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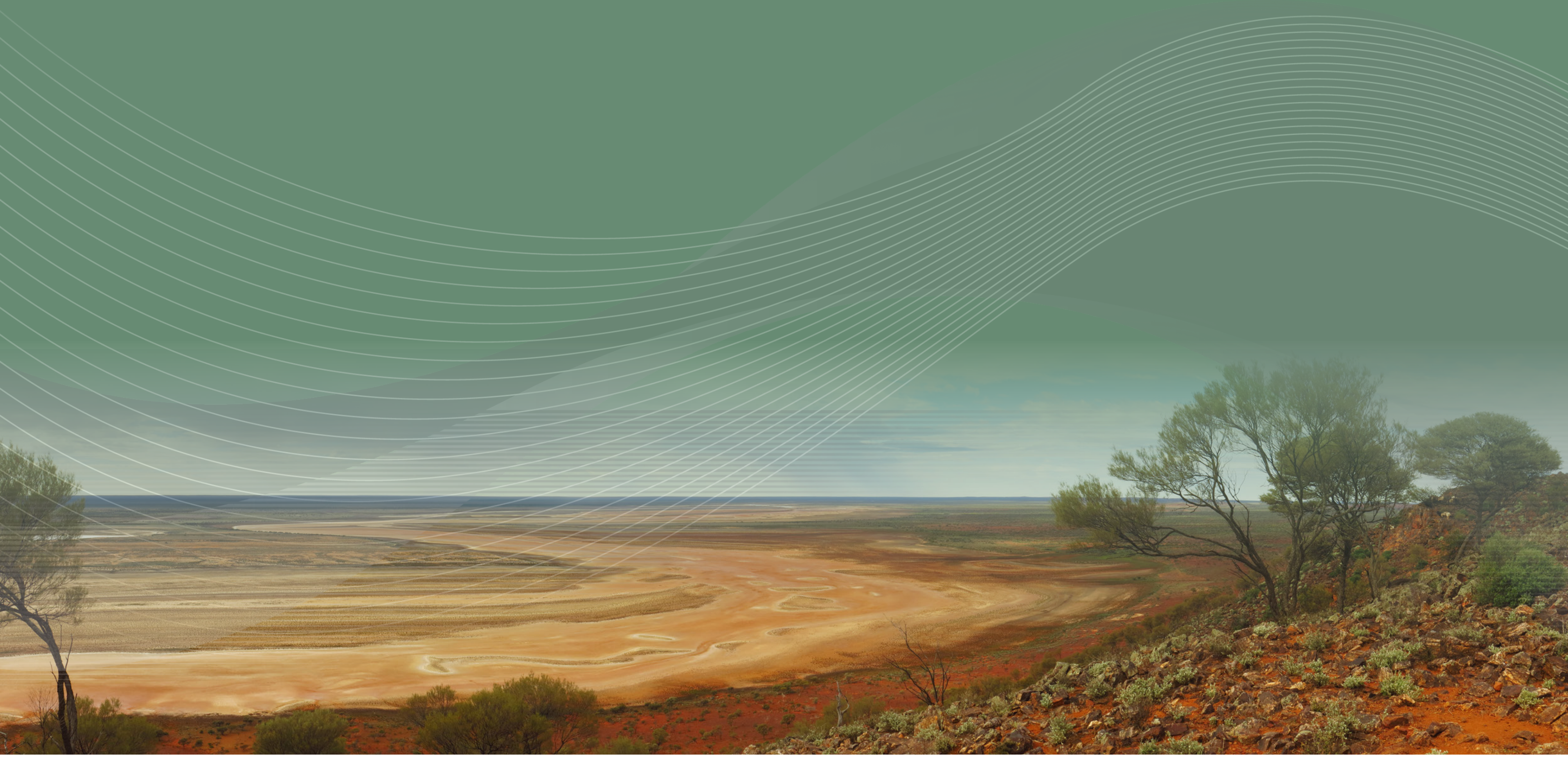
RECORD 2018/10

GEOCHEMISTRY OF ARCHEAN GRANITIC ROCKS IN THE SOUTH WEST TERRANE OF THE YILGARN CRATON

by
RH Smithies, Y Lu, K Gessner, MTD Wingate and DC Champion



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Geological Survey of Western Australia

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Cover image: Elongate salt lake on the Yilgarn Craton — part of the Moore–Monger paleovalley — here viewed from the top of Wownaminya Hill, 20 km southeast of Yalgoo, Murchison Goldfields. Photograph by I Zibra, DMIRS

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Available with the PDF online as an accompanying digital resource

Geochemistry of Archean granitic rocks in the South West Terrane of the Yilgarn Craton

by

RH Smithies, Y Lu, K Gessner, MTD Wingate and DC Champion*

Abstract

A dataset of 202 new whole-rock geochemical analyses of granitic rocks has been added to existing data to better constrain the geological evolution of the poorly understood South West Terrane of the Archean Yilgarn Craton. The granitic rocks are divided into four groups according to their K_2O/Na_2O (sodic if <1, potassic if >1) and Sr/Y (high = >1, low = <1) ratios, which are primarily a reflection of source composition and depth of melting, respectively. Variations in other trace element characteristics and in whole-rock initial $^{206}Pb/^{204}Pb$ are also considered, and regional variations in all of these parameters are used to gain insight into the composition and architecture of the lower crust. Extraction of felsic magma, leaving a dense garnet-rich crustal residuum imparts distinctively high-Sr/Y, La/Yb, Gd/Yb characteristics on those magmas. Variation in these proxies for melting-pressure shows no spatial relationship with a high-density (gravity) anomaly identified in the lower crust of the southern and western parts of the South West Terrane. This anomaly does not appear to be directly related to Archean felsic magmatism, but more likely relates to the Proterozoic evolution of the Yilgarn Craton margins or Phanerozoic events at the margins of the West Australian Craton. Geographical distribution of the main granite groups defines a northeast trend that truncates the north-northwesterly trend of the eastern boundary of the South West Terrane. An expanded dataset for the entire Yilgarn Craton shows that the same trends extend across much of the craton, including into the western part of the Eastern Goldfields Superterrane, across inferred Yilgarn Craton terrane boundaries and major visible structural trends. In particular, sodic high-Sr/Y granitic rocks with Gd/Yb >5, likely derived from the deeper levels of (basement) crustal melting within the craton, occur in two distinct northeasterly trending zones extending across the craton, separated by a zone that shows no evidence for similarly deep crustal melting in the Archean. These large-scale geochemical trends probably relate to basement domains that existed before the younger (post-2.73 Ga) terrane boundaries were imposed.

KEYWORDS: Archaean, basement domains, geochemistry, granitic rock, South West Terrane, Yilgarn Craton

Introduction

The current interpreted tectonic framework for the Yilgarn Craton (Cassidy et al., 2006) identifies six broadly north-northwesterly trending terranes, of which the easternmost four are grouped into the Eastern Goldfields Superterrane (Fig. 1). The South West Terrane, in the southwest of the craton, remains the least studied, and its geological evolution the least understood, of all the terranes. Several observations suggest a fundamental geological difference between the South West Terrane and the Archean terranes to the east, and these need to be assessed and accounted for if we are to understand the Archean evolution of the Yilgarn Craton. These apparent differences include a much lower incidence of supracrustal greenstone belts and a tendency for those belts to be dominated by metasedimentary rocks rather than by metavolcanic and metavolcaniclastic rocks. There also appears to be a higher abundance of gneissic rocks of both igneous and sedimentary protolith. Nevertheless, the terrane boundary between the South West Terrane and the Youanmi Terrane, to the east and northeast, is considered largely hypothetical (Cassidy et al., 2006), and there are no regional geophysical, geochemical, geochronological or isotopic datasets that clearly define that boundary. In addition, much of the deep crust of the South West Terrane comprises an anomalously dense mineral assemblage, imaged in regional gravity surveys (Fig. 2). The distribution of this dense crust appears to be controlled by northwest-trending structures, parallel to the inferred eastern terrane boundary and subparallel to the main regional structural trend of the craton. However, it does not extend as far east as the surface trace of the inferred terrane boundary. The density anomaly itself has been interpreted to represent a remnant eclogite residuum that resulted from Archean crustal differentiation (Dentith et al., 2000; Mjelde et al., 2013).

As with most of the Yilgarn Craton, the geology throughout most of the South West Terrane is dominated by rocks of broadly granitic protolith. Such rocks are ideal targets in regional reconnaissance whole-rock geochemical studies because their geochemistry and isotopic compositions can provide information on basement compositions (and compositional variations), and on crustal-scale petrogenetic and tectonic processes. Given sufficient geochronological data, these variations and processes can also be related to specific time intervals. Accordingly, a dataset of 202 new

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Figure 1. Terrane subdivision of the Yilgarn Craton, modified after Cassidy et al. (2006). Heavy dashed line marks the northern boundary of the Albany–Fraser Orogen

whole-rock geochemical analyses of granitic rocks has been compiled to better constrain the geological evolution of the southern part of the South West Terrane. These have been combined with an additional ~150 existing analyses. There are currently insufficient geochronological data available to provide meaningful temporal constraints on compositional or geographical variations within the dataset. However, existing geochronological datasets (see Wilde, 2001) indicate that all regional granitic magmatic events considered here were Mesoarchean to Neoarchean. Discussions here are restricted to broad-scale geographical variations in composition that almost certainly reflect variations in source compositions and petrogenetic processes. Specifically, the combined geochemical dataset is used to test the validity of the eastern boundary of the South West Terrane against the Youanmi Terrane, and to investigate the origins of the density anomaly in the deep crust of the South West Terrane.

Regional geological setting

The South West Terrane occupies the lower southwestern part of the Yilgarn Craton and is truncated from Proterozoic and younger rocks to the west by the Darling Fault, and faulted against reworked Archean and Proterozoic rocks of the Northern Foreland (Albany–Fraser Orogen) to the south (Fig. 1). The terrane is believed to expose crust of a generally higher metamorphic grade than the terranes farther northeast in the Yilgarn Craton (Gee et al., 1981; Myers, 1993; Wilde et al., 1996), and was originally referred to as the Western Gneiss Terrane (Gee, 1979; Gee et al., 1981). The higher metamorphic grade is likely related to post-cratonization tilting of the crust, as indicated by cooling ages that become younger towards the western margin of the Yilgarn Craton (Libby and De Laeter, 1979; Lu et al., 2015). North-northwesterly trending regions of high-grade metasedimentary granulite and gneiss, dominantly of pelitic and psammitic compositions, were informally named the Jimperding, Chittering and Balingup metamorphic belts by Wilde (1980) and Gee et al. (1981). Subsequent U–Pb dating of detrital zircons from these metasedimentary rocks has identified age populations as old as c. 3735 Ma and interpreted maximum ages of sediment deposition ranging from c. 3100 Ma for the Jimperding and Balingup metamorphic belts to c. 2890 Ma for the Chittering metamorphic belt (Wilde et al., 1996). Wilde et al. (1996) further divided the region into three additional tectonic units — the Balingup, Boddington and Lake Grace 'terranes' — separated by inferred north- or northwesterly trending shear zones which locally also intersect the metamorphic belts. The basement components of the South West Terrane are thought to have been accreted to the Younami Terrane after c. 2800 Ma (Myers, 1993; Nutman et al., 1993: Cassidy et al., 2005).

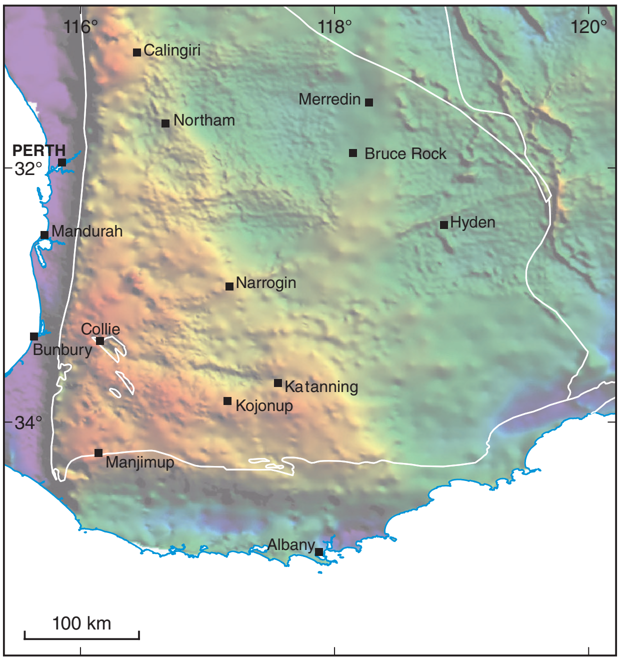

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Figure 2. **Gravity image of the southern part of the South West Terrane, in the southwestern Yilgarn Craton. Warm colours represent a strong gravity response**

Granitic rocks within the South West Terrane formed over a long, and presently poorly constrained period, from at least c. 3300 to 2600 Ma (e.g. Wilde, 2001). Their lithological, compositional and textural ranges are similar to those from other terranes of the Yilgarn Craton.

Sample details

Samples collected for this study range both mineralogically and geochemically from tonalite to syenogranite — although all are referred to here in the broad sense as ‘granitic rocks’. The samples range in texture from metamorphic (including granulites) strongly foliated granitic and gneissic rocks, to massive rocks with well-preserved igneous textures. The latter range from equigranular through seriate to porphyritic (mainly K-feldspar) and megacrystic textures. Many leucocratic granitic rocks show a strong foliation which is interpreted to be magmatic in origin, based on a lack of deformational fabrics. The magmatic fabric is typically accentuated by abundant biotite-rich schlieren, and locally also by attenuated, ductily deformed, country-rock xenoliths. At some localities, these schlieric granitic rocks are found in close association with diatexitic migmatite, to which they are probably genetically related. Most of the samples collected for this study are yet to be dated, hence no relationships between emplacement age and rock texture are interpreted.

Geochemistry

Analytical procedure for new samples

The sample sites for new and previously published data are shown in Figures 3–5. All samples specifically collected for this project were analysed by BV (Burean Veritas) Minerals, in Canning Vale, Perth, Western Australia. Samples were visibly inspected and any weathering or vein material removed. Each sample was crushed either in-house or by BV Minerals in a plate jaw crusher and low-Cr steel mill to produce a pulp with a nominal particle size of 90% <75 µm. A representative pulp aliquot was analysed for 13 elements as major components, ignition loss, and 54 elements as trace elements (ppm or ppb). Major elements were determined by X-ray fluorescence (XRF) spectrometry in a fused glass disk. A fragment of each disk was then laser ablated and analysed by ICP-MS for 51 of the 54 minor trace elements (LA-ICP-MS). Gold, Pd and Pt were analysed on a separate pulp aliquot by lead collection fire assay and ICP-MS. Data quality was monitored by ‘blind’ insertion of sample duplicates (i.e. a second pulp aliquot), internal reference materials, and the certified reference material OREAS 24b (www.ore.com.au). BV Minerals also included duplicate samples (including OREAS 24b), certified reference materials, and blanks. An assessment of accuracy and precision was made using data for 17 analyses of OREAS 24b, determined during the analysis of greenstones. For analytes where the concentration is at least 10 times the lower level of detection, a measure of accuracy is provided by the agreement between the average determined value and the certified value according to HARD (i.e. [(analysis1– analysis2)/(analysis1 + analysis2)]; Stanley and Lawie, 2007) which is <0.05 for all analytes apart from Be and Cu. In terms of precision, the percent relative standard deviation (RSD%) or covariance for analysis of OREAS 24b is <10 for all analytes apart from As, Cu, Ni, Sc and Zn. Similar levels of agreement were found for parent–duplicate pairs. All blank values were less than three times the lower level of detection. All results are presented in the Appendix (accompanies the PDF of this publication as a digital resource).

Grouping and geographical trends

K_2O/Na_2O vs Sr/Y

All 348 samples with SiO_2 >63wt% were initially classified, irrespective of texture, mineralogy, fabric or location, based on whether they are sodic (i.e. K_2O/Na_2O <1) or potassic (i.e. $K_2O/Na_2O \geq 1$) and have high (≥40) or low (<40) Sr/Y. Variations in K_2O/Na_2O mainly reflect corresponding variations in source compositions.

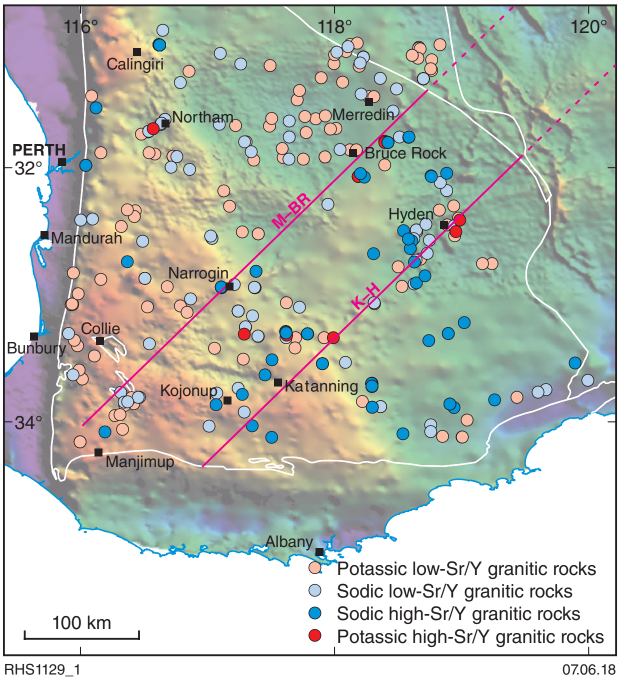

Figure 3. Distribution of sodic and potassic high- and low-Sr/Y granitic rocks in the South West Terrane and the locations of the Manjimup – Bruce Rock line (M–BR) and the Kojonup–Hyden line (K–H). Warm colours represent a strong gravity response

Variations in Sr/Y are primarily controlled by the mineralogy remaining in the source after melt extraction. For most crustal source regions, the strongest controls on the Sr/Y ratio of a magma are exerted by plagioclase (which sequesters Sr) and garnet (and to a lesser extent hornblende) which sequesters Y and heavy rare earth elements (HREE). Melting at high pressures (>7–8 kbar, Johnson et al., 2017) leaves behind a source mineralogy that is garnet rich and plagioclase poor, and which consequently has low-Sr/Y and low-La/Yb ratios, and releases a high-Sr/Y and high-La/Yb melt. Melting at lower pressures where plagioclase, but not garnet, is stable has the opposite compositional effects. The reason for using this classification scheme was to investigate potential broad-scale variations in source composition and source depth, at the time of melting.

This classification divides the samples between four groups; sodic low-Sr/Y (125 samples), sodic high-Sr/Y (59 samples), potassic low-Sr/Y (151 samples) and potassic high-Sr/Y (13 samples). The sodic high-Sr/Y group is broadly equivalent to the Archean tonalite–trondhjemite–granodiorite (TTG) series, and the combined sodic and potassic high-Sr/Y groups broadly equate to the high-Ca group of Champion and Sheraton (1997). Similarly, the combined sodic and potassic low-Sr/Y groups broadly equate to the low-Ca group of Champion and Sheraton (1997).

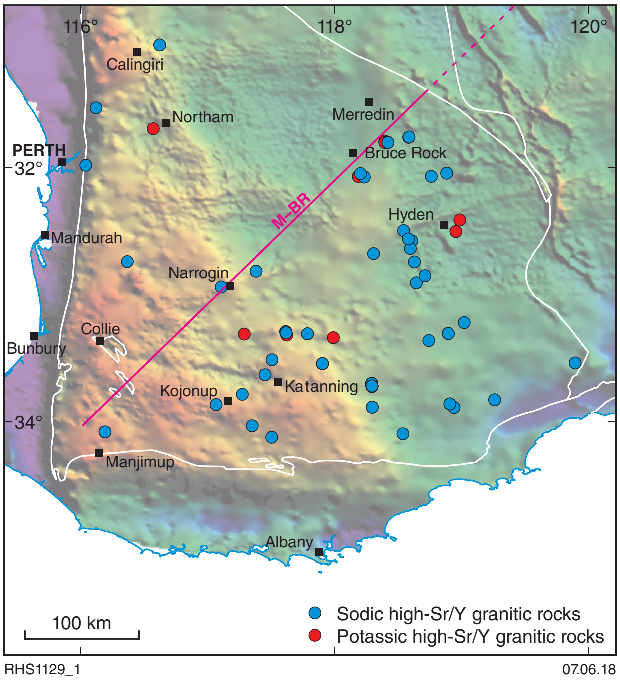

Figure 4. Distribution of sodic and potassic high-Sr/Y granitic rocks in the South West Terrane and the location of the Manjimup – Bruce Rock line (M–BR). Warm colours represent a strong gravity response

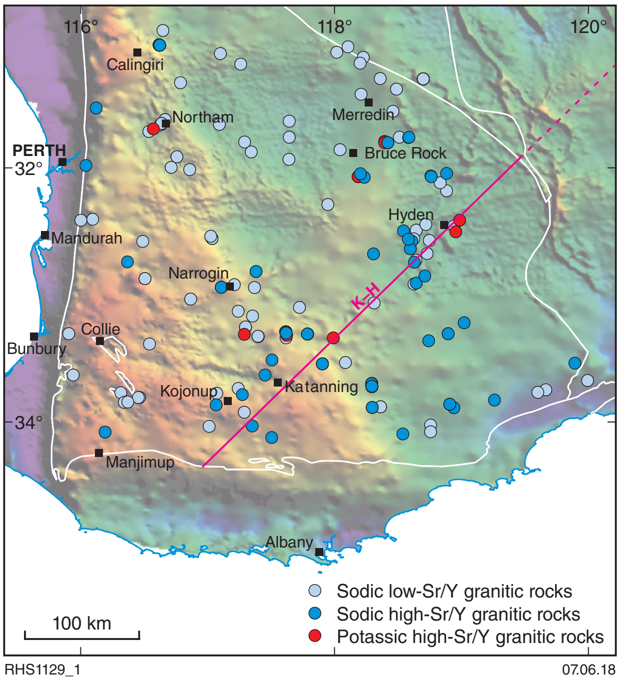

Figure 5. Distribution of sodic and potassic high-Sr/Y, and sodic low-Sr/Y granitic rocks in the South West Terrane and the location of the Kojonup–Hyden line (K–H). Warm colours represent a strong gravity response

Geographical variations

Figure 3 shows the location of all samples analysed during this study, with symbols coloured according to the (K_2O/Na_2O) – (Sr/Y) classification scheme outlined above. Based on the geochemical classification defined above, a number of compositional domains and trends can be identified in the South West Terrane.

Approximately 95% (55 of 59 samples) of sodic high-Sr/Y granitic rocks lie to the southeast of a line extending northeast from a point approximately 17 km north-northeast of Manjimup to a point approximately 26 km east-northeast of Bruce Rock (referred to here as the Manjimup – Bruce Rock line, Fig. 4). Three samples of rare sodic high-Sr/Y granitic rocks occur in a narrow north-northeast band extending from the Darling Scarp (Kalamunda region) east of Perth to a point approximately 15 km east-northeast of Calingiri (Fig. 4), and a single sample was identified from Boddington. Potassic high-Sr/Y granitic rocks are relatively uncommon (13 samples), and all but one lies within the same region as the main population of sodic high-Sr/Y granitic rocks (Fig. 4). Thus, high-Sr/Y granitic rocks are concentrated in the southeast of the terrane.

Approximately 91% (114 of 125 samples) of sodic low-Sr/Y granitic rocks lie northwest of a line stretching northeast from a point approximately 25 km southwest of Kojonup to a point approximately 7 km east of Hyden (referred to here as the Kojonup–Hyden line, Fig. 5). The remaining samples to the southeast of that line either lie along a northwest trend that closely approximates the boundary between basement blocks of distinctly contrasting density (gravity), or along an east-northeast trend close to and parallel with the tectonic boundary between the South West Terrane and the Northern Foreland of the Albany–Fraser Orogen (Fig. 5). The potassic low-Sr/Y granitic rocks show a geographic distribution identical to the sodic low-Sr/Y granitic rocks (Fig. 3), with approximately 97% (146 of 151 samples) lying to the northwest of the Kojonup–Hyden line and the remaining five samples either lying on the northwest (one sample) or east-northeast trend defined by the sodic low-Sr/Y granitic rocks to the southeast of the Kojonup–Hyden line.

Trace element patterns

New samples collected for this study were also grouped based on their incompatible trace element patterns, viewed in terms of mantle-normalized multi-trace element diagrams. The trace element concentrations of all of these samples were determined by the same analytical technique and at a single laboratory and so the results represent an internally consistent dataset. Previously existing data were obtained using a variety of techniques and at several laboratories and were not considered in this treatment. The reason for using this grouping scheme was to investigate further variations in source composition. A potential problem using this methodology is that differences in trace element patterns might simply reflect different evolutionary stages in a petrogenetic process affecting a cogenetic and comagmatic magma.

Most of the samples fall into one of two broad groups based on trace element patterns. These groups broadly correspond to the high- and low-Sr/Y groups described above. The first group (TE Group 1, Fig. 6a) is defined by an essentially continuous decrease in mantle-normalized values of decreasingly incompatible trace elements, but with prominent negative Nb–Ta anomalies, only small (positive or negative) or no anomalies for Eu or Sr, and large La/Yb and Gd/Yb. This group is almost entirely populated by high-Sr/Y (≥40) granitic rocks (sodic and potassic).

Samples in the second group (TE Group 2, Fig. 6b) have prominent negative Eu and Sr anomalies. They show a range in La/Yb and Gd/Yb but include values as high as those in TE Group 1. Those samples with high Gd/Yb typically also have mantle-normalized Nb/Ta <1, distinguishing this subgroup (TE Group 2a) from the remaining samples (TE Group 2b). TE Group 2 is almost entirely populated by low Sr/Y (<40) granitic rocks (sodic and potassic).

Geographical variations

TE Groups 1 and 2 show the same geographical distribution as high-Sr/Y and low-Sr/Y granitic rocks, respectively. However, whereas TE Group 2b occurs both northwest and southeast of the Kojonup–Hyden line, Group 2a is concentrated to the northwest of that line (Fig. 7).

Lead isotopic composition

New samples collected for this study were also analysed for Pb-isotope compositions. These analyses were a routine component of whole-rock LA-ICP-MS analyses, and involved analytical counting statistics that did not permit highly precise analyses. As expected, initial isotopic compositions calculated from these data show a large amount of scatter, but they nevertheless show some broad systematic trends against other major and trace elements, particularly in the case of initial $^{206}Pb/^{204}Pb$, which reflects the initial concentration ratio of the most abundant isotope of uranium (U^{238}).

The sodic high-Sr/Y granitic rocks show a narrow range of low (i.e. non-radiogenic, primitive) $^{206}Pb/^{204}Pb$ ratios, mostly (97%) lower than 16 irrespective of SiO_2 and K_2O contents and $Mg^\#$, but with a weak tendency to include more radiogenic compositions at high SiO_2 and K_2O contents and low $Mg^\#$ (Fig. 8). These trends indicate that a portion of the data represents more evolved crust and that this portion increases with increasing silica, although more SiO_2- and K_2O-rich samples are not necessarily more radiogenic, i.e. some high K_2O values may simply reflect fractional crystallization. A single sample with an anomalously radiogenic composition ($^{206}Pb/^{204}Pb$ ~21) also has a relatively high K_2O/Na_2O (0.93) and is transitional to a potassic high-Sr/Y granitic rock.

Data for the potassic high-Sr/Y rocks include relatively non-radiogenic samples (i.e. $^{206}Pb/^{204}Pb$ <14) but also include two samples with $^{206}Pb/^{204}Pb$ >19 (Fig. 8). Similarly, data for sodic and potassic low-Sr/Y granitic rocks also contain a large proportion (~75%) of relatively non-radiogenic ($^{206}Pb/^{204}Pb$ <16) data across a wide range of SiO_2 and K_2O contents and $Mg^\#$ (Fig. 8), with the remaining radiogenic samples tending to have higher SiO_2 and K_2O contents and lower $Mg^\#$.

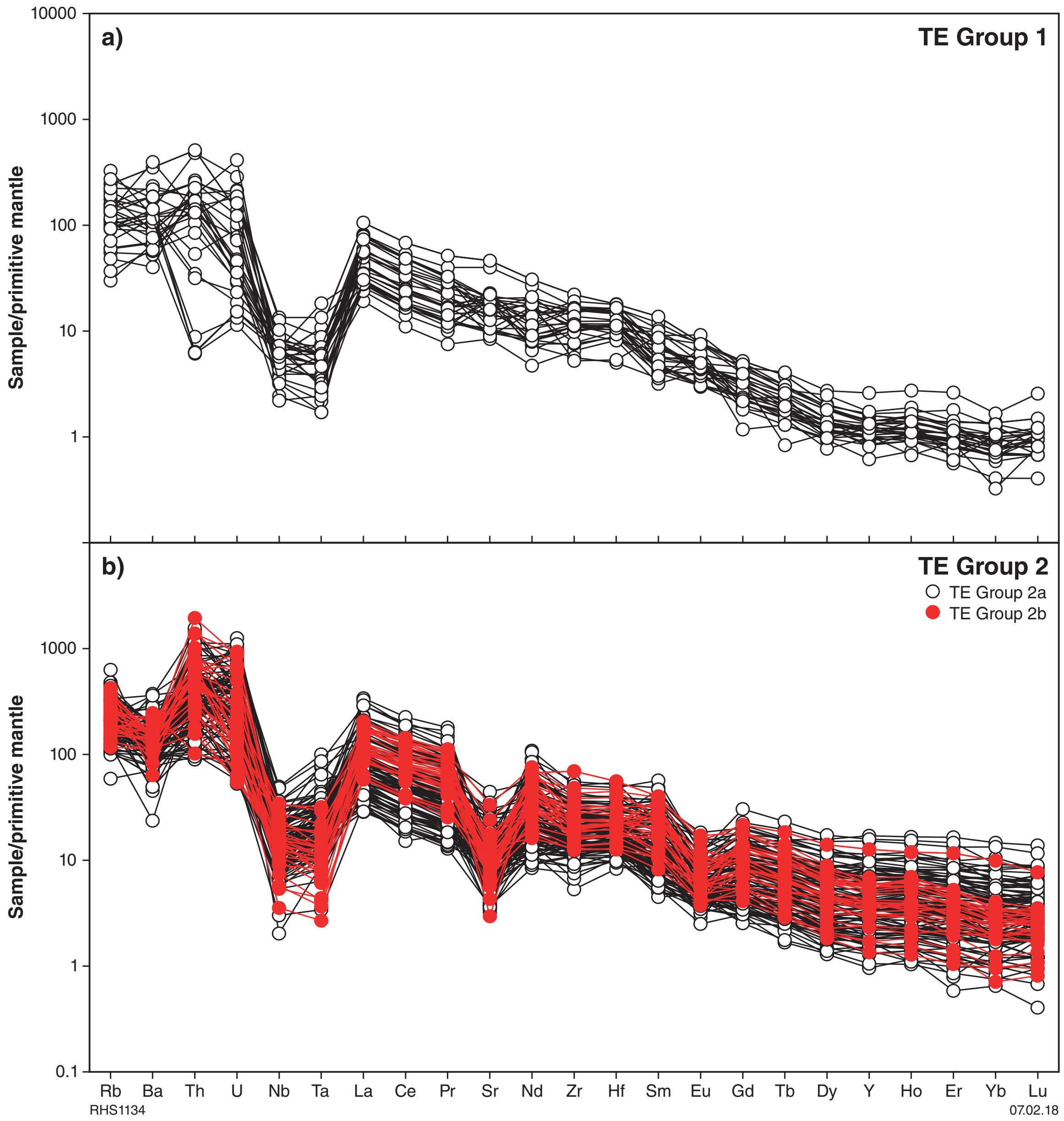

Figure 6. **Trace element patterns, normalized to primitive mantle, for a) TE Group 1 rocks and, b) TE Group 2 rocks (normalization factors after Sun and McDonough, 1989)**

Geographical variations

Relatively non-radiogenic samples (^{206}Pb/^{204}Pb <16) are distributed relatively evenly throughout the studied region (Fig. 9). However, samples with a more radiogenic character are primarily restricted to the area northwest of the Kojonup–Hyden line, with the exception of two potassic high-Sr/Y granitic rocks and one sodic granitic rock that is transitional to the potassic high-Sr/Y granite group. These data suggest that felsic magmas derived from sources that include relatively radiogenic crust are concentrated to the northwest of the Kojonup–Hyden line.

Discussion

The southern part of the South West Terrane of the Yilgarn Craton shows significant variations in the geochemistry of granitic rocks, with much of that change occurring between two northeasterly trending lines, one connecting Manjimup and Bruce Rock, the other connecting Kojonup and Hyden. Sodic high-Sr/Y rocks are primarily restricted to the southeast of this transition zone; only three have been found to the northwest, in a narrow zone from Kalamunda to Calingiri. Although less common, potassic high-Sr/Y granitic rocks have an identical geographic range. Apart from higher K_2O/Na_2O, some of these rocks have more evolved (i.e. radiogenic) Pb-isotope compositions (Fig. 8). Nevertheless, both sodic and potassic high-Sr/Y rocks typically display strongly fractionated rare earth element patterns (i.e. high mantle-normalized La/Yb and Gd/Yb) with negligible normalized Eu and Sr anomalies (Fig. 6), reflecting melting of crust at pressures high enough to destabilize plagioclase and stabilize significant amounts of garnet. The generally sodic melt products indicate that this source was broadly basaltic in composition and the

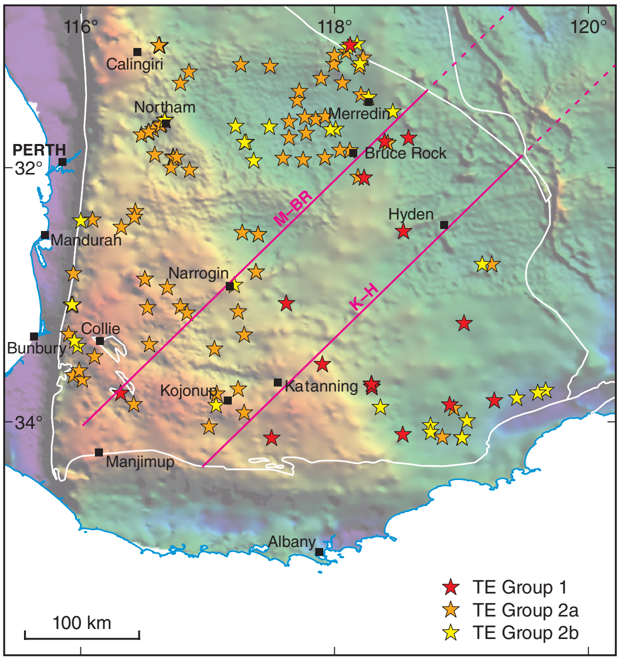

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Figure 7. **Distribution of granitic rocks in trace element Groups 1, 2a,b in the South West Terrane. Warm colours represent a strong gravity response**

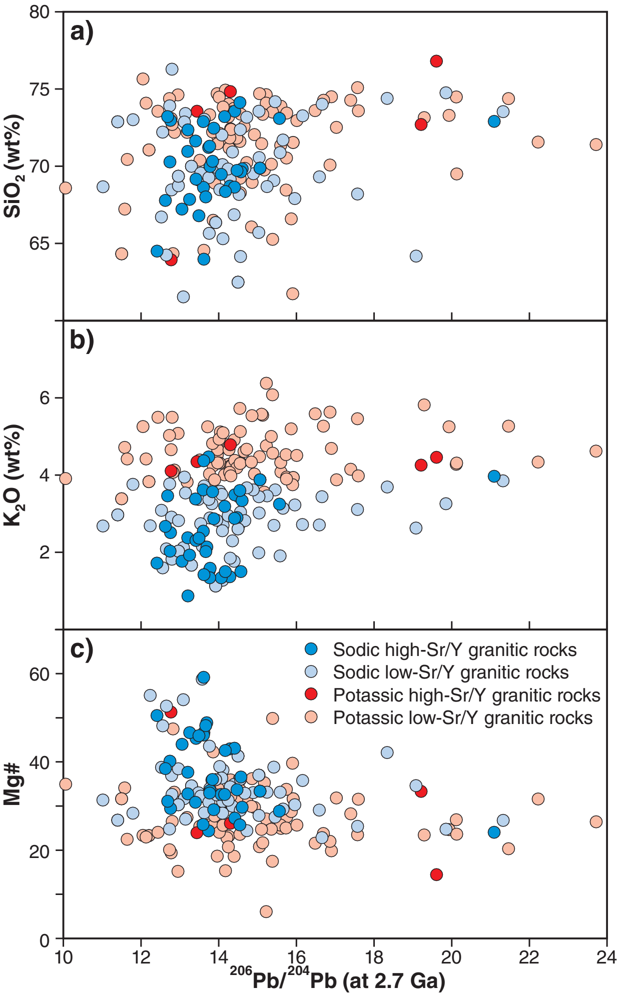

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Figure 8. **Variation in whole-rock initial $^{206}Pb/^{204}Pb$ ratio (calculated at 2.7 Ga) with SiO_2, K_2O and Mg#**

generally primitive isotopic compositions suggest it had not been significantly modified since extraction from a mantle source. However, the presence, albeit relatively rare, of potassic high-Sr/Y rocks indicates that the lower crustal source regions locally included zones or layers of compositionally more evolved (e.g. high K) crust, some of which was also isotopically evolved (e.g. high $^{206}Pb/^{204}Pb$), presumably as a result of an earlier period of crustal reprocessing.

The regions dominated by high-Sr/Y granitic rocks overlie basement that underwent deep (>25 km) crustal melting, leaving a dense, garnet-rich residuum. What is immediately apparent is that these regions do not correspond well with the geophysically defined (gravity) crustal density anomalies (Fig. 4). Instead, the northwestern boundary of the main region of high-Sr/Y granitic rocks (i.e. the Manjimup – Bruce Rock line) cuts the strongest lower crustal gravity gradients almost at right angles. These crustal gravity anomalies have previously been attributed to the presence of dense crust left over from extraction of Archean high-Sr/Y granitic rocks (TTG; Mjelde et al., 2013). Data presented here do not support this suggestion. Alternative explanations, such as the presence of mafic underplate reflecting the Proterozoic or Phanerozoic evolution of the Yilgarn Craton margin need to be considered.

Apart from the few high-Sr/Y granitic rocks lying between Kalamunda and Calingiri, all sampled granitic rocks in the region northwest of the Manjimup – Bruce Rock line are low-Sr/Y rocks (Fig. 3) with only weakly to moderately fractionated rare earth element patterns (i.e. low to moderate mantle-normalized La/Yb and Gd/Yb), or significant negative normalized Eu and Sr anomalies, or both (Fig. 6).

Another occurrence of these rocks overlaps with the southeasternmost exposure of the high-Sr/Y granitic rocks defining an east-northeasterly trending zone close to and subparallel with the tectonic boundary between the South West Terrane and the Northern Foreland of the eastern Albany–Fraser Orogen (Fig. 3). Division of these rocks into potassic or sodic groups appears unhelpful as both groups show a similar range in trace element concentrations and patterns and cover a similar range in Pb-isotope compositions. The range in K_2O/Na_2O reflects corresponding variations in source composition, and in some samples also the effects of fractional crystallization. The range in trace element patterns reflects a corresponding range in source mineralogy immediately after melt extraction.

The significant negative normalized Eu and Sr anomalies in nearly all of the low-Sr/Y rocks indicate either that the residual source was feldspar rich or that the granite melts underwent a significant amount of low-pressure differentiation, or both. The variations in La/Yb and, more directly, Gd/Yb reflect the abundance of garnet in melt-residual assemblages. Archean TTG (of which most of the sodic high-Sr/Y rocks are examples) typically have

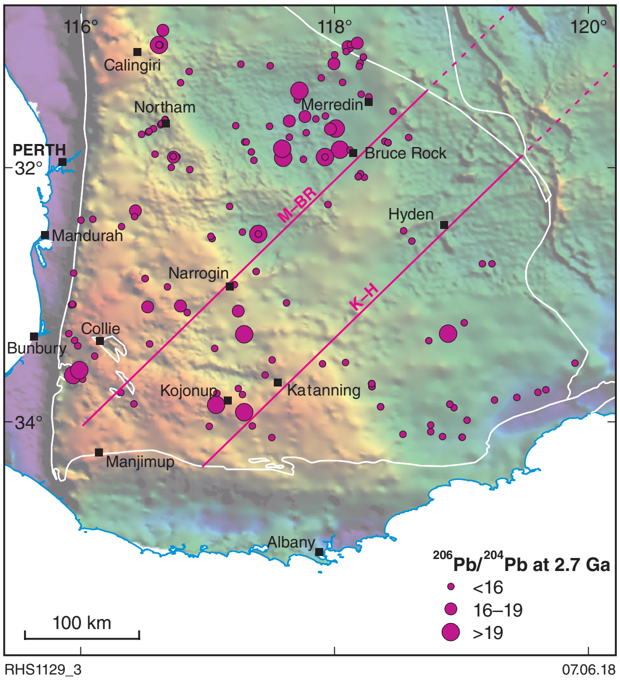

Figure 9. **Locations of new granite samples in the South West Terrane, with symbol sizes scaled according to initial ^{206}Pb/^{204}Pb ratios (calculated at 2.7 Ga). Warm colours represent a strong gravity response**

Gd/Yb ~4.0 (Martin et al., 2005), significantly higher than primitive mantle or mid-ocean ridge basalt values of ~1.2 (Sun and McDonough, 1989). The high Gd/Yb in TTG reflects a garnet-rich amphibolite melt-source residuum. Melting mafic crust (Gd/Yb ~1.2) at low pressures, i.e. below the stability field of garnet (>7–8 kbar, Johnson et al., 2017), should not significantly change the Gd/Yb of either the melt or source, as evidenced by the typically mantle-like Gd/Yb of rare, felsic, sodic magmas formed at low pressure in ophiolites and at oceanic spreading ridges (sodic dacite and plagiogranite; e.g. Rollinson, 2009). Hornblende also strongly concentrates middle to heavy REE. Its presence as a melt residue or as a fractionating phase can significantly increase La/Yb in a felsic magma, but will only slightly lower Gd/Yb such that garnet-free residues from melting mafic crust can have Gd/Yb <1.0 (e.g. Wolf and Wyllie, 1994). Thus, for melts of generally mafic crust, variations in Gd/Yb between those of TTG (or higher) and mafic crust (~1.2) can reflect the relative proportion of garnet and hornblende in the melt residue, and hence, relative melting pressures.

The low-Sr/Y rocks of the South West Terrane, with moderately fractionated rare earth element patterns (i.e. TE Group 2b) have a similar range of Gd/Yb (~3–8) to the high-Sr/Y rocks over a similar range of low Yb concentrations, strongly suggesting a source that retained garnet. This group of low-Sr/Y rocks includes all those lying close to and parallel to the tectonic boundary between the South West Terrane and the Northern Foreland of the Albany–Fraser Orogen, as well as those following the northwest-trending lineament that closely approximates the boundary between basement blocks of distinctly contrasting density (gravity) character. It also includes a large number of samples to the north of the Kojonup–Hyden line (Fig. 7). These are also the only low-Sr/Y granitic rocks to have Nb/Ta >1. The high Nb/Ta ratio possibly reflects a residual source mineralogy that included a mineral that sequesters Ta in preference to Nb (i.e. rutile or ilmenite) (e.g. Foley, 2008). Alternatively, it could also be inherited through depletion of amphibole (which sequesters Nb in preference to Ta; Foley, 2008) during melting of a source that already had a high Nb/Ta ratio (e.g. Rapp et al., 2003), perhaps through a prior episode of melting leaving a garnet amphibolite source.

The remaining low-Sr/Y granitic rocks (sodic and potassic; TE Group 2a) show a progressive range to significantly less-fractionated rare earth element patterns. These rocks only occur to the northwest of the Kojonup–Hyden line (Fig. 7). The decrease in La/Yb and Gd/Yb could reflect a decreasing relative proportion of garnet to amphibole, and could, in broad terms, be interpreted to reflect a progressive decrease in the pressure of melting. In this group of rocks, the lower range of Gd/Yb overlaps with mantle values (~1.2), almost certainly reflecting a garnet-free, low-pressure paragenesis. Many of the rocks in the area to the northwest of the Kojonup–Hyden line also trend to 'ferroan' [i.e. high Fe* (= ΣFeO/MgO – where all Fe is as FeO); Frost et al., 2001], alkali-rich, and incompatible trace element (e.g. Nb, Th, Y) enriched compositions (Fig. 10) transitional to those of A-type felsic magmas, and have zircon saturation temperatures (Watson et al., 2006) reaching temperatures >850°C. These are similar to the high-high field strength element (HFSE) group described by Champion and Sheraton (1997) and in Cassidy et al. (2002). These features point to melting at generally lower pressures and higher temperatures than those that persisted during formation of the regional high La/Yb, low-Sr/Y rocks and of the high-Sr/Y rocks to the southeast of the Kojonup–Hyden line. Since the region to the northwest of the Kojonup–Hyden line includes low-Sr/Y granitic rocks that cover the full range from high to low La/Yb, it seems likely that crustal melting in this region occurred over a wider range of depths than it did to the southeast of that line.

Variations in initial ^{206}Pb/^{204}Pb show that non-radiogenic lower crust isotopically similar to the deep source of the high-Sr/Y granitic rocks southeast of the Manjimup – Bruce Rock line also extended regionally to the northwest of that line (Fig. 9). If this represents the same crust, then this crust must also become systematically more compositionally heterogeneous to the northwest, because relatively non-radiogenic sodic and potassic rocks both occur in approximately equal proportions in that region, whereas sodic rocks overwhelmingly dominate to the southeast. Also, the garnet-rich, plagioclase-poor residual lower crustal mineralogy reflected by the high-Sr/Y rocks to the southeast of the Manjimup – Bruce Rock line suggest that non-radiogenic crust in that region melted at high pressures. In contrast, the garnet-poor, feldspar-rich residual crust reflected by the low-Sr/Y rocks that characterize the region to the northwest of that line indicate that relatively non-radiogenic crust in this region melted at lower pressures. In addition, in the region to the northwest of the Kojonup–Hyden line, compositionally similar rocks cover the full range in initial ^{206}Pb/^{204}Pb compositions, whereas rocks derived from relatively radiogenic sources are rare to the southeast.

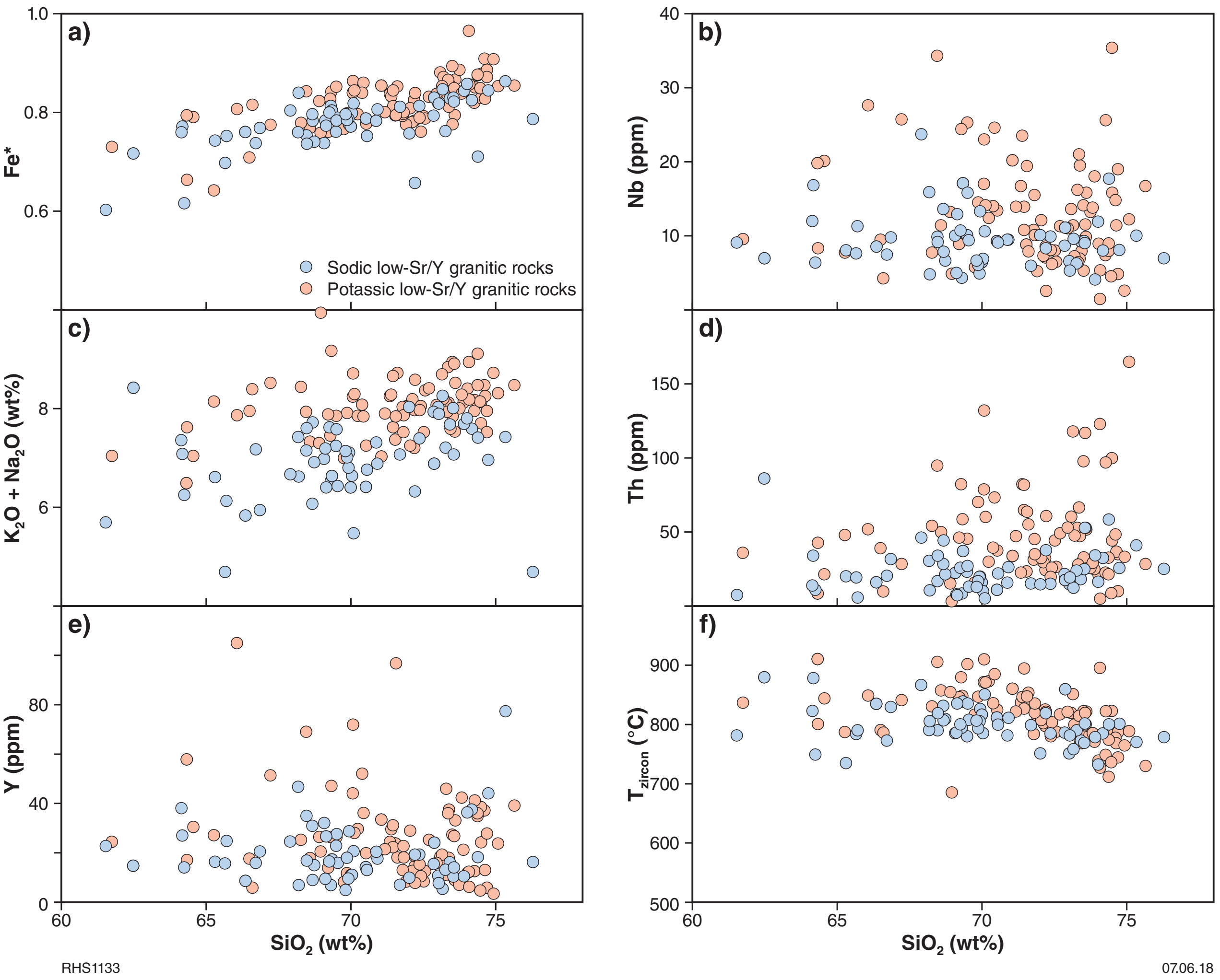

Figure 10. Variation in SiO_2 with Fe*, K_2O+Na_2O, Y, Nb, Th and zircon saturation temperature (Tzircon) for low-Sr/Y granitic rocks; Fe* = ∑FeO/MgO, where all Fe is FeO

The region between the Kojonup–Hyden line and the Manjimup – Bruce Rock line therefore represents a transition zone. To the southeast of this zone, crustal melt sources were dominantly sodic, probably mafic, and had relatively primitive Pb-isotope compositions. Melting in this region occurred at depths greater than 25 km where garnet remained stable but plagioclase was partially to largely consumed. To the northwest, the crust undergoing melting was considerably more compositionally heterogeneous. It included a wide compositional range from sodic to relatively potassic and a wide range in initial Pb-isotope compositions. The more radiogenic sources tended to be more compositionally evolved (K rich), although many (low-Sr/Y) granitic rocks derived from relatively K-rich sources also have relatively non-radiogenic Pb-isotope compositions. Perhaps more importantly, it shows no clear history of melting of any source at the crustal depths inferred for the high-Sr/Y granitic rocks to the southeast. Crustal melting in the northwest region occurred over a broad but relatively shallow crustal column, and the compositional trends towards transitionally A-type magmas suggest advection of significant amounts of heat into mid-crustal, or thinned, regions of relatively dry crust.

Sodic to potassic low-Sr/Y granitic rocks are also present in the far southeast of the South West Terrane, near the tectonic boundary with the Northern Foreland of the Albany–Fraser Orogen (Fig. 3). The location of these rocks potentially reflects a structural control and indicates that a major structural contact may have already existed between the Archean crust of the Northern Foreland and the South West Terrane at the time of magma genesis. Similarly, the most prominent change in the intensity of lower crustal gravity data in the South West Terrane defines a sharp northwesterly trending structure. This also appears to be the focus of rare sodic to potassic low-Sr/Y granitic rocks in the region to the southeast of the Kojonup–Hyden line, and might also mark a crustal-scale fault that was active during, or before, this felsic magmatism. If this is the case, and if the gravity anomaly indeed reflects a Proterozoic-aged mafic underplate, then this fault has controlled magma distribution during both the Archean and the Proterozoic.

The felsic magmatic history of the South West Terrane is known to extend from at least c. 3300 to 2600 Ma (e.g. Wilde, 2001). All of the granitic rocks considered here almost certainly formed within that age range.

However, existing geochronology data do not allow us to assess whether compositional groups described here define specific periods within that age range. As new age data become available, this aspect of the felsic magmatic evolution of the terrane will become clearer. However, the conclusion that the concentration of high-Sr/Y granitic rocks in the southeastern portion of the terrane indicates a significant difference in either the composition of the lower crust in that region, or in melting conditions, or (most likely) both, seems unlikely to change. The most obvious explanation for this is that the transition zone between the Kojonup–Hyden line and the Manjimup – Bruce Rock line represents some form of early crustal boundary. The fact that this boundary is at right angles to the inferred (largely hypothetical; Cassidy et al., 2006) eastern boundary of the South West Terrane suggests that the present terrane boundary might be meaningless.

This was further tested by interrogating a wider dataset incorporating ~3600 geochemical analyses on granitic rocks from the entire Yilgarn Craton (data from Geoscience Australia and GSWA databases). These data were also subdivided into four groups based on K_2O/Na_2O and Sr/Y (Fig. 11). This treatment of the data shows that the Kojonup–Hyden line can be extrapolated across the boundary with the Youanmi Terrane (i.e. most sodic high-Sr/Y granitic rocks are restricted to the south of the extrapolated line; Fig. 12).

Assuming similar source compositions, lower Gd/Yb in the granitic rocks reflects melting residues with lower garnet/amphibole ratios and, along with the lower Sr/Y, can be interpreted to reflect melting at lower pressures, as was suggested for most granitic rocks northwest of the Kojonup – Hyden line in the South West Terrane itself. It follows that progressively removing data points with lowest Gd/Yb effectively shows those regions where crustal melting occurred at progressively greater depth (compare Figs 12, 13). Although rare samples of sodic high-Sr/Y granitic rocks occur in the region to the north of the extrapolation of the Kojonup–Hyden line into the Youanmi Terrane, all of these are characterized by relatively low Gd/Yb (<5 at low Yb concentrations), and most have Sr/Y between 40 and 50. Removing all sodic high-Sr/Y granitic rocks with Gd/Yb <5 shows that, craton-wide, the distribution of sodic granitic rocks with the most strongly fractionated REE patterns defines two northeasterly trending zones separated by a ‘low-Gd/Yb zone’ devoid of such granitic rocks (Fig. 13). These zones do not appear to be significantly affected by the inferred boundary separating the South West and Youanmi Terranes, and also appear to be largely unaffected by the Ida Fault, which separates the Youanmi Terrane from the Kalgoorlie Terrane of the Eastern Goldfields Superterrane. The northern, northeasterly trending zone, mainly in the northern Youanmi Terrane, parallels the tectonic boundary with the Narryer Terrane, and the southern northeasterly

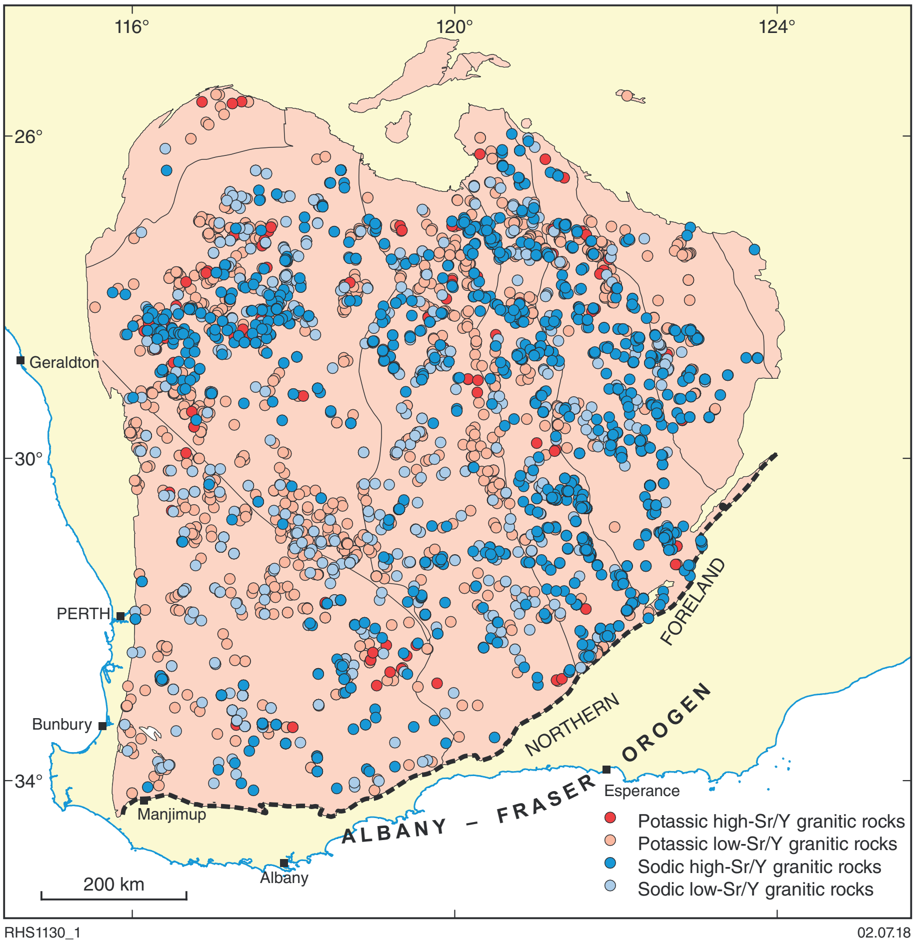

Figure 11. **Granitic rocks of the Yilgarn Craton sampled for whole-rock major and trace element geochemistry, showing distribution of the four major granite groups used in this study. Heavy dotted line marks the northern boundary of the Albany–Fraser Orogen**

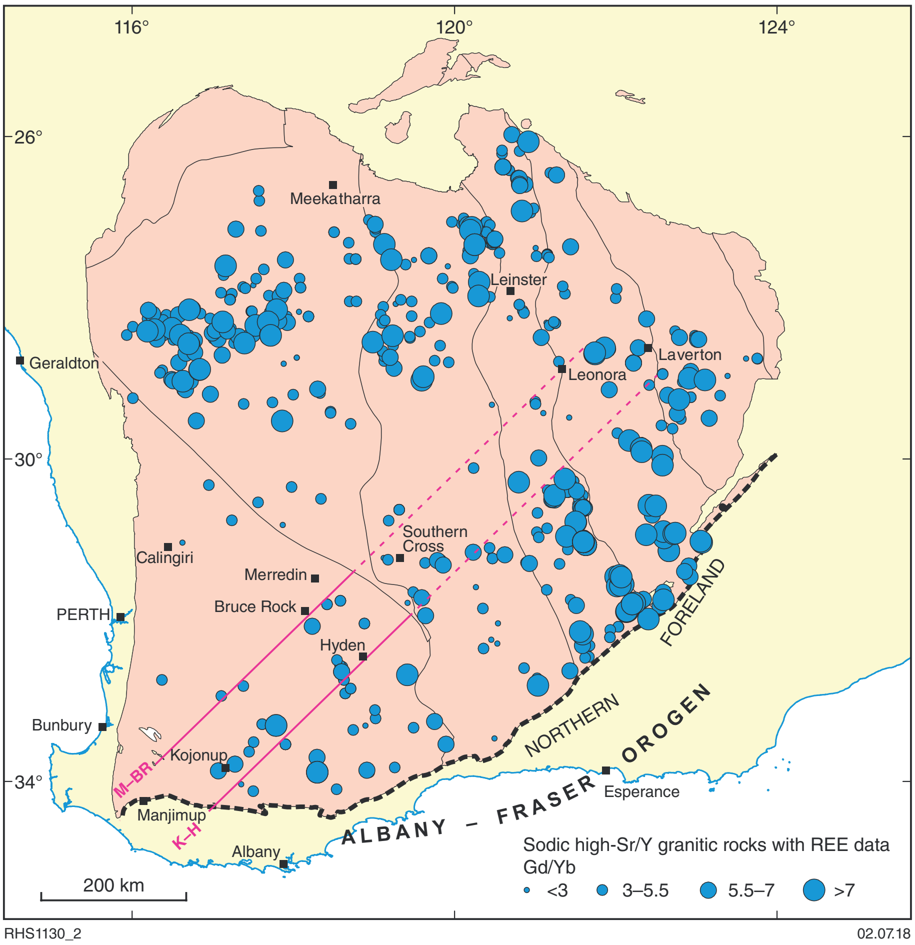

Figure 12. Sodic high-Sr/Y granitic rocks in the Yilgarn Craton for which rare earth element (REE) data exist. Data are scaled according to Gd/Yb ratio. Heavy dotted line marks the northern boundary of the Albany–Fraser Orogen

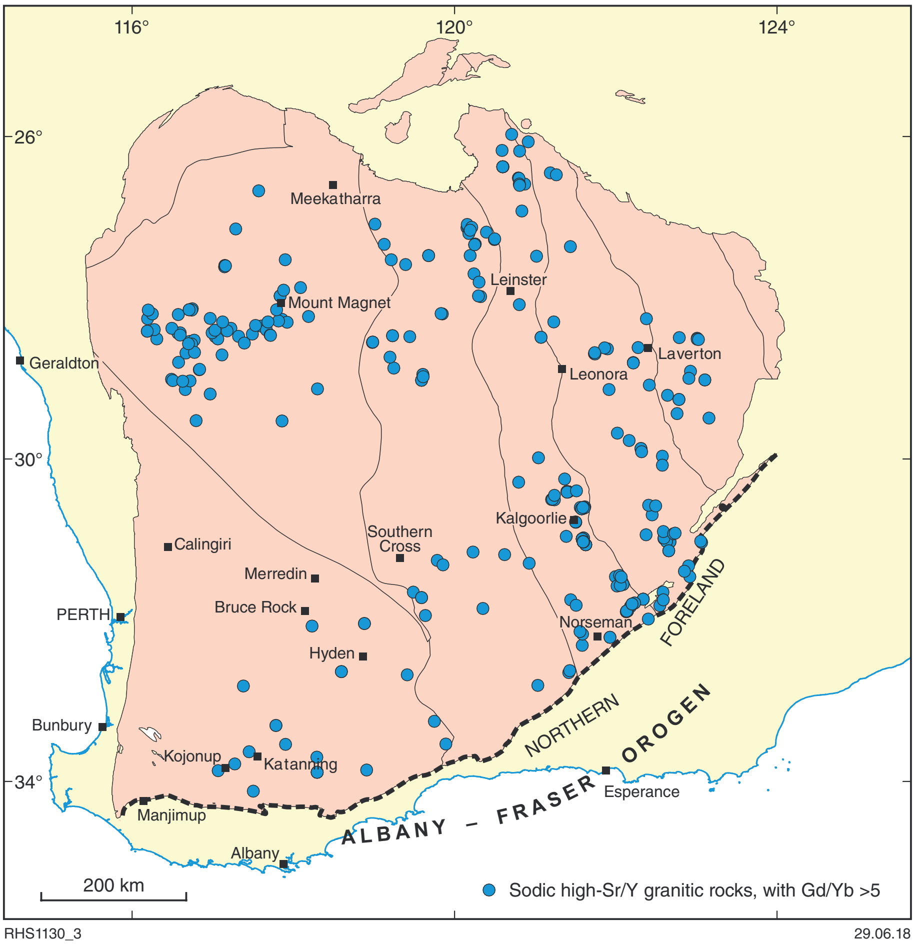

Figure 13. Sodic high-Sr/Y granitic rocks with Gd/Yb >5 in the Yilgarn Craton. Heavy dotted line marks the northern boundary of the Albany–Fraser Orogen

trending zone broadly parallels the boundary separating the Yilgarn Craton granite–greenstone terranes from the Northern Foreland of the Albany–Fraser Orogen. The sodic high-Sr/Y granitic rocks are interpreted to reflect melting in the deepest crustal source regions of the Yilgarn Craton. Hence, the distribution patterns shown by variations in Gd/Yb in these granitic rocks can be interpreted to suggest that melting of Archean Yilgarn crust in the low-Gd/Yb zone did not occur at the crustal depths that it did in the two adjacent northeasterly trending high-Gd/Yb zones. Isotopic model ages (T_{DM}^2 from Nd-isotopic data) from sodic granitic rocks suggest that compositionally suitable mafic source regions were present within the low-Gd/Yb zone from at least c. 3.1 Ga, covering most of the known Archean magmatic history of the craton. Hence, the lack of high-Sr/Y, high-Gd/Yb magmas most likely suggests that such crust did not extend to the depths that it did in two adjacent northeasterly trending high-Gd/Yb zones. If crust existed at that depth in the low-Gd/Yb zone, it was too MgO rich to melt under the prevailing conditions.

Regardless of the reason for the zonation in Gd/Yb, the clear preliminary interpretation is that it reflects basement anisotropies (or basement domains), and the orientations of these anisotropies are independent of the strong north-northwest structural trend that dominates the shallow crustal geology of the craton. In the case of the South West Terrane at least, this interpretation questions any accretionary relationship with the Younami Terrane (e.g. Myers, 1993; Nutman et al., 1993: Cassidy et al., 2006). On a broader scale, whereas it is clear that processes leading to the prominent north-northwest structural trend of the Yilgarn Craton mark differences in the younger (post-2.73 Ga) history of the craton and expose crust of contrasting metamorphic grade, it is not clear that they are relevant to the evolution of the craton-wide pre-2.73 Ga basement.

Conclusions

Whole-rock geochemistry of granitic rocks provides information on the composition of lower crustal source regions and the conditions (e.g. temperature and pressure) at which the sources melted to produce felsic magmas. Regional variations in specific geochemical features of the granitic rocks can, therefore provide insight into the composition, architecture and evolution of the lower crust. In the granitic rocks from the poorly studied South West Terrane of the Archean Yilgarn Craton, variations in proxies for source melting pressure (Sr/Y, Gd/Yb) do not coincide with the geographical distribution of a lower crustal density anomaly in the lower southwest of the terrane. These compositional variations do not support the suggestion that the density anomaly reflects residues from Archean deep crustal melting. The anomaly more likely relates to the Proterozoic evolution of the Yilgarn Craton margins or Phanerozoic events at the margins of the West Australian Craton.

In Archean granitic rocks of the South West Terrane, geographical variations in proxies for source melting pressure define a broad northeasterly trend that truncates the north-northwesterly trending eastern boundary of the South West Terrane. Viewing whole-rock compositional data of granitic rocks from the Archean terranes to the east and northeast, shows that these northeasterly compositional trends extend across almost the entire craton. Sodic rocks, broadly equivalent to the Archean TTG series, form three broad northeasterly trending belts. The northern and southern belts comprise high-Sr/Y and high Gd/Yb rocks that reflect very deep crustal melting leaving a residual source mineralogy rich in garnet, poor in plagioclase and with a high garnet/hornblende ratio. Granitic rocks in the middle zone have lower Sr/Y and Gd/Yb and their source probably melted at significantly lower pressures. The orientation of these zones is independent of the strong north-northwesterly structural trend that dominates the shallow crustal geology of the Yilgarn Craton. The zones could reflect basement domains that existed before the boundaries that define the younger (post-2.73 Ga) 'terranes' were formed. If confirmed, the presence of craton-wide northeasterly trending basement domains would cast doubt on models that invoke the east–west accretion of the Yilgarn Craton.

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