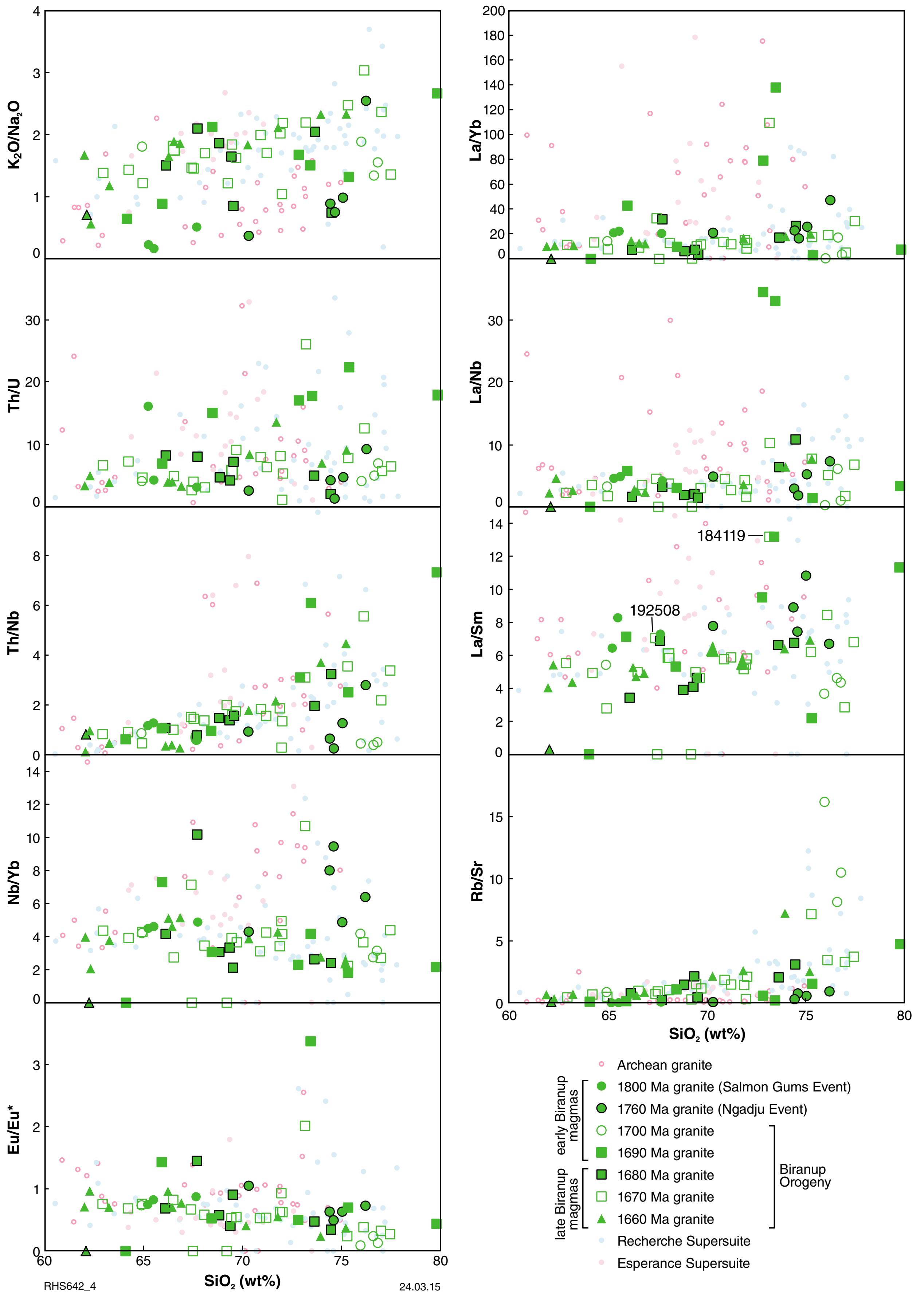

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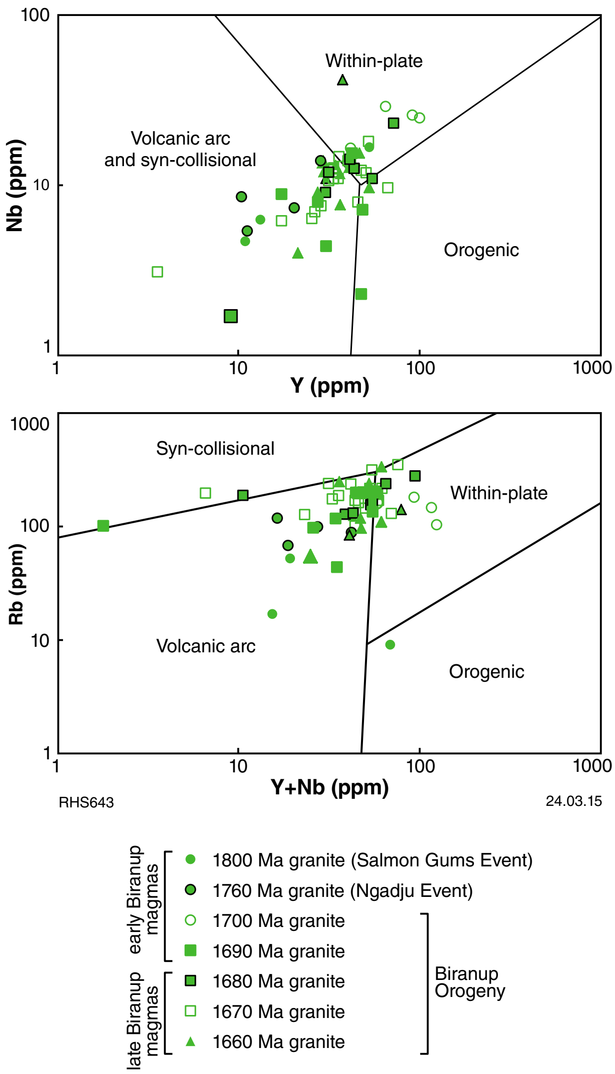


Figure 9. **Tectonic discrimination diagrams for the c. 1800–1660 Ma granite groups (Pearce et al., 1984)**

The single sample of c. 1700 Ma granite from Dingo Rock is difficult to relate to the granites at Bobbie Point. This sample shows no major or trace element features that clearly distinguish it from most of the younger pre-Albany–Fraser Orogeny granite groups, although it lies at the upper limit of the compositional range in HFSE for those younger granite groups and on the margin of their compositional range in tectonic discrimination diagrams, just within the field for within-plate granite (Fig. 9), similar to the Bobbie Point samples. The uncertainty associated with the U–Pb zircon age of this sample (1703 ± 14 Ma, GSWA 194702, Kirkland et al., 2011d) permits it being grouped with either the c. 1700 Ma or c. 1690 Ma granite groups.

c. 1690 Ma granites

Seven samples of the c. 1690 Ma granite group were taken from four localities relatively well spaced across the Biranup Zone (Fig. 7). The group comprises calc-alkalic, magnesian granites (Fig. 8) with a wide range in silica content (64.1 – 79.8 wt%) and considerable geochemical scatter, although five of the seven samples show geochemical features or trends that probably justify viewing them as a unique group. Compared to these five samples, the geochemical composition of the other two samples (184123 at 68.4 wt% SiO_2 and 182411 at 72.1 wt% SiO_2) are anomalous in many (182411) or most (184123) respects (Fig. 8).

In terms of major element compositions, the distinguishing characteristics of the c. 1690 Ma granites include slightly lower K_2O and higher Na_2O concentrations (with correspondingly lower and distinctive K_2O/Na_2O ratios) compared to younger pre-Albany–Fraser Orogeny granite groups at similar SiO_2 contents (Fig. 8). In this respect, the c. 1690 Ma granite group is transitional between these younger granite groups and the older, generally sodic, granite groups. In terms of trace element characteristics for most of the c. 1690 Ma granites, concentrations of the typically most incompatible trace elements (Th, U, Nb, Ta, Cs and Rb) and the other LILE (Ba and Sr) are also consistent with this ‘transitional’ nature between the older and younger pre-Albany–Fraser Orogeny granite groups (see below). Low Rb/Sr and high Th/U ratios, in particular, distinguish the c. 1690 Ma granites from most of the younger pre-Albany–Fraser Orogeny granites (Fig. 8). The concentrations of other HFSE (e.g. Zr, Hf and Y) are higher than those of the older granite groups (at equivalent silica contents; the HFSE-enriched c. 1700 Ma granites are an exception here — see below), although within the range of the younger pre-Albany–Fraser Orogeny granite groups. LREE concentrations show considerable scatter although they are in any case an ineffective way of distinguishing between the pre-Albany–Fraser Orogeny granite groups. HREE and Sc concentrations do effectively distinguish the older granite groups (HREE- and Sc-depleted) from the younger pre-Albany–Fraser Orogeny granite groups, although the scattered HREE and Sc concentrations in the c. 1690 Ma granites show no particular affinity for either population (Fig. 8).

Of the two regularly anomalous samples, 184123, a garnet-bearing monzogranitic gneiss from Plum Pudding Rocks, west of Esperance, plots with the younger pre-Albany–Fraser Orogeny granites for all major and trace elements and ratios, except for U and Th/U, for which it is more characteristic of the c. 1690 Ma granite group (Fig. 8). Sample 182411, a K-feldspar megacrystic granite from Pleiades Lakes, shows most compositional attributes of the main c. 1690 Ma granite group but has anomalously high REE (particularly LREE) concentrations (Fig. 8).

c. 1680 Ma granites

The seven samples of the c. 1680 Ma granite group were taken from four localities within the Biranup Zone (Fig. 7). The major and trace element compositions for four of these samples (from three localities) show a systematic variation with silica, which ranges from 66.1 to 73.6 wt%, and consistently fall within the compositional field formed by the main population of young pre-Albany–Fraser Orogeny granites (i.e. the c. 1680, 1670 and 1660 Ma granite groups; Fig. 8). This collection of pre-Albany–Fraser Orogeny granite groups is strongly dominated by marginally ferroan, calc-alkalic granites, with dominantly ‘volcanic-arc’ like compositions on tectonic discrimination diagrams (Fig. 9). Together, these groups likely reflect a source and magmatic style that persisted from c. 1685 to 1655 Ma.

Geochemical scatter within the c. 1680 Ma granite group primarily relates to three samples from separate localities (192515 [67.7 wt% SiO_2], 194730 [69.3 wt% SiO_2] and 194788 [74.5 wt% SiO_2] Fig. 8). Sample 192515, an undated syenogranite from Pleiades Lakes, has anomalously high Ba and Sr and low HREE concentrations, high Eu/Eu* and Nb/Yb ratios and low Rb/Sr ratios. In these regards, it is compositionally similar to the older, sodic Archean granites and the Munglinup Gneiss. High Zr, K_2O and K_2O/Na_2O, however, distinguish this sample from these older granites, although it remains possible that this sample contains a large component of recycled Archean material.

Sample 194730, a granitic gneiss from Ponton Creek, has anomalously high Nb, Zr, U, Th, Pb and HREE and in most regards more closely resembles granites related to the Albany–Fraser Orogeny (Recherche or Esperance Supersuites).

Sample 194788 is a leucocratic vein that cuts garnet-bearing granitic gneiss to the southwest of Harris Lake. It is unclear if the c. 1679 Ma age obtained from this sample dates the vein or the host. However, the sample is of a highly silicic rock (SiO_2 = 74.4 wt%) with high Na_2O and Al_2O_3 and low K_2O, HREE and Sc concentrations and distinctly low K_2O/Na_2O ratios, which contrast strongly with the high K_2O and generally high HREE concentrations within both the host granitic gneiss and all other c. 1800–1660 Ma granites of this region (Fig. 8). The vein is clearly not a crystallized anatectic melt of the host gneiss. Although the composition of this vein matches well with that of sodic Archean granites, age constraints preclude that origin. It is possible, however, that the leucocratic vein is a result of low degree partial melting of a nearby although unexposed piece of Archean sodic granite (trondhjemite). This interpretation could explain Rb/Sr ratios that are higher than those of the Archean granite and Munglinup Gneiss groups and within the range of other c. 1800–1660 Ma granites, although is not consistent with the lower La/Sm ratios in the vein compared with the older sodic granites. A preferred alternative is that the vein represents a very low degree partial melt of an unexposed mafic rock (basalt or gabbro), or extremely fractionated residual melt emanating from an unexposed mafic intrusion.

c. 1670 Ma granites

Twenty samples of the c. 1670 Ma granite group cover the extent of the Biranup Zone within the study area — probably forming the widest and most evenly sampled pre-Albany–Fraser Orogeny granite group (Fig. 7). One drillcore sample (192508) from the Salmon Gums prospect occurs in the Munglinup Gneiss, and is interpreted to have intruded its Archean granitic protolith. The group shows an expanded range of silica contents, from 62.9 to 77.4 wt%. It typically shows well-defined normal igneous compositional trends for most major and trace elements (Fig. 8), in most cases forming reasonably tight linear arrays that overlap extensively, for many (although not all) elements, the arrays defined by the c. 1680 and c. 1660 Ma granite groups. These trends are high-K, calc-alkalic and ferroan (Fig. 8). The degree of compositional consistency is particularly surprising given the range of overprinting metamorphic assemblages, with, for example, many of the less silicic samples (SiO_2 <68 wt%) from the southeastern Biranup Zone now represented as garnet–biotite monzogranitic gneiss.

There are, nevertheless, several widely spaced samples across the central and eastern Biranup Zone that show anomalous concentrations of several elements when compared to the main compositional field for the group. In the case of samples 192508 (a granitic gneiss with ‘pegmatite patches’ from the Salmon Gums prospect with 67.4 wt% SiO_2), 194739 (a felsic dyke with 80.0 wt% SiO_2 intruding metadiorite of the Eddy Suite of the c. 1660 Ma granite group), and 184119 (a monzogranitic gneiss from Bremer Bay with 63.2 wt% SiO_2), scatter is often to higher concentrations of Al_2O_3, Na_2O, Ba and Sr and lower Y, Nb, Zr, Sc and HREE (Fig. 8). Such trends are characteristic of the older sodic granites of the Albany–Fraser Orogen, although geochronology and field relationships (e.g. dykes in post-Archean granite) preclude these rocks belonging to one of these significantly older granite groups. It is possible that these three anomalous samples have incorporated a component (either in their crustal source or as a later contaminant) of Archean, or recycled Archean, sodic granitic material. A similar suggestion was proposed to explain the ‘Archean granite-like’ composition of sample 194788 of the c. 1680 Ma granite group (see above), but was not favoured because that sample has lower La/Sm ratios than the Archean granites and Munglinup Gneiss (Fig. 8). The three anomalous c. 1670 Ma granites have low Rb/Sr ratios within the range of the old sodic granites (and very unlike the other younger pre-Albany–Fraser Orogeny granite groups), and two of the three (192508 and 184119) have high La/Sm ratios, also within the range of the older sodic granites (Fig. 8). Hence, at least in the case of these two samples, an older, sodic source or contaminant component remains a plausible interpretation.

Included within the c. 1670 Ma granite group are a sample from southwest of Eddy Hill (194744) and a sample from southwest of Harris Lake (194724), both in the eastern Biranup Zone. Although both samples have ages that put them within the c. 1670 Ma group, the dates are also within analytical uncertainty of the c. 1660 Ma granite group, to which their petrography and several geochemical attributes suggest they better belong. They will be discussed as part of the c. 1660 Ma granite group below.

c. 1660 Ma granites

This group contains 10 samples plus two additional samples placed into the c. 1670 Ma granite group (194744 and 194724) based on age, but which share geochemical similarities with the c. 1660 Ma granite group. Despite this reasonably large dataset, samples are restricted to two small areas of the eastern Biranup Zone (Fig. 7) — the region around Eddy Hill and to the southwest of Harris Lake, and an area north of Mount Andrew. Of these, the latter locality yields only a single sample (194707) with an error on the determined age that allows it to fall within several alternative granite age groups. Additionally, this sample has a high silica content (75.2 wt%) which, combined with the general similarity in composition of all three of the 1680–1660 Ma age groups at these high silica contents, makes it very difficult to interpret. As a result, discussion of the c. 1660 Ma granite group will be restricted to the samples from the region around Eddy Hill and to the southwest of Harris Lake, where these rocks are defined as part of the c. 1665 Ma Eddy Suite (Spaggiari et al., 2011; Spaggiari and Brisbout, 2014).

The granites of the Eddy Suite form possibly the most compositionally coherent group of all granite groups of the Albany–Fraser Orogen. They form part of a bimodal magmatic association that shows abundant field evidence for at least localized magma mingling, and possibly also mixing, and identical magmatic ages (Spaggiari et al., 2011; Kirkland et al., 2011b). A silica gap of nearly 8 wt% SiO_2 (Fig. 10) separates the mafic (gabbroic) end-members of this bimodal association from the least felsic (dioritic-granodioritic) members. The overall silica range of the felsic rocks is from 62.0 to 75.3 wt% SiO_2, although it appears that within that range there is possibly a second silica gap between 66.8 and 70.3 wt% SiO_2 (Fig. 8). For the rocks with higher silica (>70 wt%), there is no difference in compositional range or trend for any major or trace elements that permits distinction from rocks of the c. 1680 or c. 1670 Ma granite groups at similar silica levels, except, perhaps, for marginally higher Th and Rb concentrations in the Eddy Suite granites (Fig. 8). The intermediate silica part of the compositional range (62.0 – 66.8 wt% SiO_2) also shows considerable overlap with samples of the c. 1680 or c. 1670 Ma granite groups at similar silica levels, except for Th, U, Sr, Cs and possibly Rb concentrations, which are generally lower in the Eddy Suite granites (Fig. 8). At these lower silica levels, higher concentrations of V and Cs clearly separate the Eddy Suite granites from most of the c. 1670 Ma granites, although not from the c. 1680 Ma granites.

Because the Eddy Suite forms part of a bimodal magmatic suite that shows evidence for mingling and mixing it is important in any geochemical discussion that the comagmatic mafic magmas also be considered. Six samples of gabbro are medium-K tholeiitic rocks which range from 47.6 to 54.2 wt% SiO_2, with a corresponding range in MgO of 13.0 – 4.7 wt% and in Mg# of 70–43 (Fig. 10). The most primitive sample has MORB-like concentrations of Nb and Zr, although elevated concentrations of Th (1.57 ppm) and other strongly incompatible trace elements (e.g. La = 8.84 ppm; see 194721 in Fig. 11). Other members of the suite have elevated concentrations of strongly incompatible trace elements, including Nb and Zr, (e.g. Th = 1.57–5.51, La = 8.48 – 18.98 ppm; Nb = 2.9–9 ppm) with elevated La/Nb, Th/Nb and La/Sm ratios compared with MORB values (Fig. 10). There is no clear tendency for these ratios to increase with increasing silica. Despite the ~8 wt% silica gap separating the gabbros from the c. 1660 Ma granites, low silica (<66 wt% SiO_2) granites share a similar range of La/Nb, Th/Nb and La/Sm ratios with the gabbros (Fig. 10) and, on most compositional variation diagrams, the gabbros extend the compositional trends shown by the granites. Exceptions here are with Nb and Ta, both of which increase in concentration with increasing silica content within the gabbros, but decrease in concentration with increasing silica within the Eddy Suite granites (Fig. 10), and also within the c. 1680 and 1670 Ma groups. Only rutile has a high enough mineral/melt partition coefficient to cause, as part of a fractionating assemblage, a decrease in magmatic Nb and Ta concentrations (ilmenite mineral/melt partition coefficients for Nb and Ta are not high enough — e.g. Klemme et al., 2006), particularly at the intermediate silica levels of the Eddy Suite. However, if sufficient rutile is removed to cause a decrease in Nb concentrations, this should also be accompanied by a significant increase in Nb/Ta ratios ($D^{rutile}_{Ta>>Nb}$; e.g. Klemme et al., 2005). For the Eddy Suite, Nb/Ta ratios remain constant or decrease slightly (Fig. 10). In addition, the initial Nd isotopic composition of the gabbros and granites (see below) both show very little variation, although values for the gabbro are around 1 to 2 ε_{Nd} units higher (–1.25 to –1.52) than those of the Eddy Suite (ε_{Nd} mainly between –2.73 and –3.66). This suggests that while the gabbro and granites are comagmatic, they are not cogenetic, and for this reason the gabbros are not included within the Eddy Suite.

Variations in time within the pre-Mesoproterozoic granites — early compositional evolution of the crust

Geochronological data confirms the widespread occurrence of what is likely now a volumetrically relatively minor, pristine (i.e. variably metamorphosed although not geochemically altered) Archean granitic component preserved within the Albany–Fraser Orogen. This includes the Northern Foreland and Munglinup Gneiss, much of the Tropicana Zone and remnant fragments within the Biranup Zone. Geochemical data are entirely consistent with the geochronology, typically showing features such as high Al_2O_3, Na_2O, Ba, and Sr and low K_2O, HREE, Sc and Rb concentrations (Fig. 5), which are characteristic of the main classes of Archean granites. Like previously published Hf(zircon)-isotopic data (Kirkland et al., 2011a,b), available Nd isotopic data for this Archean granite group of the Albany–Fraser Orogen are typically in the strongly non-radiogenic time-integrated range for felsic crust of the Yilgarn Craton (Fig. 12). The geochemical data, however, also show that within the Archean granite group of the Albany–Fraser Orogen there are at least two types of granites — broadly representing high-Al TTG, and sanukitoids. The main occurrence of sanukitoids is in the Neale Project area in the Tropicana Zone (Fig. 7).

Geochronological data show that the protolith to the Munglinup Gneiss was Archean granite and this is confirmed by strongly ‘Archean-like’ geochemistry (Fig. 5). Metamorphism during Stage II of the Albany–Fraser Orogeny was largely isochemical except for the possible loss of what was likely a high La/Yb, low La/Sm, Th/U ratio fluid.

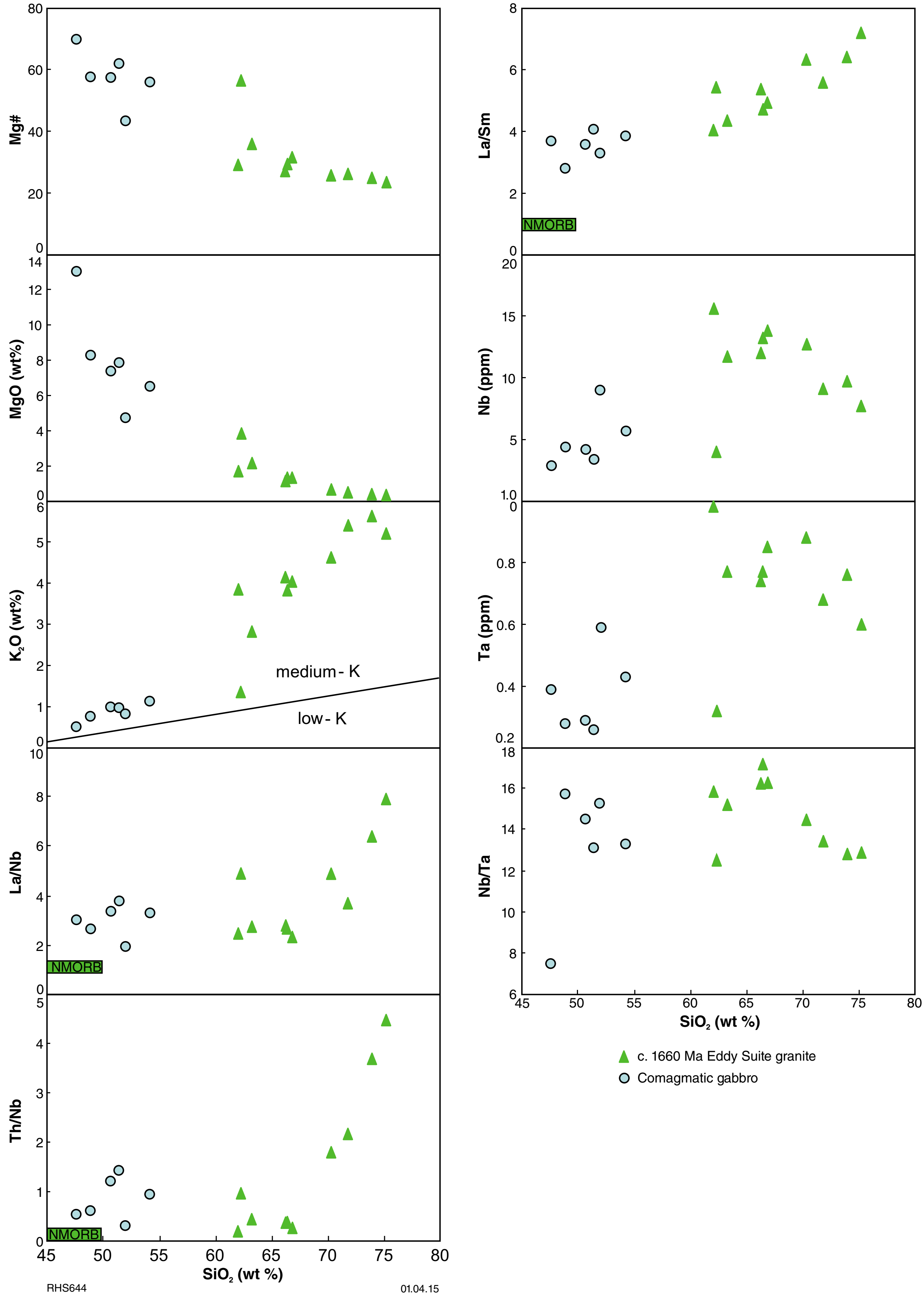


Figure 10. Compositional variation diagrams for the c. 1660 Ma granite group (Eddy Suite) and comagmatic gabbros. NMORB ratios from Sun and McDonough (1989)

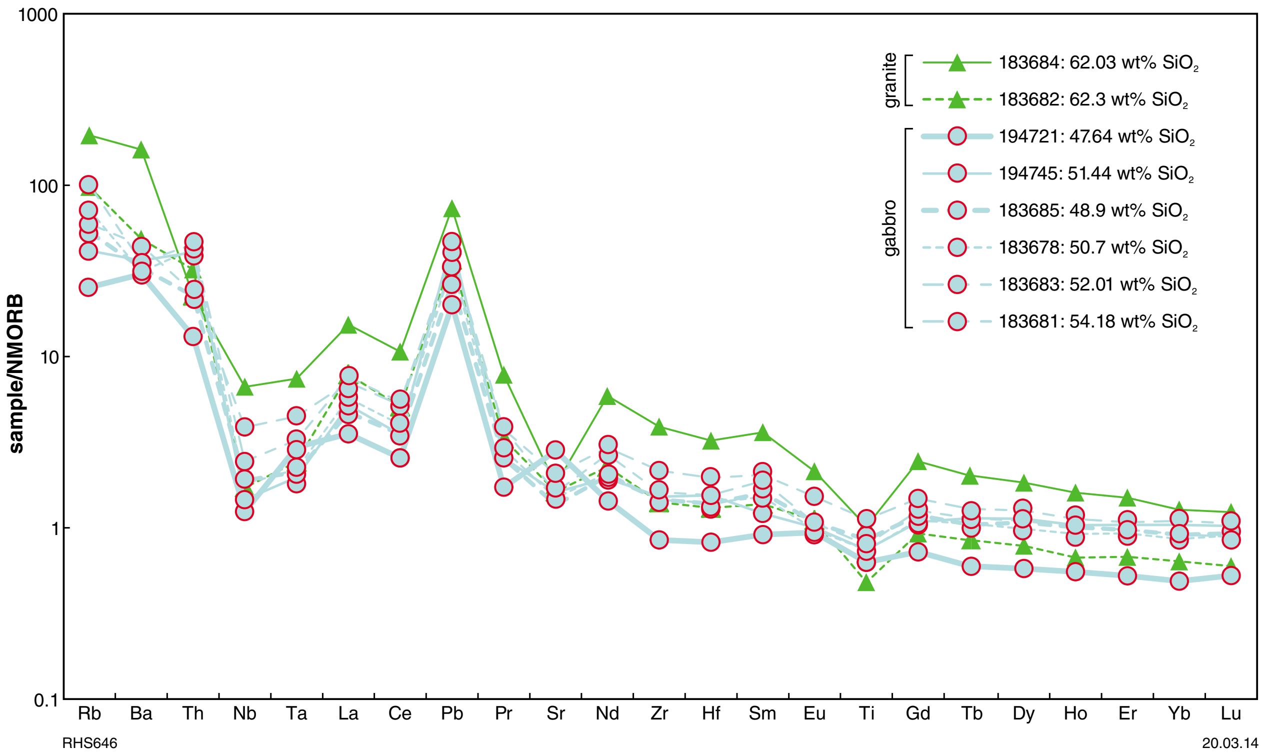


Figure 11. NMORB-normalized spider diagram showing the most silica-poor c. 1660 Ma granites of the Eddy Suite and comagmatic gabbros. Key shows sample number and SiO_2 concentrations. Normalization after Sun and McDonough (1989)

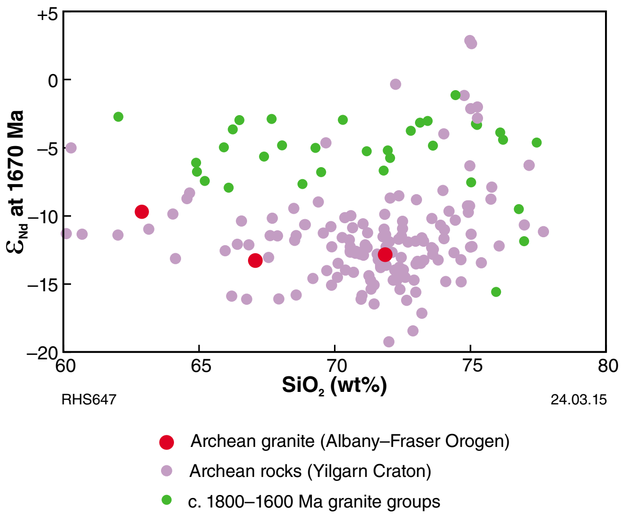


Figure 12. Nd-isotopic composition of Archean granites (data for granites of the Yilgarn Craton are from D Champion, 2014, written comm.)

Together, the Archean granites and the Munglinup Gneiss reflect the variably preserved 'ancient crust', or the precursor felsic crust to the Salmon Gums and Ngadju Events and the Biranup Orogeny, and from a geochemical perspective are relatively simple. Although physical (i.e. outcrop) evidence for Archean crust is not widespread in the Albany–Fraser Orogen, the geochemistry and isotopic compositions of felsic rocks formed in subsequent events provides compelling evidence that Archean crust was modified or recycled, although not removed. Calculated from both Hf- and Nd-isotopic data (e.g. Kirkland et al., 2011a,b) (Fig. 13), depleted mantle model ages for all post-Archean granites formed before the end of the Biranup Orogeny range between 3.3 and 2.4 Ga, and so the LREE and HFSE budget of these rocks is in fact dominated by an Archean source.

Compositional evolution of the crust before, and during, the Biranup Orogeny can be broadly divided into two main episodes — 'early Biranup magmatism' and 'late Biranup magmatism'. Note that although these granites dominantly occur within the Biranup Zone, they are not confined to it. The felsic products of these two events can be broadly distinguished on plots of SiO_2 vs Na_2O, K_2O/Na_2O or Rb/Sr (Fig. 14). For convenience, early Biranup magmatism is expanded here to include the products of the Salmon Gums and Ngadju Events as well as the 1710–1650 Ma Biranup Orogeny between c. 1800 and 1690 Ma. It included formation of the c. 1800, 1760, 1700 and 1690 Ma granite groups and was dominated

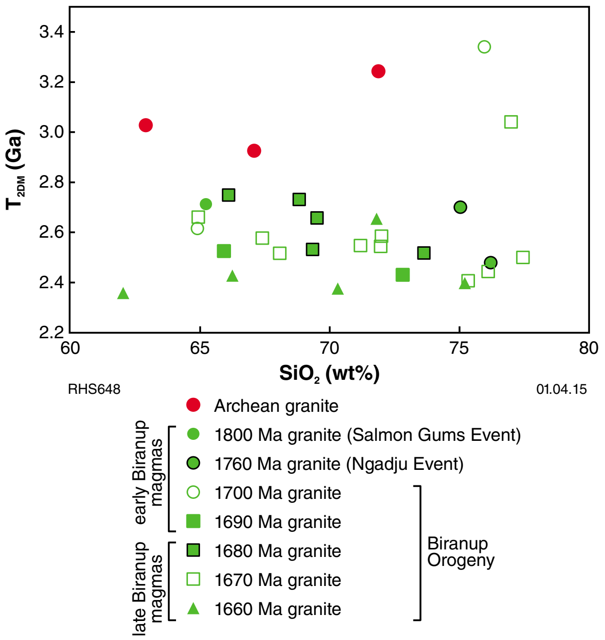


Figure 13. T_{DM} Model ages for the c. 1800–1660 Ma granite groups

by the production of granites that are generally higher in Al_2O_3, Na_2O, and LILE and lower in K_2O, Sc and HREE than subsequent 1680–1650 Ma late Biranup magmatism (Fig. 14). These compositional attributes are clearly similar to those that characterize the older Archean granites and the Munglinup Gneiss and, in many cases, the compositional field for the early Biranup magmas either overlaps that for the older sodic rocks or lies between the field for older sodic rocks and the field for late Biranup magmas (Fig. 14).

These trends suggest that modification of Archean felsic crust was a progressive process. Indeed, within the compositional range of early Biranup magmatism, the older (c. 1800 and 1760 Ma) granites typically have compositions most like those of the Archean granites and the Munglinup Gneiss, whereas the c. 1690 Ma granite group shows a large degree of overlap with the fields for late Biranup magmas (Fig. 14). The c. 1690 Ma granites also have slightly more radiogenic Nd isotopic compositions than the older early Biranup magmas (Fig. 15). These trends suggest that the proportion of unmodified Archean crust in the source of c. 1800 and 1760 Ma granites is slightly greater than that in the source of the c. 1690 Ma granite group. The concentrations of the HREE (e.g. Yb), in particular, remains very low within the c. 1800 and 1760 Ma granites (Fig. 14), perhaps suggesting that recycling of Archean crust at this stage also remained within the stability field of garnet.

Nevertheless, except in the case of the c. 1700 Ma granite group (see below), all Biranup magmas have Nd isotopic compositions significantly more radiogenic than most Yilgarn Craton felsic crust (Fig. 15). This requires an additional source component that was both younger and more radiogenic than Yilgarn Craton crust. Thus, a mantle contribution to the bulk source is required, either at the time of crustal melting or at an earlier, although most likely post-Archean, stage. The frequent association of each granite age group with mafic magmatism throughout the Biranup Orogeny, and earlier post-Archean events, might suggest that the mafic source component was comagmatic; however, such a relationship would also imply a gradual increase in the amount of older juvenile components available to the source regions of each subsequent crustal melting event.

The Bobbie Point Metasyenogranite, one of the c. 1700 Ma granite group of the early Biranup magmatism phase, was identified above as having anomalous compositions compared to immediately older and younger granite groups (the other member of the c. 1700 Ma granite group, from Dingo Rocks, shows a more 'normal' composition). Like other early Biranup magmas, the Bobbie Point Metasyenogranite is sodic but has elevated concentrations of Nb, HREE (Y), Ga and Zn, and low Th/Nb, La/Sm and La/Yb ratios and plots well within the field of within-plate granite on tectonic discrimination diagrams (Figs 9 and 10), consistent with generally alkali-calcic and ferroan compositions. Many of these compositional features point to the high temperature, anhydrous petrogenesis of many A-type granites (e.g. Frost et al., 2001). A single Nd isotopic analysis reflects an extremely non-radiogenic source ($\varepsilon_{Nd\ (1670Ma)}$ of –15.6; Fig. 15) within the time-integrated range of the most compositionally fractionated crust of the Yilgarn Craton. These granites reflect a compositional style of magmatism very unlike the preceding and subsequent sodic magmatism, likely resulting from high temperature melting of previously dehydrated Yilgarn Craton crust. Moreover, the strongly elevated HREE concentrations of the c. 1700 Ma Bobbie Point Metasyenogranite precludes melting of a garnet-bearing crustal source, although strong decoupling of Nd- and Hf-isotopic compositions in these rocks (see below) suggests a source with a history of crystallization and residence at pressures within the garnet stability field. Hence, in contrast to the c. 1800 and 1760 Ma granites, which recycled crust that was probably within the garnet stability field, the Bobbie Point granites likely reflect recycling of felsic crust uplifted from the garnet stability field.

Figure 16 compares data for Yilgarn Craton felsic crust with early and late Biranup magmas in terms of $\varepsilon_{Nd\ (1670Ma)}$ against indices of compositional evolution (e.g. La/Sm, La/Nb, Rb/Sr). Since crustal melting should result in melt fractions with higher La/Sm, La/Nb, La/Yb and Rb/Sr than the source, the observation that Biranup magmas have a rather restricted and low range in these ratios suggests either that only the relatively more juvenile terranes of the Yilgarn Craton form source components to this magmatism, or that Yilgarn Craton felsic crust was supplemented by the addition of juvenile material before forming the source to Biranup magmas, or both.

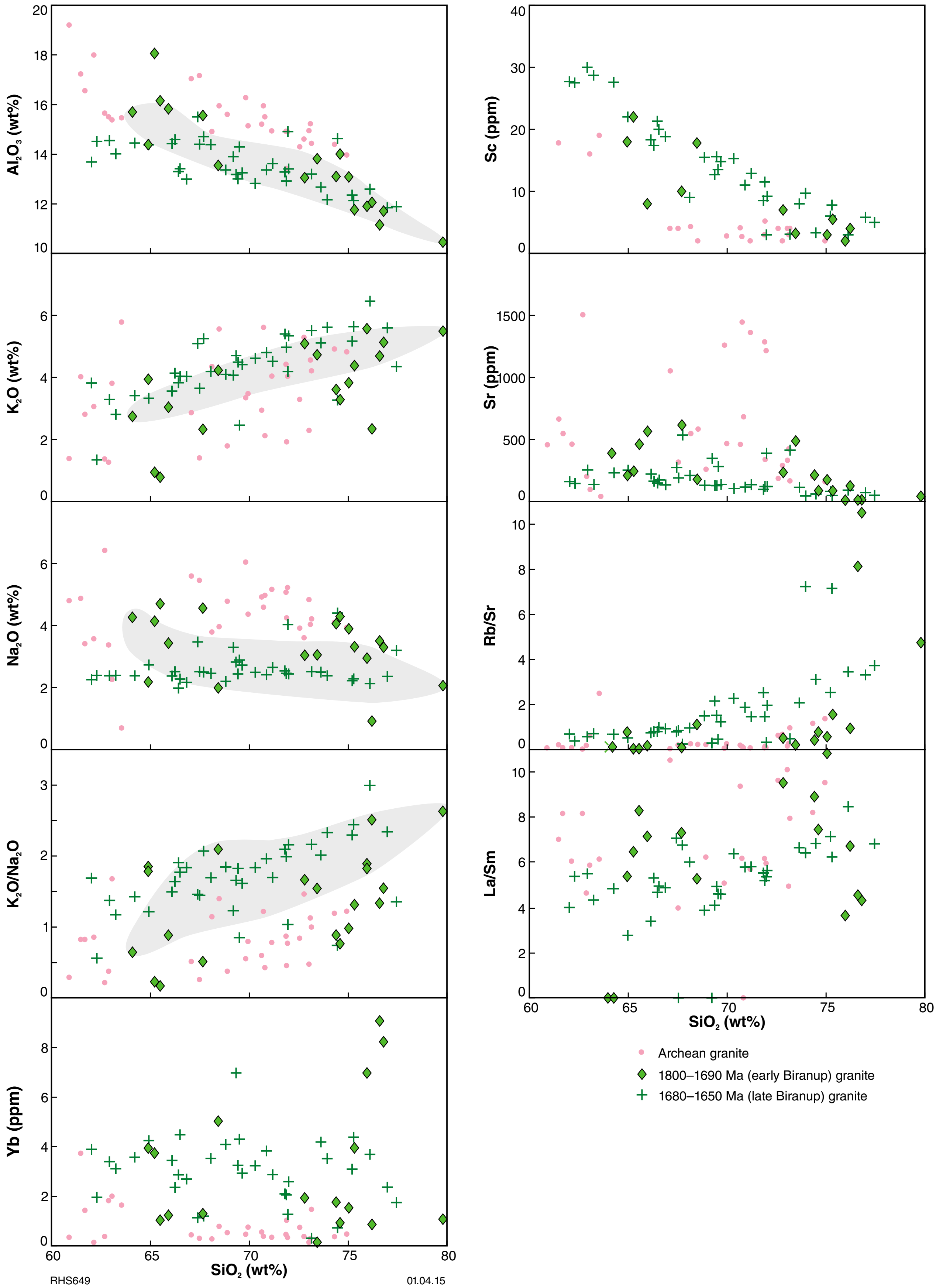


Figure 14. Compositional variation diagrams showing 'early' and 'late' Biranup granites (grey field, where drawn, outlines granites of the c. 1690 Ma group)

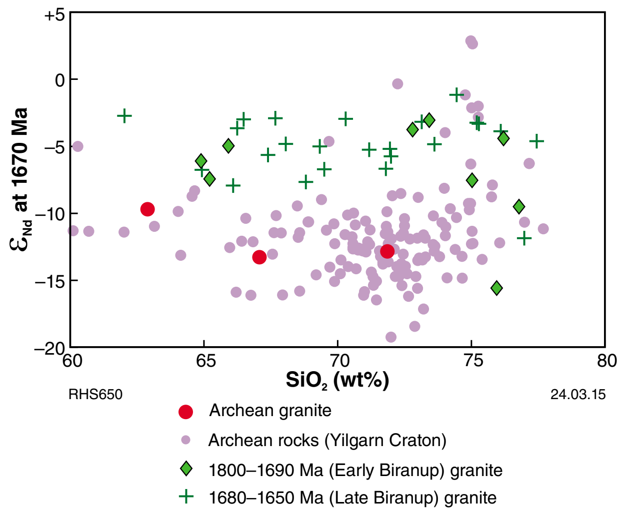


Figure 15. Nd-isotopic composition of 'early' and 'late' Biranup granites

Late Biranup magmatism spanned the period from c. 1680 to 1650 Ma and includes the c. 1680, 1670 and 1660 Ma granite groups. Compositional distinctions from early Biranup magmas are outlined above (Fig. 14), as is the more 'transitional' nature of c. 1690 Ma granite magmatism. In contrast with the sodic early Biranup magmas, the majority of the high-K late Biranup magmas show none of the enduring major or trace element compositional features that mark the source as recycled Yilgarn Craton crust (Fig. 14), although the Nd isotopic data (Fig. 15) indicates that the major 'crustal' component of the bulk source in fact changed only slightly in composition. The compositional ranges and trends shown by these granites are reasonably typical of medium- to high-K calc-alkaline rocks (although the late Biranup magmas tend to have more ferroan compositions) and there are very few, and only subtle, compositional features that can distinguish any of the three age groups of late Biranup magmas.

The Nd isotopic compositions of the late Biranup magmas is typically more radiogenic ($\varepsilon_{Nd\ (1670Ma)}$ of –2.73 to –11.86) than Yilgarn Craton felsic crust and overlaps extensively the range for the early Biranup magmas (Figs 15 and 16), although the late Biranup magmas extend to more radiogenic compositions. Within the range for the late Biranup magmas, there is also a crude trend to increasingly radiogenic compositions with decreasing age of magmatic group (average $\varepsilon_{Nd\ (1670Ma)}$ of c. 1680 Ma granites = –6.44; c. 1670 Ma granites = –5.72; c. 1660 Ma granites = –3.86). As with the early Biranup magmas, the relatively radiogenic compositions mean that recycled Yilgarn Craton felsic crust alone cannot form the source to the late Biranup magmas. An additional, younger and more isotopically juvenile component (e.g. mantle) would be required. However, if the early Biranup magmas are typical of the relatively sodic whole-rock compositions expected from recycling of Yilgarn Craton felsic crust, then the significant compositional differences shown by the late Biranup magmas suggests that the later granites are not a result of exactly the same process. The generally higher K_2O contents and K_2O/Na_2O and Rb/Sr ratios of these later granites would require a significantly lower degree of partial melting of Archean granite than is required to produce the early Biranup magmas, which is inconsistent with the generally lower La/Sm ratios in the late Biranup magmas (Fig. 14). It is possible that a putative Yilgarn Craton source region for the late Biranup magmas simply contained a higher proportion of juvenile low La/Sm mantle-derived magma, although this would likely make the bulk source composition more sodic. A preferred alternative is that the source for the high-K late Biranup magmas actually incorporated a high proportion of early Biranup granite, again with addition of a younger and more isotopically juvenile mantle component.

Granite of the c. 1665 Ma Eddy Suite (c. 1660 Ma Granite group), at the most radiogenic end of the range for the late Biranup magmas, defines an isotopically uniform ε_{Nd} array ($\varepsilon_{Nd\ (1670Ma)}$ of four of five samples between –2.73 and –3.66) that shows no correlation with indices of whole-rock compositional evolution (e.g. La/Sm, La/Nb, Rb/Sr; Fig. 17). These trends reflect the compositional evolution of a more juvenile magma within a system that was closed to any addition of less radiogenic country rock, although further contamination by isotopically similar crust is possible. A major difference between the granite of the Eddy Suite and the other granites of the late Biranup magmas is that it was sampled from a single, geographically restricted area, and hence more likely reflects a single magma batch. By contrast, granites of the c. 1680 and c. 1670 Ma groups show significantly more scatter in plots of $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb, individually and collectively forming a wedge-shaped field with $\varepsilon_{Nd\ (1670Ma)}$ lower than those of the granite of the Eddy Suite, but that converge with the granite of the Eddy Suite with increasing La/Yb, La/Sm and La/Nb ratios (Figs 16 and 17). The positive correlations between ε_{Nd} and La/Yb, La/Sm and La/Nb ratios, as well as with REE concentrations (Fig. 17), are very unusual and strongly contrast with normal mantle–crust mixing or assimilation-fractional crystallization (AFC) relationships. These wedge-shaped fields likely reflect a very complicated relationship between a wide range of compositionally distinct source regions that have interacted via a range of petrogenetic processes.

Gabbro is co-mingled (comagmatic) with the granite of the Eddy Suite and shows a much narrower and slightly more radiogenic Nd isotopic range ($\varepsilon_{Nd\ (1670Ma)}$ of –1.25 to –1.52), and overlaps the granite in terms of La/Sm and La/Nb ratios (Fig. 16). The gabbro extends to very high $Mg^{\#}$ (70) and Cr (843 ppm) and Ni (572 ppm) concentrations and is clearly dominated by a mantle source component, although high La/Yb (>4.2) and La/Sm (>2.8) ratios, and Th (>1.5 ppm) and La (>8 ppm) concentrations, as well as $\varepsilon_{Nd\ (1670Ma)}$ values below depleted mantle values, mean that a lithospheric mantle source cannot be discounted. On a plot of $\varepsilon_{Nd\ (1670Ma)}$ vs La/Sm (Fig. 16), the restricted compositional field for the gabbro is distinct from the compositional trend shown by the granites. Hence, as also suggested earlier, there is no compositional evidence for mixing, despite the observed

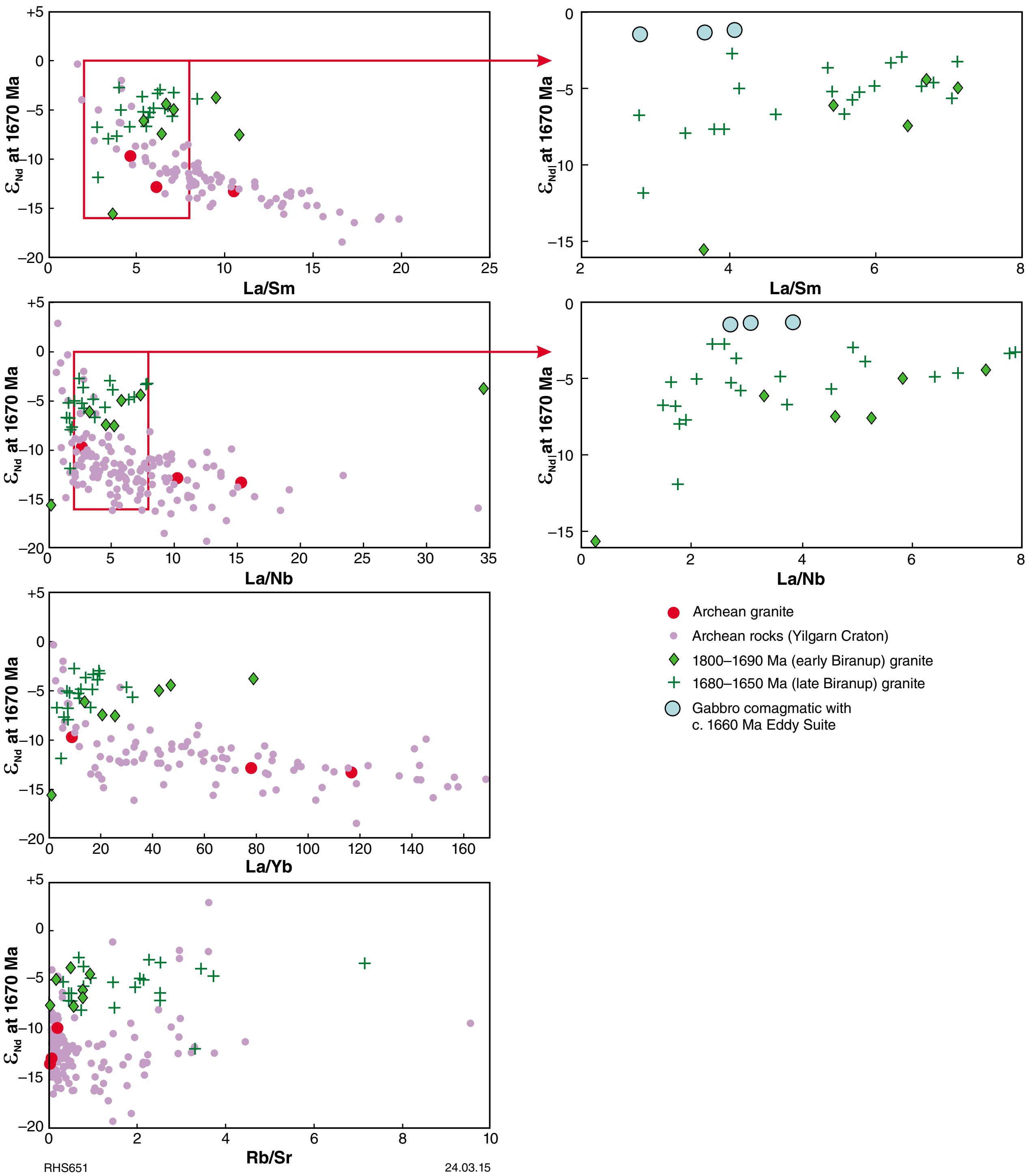


Figure 16. Compositional variation diagrams showing ε_{Nd} vs La/Sm, La/Nb, La/Yb and Rb/Sr ratios for 'early' and 'late' Biranup granites, gabbro comagmatic with the c. 1660 Ma Eddy Suite, and Archean granites (data for granites of the Yilgarn Craton are from D Champion, 2014, written comm.)

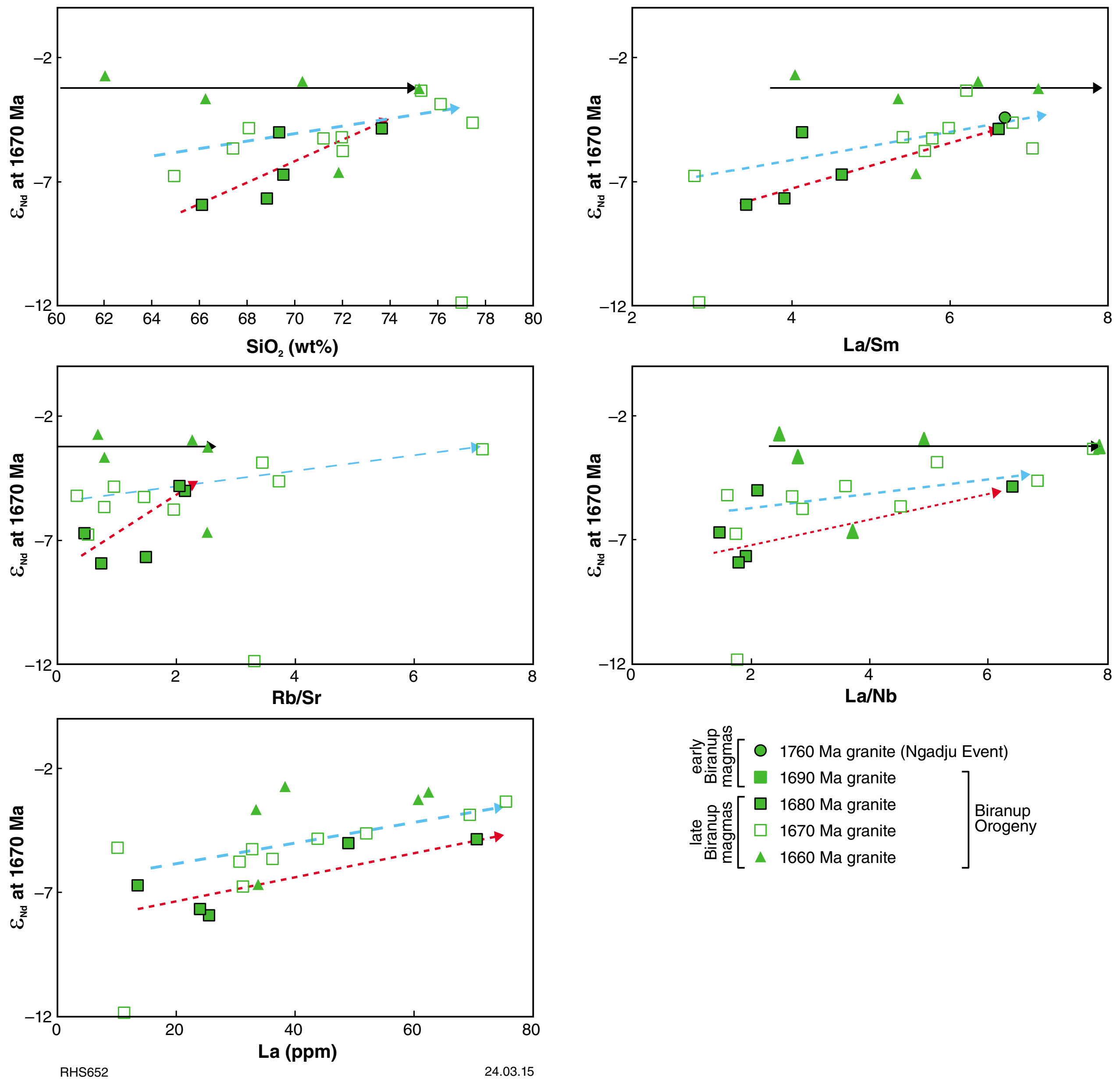


Figure 17. Compositional variation diagrams showing ε_{Nd} vs SiO_2, La/Sm, La/Nb, La/Yb and Rb/Sr ratios for 'late' Biranup granites

co-mingling textures (i.e. the gabbro and granite are not cogenetic). Nevertheless, the relatively juvenile Nd isotopic composition of the Eddy Suite, with compositions only marginally less radiogenic than the comagmatic gabbro, clearly suggests a significant mantle component in the source for the granites. The subsequent evolutionary trends for the granites show that all crustal components (early Biranup granite?) were added and homogenized before the formation of these granites. Hence, although the exposed co-mingled gabbro itself is not directly cogenetic with the granites, it is likely that at a deeper crustal level, similar mafic magmas were directly cogenetic.

The Eddy Suite granites are highly significant because, on the one hand, they are compositionally characteristic of late Biranup magmatism and, on the other hand, their compositional range and field relationships with comagmatic gabbros give significant clues as to their petrogenesis. The simplest explanation for the wedge-shaped field defined by the late Biranup magmas on plots of $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb ratios (Figs 16 and 17) is that it reflects the contribution from at least three distinct components: a radiogenic and geochemically unevolved component (high ε_{Nd}, low SiO_2, La/Sm, La/Nb); a radiogenic and geochemically evolved component (high ε_{Nd}, high SiO_2, La/Sm, La/Nb); and a relatively unradiogenic and geochemically unevolved component (low ε_{Nd}, low SiO_2, La/Sm, La/Nb). For many indices of compositional evolution (Fig. 17), the c. 1670 Ma granite group (and to a lesser extent the c. 1680 Ma group) shows a well-developed positive correlation with

$\varepsilon_{Nd\ (1670Ma)}$ that requires at least a degree of involvement of both the radiogenic and geochemically evolved source component and the unradiogenic and geochemically unevolved source component. The two radiogenic components could reflect unfractionated and fractionated end-members of various closed-system magma batches formed through early homogeneous contamination of mantle-derived mafic magmas by small volumes of felsic crust. The Eddy Suite might be representative of this range. The unradiogenic and geochemically unevolved component could be interpreted as reflecting a range of source mixing proportions between a radiogenic mantle-derived component (e.g. the gabbros) and felsic crust. A problem with this explanation is that there is no good reason why a homogenized magma originating at the non-radiogenic and geochemically unevolved compositional end-member could not undergo compositional evolution in a closed system. This would produce horizontal arrays in Figure 17, similar to those shown by the Eddy Suite, and a rectangular compositional field. Another problem is that the unradiogenic and geochemically unevolved end-member for both the c. 1680 and 1670 Ma 'apparent mixing trends' has a composition that lies at the extreme end of the range for known Albany–Fraser Orogen felsic crust (Fig. 16). In other words, the very low La/Yb and La/Nb ratios of late Biranup granites defining this end-member cannot be easily explained through incorporation of either Archean granite or early Biranup magmas.

Trends in the covariation of Nd- and Hf-isotopic compositions (Hf data are averages of isotopic data from zircon; data from Kirkland et al., 2011a,b) possibly provide some insight into the evolution of the late Biranup magmas. There is a strong tendency for the Nd- and Hf-isotopic compositions of all rocks to fall along a uniform 'mantle array'. The existence of this array has been interpreted as evidence of an efficient mixing process in the crust, and an indication that none of the minerals that account for substantial fractionation of Sm/Nd and Lu/Hf (e.g. garnet) achieves extensive Hf–Nd decoupling on a crustal scale within the terrestrial system. Nevertheless, whereas decoupling of the two isotopic systems is very rare in any magmatic environment, it has been documented (Schmidberger et al., 2002; Salters and Zindler, 1995; Bizimis et al., 2003; Ionov et al., 2005, 2006; Wu et al., 2006; Bianchini et al., 2007). One of the mechanisms proposed to account for this decoupling is melting in the presence of garnet (Schmidberger et al., 2002). This should not significantly alter Sm/Nd ratios but will fractionate Lu from Hf, producing Lu-enriched residual crust. Since ^{176}Lu decays to ^{176}Hf, remelting of this residual Lu-enriched crust will result in melts with more radiogenic Hf-isotopic compositions. A measure of this decoupling ($\Delta\varepsilon_{Hf}$) defines Hf isotope deviations from the principal axis of dispersion on the terrestrial array, and is calculated as the difference between the measured ε_{Hf} value and that predicted based on the whole-rock ε_{Nd}.

Data for the early and late Biranup magmas show a cluster at the mantle array but also show a distinct trend away to compositions with increasingly anomalously radiogenic Hf (Fig. 18). Values of $\Delta\varepsilon_{Hf}$ are negatively correlated with La/Sm, La/Yb and La/Nb ratios (Fig. 19), such that the most affected granites have the least fractionated REE profiles. In terms of age, three of the four late Biranup granite samples showing significant decoupling are from the c. 1680 Ma granite group and the other sample is from the c. 1670 Ma group. One of the three analysed c. 1660 Ma granites shows a moderate degree of decoupling (Fig. 20). Hence, it appears that there is possibly a broad relationship with age. The four strongly decoupled late Biranup granite samples also define the unradiogenic and geochemically unevolved corner of the $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb field (Fig. 19). The only early Biranup granite sample to show significant isotopic decoupling is the geochemically anomalous, A-type, c. 1700 Ma Bobbie Point Metasyenogranite (Fig. 20).

Production of garnet-bearing residual crust is required to produce the HREE-depleted geochemical characteristics of Archean TTG (e.g. Martin et al., 2005). Later incorporation of this material into a crustal melting source has the potential to produce high $\Delta\varepsilon_{Hf}$ magmas like those of the late Biranup granites. The crust left after TTG production would also have had significantly lower La/Yb, La/Sm and La/Nb (Nb retained in rutile) ratios, and lower LREE concentrations than either the original mafic melting source or TTG (and most likely lower than MORB values of ~0.8, 0.9 and 1.1 respectively — Sun and McDonough, 1989) and would still likely evolve to low ε_{Nd} values with time, although it should remain more radiogenic than its TTG source. Hence, a lower crustal source region that was residual or complementary to the formation of the Archean granites (including reworked Archean material in early Biranup magmas) might provide

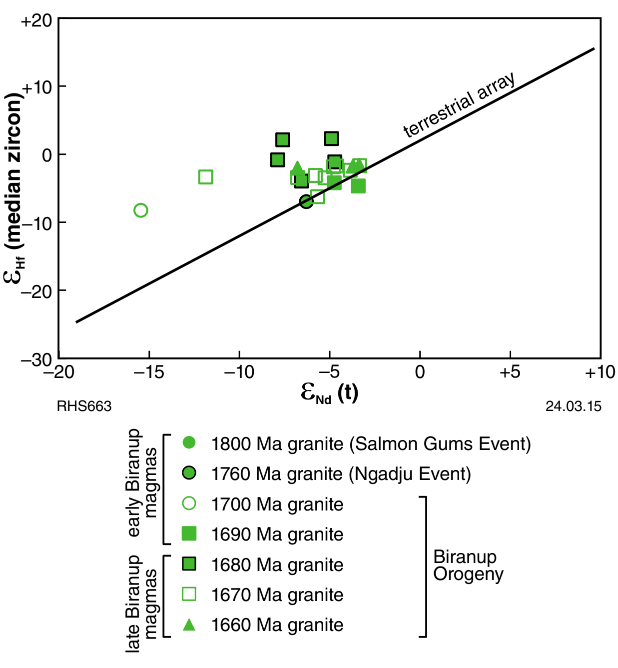


Figure 18. Variations in ε_{Hf} vs ε_{Nd} for Biranup granites. Values of ε_{Hf} represent median values from analyses of zircon whereas ε_{Nd} are whole-rock analyses

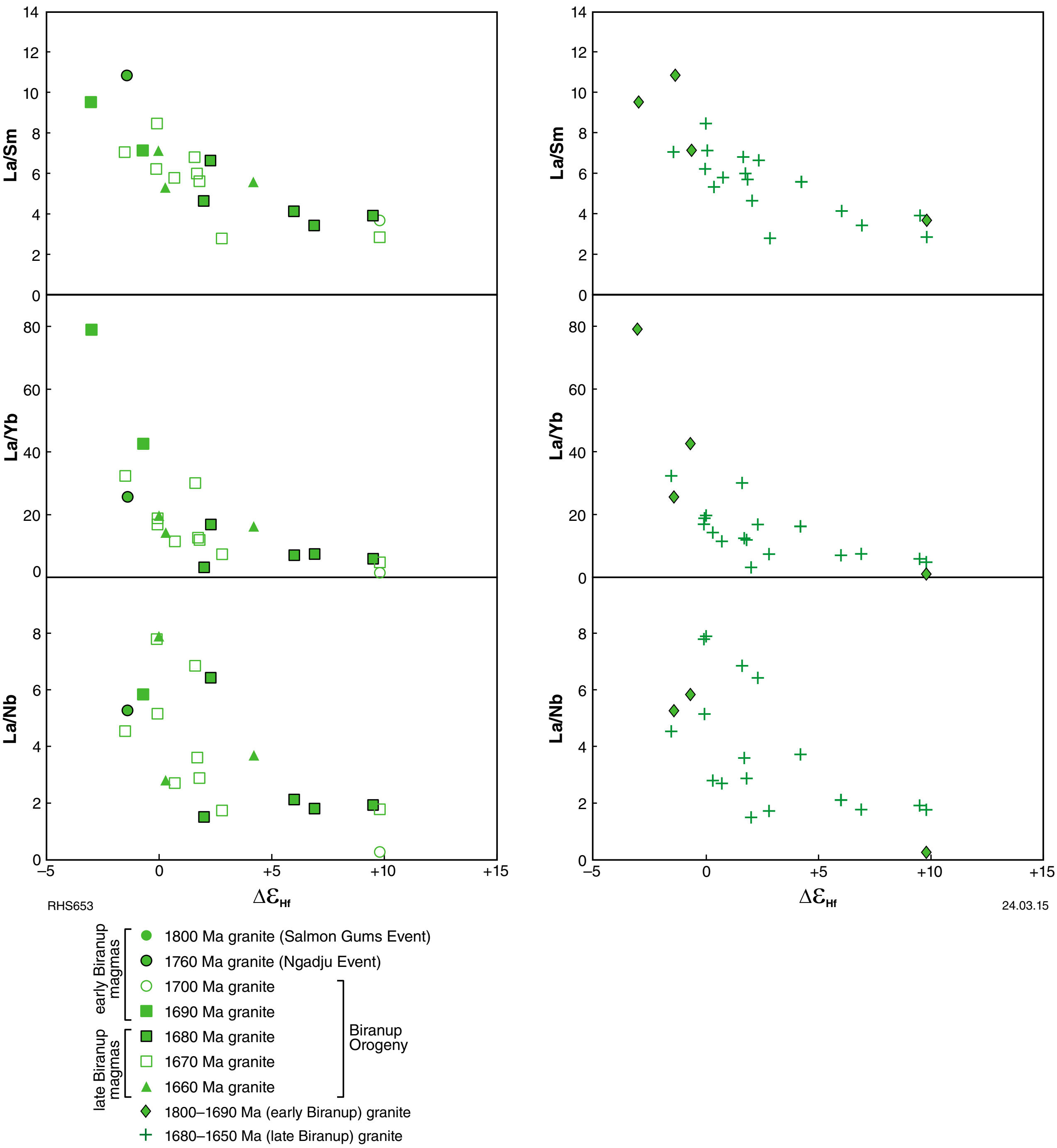


Figure 19. Variations in $\Delta\varepsilon_{Hf}$ vs La/Sm, La/Yb and La/Nb ratios for 'early' and 'late' Biranup granites

a candidate for the unradiogenic and geochemically unevolved corner of the $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb field (Figs 16, 17), and would additionally explain the Hf–Nd isotopic decoupling of the samples defining that corner (Fig. 20). Another possible candidate for the unradiogenic and geochemically unevolved source component might be Archean mafic crust, although this would not explain the observed range in $\Delta\varepsilon_{Hf}$ values.

The radiogenic end of the $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb field (Figs 16, 17), defined by the Eddy Suite, is also very interesting. That few granites with more radiogenic Nd are found suggests that the Eddy Suite granites approximate the upper $\varepsilon_{Nd\ (1670Ma)}$ limit of crustal components. In addition, the few sampled mafic magmas that are contemporaneous with the late Biranup granites extend to very primitive compositions ($Mg^{\#} = 70$, Cr = 843 ppm, Ni = 572 ppm) but have $\varepsilon_{Nd\ (1670Ma)}$ values only marginally more radiogenic than the Eddy Suite granite itself. The absence of more radiogenic mafic magmas might suggest a source within the lithospheric mantle. Thus, perhaps a more inviting explanation for the observed $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb field for late Biranup granites is that it reflects a chemically primitive component formed through variable interaction between relatively radiogenic mafic mantle (lithospheric?) melts and relatively unradiogenic deep crustal components (residuals of Archean TTG production?, Archean mafic crust?), and mixing between these and crustal melts dominated by relatively evolved and radiogenic early Biranup source material (Fig. 21). In the case of the Eddy Suite granites, the system was then not necessarily closed at an early stage to crustal contamination, although any progressive contamination was from similarly radiogenic crust, such as c. 1690 Ma granites, which additionally range to suitably high La/Yb, La/Sm and La/Nb ratios.

How the inferred source components involved in producing the late Biranup magmas interacted is open to speculation. Given the geographical range of some granite groups and geographical separation between sample sites, and also the wide compositional range of possible source components permitted by the observed $\varepsilon_{Nd\ (1670Ma)}$ vs La/Yb, La/Sm and La/Nb field, we clearly cannot invoke simple mixing processes in a three-component system. The evolving crust of the Albany–Fraser Orogen was clearly compositionally inhomogeneous although it is possible that the same range of compositionally similar materials (e.g. mantle melts/juvenile crust, unradiogenic Archean crust, compositionally evolved crust) were regionally available as components in the source of most late Biranup magmas. Evolution of these magmas might have been controlled more by crustal contamination of mantle (perhaps lithospheric) magmas, including MASH (melting–assimilation–storage–homogenization) processes, than by crustal melting alone. Any existing deep crustal sources remaining after Archean TTG production would likely be very refractory and so the capacity to contribute significant melt volumes to the late Biranup magmas is critically limited; an argument that perhaps points more to Archean mafic crust as the main source for the unradiogenic and geochemically unevolved source component.

In summary, early Biranup magmas primarily reflect large-scale recycling of Archean granite (including Munglinup Gneiss). Nd isotopic compositions more radiogenic than Yilgarn Craton crust require that post-Yilgarn Craton mantle source components also contributed to this magmatism. The geochemical ‘signal’ of crustal recycling appears to weaken, possibly along with a trend to compositions with slightly more radiogenic Nd, after c. 1700 Ma (i.e. in the c. 1690 Ma granite group). This shift could be interpreted in terms of a greater mantle contribution to melting sources and might reflect crustal thinning. The c. 1700 Ma Bobbie Point granites are anomalous in that they reflect A-type magmatism requiring strongly enhanced geotherms, at least locally. The combination of high HREE concentrations and high $\Delta\varepsilon_{Hf}$ values suggest melting of a crustal source that previously resided at a deeper level (Kirkland et al., 2011a), and so c. 1700 Ma magmatism might also reflect a period of significant crustal thinning. Whereas crustal recycling appears the general theme of early Biranup magmatism, late Biranup magmatism heralds an important change (or progression) to more K-rich magmatism. Instead of directly melting Archean felsic crust, already recycled Archean crust, in the form of the early Biranup granites, formed the crustal component of the bulk source for late Biranup magmatism. In addition, late Biranup magmatism might have been controlled more by crustal contamination of mantle (perhaps lithospheric) magmas, or MASH processes, than by crustal melting alone. Archean source components also remained in the form of lower crustal material representing the refractory, complementary material left behind during extraction of Archean TTG. Melting of this previously untapped refractory source to Archean TTG production likely reflects lithospheric thinning. The amount of interaction with the refractory source to Archean TTG production decreases with decreasing age (c. 1680–1660 Ma), with a corresponding increase in the proportion of a mantle component and is probably also best interpreted in terms of crustal thinning.

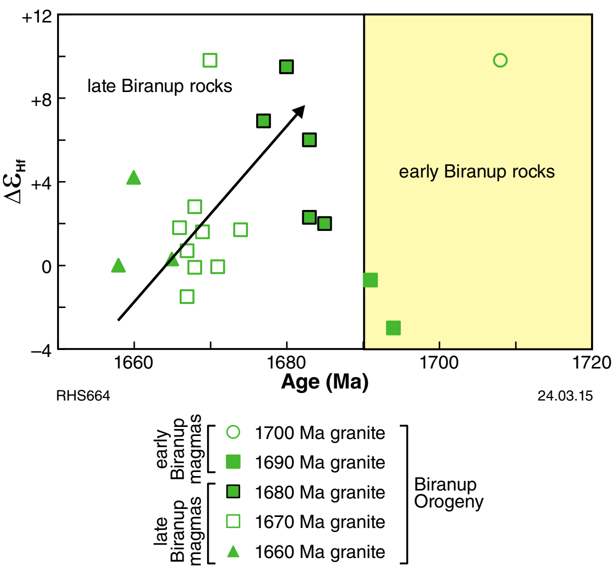


Figure 20. Variations in age vs $\Delta\varepsilon_{Hf}$ for ‘early’ and ‘late’ Biranup granites

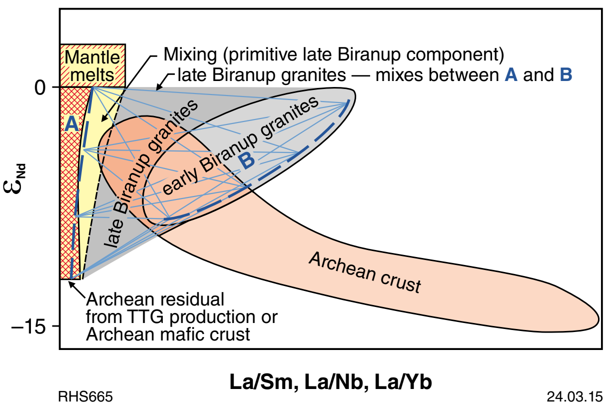


Figure 21. Schematic diagram showing potential source mixing model for the late Biranup granites. Yellow field encompasses the most primitive magmatic components of the late Biranup granite formed through interaction (mixing, mingling, assimilation) of mantle-derived melts (simple hatch) with either the depleted mafic material left over from Archean TTG production or Archean mafic crust (crosshatch). Blue lines reflect the range of possible mixing lines between primitive magmatic components of the late Biranup granite and early Biranup granite (either as partial melts or as a bulk assimilant)

Mesoproterozoic granite evolution

The geographical distribution of sampled granites formed during the Albany–Fraser Orogeny is shown in Figure 22. Compared with the earlier granite groups, less age data currently exists for granite groups thought to relate to the Albany–Fraser Orogeny. This is a considerably greater problem for the granite group interpreted to belong to Stage II (1225–1140 Ma) of the orogeny, in particular those of the Booanya Suite, than with the group interpreted to belong to Stage I (1330–1260 Ma). However, the two dated samples of the Booanya Suite have a distinctive geochemistry and geophysical (strongly magnetic) signature that together allows other samples to be assigned to that suite with a reasonable degree of confidence.

Stage I Recherche Supersuite

Granites crystallized during Stage I of the Albany–Fraser Orogeny (Recherche Supersuite) have been grouped by silica content into granodiorites (SiO_2 <64 wt%), monzogranites (SiO_2 64–70.5 wt%), and syenogranites (SiO_2 >70.5 wt%) (Fig. 23), and are collectively referred to, and here named as, the Gora Hill Suite (after Gora Hill). An additional group (SiO_2 >72 wt%) typically with notable depletions in HFSE, REE, Th and U compared to other granites of the Recherche Supersuite at similar silica values (Fig. 23) is here named the Southern Hills Suite (after Southern Hills Station).

Gora Hill Suite

Together, these rocks form an expanded silica range from 60.5 to 76.8 wt%. Compositional boundaries within this range are arbitrary and only for convenience in describing the compositional and geographic range. The concentrations of most major and trace elements, in fact, vary systematically with silica concentrations (Fig. 23), and in this sense the Gora Hill Suite might be viewed as a single magmatic series. However, the age range of dated samples is from c. 1330 to 1283 Ma and precludes any cogenetic relationship between all members.

In terms of major and trace element compositional variation, it is extremely difficult to separate the Gora Hill Suite from the late Biranup granite groups. All of these rocks or groups are generally calc-alkalic and weakly ferroan and show extensive compositional overlap for most elements (Fig. 23). Exceptions are Sc, Cr and to a lesser extent V which, at SiO_2 <~72 wt%, are generally depleted within the Gora Hill Suite, and Ba and Pb, which range to higher concentrations at a given SiO_2 content within the Gora Hill Suite. However, in terms of overall trends, the Gora Hill Suite is distinct in that concentrations of Nb, Ta, Y and Yb increase with increasing SiO_2, whereas those trace elements decrease with increasing SiO_2 in the late Biranup granite groups. Like the late Biranup granites, the Gora Hill Suite generally has lower Na_2O and higher K_2O concentrations and higher K_2O/Na_2O ratios than early Biranup granite groups and Archean granites, including the Munglinup Gneiss.

It is also difficult to distinguish some syenogranitic members of the Gora Hill Suite from Booanya Suite granites of the Esperance Supersuite (see below) on the basis of geochemistry, although a plot of SiO_2 vs Sc appears to support the present classification (Fig. 23). These two granite groups overlap geographically (Fig. 22) and several of the undated samples of Gora Hill Suite syenogranites have slightly anomalous concentrations of, for example, LREE (Fig. 23) that would support an affiliation with the younger Booanya Suite (see below). This problem can be resolved only through geochronology.

Southern Hills Suite

Like the Gora Hill Suite, the Southern Hills Suite has a wide emplacement age range, from c. 1320 to 1287 Ma (although 9 of 10 dated samples lie within the narrower range of c. 1305–1287 Ma), which precludes any cogenetic relationship between all members. The Southern Hills Suite granites are leucocratic, weakly peraluminous (ASI = 1.00–1.08) syenogranites with a very restricted and high silica range from 72.4 to 77.8 wt% (Fig. 23). Within that silica range, they are virtually indistinguishable from the syenogranitic range of the Gora Hill Suite in terms of major element compositions (except for slightly lower concentrations of TiO_2 in the Southern Hills Suite). They are, however, readily distinguished from the Gora Hill Suite syenogranites in terms of incompatible trace element concentrations, having lower H-MREE, Nb, Ta, Zr, Hf, U, Th, Pb and Rb concentrations at a given silica content (i.e. the Southern Hills granites are significantly depleted in incompatible trace elements; Fig. 23). Incompatible trace element ratios also show a wider range than for any other granite group from the Albany–Fraser Orogen, except for the Archean granites and the granites of the Esperance Supersuite (Fig. 23).

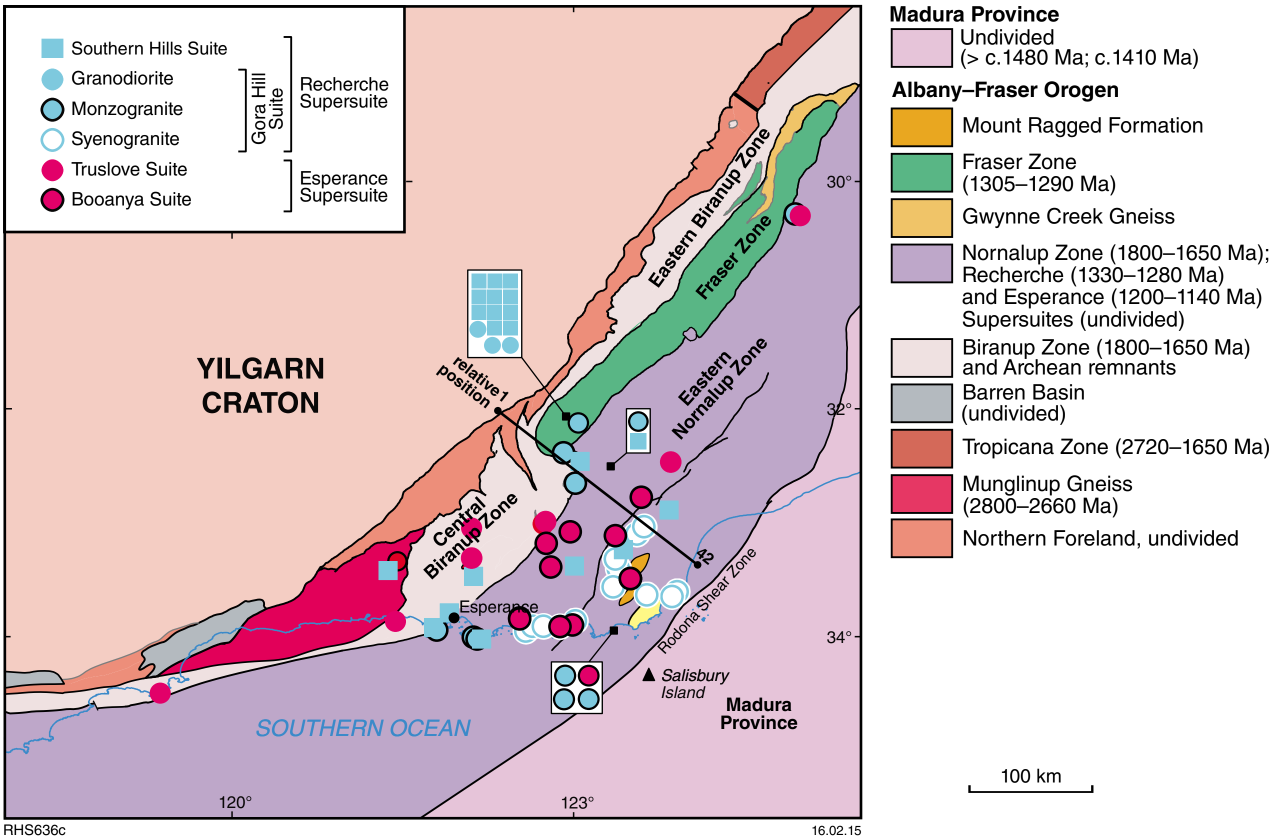


Figure 22. Simplified, pre-Mesozoic interpreted bedrock geology of the east Albany–Fraser Orogen showing the distribution of granites formed during the Albany–Fraser Orogeny

Tectonic discrimination diagrams suggest affinities with syn-collisional regimes (Fig. 24), essentially reflecting melting of a source dominated by crustal (including reworked) material.

Magmatic evolution during Stage I

Available Nd isotopic data for the Gora Hill Suite (Fig. 25) show a wide range in $\varepsilon_{Nd\ (1300Ma)}$ from –3.49 to –9.36. Within this range, granodiorites vary from –3.4 to –3.49 (two analyses only) and monzogranites (five analyses) vary between –4.32 and –9.36. Two Nd isotopic analyses of syenogranites are very similar, at values of –4.45 and –4.53. However, a third analysis (sample 194848, from near Nares Island) is considerably less radiogenic, with an $\varepsilon_{Nd\ (1300Ma)}$ value of –8.4. As discussed later, this less radiogenic sample is one of a group of syenogranitic samples from the coastal part of the eastern Nornalup Zone that are tentatively placed within the Gora Hill Suite of the Recherche Supersuite, although they might belong to the Booanya Suite of the Esperance Supersuite. The Nd isotopic values for the Gora Hill Suite are generally slightly more radiogenic than those for older felsic crustal components of the Albany–Fraser Orogen, although there is overlap with late Biranup magmas, and the mafic material that likely formed a source component to the late Biranup magmas (e.g. gabbros comagmatic with the c. 1600 Ma Eddy Suite) has equivalent $\varepsilon_{Nd\ (1300Ma)}$ values (–3.66 to –4.23) to the Gora Hill Suite (Fig. 25). $Hf_{(zircon)}$-isotopic data for the Gora Hill Suite and late Biranup magmas also show a similar degree of time-integrated compositional overlap (Kirkland et al., 2011a,b) as the Nd isotopic data. It is therefore possible to explain much of the Nd isotopic range for the Gora Hill Suite by invoking crustal sources alone as long as they are dominated by c. 1680–1660 Ma mafic crust. More likely, however, is that the relatively radiogenic compositions of the Gora Hill Suite reflect a renewed juvenile addition to crustal source components (i.e. a petrogenesis similar to that of the late Biranup granites).

Felsic magmatism during Stage I of the Albany–Fraser Orogeny overlaps in time with the emplacement of the volumetrically extensive gabbroic rocks of the Fraser Zone (Smithies et al., 2013). These gabbros show a wide range of slightly more radiogenic Nd isotopic compositions ($\varepsilon_{Nd\ (1300Ma)}$ from –0.39 to –3.79) than both the Gora Hill Suite and the late Biranup mafic rocks (Fig. 25). The ε_{Nd} values for the Fraser gabbros show a strong negative correlation with SiO_2 and La concentrations, reflecting progressive crustal contamination of the mafic magmas.

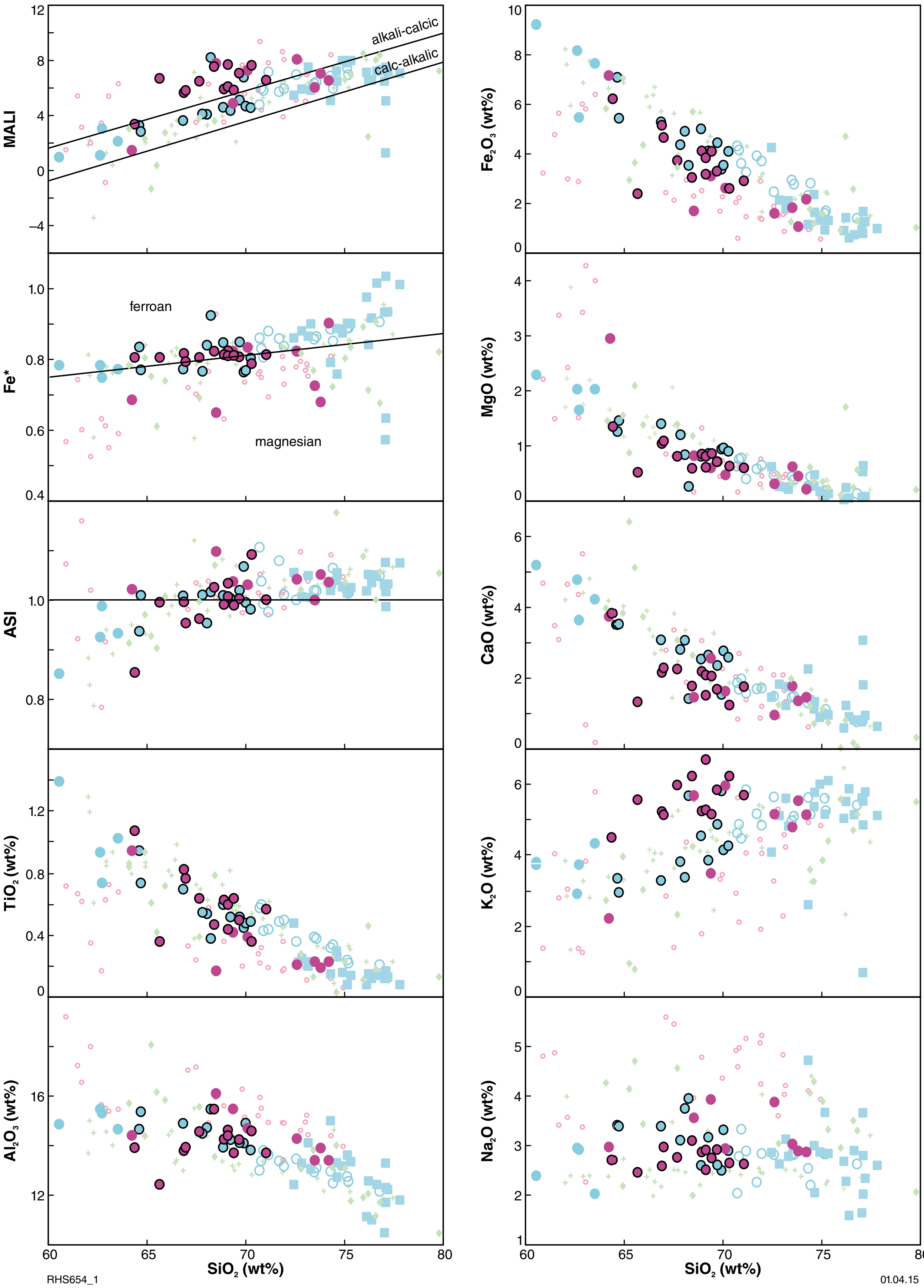
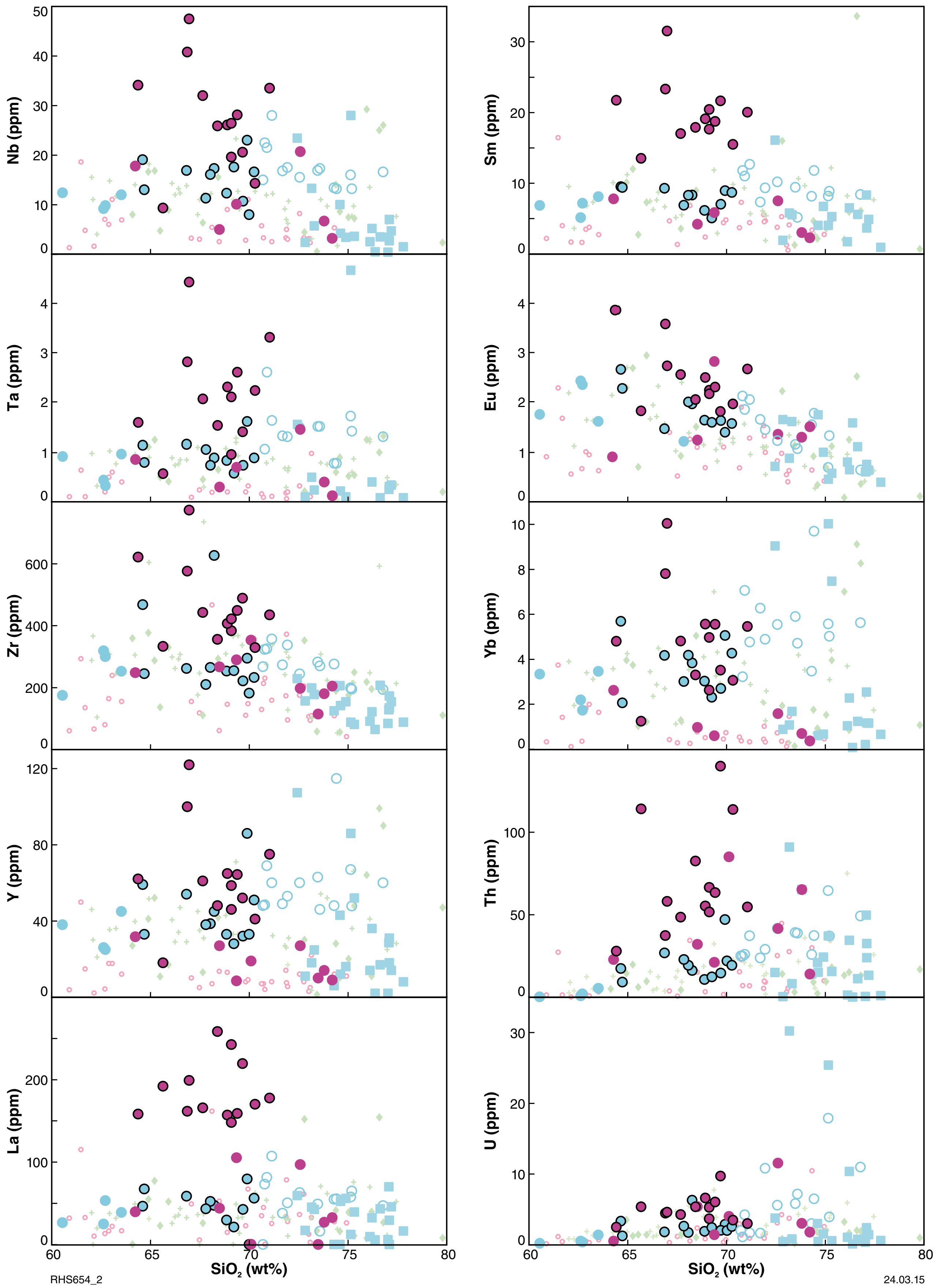


Figure 23. Compositional variation diagrams for granites formed during the Albany–Fraser Orogeny. MALI = modified alkali lime index ($Na_2O+K_2O–CaO$) and boundaries are after Frost et al. (2001). ASI = aluminium saturation index [= molecular ratio of Al/(Ca+Na+K)]. Fe* = Fe number [ratio of FeO/(FeO+MgO) with all Fe as Fe^{2+}], with boundaries after Frost et al. (2001) (continued on pages 35–37)



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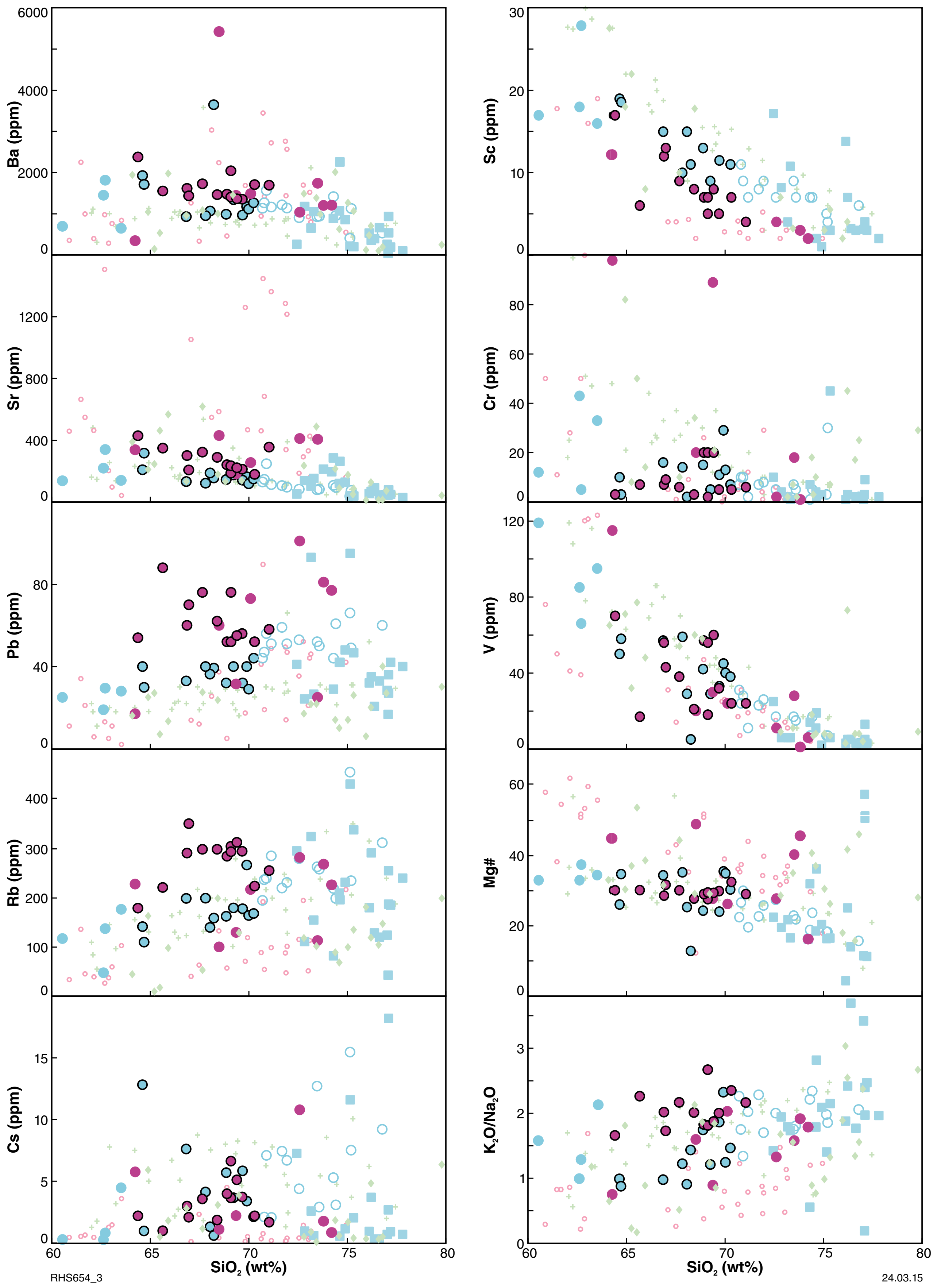

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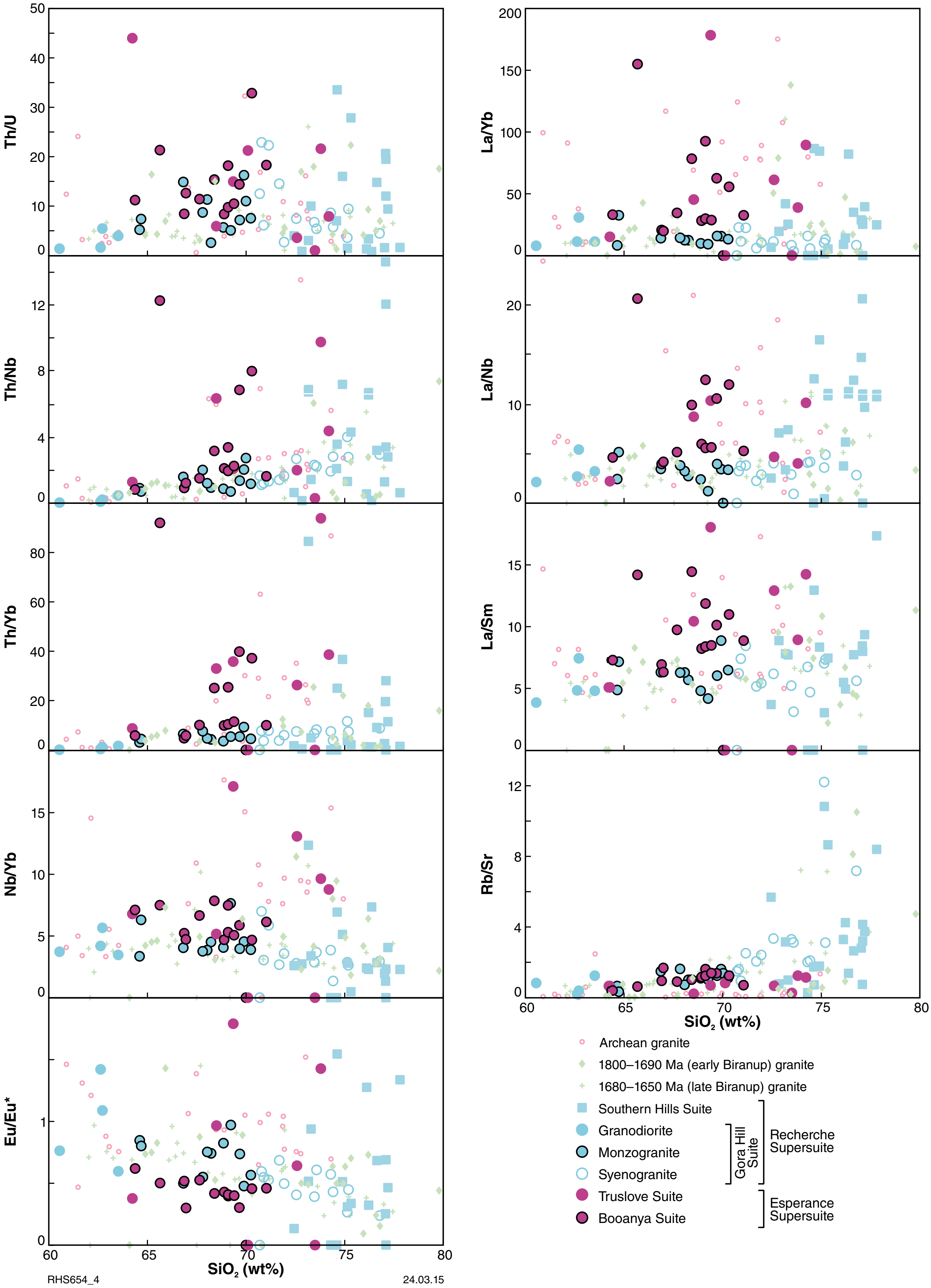

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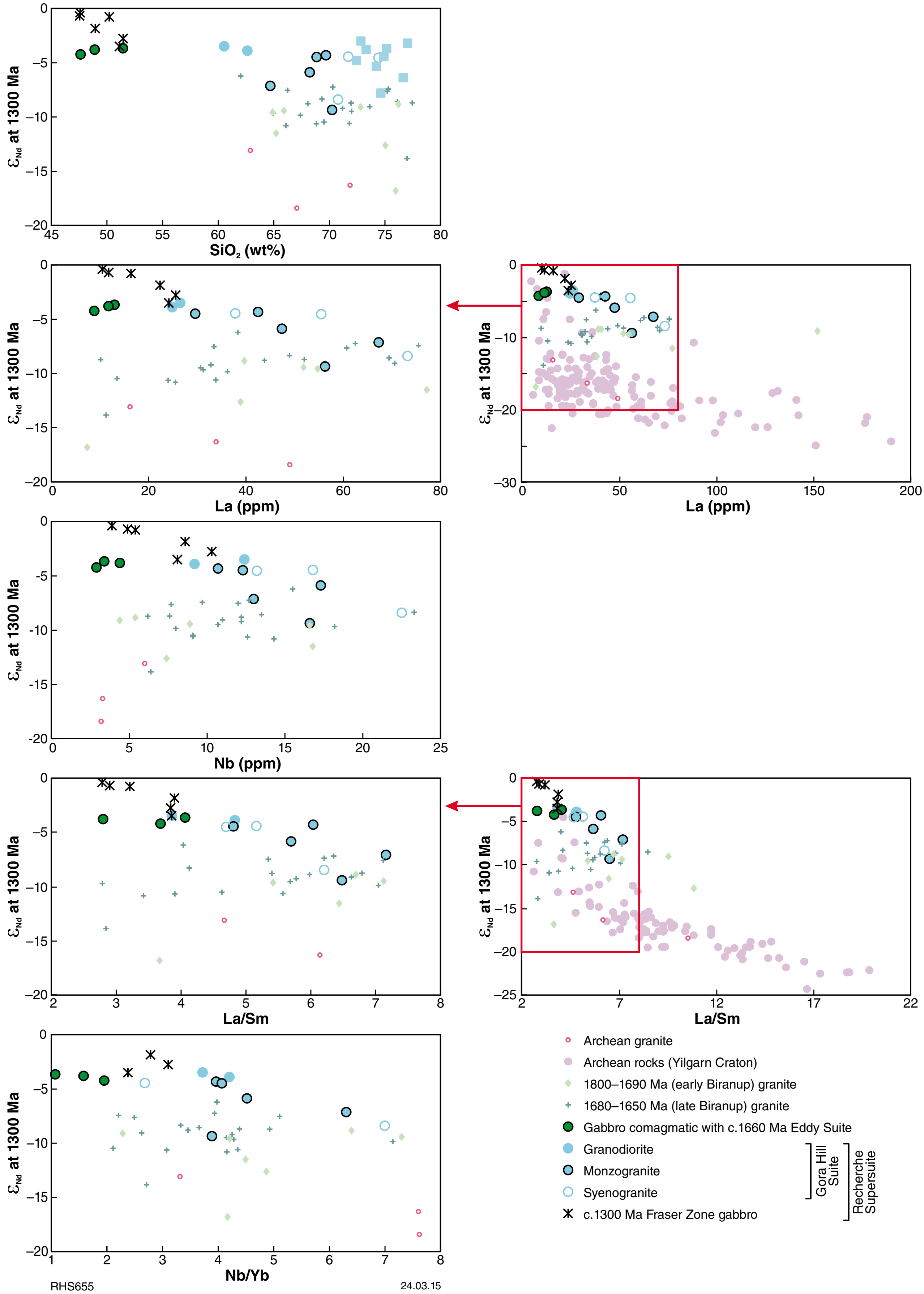

Figure 24. Variations in ε_{Nd} vs SiO_2, La, Nb, La/Sm, and Nb/Yb for granites formed during Stage I of the Albany–Fraser Orogeny

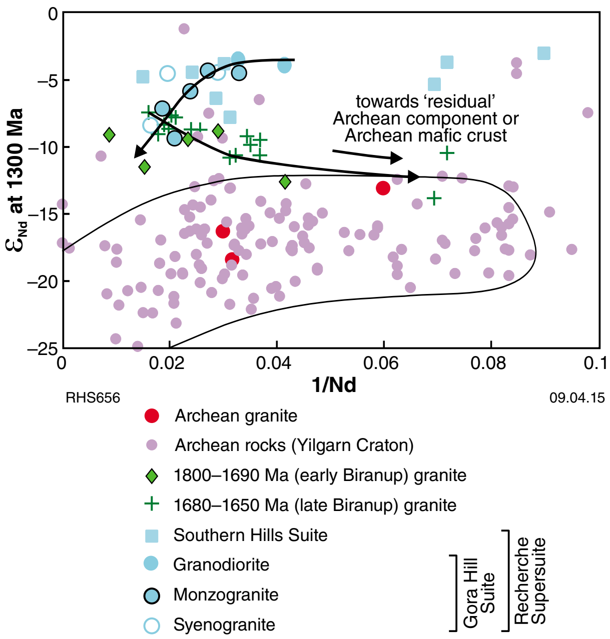

Figure 25. Variations in ε_{Nd} vs 1/Nd for rocks of the Biranup and Albany–Fraser Orogenies

The effect that crustal contamination had on producing the trace element enrichments in these gabbros was previously discussed by Smithies et al. (2013), and it seems quite likely that this might also be the process leading to the relatively unradiogenic Hf signature of those evolved (high SiO_2) gabbros capable of crystallizing zircon (for which no Nd isotopic data yet exist). From an element budget perspective, the gabbros of the Fraser Zone have both more radiogenic Nd and much higher Nd concentrations (29.7 ppm Nd), particularly where they had already undergone crustal contamination, than exposed mafic late Biranup crust (14.7 ppm Nd), and on this basis would make a more viable source component for the Gora Hill Suite. Moreover, in plots showing variations of ε_{Nd} values against incompatible trace element concentrations and incompatible trace element ratios (Fig. 25), the Fraser gabbros and the Gora Hill Suite together form a continuous array strongly suggestive of mixing or AFC processes — with negative correlations between ε_{Nd} and La, contrasting with the unusual positive correlations shown by the late Biranup magmas. Thus, it is inviting to suggest that the Gora Hill Suite is the result of variable mixing between mantle-derived gabbroic magmas (or subsequent melts of these gabbros), such as the contemporaneous gabbros now exposed in the Fraser Zone, and existing felsic crust. The mixing arrays intersect only the most evolved components of pre-existing felsic crust (i.e. Biranup granite and Archean felsic crust; Fig. 25). If bulk assimilation of felsic crust into the gabbro is proposed as the mixing process, then it is only these evolved portions of the pre-existing crust that were involved. It is more likely that trace element-enriched (e.g. high La, La/Sm) partial melts of pre-existing crust were incorporated into the contemporaneous gabbroic magmas. Monzogranitic and syenogranitic members of the Gora Hill Suite with particularly high La concentrations and La/Sm ratios are dominated by this crustal-melt component. Interestingly, a plot of ε_{Nd} vs 1/Nd (Fig. 26) suggests that the source for the Gora Hill Suite, as well as the Southern Hills Suite (see below), is a combination of variably evolved radiogenic material (considerably evolved in the case of the Southern Hills Suite) and relatively non-radiogenic crustal material. These rocks show no evidence for the unradiogenic and LREE-depleted source component that contributed to the late Biranup granites. It is possible that this deep source component was removed before, or at the beginning of, the Albany–Fraser Orogeny.

Mixing between mafic magmas and felsic Biranup crust is consistent with the suggestion (Smithies et al., 2013) that a large part of the Fraser Zone represents an exhumed lower crustal hot zone (e.g. Annen et al., 2006). Such a model has the potential to derive the range of gabbroic and Gora Hill Suite compositions (possibly excluding some of the syenogranitic members — see below), and also suggests that the overall compositional coherence of much of the Gora Hill Suite, from c. 1330 to 1283 Ma, reflects a common source compositional range and petrogenesis, not a common parental magma. Interestingly, Gora Hill Suite granites in southeastern exposures of the eastern Nornalup Zone contain mafic enclaves compositionally equivalent to gabbro of the Fraser Zone, possibly suggesting that the gabbro-dominated hot zone beneath the Fraser Zone was indeed originally a regional feature that evolved between 1330 and 1283 Ma.

The major and trace element compositional range shown by the Southern Hills Suite granites is typical of highly evolved, small-degree anatectic melts derived from felsic or quartzofeldspathic sources that were either compositionally heterogeneous or melted under disequilibrium conditions, or both. The peraluminous nature of the group in general, the presence of garnet in some samples and a common field association with sedimentary rocks suggest that the source for many Southern Hills Suite granites was dominated by sedimentary material. Certainly within the Fraser Zone, field relationships indicate that the syenogranitic Southern Hills Suite granites do represent anatectic melts of the metasedimentary rocks (the Snowys Dam Formation — see Spaggiari et al., 2014a) into which the Fraser gabbro intruded. However, the Southern Hills Suite granites are not exclusive to the Fraser Zone, but are also found within the Biranup and eastern Nornalup Zones (Fig. 22).

The Nd isotopic compositions of the Southern Hills Suite granites ($\varepsilon_{Nd\,(1300Ma)}$ from –3.01 to –7.8; Fig. 26) range from $\varepsilon_{Nd\,(1300Ma)}$ values similar to those of the most radiogenic granites of the Biranup Orogeny to compositions more radiogenic than either the Gora Hill Suite ($\varepsilon_{Nd\,(1300Ma)}$ from –4.32 to –5.88) or the late Biranup gabbro associated with the Eddy Suite ($\varepsilon_{Nd\,(1300Ma)}$ from –3.66 to –4.23). Only the contemporaneous Fraser gabbro extends to more radiogenic compositions ($\varepsilon_{Nd\,(1300Ma)}$ from –0.39 to –3.79).

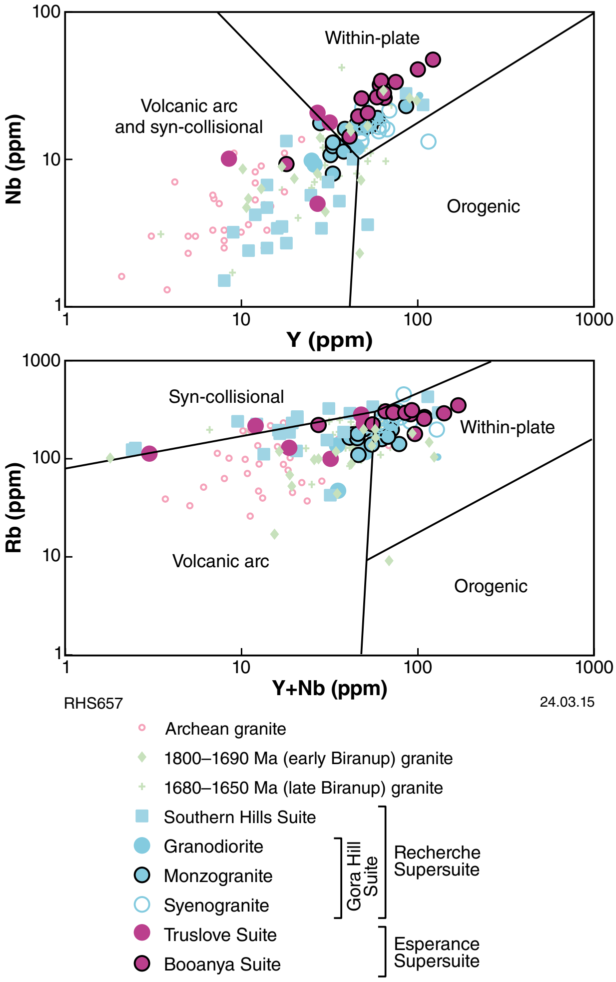

Figure 26. Tectonic discrimination diagrams for granites formed during the Albany–Fraser Orogeny (Pearce et al., 1984)

This isotopic range clearly precludes older felsic crust as the sole source for the Southern Hills Suite granites. Whereas it is possible that older pre-existing crust has mixed with, or has been assimilated into, a relatively juvenile mantle component such as the Fraser gabbro, the geochemical features of the Southern Hills Suite granites are not compatible with such an origin and no igneous rocks of intermediate compositions are known (in this regard, the Southern Hills Suite granites also differ strongly from the Gora Hill Suite that extend to much lower SiO_2 and higher MgO and total Fe concentrations). However, the metasedimentary Snowys Dam Formation of the Arid Basin (Spaggiari et al., 2014a,b) is known to contain abundant c. 1400 Ma zircons with Hf isotopic compositions that range to more radiogenic values (virtually from depleted mantle to bulk earth) than all older crustal components of the Albany–Fraser Orogen. The detrital source for these sedimentary rocks is believed to be exotic — from the Madura Province, to the east of the Albany–Fraser Orogen (Spaggiari et al., 2014a,b), where gabbro and oceanic plagiogranite contain c. 1400 Ma zircon with a similar range of $\varepsilon_{Hf\ (1300Ma)}$ values (up to 9.5) and have whole-rock $\varepsilon_{Nd\ (1300Ma)}$ values between 3.33 and –2.83. These isotopic data support the suggestion that the Southern Hills Suite granites within the Fraser Zone are derived from a crustal source dominated by sediment of the Snowys Dam Formation, mixed with variable amounts of older Albany–Fraser Orogen crust. The presence of Southern Hills granite at another locality to the southwest (Brianup Zone) and south (eastern Nornalup Zone) of the Fraser Zone (Fig. 22) suggests that sedimentary sources equivalent to (and perhaps originally contiguous with) the Snowys Dam Formation were deposited between c. 1400 and 1300 Ma more widely across the Albany–Fraser Orogen (although not necessarily continuously), forming what Spaggiari et al. (2014a,b) refer to as the Arid Basin.

Spatial trends for the Gora Hill and Southern Hills Suites

In a broad sense, there is a clear and systematic spatial variation in the composition of the Gora Hill Suite more or less across the strike of the regional structural trend of the Albany–Fraser Orogen, such that granodiorite occurs only in the northwest, and syenogranite dominates in the southeast (Fig. 22). The Southern Hills Suite granites show a reasonable degree of geochemical scatter, although no obvious systematic variation across the orogen. To investigate spatial variations in composition further, the Gora Hill Suite and Southern Hills Suite granites have been roughly ordered according to their distance away from an orogen-parallel, northeasterly trending line that intersects the most northwesterly sample (i.e. this sample [194779] is given position 1). Sample 'position' determined in this way is plotted against composition in Figure 27. Although it remains possible that several syenogranitic samples of the Gora Hill Suite may actually belong to the younger Booanya Suite, the trends described below are not invalidated by the exclusion of those samples.

From the northwest to the southeast, the Gora Hill Suite shows broad trends to higher SiO_2 and possibly K_2O, and lower Al_2O_3, TiO_2, MgO, total Fe and CaO (Fig. 27). Trace element patterns also indicate that the Gora Hill Suite becomes generally more evolved to the southeast. The northwesternmost monzogranite samples have compositions that deviate from these trends towards compositions more like those of the broadly contemporaneous Southern Hills Suite granites (Fig. 27). These monzogranites occur within or adjacent to the Fraser Zone, in the area where the Southern Hills Suite granites are most common. Likewise, farther to the southeast (between positions 28 and 36), syenogranitic members of the Gora Hill Suite have anomalously high SiO_2 and K_2O and lower total Fe, and strongly anomalously high U and Th concentrations, and in these respects are also similar to Southern Hills Suite granites found in that region. As discussed above, the Southern Hills Suite granites are thought to be melts of felsic crustal material dominated by a sedimentary component, and it

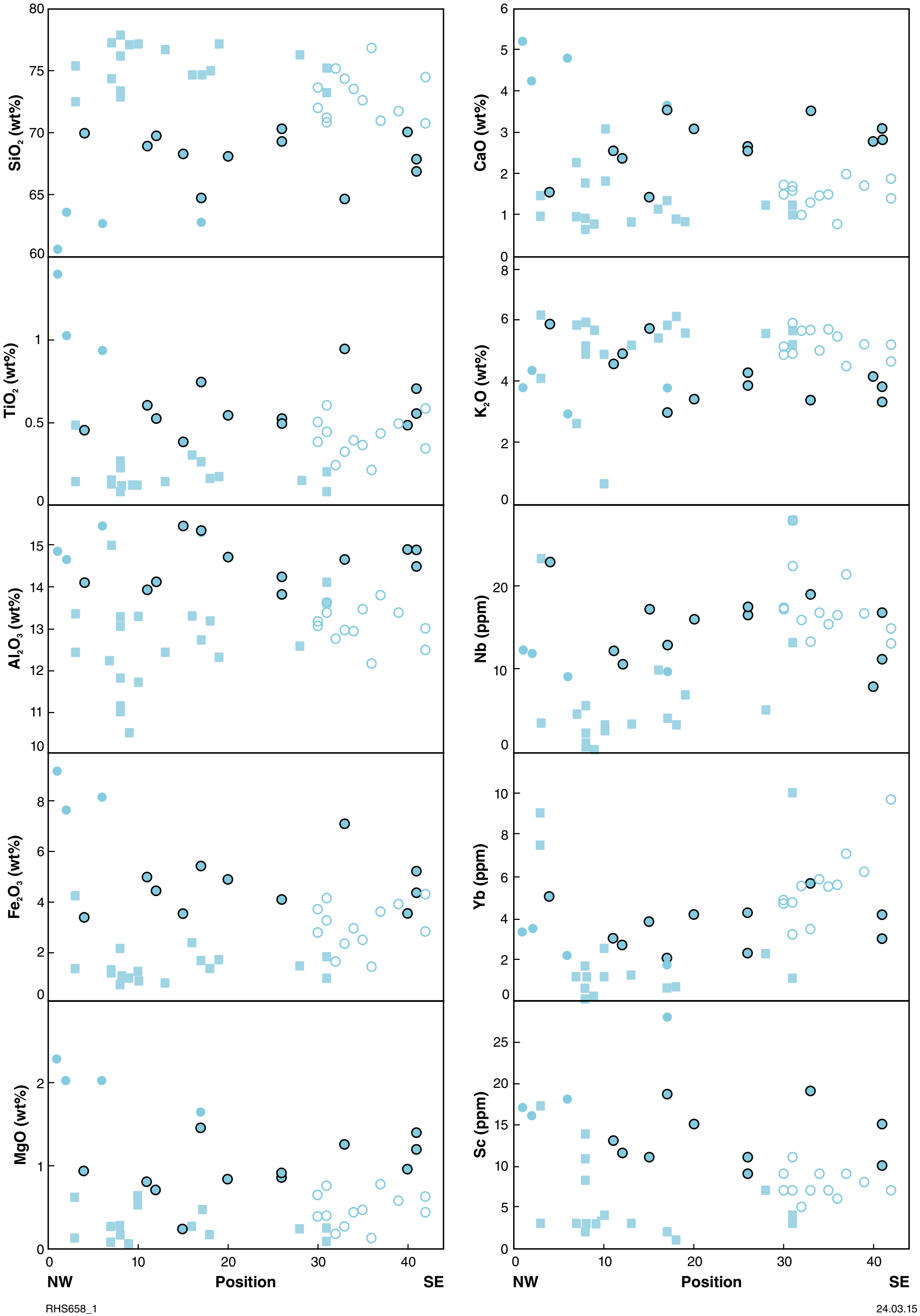

Figure 27. see page 43 for full caption

seems quite likely that the ‘anomalous’ Gora Hill Suite monzogranites and syenogranites may have incorporated, or mixed with, Southern Hills granite, including partial melts of country rock (Southern Hills granite or source), actually induced by intrusion of granites of the Gora Hill Suite themselves. Because the effects of this process are clearly recognizable geochemically, it might be concluded that this process has had little or no effect on the main population of the Gora Hill Suite. It is likely that the Southern Hills Suite granites (and their source) are variably restricted to distinct geographical zones (?earlier graben structures) and crustal levels that were not everywhere part of the lower crustal hot zones where we suggest the Gora Hill Suite evolved.

The magmatic age of Gora Hill Suite granites also increases systematically to the southeast (Fig. 28) such that the relatively evolved syenogranitic rocks to the southeast are older (c. 1330–1314 Ma) than the granodioritic rocks to the northwest (c. 1310–1283 Ma). However, perhaps the most significant compositional variation is a systematic southeastward trend to less radiogenic Nd isotopic compositions and older $T_{(2DM)}$ model ages, at least to a point somewhere between positions 31 and 39, southeastward of which compositions revert to significantly more radiogenic values, with younger $T_{(2DM)}$ model ages. These trends indicate that a significant process controlling compositional evolution within the Gora Hills Suite group, at least to the northwest of position 31, is a broadly systematic variation in the relative proportions of source components —contemporaneous mafic magma and partially melted pre-existing felsic crust.

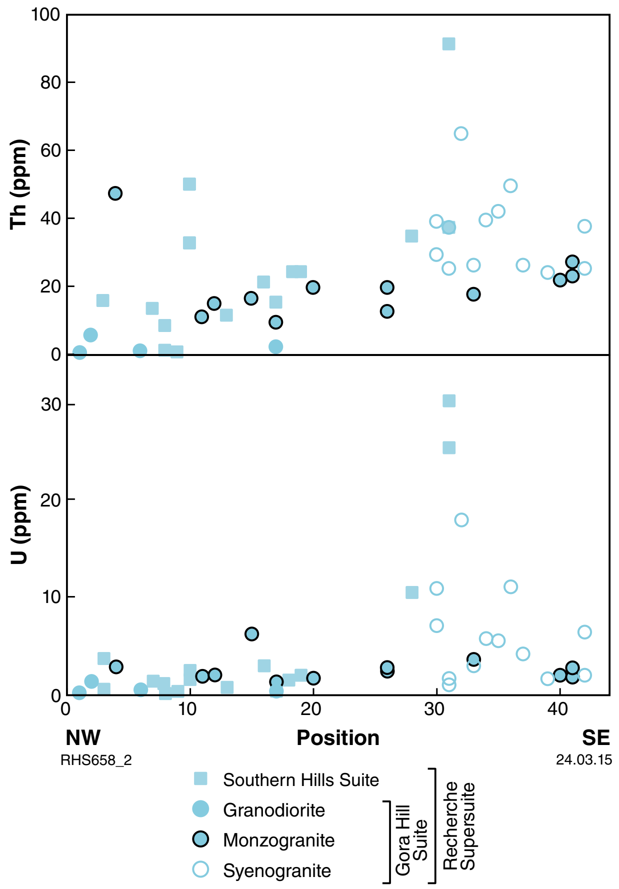

Figure 27. (left and above) Geographical variation in composition for granites formed during Stage I of the Albany–Fraser Orogeny. ‘Position’ refers to the relative order of samples, in a southeast direction, when their true position is extrapolated along northeasterly trending lines, on to the traverse line shown in Figure 22

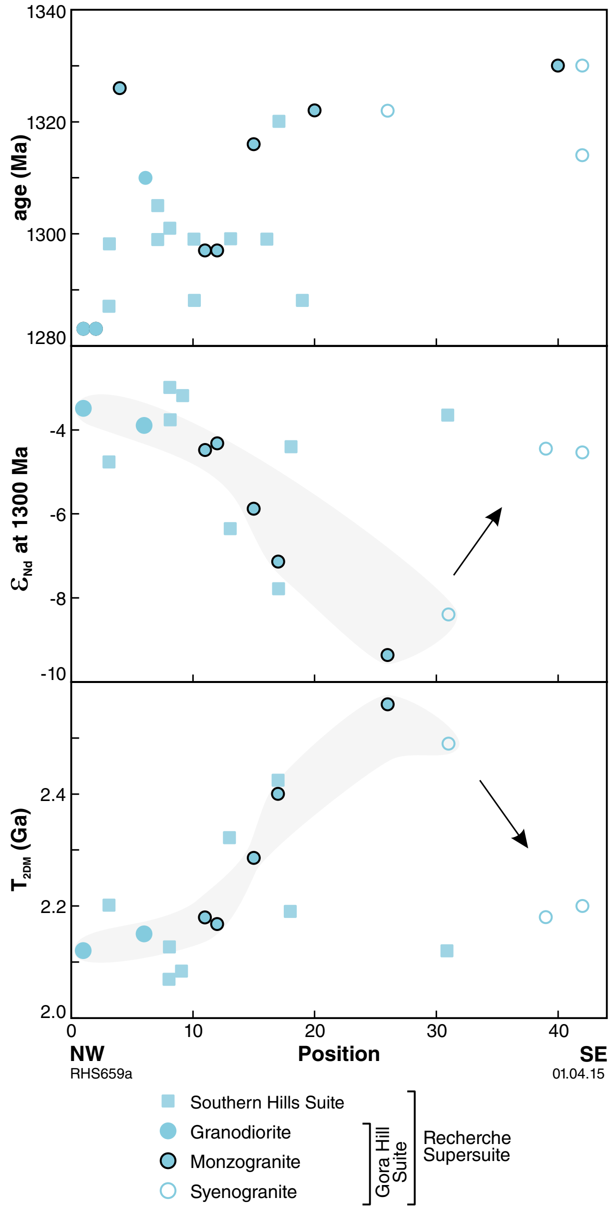

Figure 28. Geographical variation in Nd isotopic composition for granites formed during Stage I of the Albany–Fraser Orogeny. ‘Position’ refers to the relative order of samples, in a southeast direction, when their true position is extrapolated along northeasterly trending lines, on to the traverse line shown in Figure 22. Grey field encloses all but the most southeasterly samples of the Gora Hill Suite

The mantle component dominates the evolution of rocks to the northwest of position 15 (sample 194710 —east of Mount Andrew and the Coramup Shear Zone, which separates the Biranup and Nornalup Zones) although granites to the southeast (possibly up to position 39) are increasingly dominated by the less radiogenic crustal component. Gora Hill Suite granites with the least radiogenic compositions have $T_{(2DM)}$ model ages as old as 2.56 Ga, confirming that Archean material was the ultimate source for crustal components within granites perhaps as far to the southeast as near Sheoaks Hill (position 39; Fig. 28). Here, syenogranitic sample 194873 shows an abrupt change to more radiogenic compositions and younger (2.18 Ga) $T_{(2DM)}$ model ages. The radiogenic syenogranites are clearly members of the Gora Hill Suite, with U–Pb dating of zircon giving crystallization ages of c. 1330 and 1314 Ma, making them the oldest members of that suite. Despite their rather radiogenic compositions, they are ferroan and among the most potassic granites of any age within the Albany–Fraser Orogen (Fig. 23). In view of their highly evolved geochemistry, it is unlikely that their radiogenic compositions and relatively young $T_{(2DM)}$ model ages reflect the same radiogenic mafic mantle component seen in the Gora Hill Suite in and near the Fraser Zone (i.e. gabbro of the Fraser Zone) to the northwest. It is more likely that they reflect a dominant felsic crustal source component that was significantly younger and more juvenile than that within the other members of the Gora Hill Suite group to the northwest. In this regard, it is interesting that the radiogenic Gora Hill Suite syenogranite samples have similar Nd isotopic compositions, $T_{(2DM)}$ model ages and K_2O concentrations as nearby (positions 27–31; Figs 27 and 28) Southern Hills Suite granites. The latter are interpreted to have inherited these compositional features through incorporation of an isotopically juvenile sedimentary source component derived through erosion of c. 1400 Ma primitive Loongana arc crust, including abundant plagiogranites, from the Madura Province to the east. Spaggiari et al., (2014b) suggest that the Loongana arc was accreted to the eastern Nornalup Zone margin immediately before, or at the beginning of, the Albany–Fraser Orogeny, and possibly thrust over the eastern Nornalup Zone to provide the elevated sedimentary hinterland source of the isotopically juvenile sediment component of the Arid Basin. The tectonic boundary (and suture) between the eastern Nornalup Zone and the Madura Province is the broad, northeasterly trending Rodona Shear Zone (Spaggiari et al., 2012, 2014a,b), which lies only a short distance to the east of the radiogenic Gora Hill Suite syenogranites. It is quite possible that the felsic crustal source component to the radiogenic syenogranites was a tectonically emplaced slice of the Loongana oceanic arc (Madura Province) itself, that is, part of the Rodona Shear Zone system. If this is the case, then juxtaposition of the two provinces predates Gora Hill Suite magmatism at c. 1330 Ma.

Thus, based on these spatial trends, it might be speculated that a lower crustal hot zone was established first in the southeast as Fraser gabbros invaded the lower Nornalup crust, and that the syenogranites are a relatively distal, or compositionally evolved, manifestation of this feature. Subsequent hot zones were established, or migrated, to the northwest. Successive hot zones either became progressively more intense (?progressive northwestward increase in crustal extension) or their presently exposed magmatic products progressively reflect deeper structural levels. Magmatic products of Stage I of the Albany–Fraser Orogeny overstep the boundary between the eastern Nornalup Zone of the Albany–Fraser Orogen and the Madura Province, which must have been juxtaposed before the earliest Gora Hill Suite magmatism at c. 1330 Ma. The sharp change in the isotopic composition of the Gora Hill Suite magmas across this tectonic boundary reflects a significant change in basement composition that also marks the southeastern edge of reworked Archean crust. Since this boundary zone is where Gora Hill Suite magmatism began, this magmatism, and the lower crustal hot zone itself, may have initiated through orogenic collapse following accretion and overthrusting of the Madura Province over the eastern Nornalup Zone. Interestingly, the available Nd isotopic data from the Madura Province show a crustal evolution trend that strongly contrasts with that of the Albany–Fraser Orogen, but that overlaps the main basement evolution trend for the Musgrave Province to the northeast (Fig. 29). Based on these trends, the suggestion that the Musgrave Province and the Albany–Fraser Orogen evolved over a common basement (Smits et al., 2014) is untenable. It is, however, plausible that the Madura Province forms basement to the Musgrave Province.

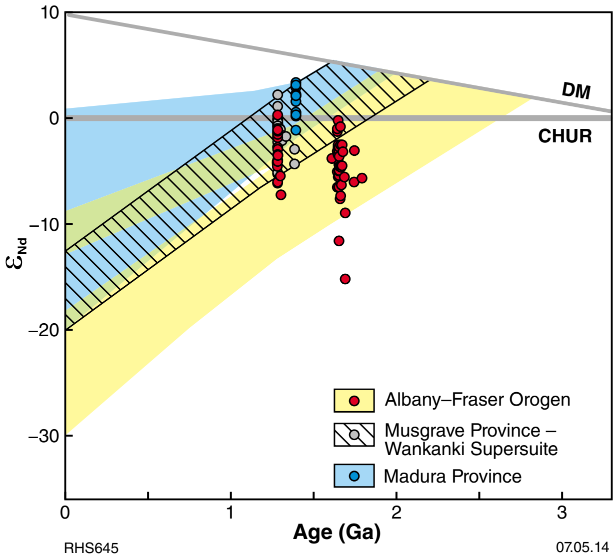

Figure 29. Nd isotopic evolution of the Albany–Fraser Orogeny and the Madura and Musgrave Provinces

Stage II — Esperance Supersuite

In the eastern Albany–Fraser Orogen 10 granites are so far confirmed by U–Pb zircon dating to have formed during Stage II of the Albany–Fraser Orogeny. These have crystallization ages between 1196 and 1135 Ma. Eleven samples from the eastern Nornalup Zone are tentatively added to this group based on field and geophysical similarities with the dated samples. Eight of the 10 dated samples were subsequently found to form a group with (for example) distinctly low LREE concentrations compared to the other samples. These were initially referred to as 'sodic Esperance Supersuite' granites (Smithies et al., 2014) although are here named the Truslove Suite (after Truslove historical townsite, north of Esperance) (Fig. 23). Four of these samples straddle the broad sheared boundary between the eastern Nornalup Zone and the Biranup Zone, while the remaining four occur in the central Biranup Zone at Bremer Bay, and in the eastern Nornalup Zone at the Big Red prospect, Thistle Cove, and Balladonia Rock (Fig. 22). Field relationships for at least some of these (e.g. 182474 from the Big Red prospect) indicate that they result through partial melting of local crust.

The remaining granites include a sample from Scott Rock near Mount Ragged dated at 1175 ± 12 Ma (192586; Kirkland et al., 2014f) and a sample from near the corner of Merivale and Orleans Bay Roads east of Esperance dated at 1172 ± 5 Ma (194849; preliminary data). This group of rocks is geochemically distinctive from all other granites of the Albany–Fraser Orogen and all lie to the southeast of the Truslove Suite granites, with the exception of the Truslove Suite sample at Balladonia Rock. They were referred to as the 'Enriched Esperance Supersuite' granites by Smithies et al. (2014) although are here named the Booanya Suite (after Booanya Rock, northeast of Esperance). Two further samples (194855 and 194856) are from the coastal region of the eastern Nornalup Zone where granites from both the Gora Hill Suite of the Recherche Supersuite and the Booanya Suite appear. These two samples have the distinctive geochemistry of the Booanya Suite, although have been tentatively classified based on field criteria, as early Gora Hill Suite granites, and one of these samples (194855) occurs as xenoliths within granite thought to be a younger member of the Gora Hill Suite. However, as discussed earlier, it remains possible that planned geochronology will show that several samples tentatively placed into the Gora Hill Suite from this region (including xenolith 194855 and the host granite 194854) actually belong to the Esperance Supersuite.

Truslove Suite

The eight dated samples that form this granite group are distinct from the Booanya Suite granites in having generally higher Al_2O_3 and Na_2O and lower K_2O, TiO_2 and total Fe concentrations (Fig. 23). They are all slightly peraluminous (ASI >1) and fall in or straddle the boundary with the field for arc-related granites (e.g. Pearce et al., 1984), in contrast with the distinct within-plate compositional characteristics of the Booanya Suite (Fig. 24). At higher silica contents, the Truslove Suite granites appear transitional to the Southern Hills Suite of Stage I of the Albany–Fraser Orogeny, except for the elements Ba and Sr, which are in higher concentrations in the Truslove Suite (Fig. 23). It is with the older sodic granites of the Archean, Munglinup Gneiss and early Biranup magma groups that the Truslove Suite granites share some geochemical similarities. These similarities extend to generally high Na_2O, Ba, Sr and low Rb, HREE concentrations and low K_2O/Na_2O ratios (Fig. 23), and there is possibly a subset of this suite characterized by a combination of slightly higher Al_2O_3, Na_2O, and Sr and lower Y.

Booanya Suite

Booanya Suite granites all lie within the eastern Nornalup Zone and within an approximately 90 km-wide, northeasterly trending, generally moderately to strongly magnetic belt (Fig. 22; see also Spaggiari et al., 2014c). These granites are ferroan, range from alkali-calcic to alkalic, and fall within the within-plate field on tectonic discrimination diagrams (Fig. 26). They are generally enriched in K_2O, TiO_2 and P_2O_5 compared with the Truslove Suite granites, although it is the strong enrichments in LREE (in particular) that distinguish granites of the Booanya Suite from those of the Truslove Suite, and from all other granite groups of the Albany–Fraser Orogen (Fig. 23). These enriched characteristics extend across the full REE spectrum, and also to Th, U and HFSE (Fig. 23).

Magmatic evolution during Stage II

A single Nd isotopic analysis from the Truslove Suite (Fig. 30) indicates more radiogenic compositions ($\varepsilon_{Nd\ (1200Ma)}$ –6.91; sample 184374) than those expected from melting of crust formed from early and late Biranup magmas or Archean crust alone ($\varepsilon_{Nd\ (1200Ma)}$ generally < –8). The source for this sample may have included early Biranup magmas or Archean crust accompanied by further addition of juvenile (radiogenic) mantle material. In contrast, the zircon population from another sample (182474) is dominated by c. 1170 Ma aged grains with strongly non-radiogenic Hf and by older inherited grains with Biranup Orogeny ages (Kirkland et al., 2014 a,b), consistent with this sample being a locally derived partial melt of a garnet-bearing paragniess (part of the Barren Basin; Spaggiari et al., 2014a,b), itself derived from sedimentary accumulation from Biranup Orogeny aged felsic crust. It is possibly that the Truslove Suite granites in general represent partial melts of locally available lithologies — mainly felsic rocks formed during the Biranup Orogeny. Melting was possibly generally constrained along the broad, sheared boundary between the Nornalup and Biranup Zones (Red Island, Coramup, and Heywood–Cheyne Shear Zones) and, at least in the case of the higher Al_2O_3, Na_2O, and Sr and lower Y subset, at depths where residual garnet was available to sequester HREE. These shear zones are interpreted to extend to significant crustal depths, down to about 30 km (Spaggiari et al., 2014b,c), and could have facilitated emplacement of these granites.

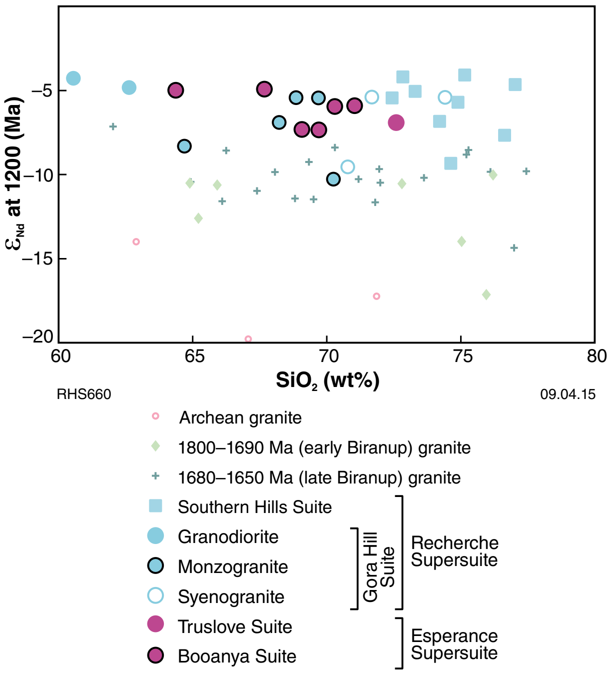

Figure 30. Nd isotopic composition vs SiO_2 content of the Recherche and Esperance Supersuites

The ferroan, felsic composition of the Booanya Suite, with strong enrichments in a range of incompatible trace elements as well as K_2O, TiO_2 and P_2O_5, is characteristic of a specific type of A-type magmatism that results through very high temperature melting of anhydrous lower crust, likely in association with a significant juvenile mantle input (e.g. Kilpatrick and Ellis, 1992; Frost and Frost, 1997, 2008; Smithies et al., 2011). It heralds a significant change in magmatism compared with both the Truslove Suite granites and the Recherche Supersuite, probably related to higher crustal temperatures associated with significant crustal extension. Five Nd isotopic analyses (Fig. 30) from the Booanya Suite granites give relatively radiogenic values ($\varepsilon_{Nd\ (1200Ma)}$ ~ –4.87 to –7.34) similar to those of both the Truslove Suite ($\varepsilon_{Nd\ (1200Ma)}$ –6.91) and the Gora Hill Suite ($\varepsilon_{Nd\ (1200Ma)}$ –3.49 to –9.36), suggesting compositionally similar bulk source regions. If this is the case, then the distinct compositions of the Booanya Suite must then relate to a significant change in melting conditions (i.e. low pressures and higher temperatures) or process, or both. A small but clear negative correlation between ε_{Nd} and SiO_2 likely reflects an AFC-type process with a radiogenic mafic end-member compositionally similar to known gabbroic rocks of the Albany–Fraser Orogen, possibly indicating a mantle-derived parental magmatic source component. In this respect, petrogenesis of these rocks is not significantly different to that of most other post-Archean granites of the Albany–Fraser Orogen (variable mixtures of mantle magma and partial melts of crustal components). An additional possibility is that the source for the Booanya Suite included the lower crustal equivalents of the Gora Hill Suite itself, remobilized into a new MASH chamber formed as more mafic magma was injected into the lower crust.

Conclusions

- At least 12 granite age groups covering from c. 2722 to 1135 Ma can be identified within the Albany–Fraser Orogen, each with a generally distinctive compositional range.
- Based on geochronological and geochemical (including isotopic) data from these granites, it can be shown that a large proportion (possibly the majority) of crust within the Northern Foreland, Tropicana, Biranup and eastern Nornalup Zones, is multiply reworked Archean crust.
- Pristine (i.e. has not remelted) Archean crust that remains in the Northern Foreland and Tropicana Zone and as remnants in the eastern Biranup Zone can be divided between granites representative of the TTG series and Archean sanukitoids.
- The presence of sanukitoids suggests a subduction-modified Archean mantle source and hence, the likelihood of one or more proximal Archean crustal plate boundaries.
- The Munglinup Gneiss comprises an Archean granite protolith that has undergone Mesoproterozoic high-grade metamorphism that involved metamorphic segregation, though only very minimal anatectic melt loss beyond the sample scale.
- Post-Archean crustal evolution of the Albany–Fraser Orogen involves recycling of Archean felsic material in several episodes, each involving variable inputs of juvenile mantle material. These events progressively mask, although do not destroy, the Archean compositional heritage of the crust.
- In terms of granite petrogenesis and crustal evolution, the period from c. 1800 Ma to the end of the Biranup Orogeny at c. 1650 Ma can be divided into two phases: ‘early’ and ‘late’ Biranup magmas. The early period (1800–1690 Ma) essentially involved large-scale remelting of TTG-like Archean crust, and the range to Nd isotopic compositions less radiogenic than those of the Archean granites indicate that crustal evolution throughout this period also involved mantle additions. The late period (c. 1680–1650 Ma) heralds a change in the style of crustal evolution, which involved recycling of previously recycled Archean felsic crust, with more significant mantle additions. Crustal evolution from c. 1800 Ma to the end of the Biranup Orogeny at 1650 Ma was most likely controlled by crustal thinning events.
- The c. 1700 Ma Bobbie Point Metasyenogranite in the Tropicana Zone is a notable exception within the early Biranup magma group, having an A-type composition reflecting higher-temperature melting. Its Archean crustal source had a prehistory of melting at depths within the garnet stability field, although melting to form the Bobbie Point Metasyenogranite was at a shallower crustal depth where garnet was no longer stable.

- Granites formed during Stage I of the Albany–Fraser Orogeny (Recherche Supersuite) are divided into the Southern Hills Suite and the Gora Hill Suite. The Southern Hills Suite granites reflect melting of supercrustal sequences dominated by sedimentary rocks with a major source component that was isotopically primitive and exotic with respect to the Albany–Fraser Orogen. The Gora Hill Suite granites represent mixing between a crustal source (most likely early to late Biranup magmas rocks — themselves containing a significant component of recycled Archean crust) and mantle material similar to that which formed the Fraser gabbro in an orogen-wide, lower crustal hot zone. The magmatically active portion of this hot zone migrated from southeast to northwest with decreasing age.

- Magmatic products of Stage I of the Albany–Fraser Orogeny overstep the broad shear zone boundary (Rodona Shear Zone) between the eastern Nornalup Zone of the Albany–Fraser Orogen and the Madura Province, constraining the timing of initial formation of the Rodona Shear Zone to before the earliest Gora Hill Suite magmatism at c. 1330 Ma. A sharp change in the isotopic composition of the Gora Hill Suite magmas across this shear zone boundary reflects a significant change in basement composition that also marks the southeastern edge of reworked Archean crust.

- Since the boundary between the eastern Nornalup Zone and the Madura Province is where Gora Hill Suite magmatism began, this magmatism, and the lower crustal hot zone where melting occurred, may have initiated through orogenic collapse following thrusting of the Madura Province over the eastern Nornalup Zone.

- Truslove Suite granites of the Esperance Supersuite are widespread although mostly occur in the Biranup Zone and within the broad sheared boundary between the Nornalup and Biranup Zones. These rocks in general represent low degree partial melts of locally available lithologies — mainly rocks from early and late Biranup magmas. Melting is broadly constrained along the sheared boundary between the Nornalup and Biranup Zones and at various depths, including deep regions where residual garnet was available to sequester HREE.

- Booanya Suite granites of the Esperance Supersuite mostly occur in the eastern Nornalup Zone and are ferroan, alkali-calcic to alkali rocks with strong enrichments in incompatible trace elements, characteristic of a specific type of A-type magmatism that results through very high temperature melting of anhydrous lower crust, likely in association with significant mantle input. These rocks herald a significant change in magmatism compared with both the Truslove Suite granites and the Recherche Supersuite, probably related to higher crustal temperatures associated with significant crustal extension.

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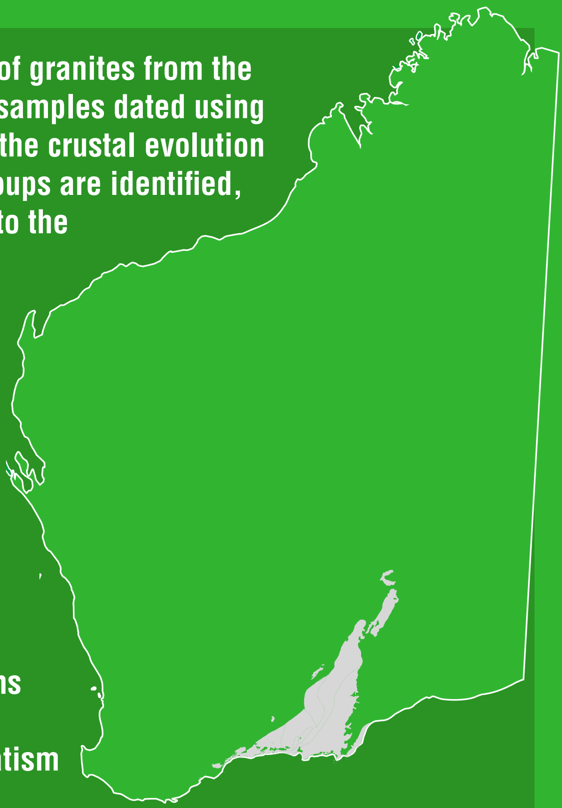
BUILDING THE CRUST OF THE ALBANY–FRASER OROGEN: CONSTRAINTS FROM GRANITE GEOCHEMISTRY

REPORT 150



This Report uses a whole rock geochemical dataset of granites from the Albany–Fraser Orogen, including a large number of samples dated using U–Pb zircon geochronology, to constrain models for the crustal evolution of the Albany–Fraser Orogen. Twelve granite age groups are identified, spanning crustal evolution events from the Archean to the c. 1140 Ma end of the Albany–Fraser Orogeny. Throughout that period, the dominant geochemical and isotopic trend is to increasingly mask, although not destroy, the Archean heritage of the orogen through processes of crustal reworking and mantle-melt addition. The prevailing tectonic regime likely involved crustal thinning, with periodic mid-crustal melting of various, originally deep-crustal source regions. At times, this was at unusually high crustal temperatures. Granites that formed at c. 1330 Ma, near the beginning of the Albany–Fraser Orogeny, have sampled source regions belonging to the Madura Province, which lies to the southeast of the Albany–Fraser Orogen. This magmatism most likely post-dates accretion of the c. 1410 Ma Loongana arc (Madura Province) to the east Albany–Fraser Orogen.

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