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TOWARDS A GEOCHEMICAL BARCODE FOR EASTERN GOLDFIELDS SUPERTERRANE GREENSTONE STRATIGRAPHY — PRELIMINARY DATA FROM THE KAMBALDA–KALGOORLIE AREA

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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 taken by I Zibra for the Geological Survey of Western Australia

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Towards a geochemical barcode for Eastern Goldfields Superterrane greenstone stratigraphy — preliminary data from the Kambalda–Kalgoorlie area

by

RH Smithies, PA Morris, S Wyche, M De Paoli and J Sapkota

Abstract

As part of ongoing stratigraphic revisions of the Eastern Goldfields, the Geological Survey of Western Australia (GSWA) is collecting high-quality, multi-element, geochemical data from diamond drillcore that samples the most geologically well-constrained, or best-understood, parts of greenstone stratigraphy in greenstone belts throughout the Eastern Goldfields Superterrane. This project aims to establish a geochemical 'barcode' of the stratigraphy (including local variations) from better known sections of greenstone belts. It aims to establish whether current local and/or regional greenstone stratigraphies are valid, and the geological reasons for local and regional stratigraphic variations. It also aims to provide a reasonable geochemical proxy for stratigraphy that will allow users to better establish where a particular lithology or lithological association fits in a local or regional stratigraphy. The first phase of this project was undertaken in the Kalgoorlie–Kambalda region. From these results, it is clear that the broad stratigraphic groups that make up the Kambalda–Kalgoorlie stratigraphy can normally be distinguished geochemically. However, detailed geochemical sampling has also identified stratigraphic complexities and several potential problems with using geochemistry in assigning individual analyses or even groups of analyses of greenstones to a particular stratigraphic unit. Overcoming these problems is mainly a matter of better understanding local stratigraphic variations and their geochemical manifestations. All stratigraphic complexities identified here in the Kambalda–Kalgoorlie stratigraphy can be readily accounted for using various additional geochemical tests.

KEYWORDS: Archean, geochemistry, greenstone, stratigraphy

Introduction

The Geological Survey of Western Australia (GSWA) is progressively compiling a seamless geological map of the Eastern Goldfields of Western Australia, incorporating stratigraphic revisions resulting from mapping, and new geochronological, geochemical and geophysical data. The current project area extends between Leinster in the north and Norseman in the south (Fig. 1) of the Eastern Goldfields (GSWA, 2017).

A major problem in revising greenstone stratigraphy according to lithology is that Archean greenstones are limited to few rock types, often dominated by fine-grained mafic rocks, and characterized by poor outcrop which offers a limited geological context. Whole-rock geochemistry offers a means of stratigraphic correlation, and diamond drillcore provides some compensation for poor surface exposure. Using whole-rock geochemical data in this way has met with some success at the local level, but extending the approach to a regional scale means combining existing geochemical datasets. Such datasets are often characterized by variable data quality, data generated by relatively insensitive techniques for key elements (e.g. XRF determination of high field strength elements [HFSE], rare earth elements [REE], Th), a limited range in elements, or a bias towards certain rocks types, parts of the stratigraphy, or towards a specific project or research outcome. To date, there has been no detailed and systematic geochemical approach to stratigraphic correlation.

GSWA has recently undertaken a project aimed at substantially increasing the amount of high-quality, multi-element, geochemical data for greenstones, targeting available diamond drillcore that samples the most geologically well-constrained, or best-understood, parts of various greenstone belts. This has initially been undertaken in the Kambalda–Kalgoorlie region but will ultimately extend throughout the Eastern Goldfields Superterrane. Through detailed geochemical sampling of diamond drillcore, we hope to establish a geochemical 'barcode' of the stratigraphy (including local variations) in these better known sections of greenstone belts.

The ultimate goals of this project are:

- to establish whether local and/or regional greenstone stratigraphies are valid, and the geological reasons for local and regional stratigraphic variations
- to provide a reasonable geochemical proxy for stratigraphy that will allow users to better establish where a particular lithology or lithological association fits in a local or regional stratigraphy.

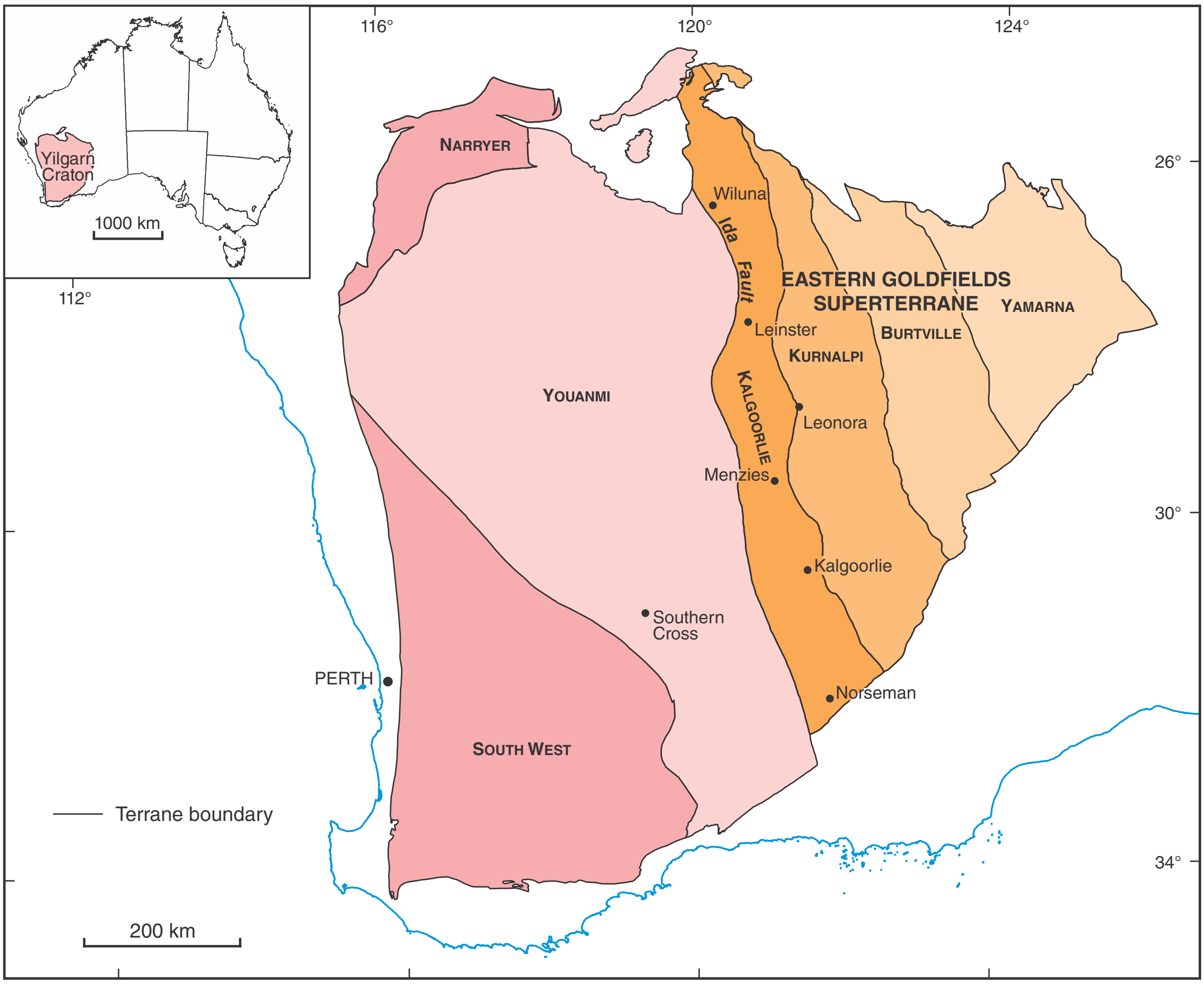


Figure 1. Terrane subdivision of the Yilgarn Craton modified after Cassidy et al. (2006) and Pawley et al. (2012)

We present here some preliminary results from the first stage of this project, for greenstones of the Kambalda and Kalgoorlie regions, within the Kalgoorlie Terrane of the Eastern Goldfields Superterrane. The aim here is not to discuss the petrogenesis of the various lithological or compositional groups, or to describe in detail the stratigraphy of the area, but simply to investigate the potential of applying a geochemical stratigraphy within a specific greenstone belt. We do this by assessing how well specific stratigraphic units can be uniquely identified geochemically.

Regional geological introduction

The Yilgarn Craton is subdivided into seven terranes based on distinct sedimentary and magmatic characteristics, geochemistry and age (Fig. 1). The western part includes the Narryer, Youanmi and South West Terranes. The eastern part includes the Kalgoorlie, Kurnalpi, Burtville and Yamarna Terranes, which comprise the Eastern Goldfields Superterrane (Cassidy et al., 2006; Pawley et al., 2012). Terrane boundaries in the eastern half of the craton correlate with large-scale shear zones active during late Archean tectonic events. Geophysical data show them to be east-dipping structures that penetrate deep into the crust (Blewett et al., 2010).

Stratigraphic revisions resulting from GSWA's seamless geological mapping program in the Eastern Goldfields Superterrane have so far concentrated on the western part of the superterrane, mainly in the Kalgoorlie Terrane. The Kalgoorlie Group (2726–2680 Ma) comprises most of the lower mafic–ultramafic package in greenstone belts between Norseman and Leinster (Figs 1, 2). This group locally overlies, or is structurally juxtaposed against, poorly known, older (>2800 Ma) mafic–ultramafic successions. The various rock successions that form the Kalgoorlie Group, although linked in terms of broadly similar stratigraphy and the same age range, are not physically continuous throughout the Kalgoorlie Terrane.

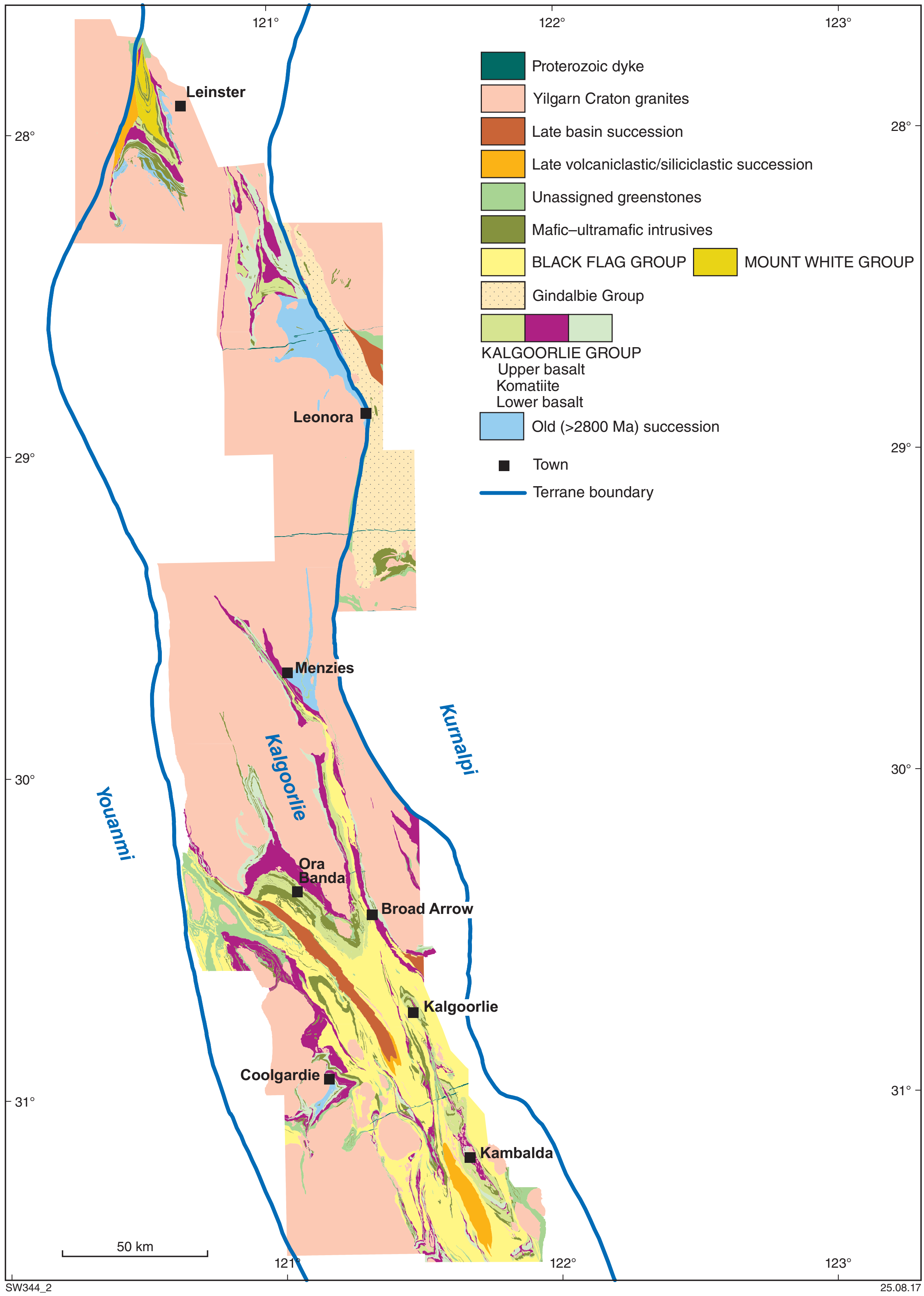


Figure 2. Distribution of the main lithologies of the Kalgoorlie Group between Kambalda and Leinster

Variations in detailed stratigraphy and the chemical character of stratigraphically equivalent units across major structures and between greenstone belts suggest that, although products of the same geological event, at least some of the successions may have been originally deposited in distinct basins. Where these structurally or geographically isolated sequences form stratigraphically continuous successions of the Kalgoorlie Group, they have each been distinguished as a distinct subgroup (Fig. 3). In the Kalgoorlie–Kambalda region, this part of the stratigraphy is assigned to the Hannans Subgroup.

The Kalgoorlie–Kambalda region contains the 'classic' Kalgoorlie stratigraphy, first described by Woodall (1965) and extended to Kambalda by Gresham and Loftus-Hills (1981), although the formal nomenclature for the mafic–ultramafic succession that now comprises the lower Hannans Subgroup was first published by Roberts (1988). The Hannans Subgroup of the Kalgoorlie Group (2726–2680 Ma) comprises most of the lower mafic–ultramafic package (Fig. 2). The basement to this subgroup is not known in the Kambalda and Kalgoorlie regions, where the Lunnon Basalt is currently considered to be the lowest formation. This is overlain in turn by the Kambalda Komatiite, Devon Consols Basalt, Kapai Slate and Paringa Basalt (Fig. 4). The Hannans Subgroup is unconformably or disconformably overlain by the Black Flag Group (2692–2665 Ma), which mainly comprises felsic and mafic volcanic and volcaniclastic rocks. All parts of this stratigraphy have been extensively intruded by mafic or mafic–ultramafic sills.

Sample selection and analytical techniques

Dataset content

We use a dataset of 620 whole rock major and trace element data covering all supracrustal igneous (or meta-igneous) lithologies including volcaniclastic rocks. Of these, 245 samples are from the Kalgoorlie region and 375 are from the Kambalda region (Figs 4, 5). The dataset incorporates 400 new analyses (see analytical techniques below) from 11 diamond drillcores (Table 1). It also includes 70 new analyses either of diamond drillcore or outcrop samples from the GSWA archive, and additional published data. Only analyses that incorporate a wide range of trace element determinations (including the full suite of rare earth elements, Nb and Th) determined to a high level of precision and accuracy at low levels of detection, were included in our dataset. New GSWA data are presented in the Appendix (on zip file).

Analytical procedure for new GSWA samples

All samples specifically collected for this project, and re-analysis of greenstone samples previously collected by GSWA, were analysed by BV Minerals, Canning Vale, Perth. Both drillcore and surface samples were visibly inspected and any weathering or excessive 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 on a fused glass disk. A fragment of each disk was then laser ablated and analysed by ICP-MS for 51 of the 54 minor 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), GSWA internal reference materials, and the certified reference material OREAS 24b (www.ore.com.au). BV Minerals also included duplicate samples (including OREAS 24b), variably 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.

Sample classification and screening

For classification and screening of rocks of broadly mafic to ultramafic compositions, we have slightly modified the approach used by Barnes et al. (2012). In particular, the maximum SiO_2 content used to identify rocks of broadly basaltic composition has been raised from 56 wt% to 59 wt% and Na_2O+K_2O from 5 wt% to 6 wt% (all major element concentrations quoted here have been recalculated on a volatile-free basis). These modifications recognize that even diamond drillcore samples from the Eastern Goldfields Superterrane, and particularly in regions close to known mineralization, are commonly hydrothermally altered, often with significant effects on the concentrations of important major elements such as SiO_2, MgO, Na_2O and K_2O. This alteration is often not obvious during visual inspection of samples prior to selection for analyses. All samples taken as part of the Eastern Goldfields Superterrane regional stratigraphy project represent what are visually the least-altered examples of lithologically, texturally and mineralogically homogeneous intervals of core. Nevertheless, it is not uncommon that one or more of a group of samples taken from within a lithologically uniform segment of drillcore has anomalous concentrations of SiO_2 (e.g. above the 56 wt% maximum value of Barnes et al., 2012), or other

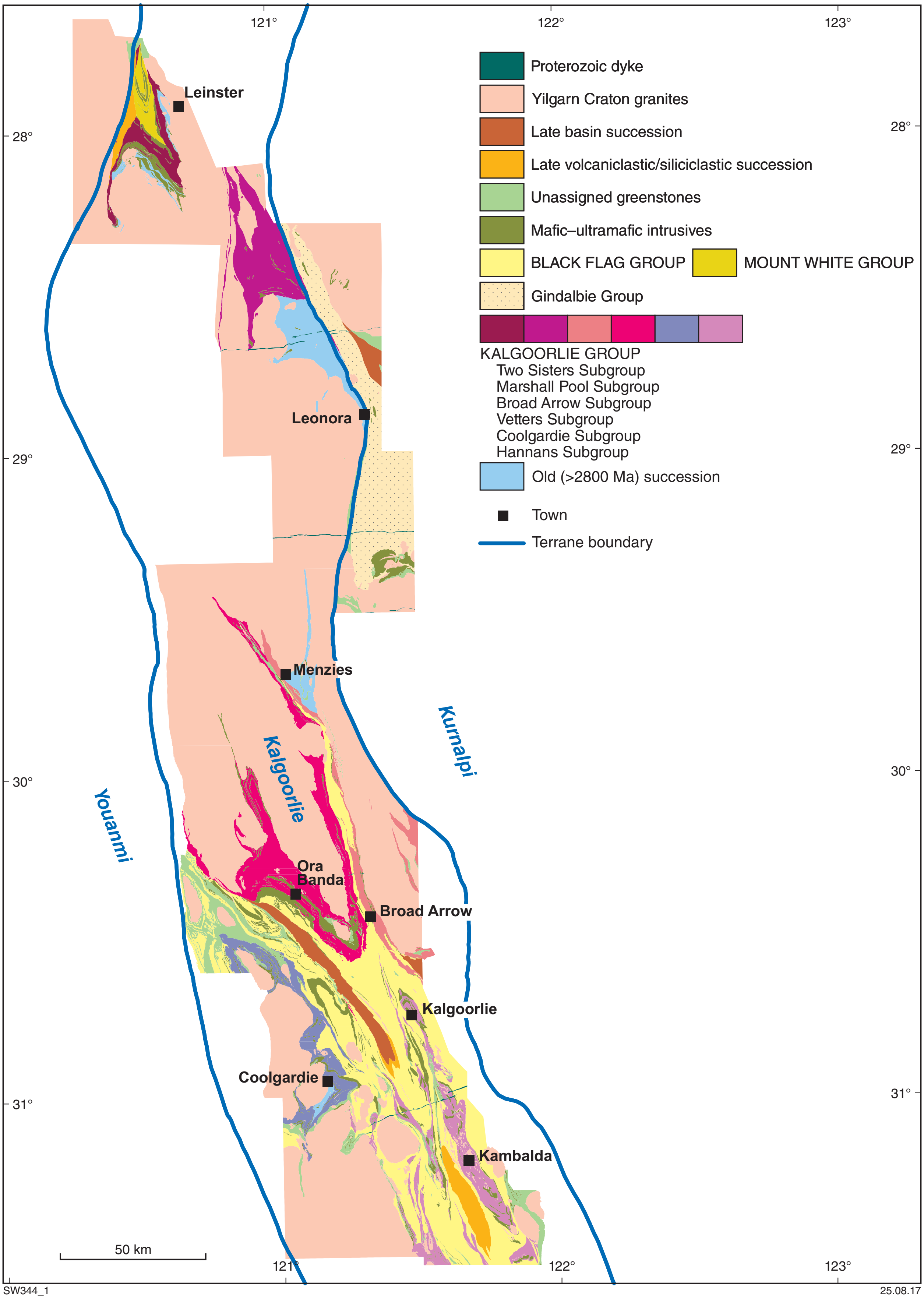
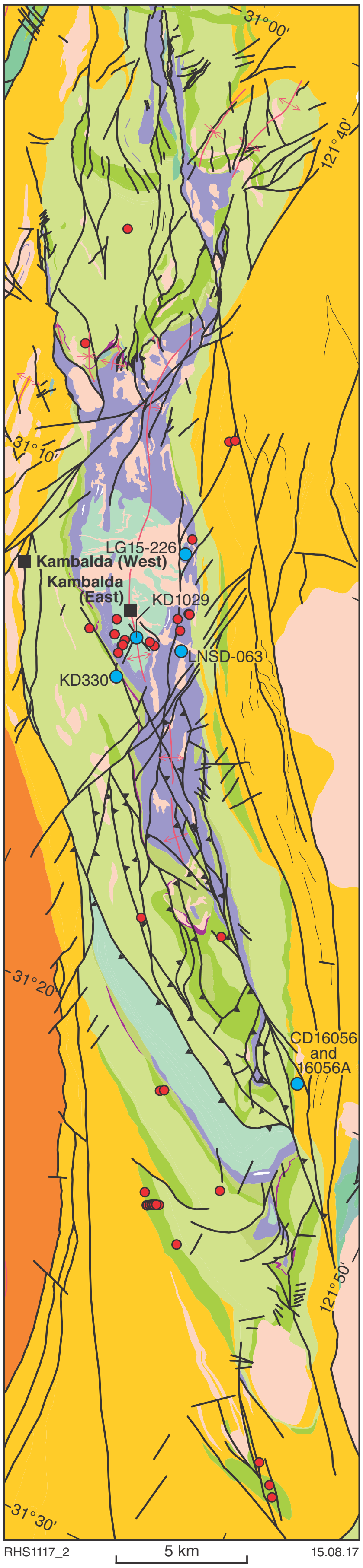


Figure 3. **Subgroups of the Kalgoorlie Group between Kalgoorlie and Leinster**



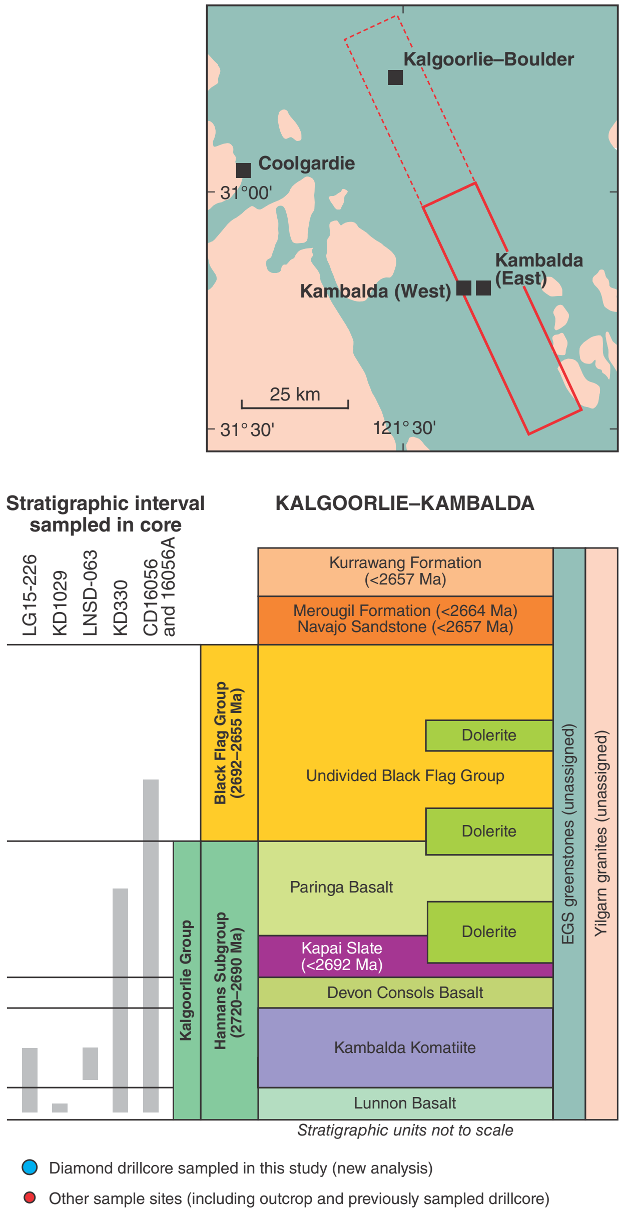


Figure 4. Interpreted bedrock geology of the Kambalda region showing locality of sampling sites, including diamond drillholes, and the stratigraphic interval over which the various drillcores were sampled

major elements, despite being visually indistinguishable from other samples. The approach used by Barnes et al. (2012) allows for expansion of these parameters for classification of various basaltic rock types since it primarily uses variations in ratios of incompatible trace elements (Ti, Th, La, Nb, Zr) that are relatively immobile during hydrothermal alteration.

The following screens and caveats were used here:

- Intrusive rocks with SiO_2 <56 wt% and MgO <18 wt% were classified as dolerite or gabbro, depending upon grain size. Those samples with MgO >18 wt% were classified as peridotite
- Volcanic rocks with SiO_2 <59 wt% were classified as basaltic if MgO < 16wt% and >3 wt%, or komatiite where MgO > 18 wt%
- Nearly all samples with MgO between 16 and 18 wt% (and a few with MgO <16 wt%) have Al/Ti ratios of 0.75 – 1.1, a criterion Barnes et al. (2012) use to identify 'komatiitic basalts'. In nearly every case, these were directly associated in drillcore with true komatiites and have been classified as such (hence, some data shown here with MgO <18 wt% are classified as komatiite)
- Samples identified as basaltic were further divided into the Low-Th Basalt (LTB), High-Th Siliceous Basalt (HTSB) and Intermediate-Th Basalt (ITB) groups defined by Barnes et al. (2012). This was done by assessing where our samples lie relative to the data of Barnes et al. (2012) on plots of TiO_2 vs Th, Nb, La, and Zr (Fig. 6). It is important to stress that even the dataset used by Barnes et al. (2012) contains individual samples, classified (for example) as ITB, that may on one or more of these plots lie within the data fields of other basalt groups. In these cases, available lithological relationships must also be considered in assigning samples to a specific group.
- Intrusive rocks with SiO_2 >56 wt% were almost invariably plagioclase-porphyritic and were simply classified as felsic dykes. These are not discussed further here
- Volcanic and volcaniclastic rocks with SiO_2 >59 wt% were classified as felsic volcanic or volcaniclastic rocks.

Kambalda stratigraphy

Outcrop and diamond drillcore samples were assigned to a level within a generalized stratigraphic column (Fig. 4) based on their perceived stratigraphic position. In general, stratigraphic intervals of compositionally similar rocks have geochemical characteristics that correlate well with those documented from units within the well-established stratigraphy for this region (e.g. Barnes et al., 2012; De Paoli et al., 2017). This provides initial confidence that the geochemistry of the supracrustal units might provide a useful proxy for stratigraphic position. Figure 6 shows analyses for basaltic rocks from the GSWA database and compares them with the data used by Barnes et al. (2012) to distinguish their LTB, ITB and HTSB basalt groups on plots of TiO_2 vs Th, Nb, Zr and La. The geochemical variation in the identified geochemical groups is described below in broad terms (ignoring obvious outliers) and with reference to Figures 7 to 10.

LTB

The stratigraphically lowest unit, the Lunnon Basalt (Barnes et al., 2012; De Paoli et al., 2017; Fig. 4) is composed of LTB. The range in Mg# for LTB is 62–39, which decreases with increasing SiO_2 (~48–55 wt%), TiO_2 (~0.6 – 0.95 wt%), Al_2O_3 (~14.1 – 15.3 wt%), CaO (~9.5 – 11 wt%) and P_2O_5 (~0.06 – 0.1 wt%). Concentrations of Na_2O scatter between ~1.2 and 3.5 wt% whereas K_2O mainly remains constant at <0.4 wt%, except for a few higher values (up to ~2.6 wt%) reflecting alteration. With decreasing Mg#, total Fe as Fe_2O_3 shows an initial increase in concentration (~11–14 wt%) followed, at Mg#~55, with a decrease to ~9 wt% and reflects a generally tholeiitic evolution trend. By definition, these rocks have lower concentrations of Th, high field strength elements (HFSE: Nb, Ta, Zr, Hf) and light rare earth elements (LREE: e.g. La, Ce) at a given TiO_2 concentration (and Mg# or MgO concentration) than the other basalt types described here.

Komatiite

Stratigraphically above LTB assigned to the Lunnon Basalt are ultramafic eruptive and intrusive rocks of the Kambalda Komatiite (Fig. 2). These rocks range in Mg# from 90 to 66 and in MgO up to ~ 41 wt%. Decreasing Mg# correlates broadly with increasing concentrations of SiO_2 (~43–52 wt%), TiO_2 (~0.13 – 0.57 wt%), Al_2O_3 (~2.9 – 12 wt%), total Fe as Fe_2O_3 (~9.4 – 14.5 wt%), CaO (~0.4 – 12 wt%), Na_2O (~0.05 – 2 wt%) and P_2O_5 (~0.01 – 0.09 wt%). The range in CaO and the large scatter in K_2O (up to ~4 wt%) reflect localized carbonate alteration and K-metasomatism. Concentrations of Ni decrease with decreasing Mg# from ~2840 to 150 ppm while Cr increases from ~1600 ppm to >4000 ppm at an Mg# ~78 and then systematically decreases to ~450 ppm.

HTSB-like rocks interlayered with LTB; enriched HTSB

Within two diamond drillholes (CD16056A and LG15–226), metre-scale units of HTSB-like rocks are interlayered with the lower LTB sequences stratigraphically assigned to the Lunnon Basalt. Contacts do not appear intrusive and both basalt types locally show features resembling pillow margins and hyaloclastite breccia (Fig. 11a). The HTSB-like rocks have a range of Mg# (76–57) that overlaps with both the LTB and the komatiite units, but have higher concentrations of SiO_2 (~52 – 59.6 wt%), ~Al_2O_3 (~11.7 – 16.8 wt%), Na_2O (~2.3 – 7.5 wt% — although mainly <5.5 wt%) and P_2O_5 (~0.1 – 0.54 wt%) and lower total Fe as Fe_2O_3 (~4.4 – 9.7 wt%) and MgO (~3.1 – 11.9 wt%) (Fig. 7).

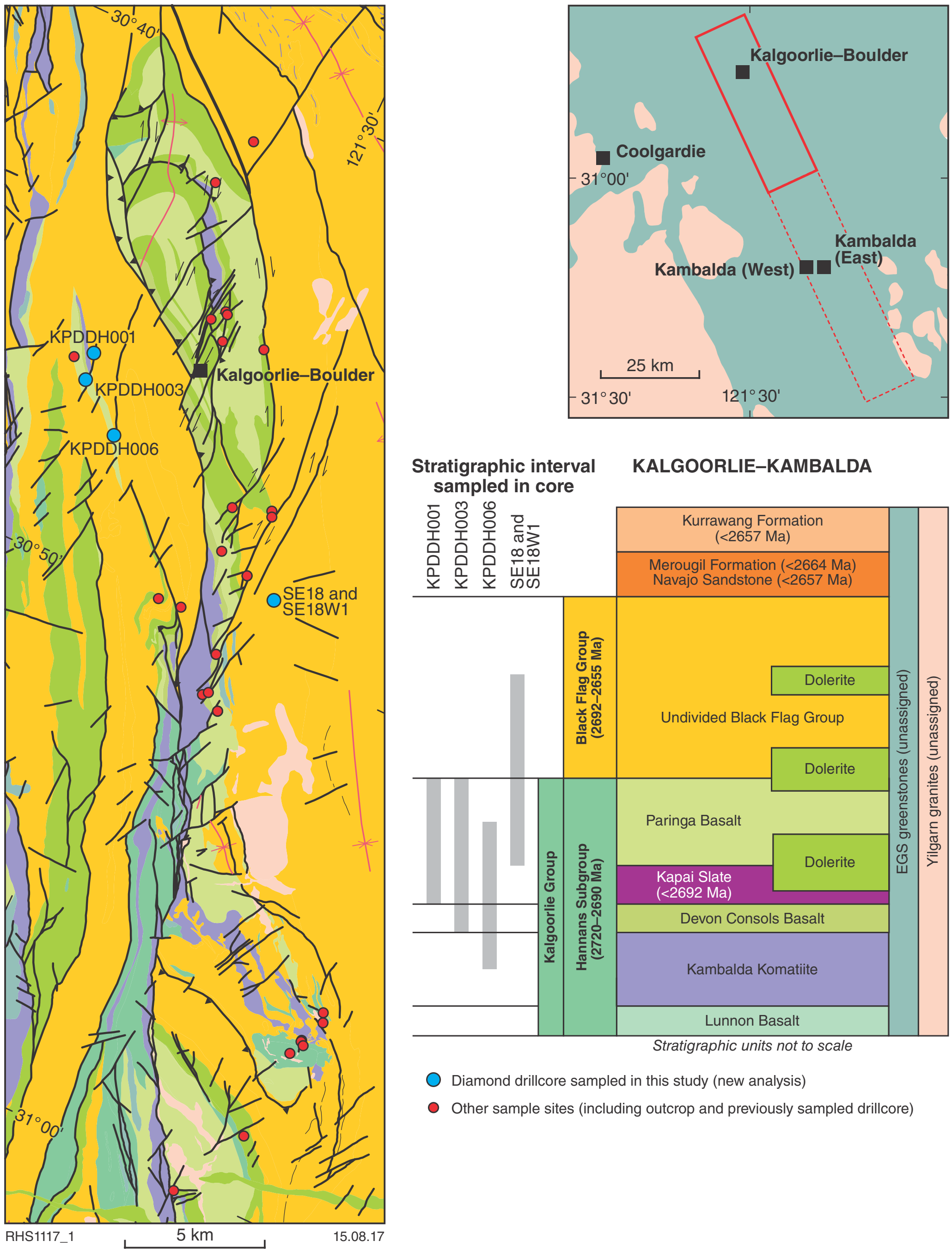


Figure 5. **Interpreted bedrock geology of the Kalgoorlie region showing locality of sampling sites, including diamond drillholes, and the stratigraphic interval over which the various drillcores were sampled**

Table 1. Details of diamond drillholes sampled during this study

Region	*Hole ID*	*Latitude*	*Longitude*	*Dip*	*Azimuth*	*Length*	*Samples*
Kambalda region	LNSD-063	–31.20834	121.69117	–79°	107°	888.3	33
Kambalda region	LG15-226	–31.17749	121.67837	–49°	070°	800.8	68
Kambalda region	KD1029	–31.20758	121.67489	–90°		1676.4	14
Kambalda region	KD330	–31.22572	121.67464	–90°		650.14	62
Kambalda region	CD16056	–31.32634	121.79052	–70°	270°	988	50
Kambalda region	CD16056A	–31.32634	121.79052	–70°	270°	599	46
Kalgoorlie region	KPDDH001	–30.76784	121.45003	–60°	043°	462.6	45
Kalgoorlie region	KPDDH003	–30.77674	121.45127	–60°	045°	279.2	11
Kalgoorlie region	KPDDH006	–30.78918	121.46707	–61°	245°	408.5	28
Kalgoorlie region	SE18	–30.81545	121.53623	–60°	220°	1536.8	29
Kalgoorlie region	SE18W1	–30.81545	121.53623	–28°	240°	895.8	56

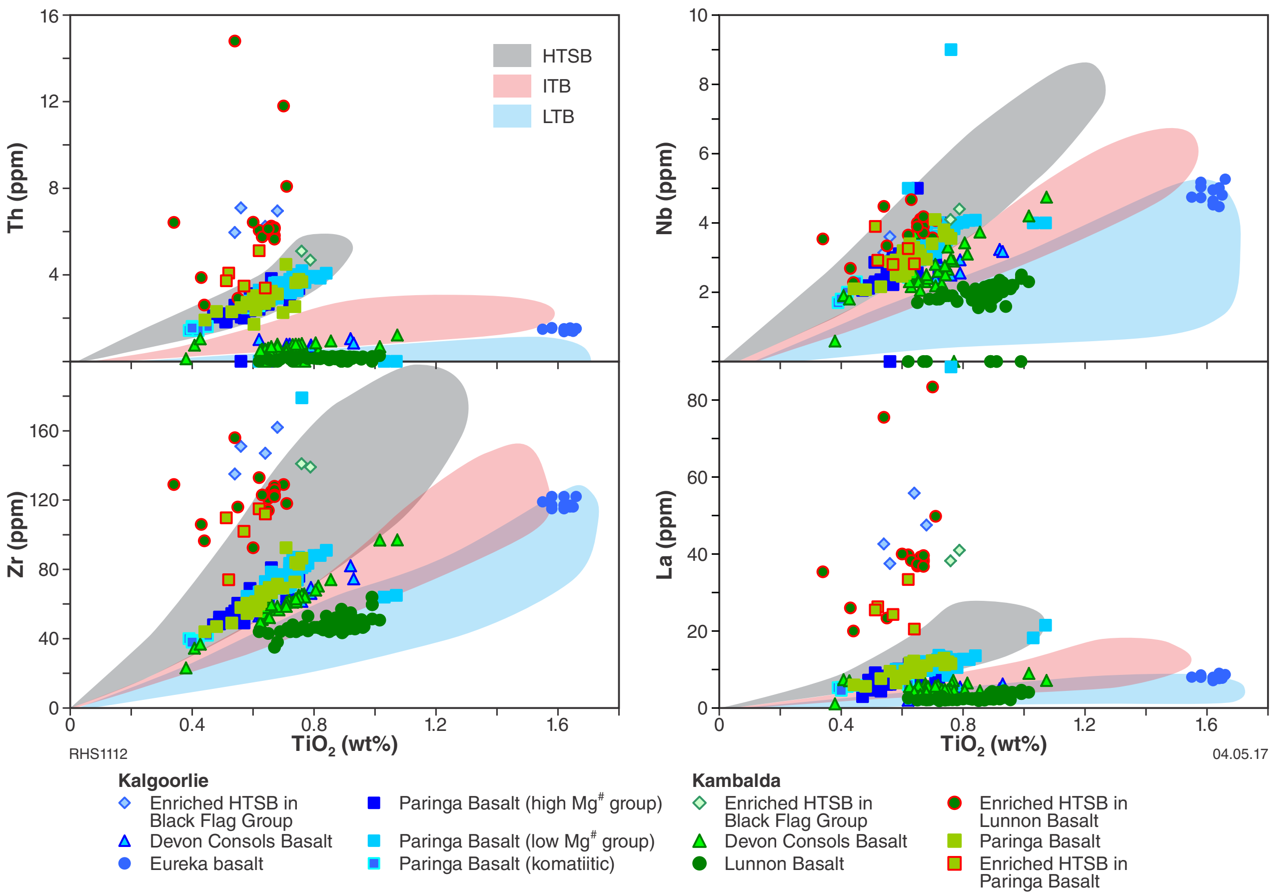


Figure 6. Plot of TiO_2 vs Th, Nb, Zr, and La. Fields for HTSB, ITB and LTB are from Barnes et al. (2012)

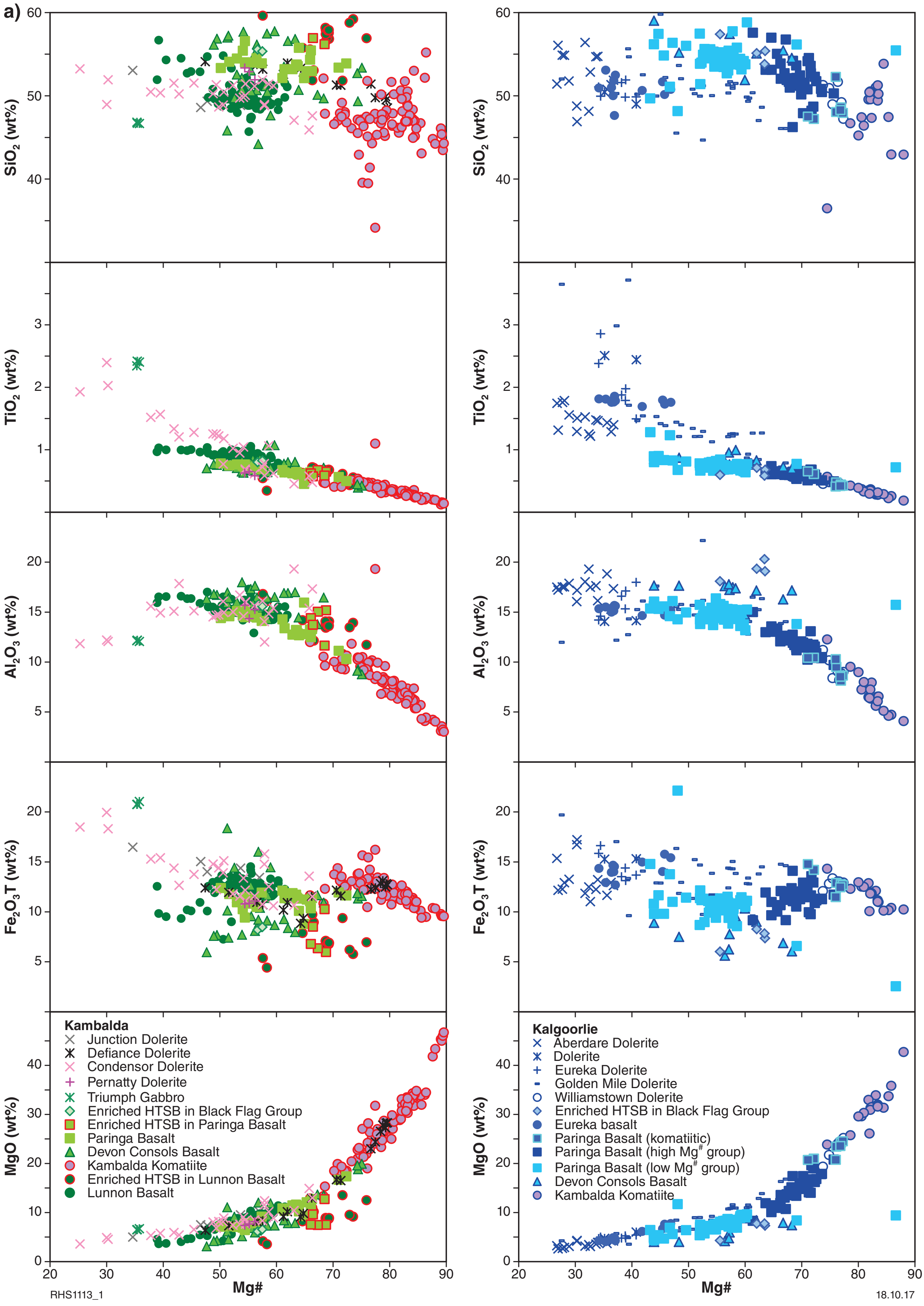


Figure 7. **Major element variations against Mg# in mafic and ultramafic rocks from the Kambalda region and the Kalgoorlie region. All major element concentrations are recalculated on a volatile-free basis**

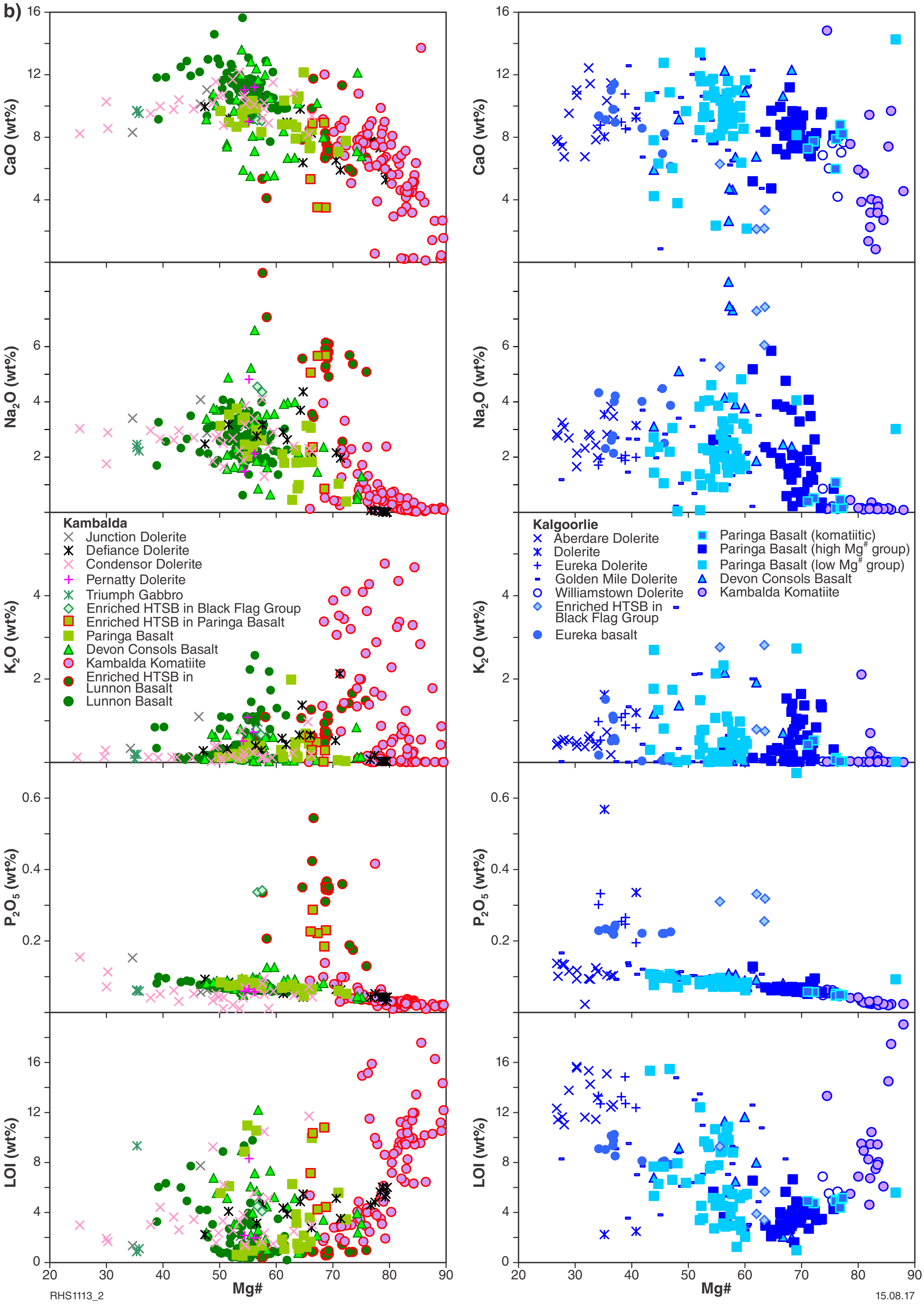


Figure 7. **continued**

Compared with all other basalt types described here (see below), including other HTSB, these rocks are highly enriched in Ba (to 1110 ppm), Sr (to 967 ppm), Th (to 15 ppm) (Fig. 8), HFSE and LREE and slightly depleted in HREE and have significantly higher La/Sm, La/Yb and La/Nb ratios. They are also slightly depleted in Ni and significantly depleted in Cr compared with other HTSB and komatiite at a given Mg# (Fig. 8). These and similar HTSB-like rocks will be referred to here as 'enriched-HTSB' rocks.

ITB

Overlying the Kambalda Komatiite is a sequence of flow units of ITB composition at a stratigraphic position consistent with the Devon Consols Basalt. The Mg# range of ITB (~68–47) is similar to that of LTB, and there is overlap in most major elements, although many ITB samples cluster at the higher end of the combined range in terms of SiO_2, Al_2O_3, and P_2O_5 concentrations and the lower part in terms of TiO_2, total Fe as Fe_2O_3, MgO, CaO concentrations (Fig. 7). The two groups are, however, clearly distinguished in plots of TiO_2 vs Th, Nb, La and Zr, in particular TiO_2 vs Th or La (Fig. 6). ITB samples also tend to be more Cr-rich at a given Mg# (Fig. 8) than all other basalt groups discussed here.

HTSB

A sequence of HTSB overlies the ITB, in the stratigraphic position of the Paringa Basalt. The range in Mg# for HTSB (~72–50; MgO ~14.8 – 5.5 wt%) overlaps the range for both LTB and ITB, as does the range for most major elements (Fig. 7). However, and in common with ITB, HTSB tend to cluster at the high SiO_2 part of the LTB range. They typically have higher MgO and total Fe as Fe_2O_3 and lower Al_2O_3 than the ITB at a given Mg#. By definition, HTSB have high concentrations of Th, HFSE and LREE at a given TiO_2 concentration than the other main basalt types described here (Fig. 6). An exception is enriched HTSB interbedded with stratigraphically lower LTB (Lunnon Basalt),which show extreme Th, HFSE and LREE enrichment, and are more SiO_2 rich (mainly >55 wt%) than HTSB of the Paringa Basalt (mainly <55 wt%).

A subset of HTSB from the lower to middle stratigraphic part of the Paringa Basalt in diamond drillcore KD330 has slightly different geochemistry, although they are macroscopically indistinguishable from the other variolitic basalts that dominant the Paringa Basalt. This subset of rocks shows a narrow range in high Mg# from 66 to 69 and, compared with the main population of HTSB at equivalent Mg#, ranges to higher SiO_2, Al_2O_3, and Na_2O concentrations, with distinctly higher P_2O_5, Sr, Th, HFSE, LREE and lower total Fe (as Fe_2O_3), MgO, CaO and Cr. They strongly resemble in composition enriched HTSB found within the Lunnon Basalt.

Stratigraphically higher enriched HTSB rocks

The stratigraphic unit overlying the Paringa Basalt is dominated by felsic volcanic and volcaniclastic rocks collectively referred to as the Black Flag Group. Locally included within this succession are mafic extrusive rocks, two samples of which are from outcrop from the eastern flank of the Kambalda Dome. Both are enriched HTSB, with Mg# ~57, SiO_2 ~55 wt% and MgO ~5.5 wt% (Fig. 7). Compared with HTSB of the Paringa Basalt, these two samples are distinctly enriched in Na2O (~3.9 wt%), P_2O_5 (~0.33 wt%), Th, HFSE and LREE, and depleted in total Fe as Fe_2O_3 (~8 wt%). In this respect, they closely resemble enriched HTSB found within the Lunnon Basalt.

Possible felsic volcanic or volcaniclastic rocks interlayered with LTB

In diamond drillcore CD16056A, the basalt corresponding to the stratigraphic position of the Lunnon Basalt is dominated by LTB with less common HTSB-like rocks. Also present are intervals of fine- to medium-grained felsic rock interpreted as possible volcanic or volcaniclastic rocks based on gradational contacts, ripped-up clasts, and a lack of intrusive relationships, possibly providing evidence for eruption contemporaneous with the basalt (Fig. 11b). These rocks range in SiO_2 between ~61 and 66.5 wt% (one outlier at 71.6 wt%), are sodic with Na_2O > 5 wt% and K_2O/Na_2O < 0.35, and relatively MgO rich (~1.9 – 5.2 wt%) with unusually high Mg# (52–68) (Figs 9, 10). When plotted against either SiO_2 or Mg#, major and trace element variations form trends that extend those shown by the enriched HTSB rocks which are also interlayered within the Lunnon Basalt and often lie stratigraphically close to the felsic rocks. On this basis, it appears possible that the felsic units and the enriched HTSB rocks within the Lunnon Basalt are both comagmatic and cogenetic. The geochemical characteristics of the felsic units are those of Archean sanukitoid (e.g. Shirey and Hanson, 1984; Smithies and Champion, 2000; Morris and Kirkland, 2014) and their petrogenesis is distinct from that of the Lunnon Basalt itself.

Felsic volcanic or volcaniclastic rocks of the Black Flag Group

Felsic volcanic or volcaniclastic rocks analysed from the Black Flag Group range in SiO_2 from ~65 to 70 wt%. They typically have higher concentrations of Al_2O_3 (~15 – 16.5 wt%) than the sanukitoid-like rocks interleaved with the Lunnon Basalt, and lower concentrations of Na_2O (mainly <6 wt%, with correspondingly higher K_2O/Na_2O ratios of 0.2 – 0.6), Ba, Sr and LREE.

Dolerite sills

Diamond drillholes sampled from the Kambalda region have intersected several dolerite sills, including those assigned to the Condensor Dolerite, Defiance Dolerite, Junction Dolerite, Pernatty Dolerite and the Triumph Gabbro. Of these sills, samples of the Condensor and Junction Dolerites are indistinguishable from LTB on plots of TiO_2 vs Nb, Th, Zr and La (dolerites not shown on

Fig. 6) and, similarly, the Pernatty and Defiance Dolerites plot with HTSB. The Triumph Gabbro resembles LTB, with the higher TiO_2 concentrations of some samples (up to ~2.4 wt%) attributed to cumulus Ti-rich minerals.

Kalgoorlie stratigraphy

Samples collected at sites identified in Figure 5, including outcrop and diamond drillcore samples, were assigned to a level within a generalized stratigraphic column based on established field relationships indicating facing directions and relative stratigraphic order. The stratigraphy in the Kalgoorlie region (Fig. 5; De Paoli et al., 2017) is commonly accepted to be similar to that part of the Kambalda stratigraphy above the Lunnon Basalt, but although this is consistent with available geochronology, the lack of intervening outcrop makes this impossible to verify. To date, mafic volcanic rocks at a stratigraphically equivalent level to the Lunnon Basalt at Kambalda have not been identified in the Kalgoorlie area and were not found during our sampling program. The geochemical variation within the identified geochemical groups is described below and is compared with notionally stratigraphically equivalent units from the Kambalda region.

Komatiite

Komatiite was sampled in the upper part of diamond drillhole KPDDH006, which, based on analogies with the greenstone stratigraphy in the Kambalda region, must intersect overturned stratigraphy. The komatiites here (Kambalda Komatiite) are geochemically identical to those of the Kambalda greenstone stratigraphy except that they are mainly restricted to Mg# values above ~77.

ITB

Basalts with ITB-like geochemistry do not form a large proportion of the dataset from the Kalgoorlie region (11 out of 245 analyses) and most (eight) of these are from the western part of the region in diamond drillholes KPDDH003 and 006. The significance, if any, of this observation is as yet unclear. Nevertheless, of the ITB-like basalts identified from the western part of the Kalgoorlie region, those sampled from KPDDH003 (n = 3) were stratigraphically assigned in previous drill logs to the Black Flag Group rather than the Devon Consols Basalt (Bryan Smith Geosciences Pty Ltd, 2013), which was not identified at all in the logs. Our inspection of KPDDH003 found no evidence of Black Flag Group lithologies and we believe that these three ITB samples more likely belong to the Devon Consols Basalt.

In terms of major element chemistry, ITB from the Kalgoorlie region generally lie within the scattered field defined by ITB from Kambalda, except for a few samples from KPDDH006. ITB from this drillhole includes samples with unusually high concentrations of Na_2O (to 7.4 wt%) and K_2O (to 2.1 wt%) and low concentrations of CaO (to 2.6 wt%), most likely reflecting alteration. Trace element variations for ITB from the Kambalda and Kalgoorlie regions show extensive overlap (Fig. 7).

HTSB

Basalts with HTSB geochemistry form a common component of our Kalgoorlie dataset and have been sampled throughout the Kalgoorlie region. Compared with HTSB of the Paringa Basalt from the Kambalda region, HTSB sampled in the Kalgoorlie region appear to cover a wider range in Mg# (~77–43). Although samples with the highest Mg# also have MgO contents up to 21.6 wt% and in this respect could be classified as komatiite, their trace-element characteristics are clearly those of HTSB.

Over the range of overlapping Mg#, HTSB of the Paringa Basalt from the Kambalda region and HTSB sampled in the Kalgoorlie region show the same variation in major and trace element chemistry (Figs 7, 8). There appears to be no geochemical criterion for distinguishing samples from these geographically separate regions, supporting the view that the Paringa Basalt occurs at both localities.

Nevertheless, the Kalgoorlie HTSB can be divided into two broad compositional groups. One group has Mg# > 61 (high-Mg# group in Figs 6–8) and for these, concentrations of SiO_2 increase and LOI decreases with decreasing Mg#. The second group has Mg# <61 (low-Mg# group in Figs 6–8) and shows constant or slightly decreasing SiO_2 and increasing LOI with decreasing Mg#. Interestingly, most samples of the high-Mg# group are variolitic and, where it can be determined (e.g. SE18W1), are stratigraphically lower (older), whereas most low-Mg# samples are nonvariolitic and younger. Each group covers a similar range in SiO_2 concentration (high Mg# group = 57.6 – 46.2 wt%; low Mg# group = 58.8 – 48.2 wt%) but within that range the low Mg# group has higher concentrations of TiO_2, Al_2O_3, P_2O_5, Th, HFSE, and REE and lower concentrations of MgO, Cr and Ni (Figs 7, 8).

Basaltic units overlying the Paringa Basalt

Diamond drillcore SE18W1 contains an aphanitic pillow basalt unit sampled between 1897 and 2083 m. This unit is macroscopically distinct from immediately underlying and locally variolitic basalt sampled between 2117 and 2331 m. The pillow basalt was intruded by dolerite which at higher stratigraphic levels also intruded felsic volcanic and volcaniclastic units logged as Black Flag Group (Nixon, 2015). The pillow basalt was previously logged as Paringa Basalt, and the underlying variolitic unit as Devon Consols Basalt (Nixon, 2015). However, the variolitic basalt is compositionally HTSB, typical of part of the Paringa Basalt (low-Mg# Paringa Basalt at the contact).

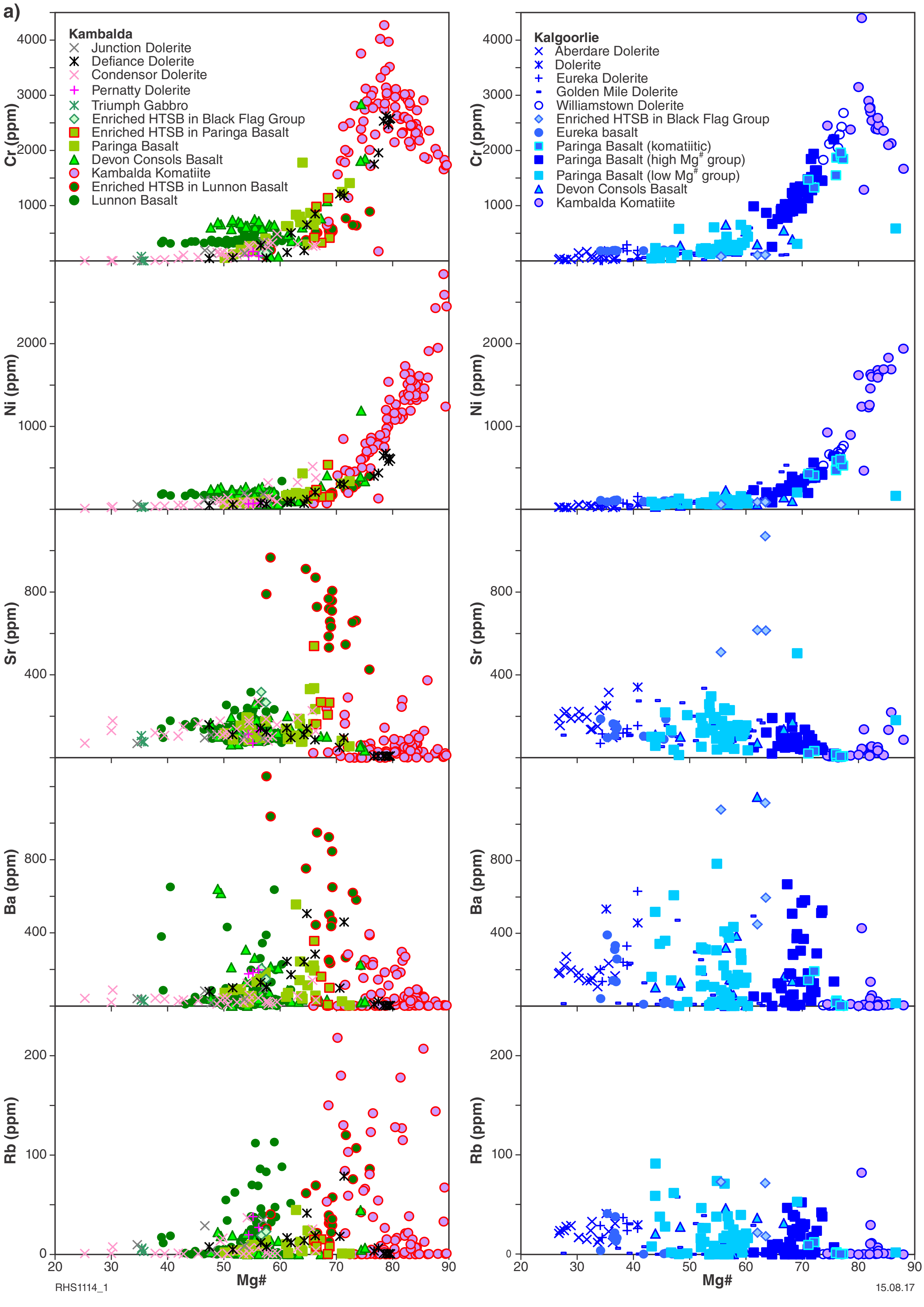
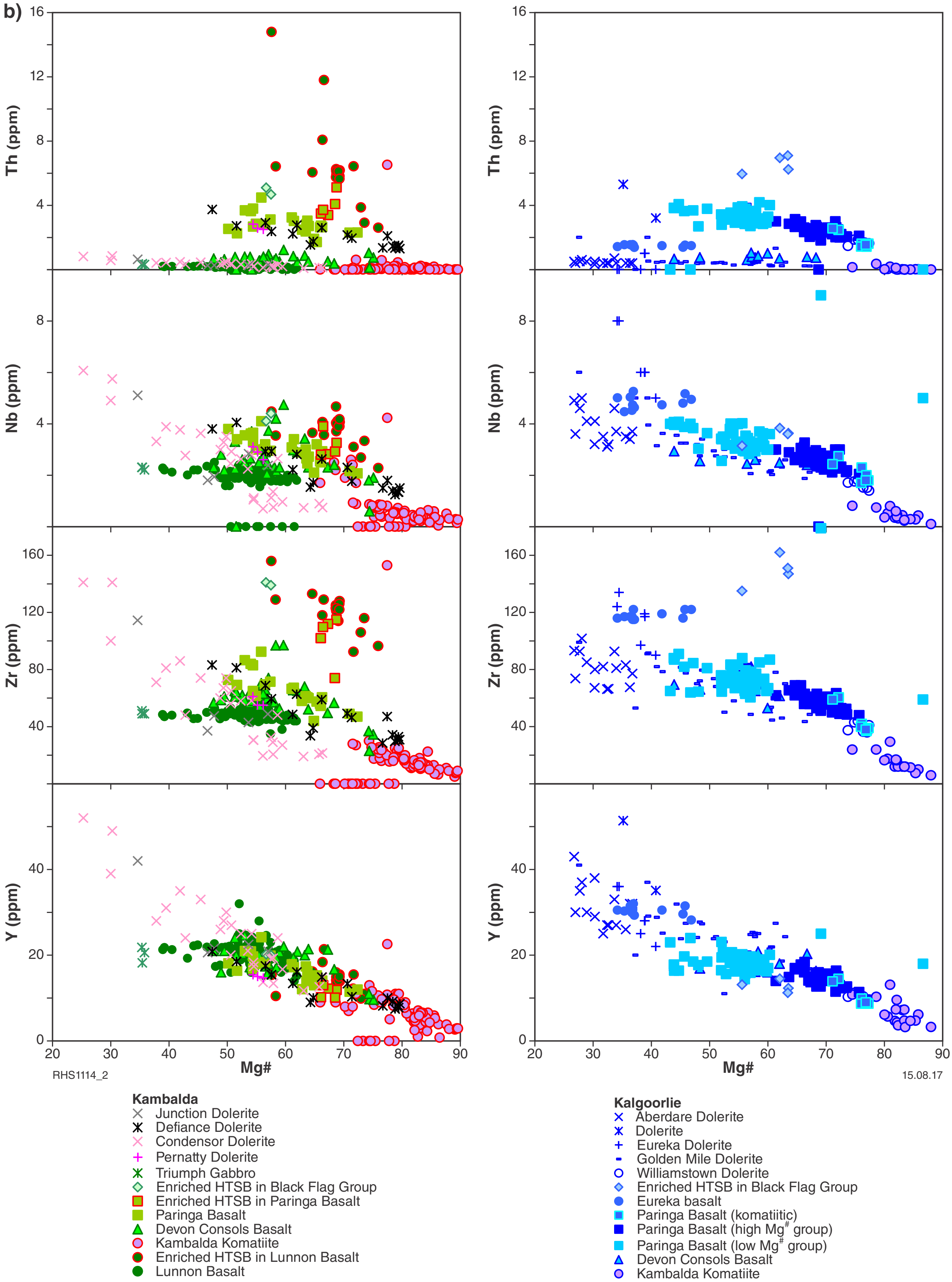


Figure 8. **Variations in trace elements and trace element ratios against Mg# for mafic and ultramafic rocks from the Kambalda region and the Kalgoorlie region**



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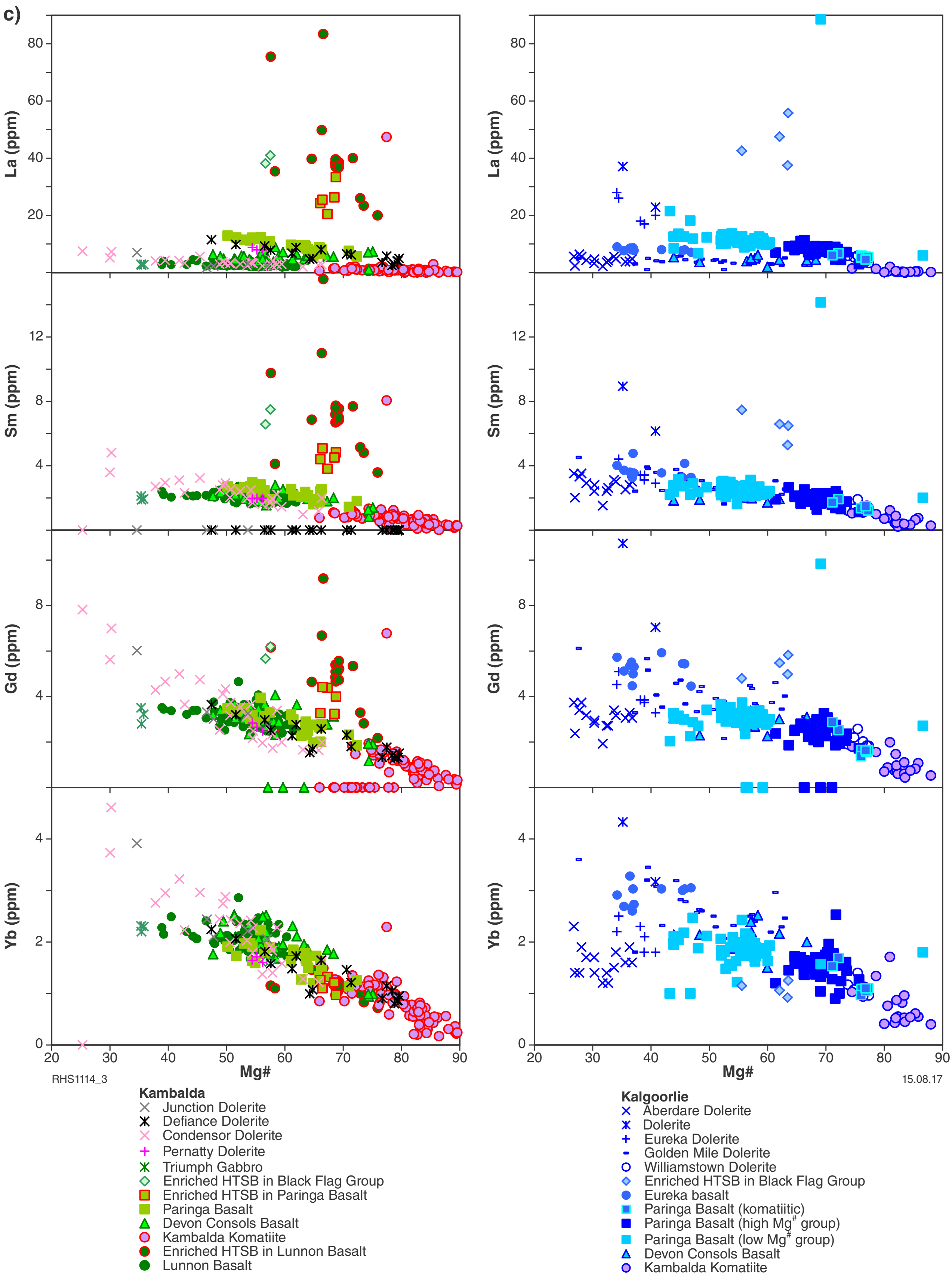
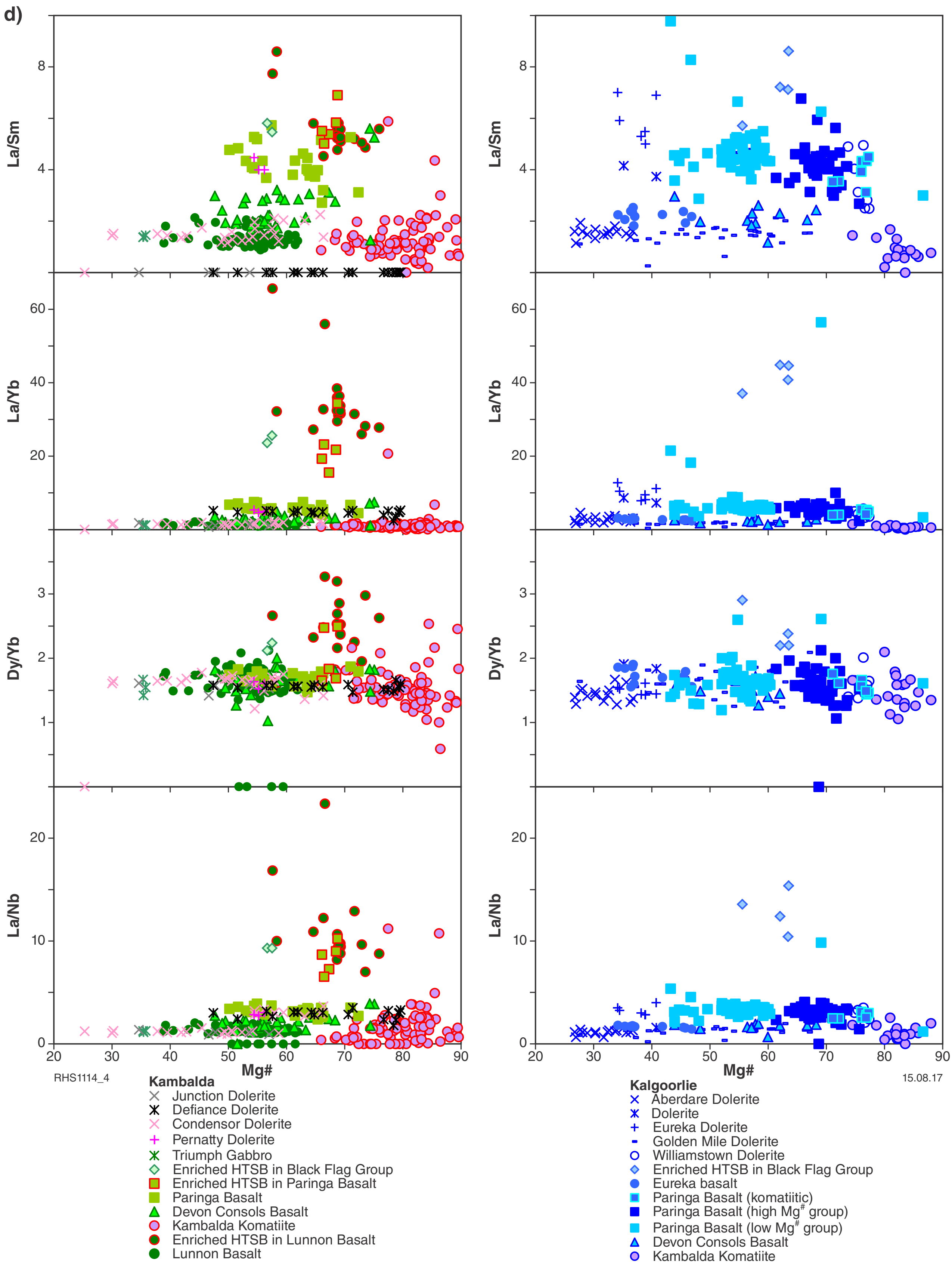


Figure 8. **continued**



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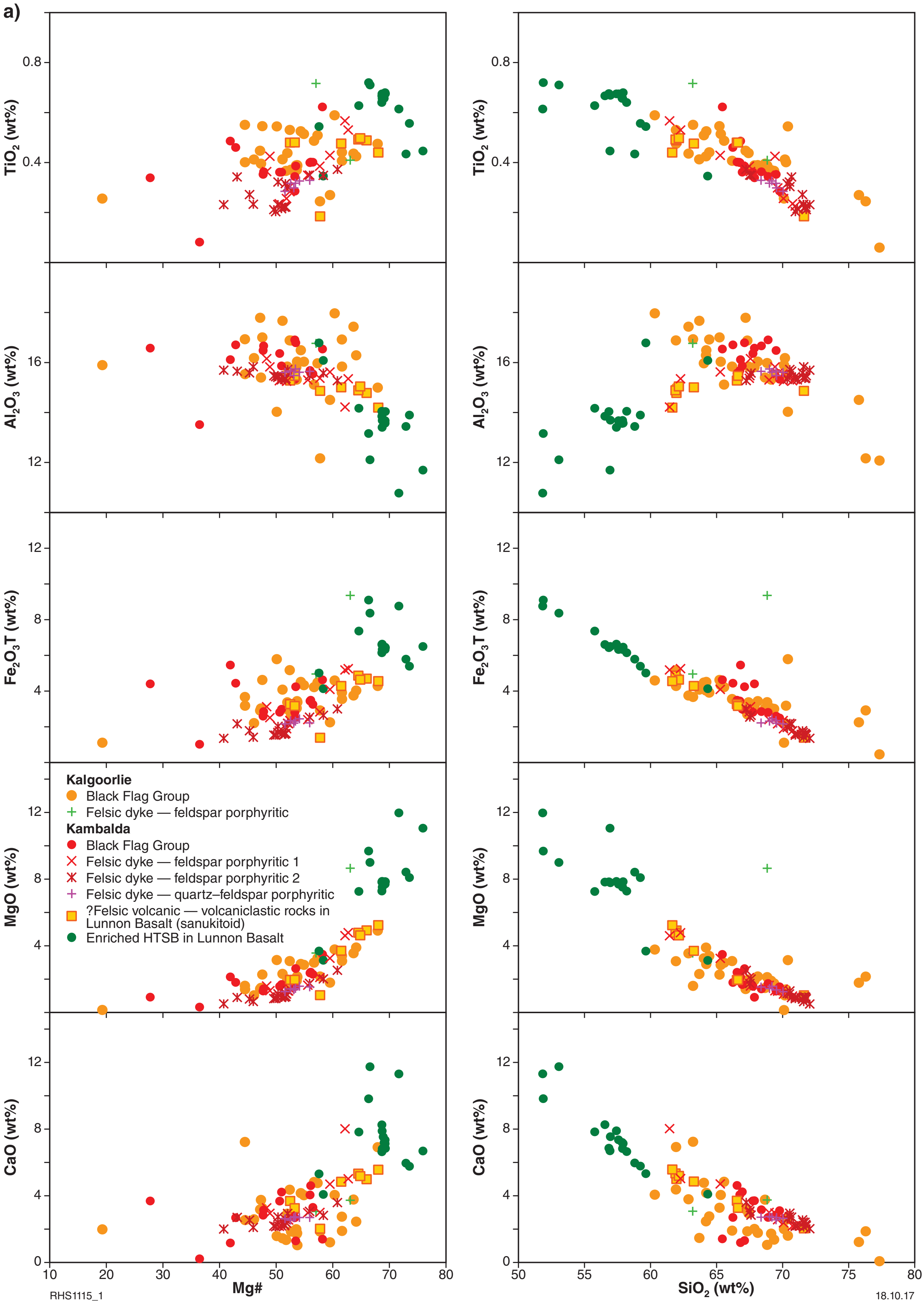


Figure 9. **Major element variations against Mg# and SiO_2 in felsic rocks from the Kambalda and the Kalgoorlie regions. All major element concentrations are recalculated on a volatile-free basis**

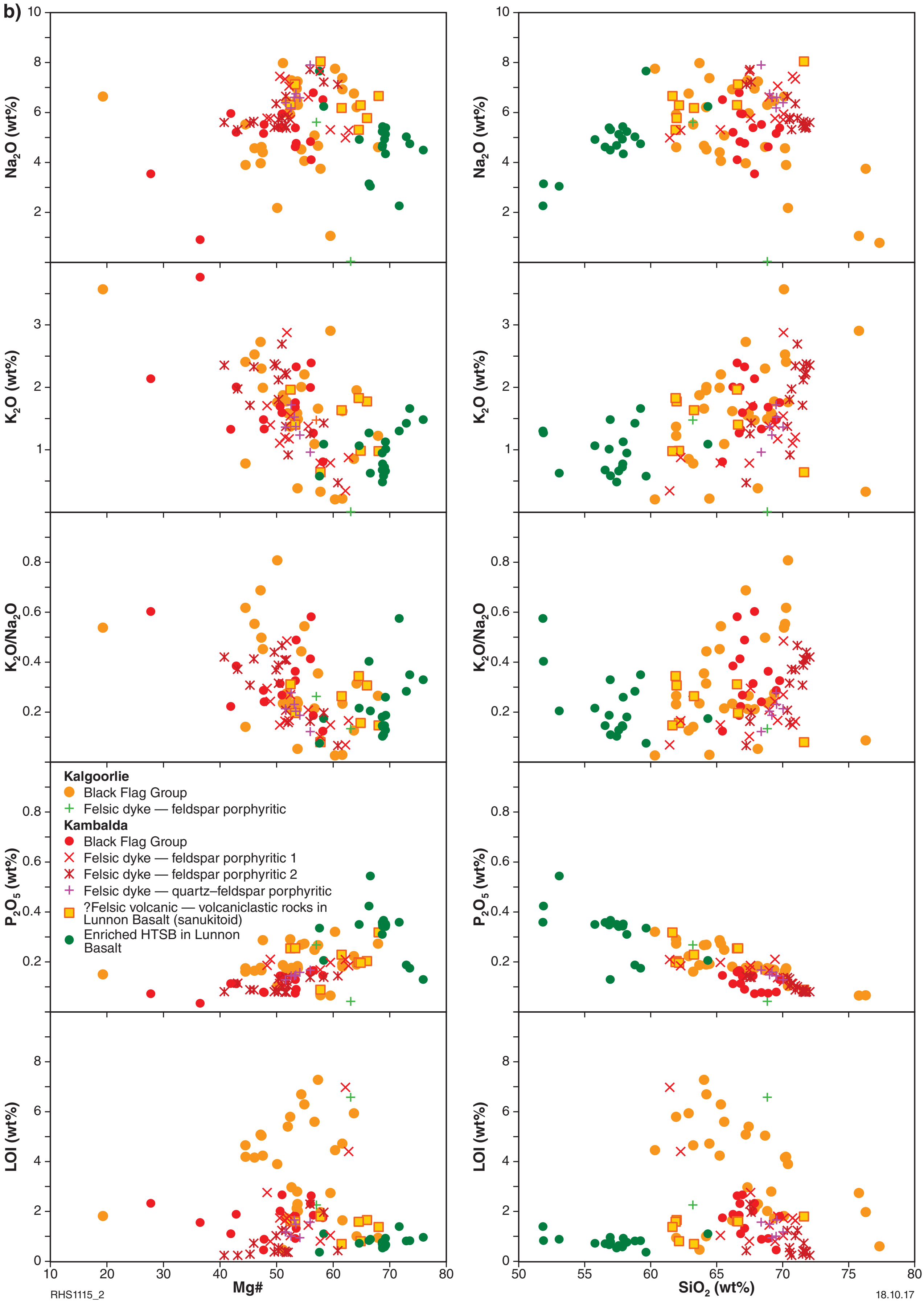


Figure 9. continued

The overlying pillow basalt has a composition unique among mafic eruptive units of the Kalgoorlie–Kambalda region, but very similar to that of the Eureka Dolerite sill, which is mapped approximately 5 km to the north-northwest, at a similar stratigraphic interval as the Golden Mile Dolerite. The pillow basalt can be distinguished from the other basalt units by its very high concentrations of TiO_2 (1.55 – 1.66 wt%), P_2O_5 (0.19 – 0.22 wt%) and HFSE, at relatively low Mg# (47–34).

Stratigraphically higher enriched HTSB rocks

The stratigraphic unit overlying the Paringa Basalt and TiO_2-enriched pillow basalt consists largely of felsic volcanic and volcaniclastic rocks collectively referred to as the Black Flag Group. One drillcore intersection of the Black Flag Group (SE18) included units at depths of 75.36 m, and several horizons between 289.7 and 323.4 m described as dark-grey aphanitic to plagioclase phyric mafic volcanic rock. Four samples of this rock range in Mg# from 63 to 55 and in SiO_2 from 53.8 – 57.4 wt%. At a given TiO_2 concentration, these rocks have a higher concentration of Th, Nb, La and Zr than most HTSB of the Paringa Basalt (Fig. 6) and in this respect are similar to the enriched HTSB rocks found in the Kambalda region within the lower LTB unit (Lunnon Basalt) and within the Black Flag Group. Also like these other enriched HTSB rocks, the units within the Black Flag Group in the Kalgoorlie region are enriched in Al_2O_3, Na_2O and P_2O_5 and depleted in total Fe as Fe_2O_3, MgO and CaO. The correspondingly higher Na_2O/CaO ratios suggest these rocks are probably high-Mg andesites rather than high-Si basalts.

Felsic volcanic or volcaniclastic rocks of the Black Flag Group

Felsic volcanic or volcaniclastic rock samples taken from the Black Flag Group in the Kalgoorlie region show a compositional range that spans data for Black Flag Group samples from the Kambalda region. A subset of the Kalgoorlie data have high Mg# and, at least for major elements (Fig. 9), are compositionally similar to the felsic volcanic and volcaniclastic rocks interlayered with the Lunnon Basalt in the Kambalda region, but are depleted in Ni and Cr at a given Mg# (Fig. 10).

Dolerite sills

Diamond drillholes sampled from the Kalgoorlie region have intersected several dolerite sills, including those assigned to the Golden Mile Dolerite, Aberdare Dolerite, Eureka Dolerite and the Williamstown Dolerite. The most TiO_2-enriched dolerite sill, the Eureka Dolerite, has TiO_2 concentrations up to 2.8 wt%. Samples of the Williamstown Dolerite are all ultramafic (MgO >18 wt%), but as they are also enriched in Th, HFSE and LREE, there is likely a petrogenetic link with HTSB magmas such as those forming the Paringa Basalt. Samples of the Aberdare Dolerite are distinctly more fractionated (Mg# <37) than other dolerite samples included within our dataset. Most samples of the Golden Mile Dolerite were collected from diamond drillholes SE18 and SE18W1. Interestingly, our samples of the Golden Mile Dolerite are compositionally indistinguishable from LTB, such as the Lunnon Basalt (from the Kambalda region) over a wide compositional interval, with Golden Mile Dolerite having only slightly lower concentrations of Ni and Cr and higher concentrations of Zr and Nb. The Condensor Dolerite from the Kambalda region is also compositionally similar to the Golden Mile Dolerite. Both dolerites are distinguishable from LTB when trends for extended geochemical arrays (e.g. Mg# vs TiO_2, Fe_2O_3, Nb, Zr) are considered.

Discussion — use of a geochemical stratigraphy

The main purpose of this Record is to highlight some of the benefits and potential problems in the application of geochemistry to assign igneous rocks to an established greenstone stratigraphy. The obvious caveat in this approach is that, in any given region, there is sufficient outcrop or drillcore data to confidently establish a stratigraphy. Another caveat is that each stratigraphic interval is geochemically unique. In the case of the Kambalda–Kalgoorlie region, a greenstone stratigraphy has long been established, based mainly on relationships observed in the Kambalda region where stratigraphic drilling has identified complete sections of the greenstone succession.

It is clear that the broad stratigraphic groups that make up the Kambalda–Kalgoorlie stratigraphy can normally be distinguished geochemically (e.g. the Lunnon Basalt can typically be distinguished from the Paringa Basalt) (e.g. Barnes et al., 2012). However, our detailed geochemical sampling has identified stratigraphic complexities, and hence, also revealed several potential problems in using geochemistry alone in assigning individual analyses or even groups of analyses of greenstones to a particular stratigraphic unit.

We list below circumstances (identified so far) where a geochemical approach may introduce errors in stratigraphic classification and we suggest some further geochemical checks that might prevent this.

- The Lunnon Basalt, identified so far only in the Kambalda region, has LTB compositions which, when only the TiO_2 vs Th, Nb, Zr, La diagrams are considered, is impossible to distinguish geochemically from some dolerite intrusions, including the Condensor Dolerite in the Kambalda region and units of the Golden Mile Dolerite and Aberdare Dolerite in the Kalgoorlie region. Fine-grained mafic rocks sampled without firm geological context and assessed only in terms of a limited suite of elements could clearly be attributed to the wrong lithostratigraphic unit.

Over much of the range of Mg#, however, our preliminary data suggests the LTB-like dolerites are slightly depleted in Ni and Cr compared with the Lunnon Basalt and the Aberdare Dolerite and LTB-like samples of the Golden Mile Dolerite are additionally slightly enriched in Nb and Zr.

- Basaltic rock with HTSB-like geochemistry based on the TiO_2 vs Th, Nb, Zr, La diagrams would typically be assigned to the Paringa Basalt but our data show that extrusive rocks with similar composition (enriched HTSB) may also form part of the Lunnon Basalt and the Black Flag Group.

  Preliminary data, however, suggests that true Paringa Basalt is, at any given TiO_2 concentration, less enriched in Th, Nb and, in particular, Zr and LREE than the enriched HTSB (Fig. 6). The enriched HTSB additionally have slightly more silica-rich compositions and higher Na_2O/CaO ratios, more consistent with high-MgO andesites than with high-SiO_2 basalts. An additional field in TiO_2 vs Zr and La diagrams should adequately identify these volcanic rocks, which also form a component interlayered within the 'true' Paringa Basalt in the Kalgoorlie region. A modified TiO_2 vs Zr and La diagram, however, will not identify to which of the three stratigraphic levels so far identified, a particular enriched HTSB sample belongs.

- As is the case with LTB-like extrusive and intrusive rocks, HTSB of the Paringa Basalt have intrusive compositional equivalents (e.g. the high-MgO to ultramafic Williamstown Dolerite in the Kalgoorlie region and the mafic Pernatty Dolerite in the Kambalda region). Hence, fine-grained HTSB sampled without any clear geological context could potentially be assigned to an incorrect stratigraphic unit based on geochemistry alone.

The potential for such errors decreases, and the capacity to correct them increases, with increasing data and data quality. There are also cases where present lithostratigraphic logging of drillcore differs from how it might be logged based on established geochemical characteristics of various lithostratigraphic units. For example, in the log for diamond drillhole SE18W1 from the Kalgoorlie region, grey-green aphanitic basalt underlying volcaniclastic rocks of the Black Flag Group has been assigned to the Paringa Basalt. The grey-green, aphanitic and locally *variolitic* basalt beneath this has been assigned to the Devon Consols Basalt, and this unit is in contact with ultramafic rocks assigned to the Kambalda Komatiite. However, the basalt directly underlying the Black Flag Group is a TiO_2-rich, low-Mg# unit significantly enriched in HFSE and depleted in Th and La compared with HTSB typical of the Paringa Basalt. We suggest it is more likely a volcanic equivalent of the locally outcropping Eureka Dolerite. The variolitic basalt beneath this unit, assigned in the log to the Devon Consols Basalt, is HTSB geochemically indistinguishable from Paringa Basalt. If the geochemical interpretation of this part of the stratigraphy in SE18W1 is correct, this drillhole does not intersect the Devon Consols Basalt, and the Paringa Basalt directly overlies the Kambalda Komatiite. Similarly ITB-like basalts identified from KPDDH003 in the western part of the Kalgoorlie region were assigned in the drill log to the Black Flag Group rather than the Devon Consols Basalt (Bryan Smith Geosciences Pty Ltd, 2013). Our interpretation of this part of the drillcore is that it comprises sheared and deformed basalt, whose chemistry is consistent with it being a part of the Devon Consols Basalt. Depending upon which interpretation is correct, the stratigraphic interval sampled by the drillcore could be vastly different as could the facing direction of the greenstone stratigraphy.

One of the benefits of the detailed geochemical sampling strategy adopted here is that it almost inevitably leads to results that raise questions relating to tectono-magmatic evolution — in this case of the Kambalda–Kalgoorlie greenstones. Among the main issues and questions to arise so far include:

- LTB-style magmatism does not appear to be restricted to the lowest stratigraphic part of the Kambalda–Kalgoorlie sequence, but recurs at younger stages forming dolerites that have intruded all higher stratigraphic levels. This indicates the existence of a distinct and long-lived mantle source that was periodically tapped.
- In a general sense, the evolution of the basaltic stratigraphy — from LTB-like Lunnon Basalt to ITB-like Devon Consols Basalt to HTSB-like Paringa Basalt — reflects a progressive increase in the extent to which evolved crust has contaminated primitive mantle-derived magmas (e.g. Barnes et al., 2012). This trend is incompatible with subduction modification of a mantle source but, rather, reflects variable (in this case systematically increasing) amounts of crustal contamination during magma assent. However, both the Devon Consols and Paringa Basalts show trends that reflect variable degrees of melting or of fractional crystallization of an already homogeneously contaminated (e.g. constant Th/Nb ratio) source or source magma. The dynamics of the processes resulting in these trends will likely be important within the general geological evolution of the Eastern Goldfields Superterrane.
- The Lunnon Basalt at the base of the Kambalda–Kalgoorlie stratigraphy has not been directly dated but pre-dates regional c. 2705 Ma komatiite magmatism. The identification of felsic units that possibly appear to be volcanic and volcaniclastic in origin within the Lunnon Basalt potentially provides an opportunity to directly date both the mafic and felsic magmatism. Moreover, the recognition that the felsic magmas have the composition of Archean sanukitoid may have significant implications. This is because, irrespective of the various petrogenetic models used to explain sanukitoid magmatism (Smithies and Champion, 2000; Martin et al., 2005; Barnes and Van Kranendonk, 2014), empirical observations indicate a link between such magmatism and gold mineralization (e.g. Champion and Sheraton, 1997). What forms the base to the Lunnon Basalt is unknown. Did an early stage of voluminous sanukitoid-style magmatism pre-date and locally overlap with deposition of the basalt and might this have led to early enrichment of Eastern Goldfields Superterrane crust in gold?

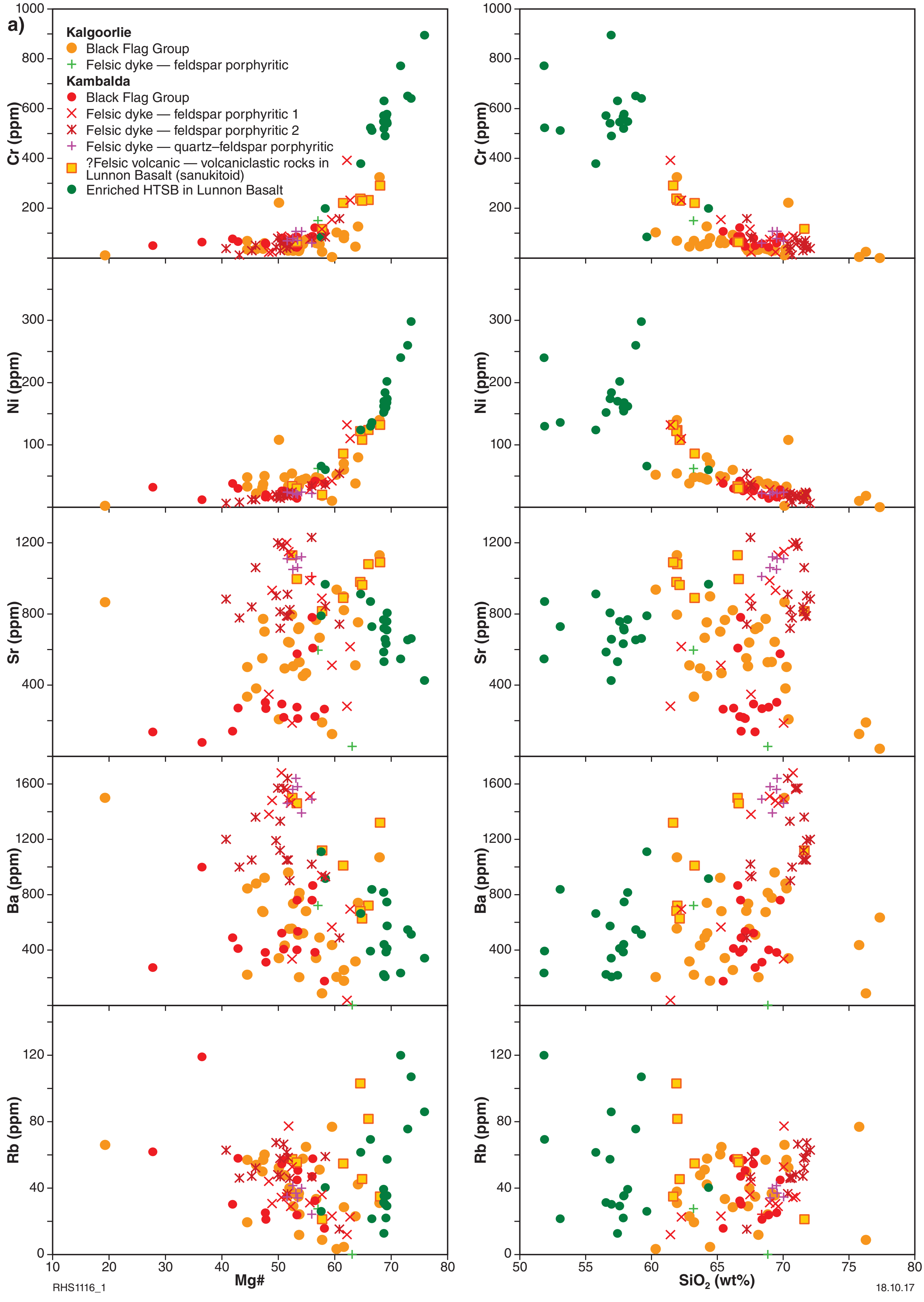
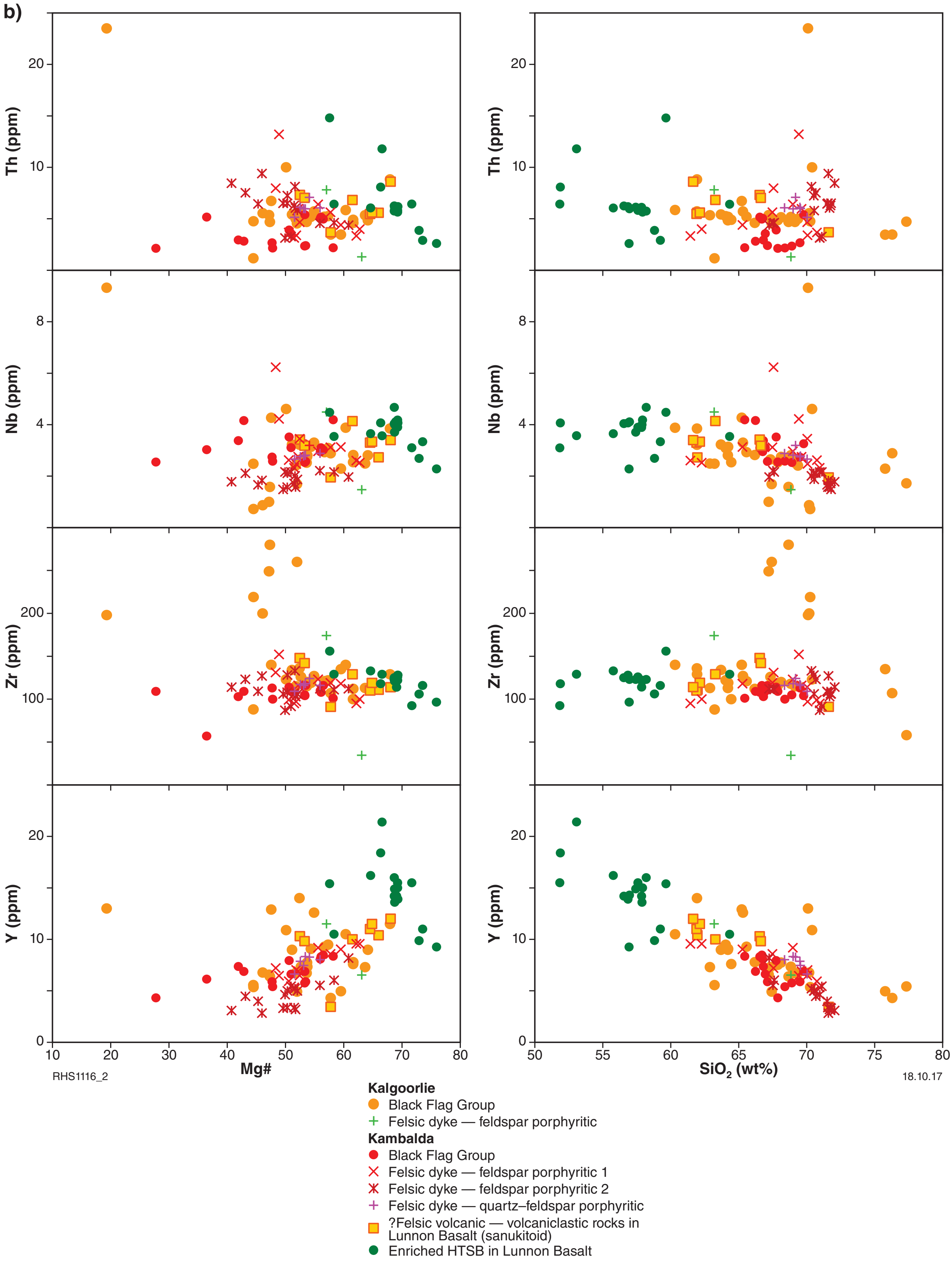


Figure 10. Variations in trace elements and trace element ratios against Mg# and SiO_2 in felsic rocks from the Kambalda and Kalgoorlie regions



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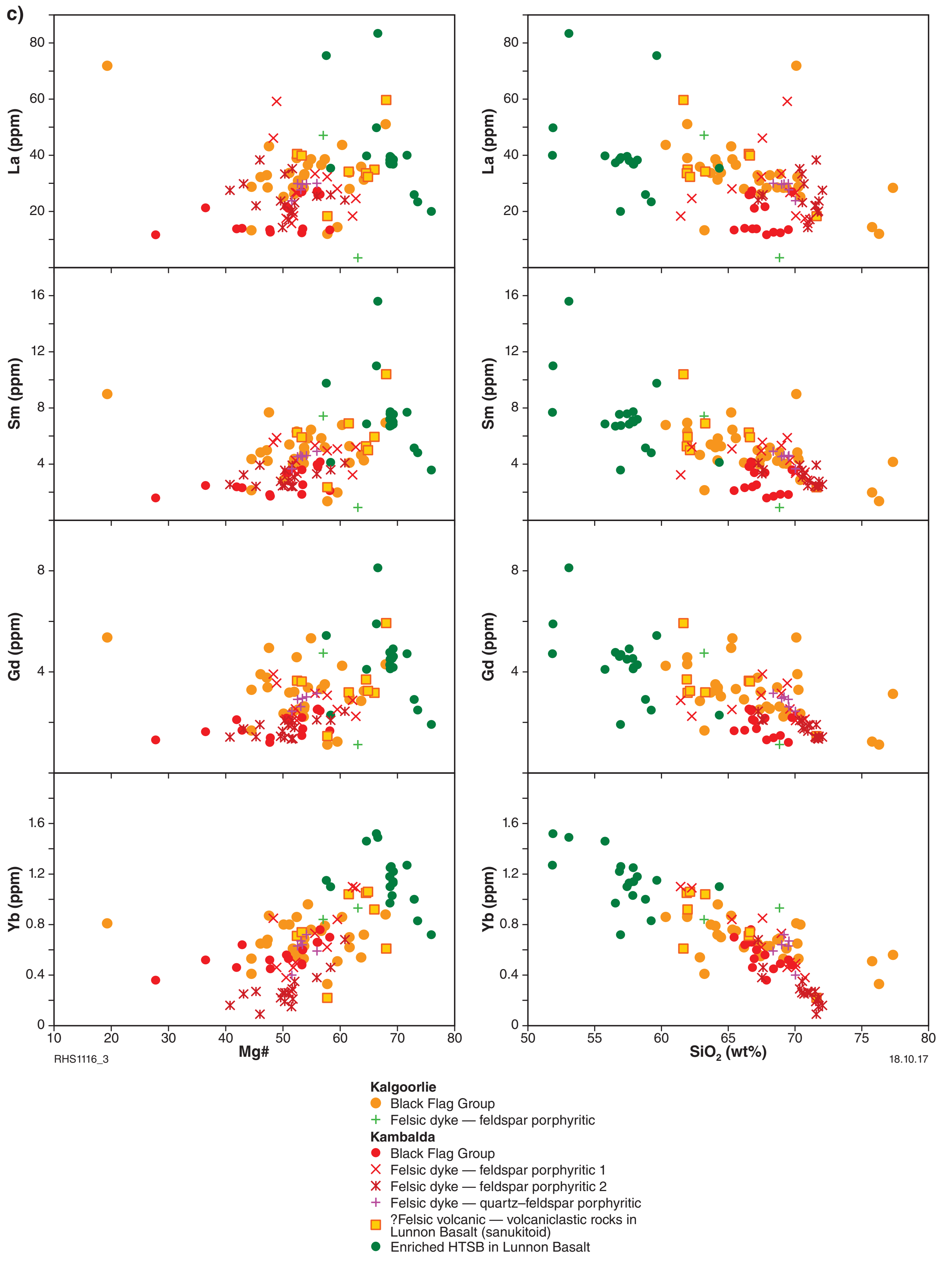

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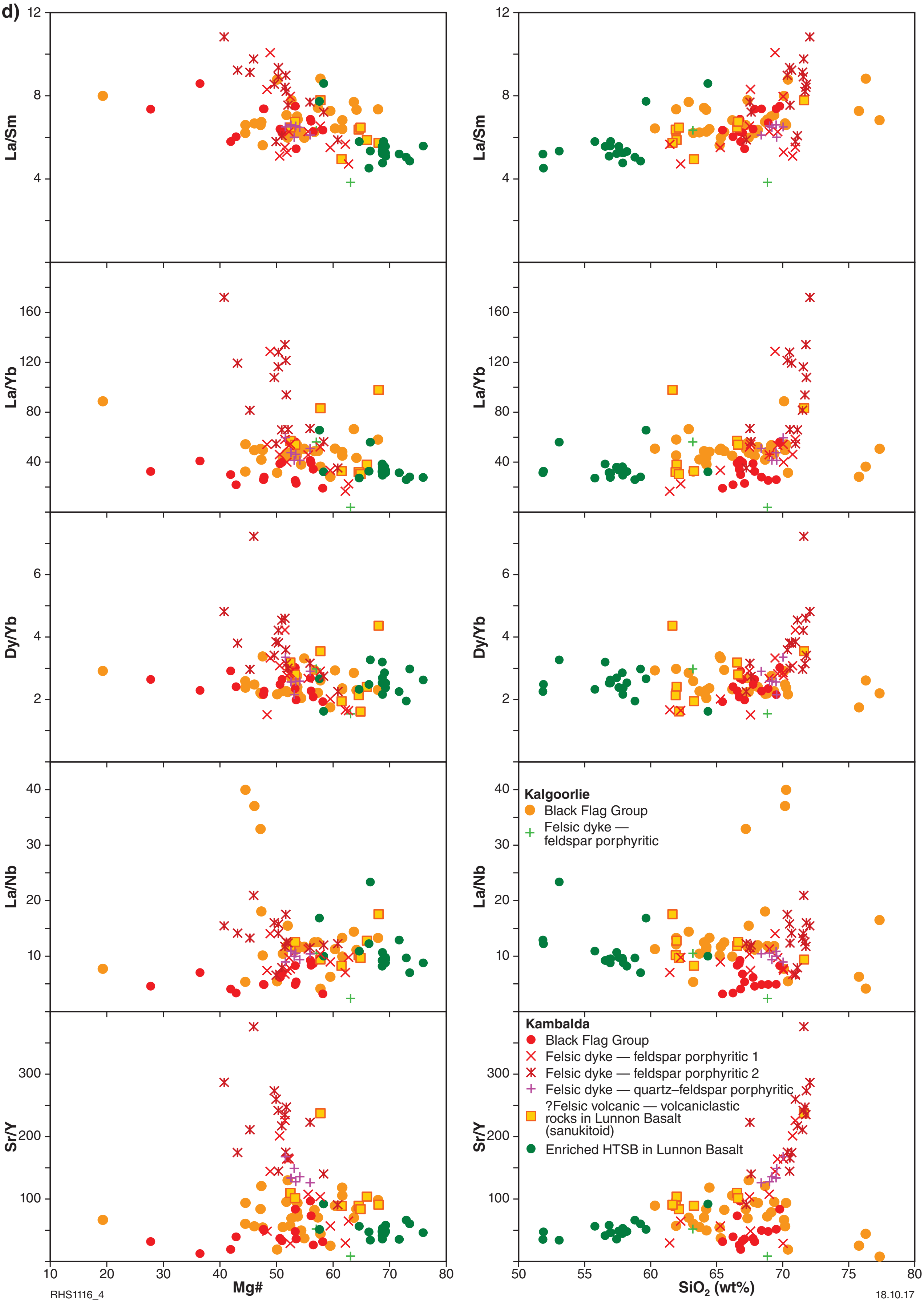

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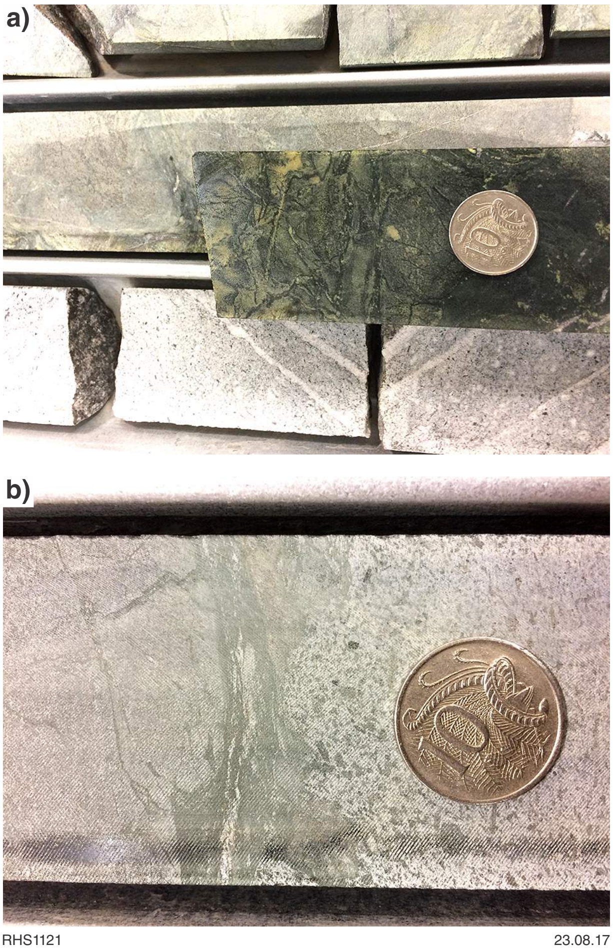

Figure 11. Photos of drillcore from CD16056A showing: a) hyaloclastitic brecciation of an enriched HTSB unit within Lunnon Basalt; b) contacts between Lunnon Basalt and interbedded fine- to medium-grained felsic volcanic units

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TOWARDS A GEOCHEMICAL BARCODE FOR EASTERN GOLDFIELDS SUPERTERRANE GREENSTONE STRATIGRAPHY — PRELIMINARY DATA FROM THE KAMBALDA–KALGOORLIE AREA

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