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EXTREME RARE EARTH ELEMENT ENRICHMENT IN ALTERED BASALTIC ROCKS OF THE EASTERN GOLDFIELDS

RH Smithies and JR Lowrey



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PERTH 2022



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Appendix

Available with the PDF online as an accompanying digital resource

Whole-rock geochemical data

Extreme rare earth element enrichment in altered basaltic rocks of the Eastern Goldfields

RH Smithies and JR Lowrey

Abstract

Archean basalts with distinctive rare earth element (REE)-enrichment patterns that appear inconsistent with normal igneous processes are sporadically distributed close to the major, north-northwesterly trending structures – including terrane boundary faults or shear zones – within the Eastern Yilgarn Superterrane. Only surface samples are affected by this alteration, suggesting that it is primarily related to recent (Tertiary) near-surface processes. Only the REE and Y appear to have been significantly affected, producing a highly distinctive decoupling pattern in normalized trace element patterns, with maximum enrichment factors up to 40 and total enrichments in light rare earth element (LREE; Σ LREE = sum of La–Eu) up to 687 ppm and in heavy rare earth elements (HREE; Σ HREE = sum of Gd–Lu+Y) of up to 1428 ppm (68% of which is Y). The occurrence of these rocks is regional, but within a very specific structural setting. Such enrichments of basalts in REE do not constitute a resource in itself, but accumulations of the weathering products from a range of REE-enriched rock types have the potential to form economically important regolith-hosted ion-adsorption deposits.

KEYWORDS: rare earth element mineralization, regolith-hosted ion-adsorption deposits, Yilgarn Craton

Background

The Eastern Goldfields greenstone geochemical barcoding project (Lowrey et al., 2021) is an initiative under the Exploration Incentive Scheme (EIS) aimed at providing a high-quality whole-rock geochemical dataset that significantly aids in investigating stratigraphic links within and between greenstone belts, particularly in areas where primary geological context (mainly outcrop) is limited. The project seeks to substantially increase the amount of publically available high-quality, multi-element, geochemical data from igneous lithologies forming greenstone stratigraphy, targeting diamond drillcores and fresh outcrop that sample the most geologically well-constrained parts of various greenstone belts (Fig. 1).

All samples taken, represent what are, visually, the least-altered examples of lithologically, texturally and mineralogically homogeneous material. On rare occasions, inspection of the geochemical data identifies samples that, despite showing no obvious evidence of alteration in hand specimen, show evidence for significant subsolidus element mobility. Such evidence might comprise co-variation of typically fluid-mobile components or proxies, including concentrations of Pb, Sr, Ba, alkali elements (e.g. Na or K), analytical loss on ignition (LOI) or the aluminium saturation index (ASI). In other cases, such alteration can be identified through mantle-normalized trace element variation patterns that are significantly anomalous compared with patterns expected through normal igneous magma evolution. Here, we report on a series of visually fresh basalts, which show an extreme style and degree of enrichment in rare earth elements (REE) that is inconsistent with a solely igneous (tholeiitic) origin. All of the naturally occurring REE, with the exception of Ce in many cases, show an enrichment factor of up to 40. The occurrence of these altered rocks is regional, but within a very specific structural setting. Such enrichments of basalts in REE do not constitute a resource

in itself, but accumulations of the weathering products of these rocks might have potential for economically important heavy REE mineralization.

Geochemical characteristics

Details on the analytical procedures used for the Eastern Goldfields greenstone geochemical barcoding project are presented in Lowrey et al. (2021) and all whole-rock geochemical data are presented in Appendix 1. All of the samples considered here have broadly ‘basaltic’ major element chemistry, with SiO₂ between 44.8 and 58.9wt% and MgO between 3.4 and 17.1 wt%.

The greenstone geochemical barcoding project has constrained the primary compositional characteristics of all basaltic units within the Ora Banda – Kambalda region (Smithies et al., 2022). Using these criteria, it can be shown that most of the REE-altered basalts are indistinguishable from locally sampled ‘fresh’ basalt in terms of major element compositions and compositions of incompatible trace elements, including high field strength elements (HFSE; Ti, Zr, Hf, Nb, Ta), Th, U, and large ion lithophile elements (LILE; Sr, Ba, Pb: although these do show considerably greater scatter in both the fresh and altered rocks; Fig. 2). Only the REE and Y appear to have been significantly affected, producing a highly distinctive decoupling pattern in normalized trace element patterns (Fig. 2), which reflects no known igneous process. Moreover, normalizing the measured enrichments against concentrations expected in unaltered basalt of equivalent major element compositions (Fig. 3) shows that all REE, except for Ce, are enriched to more or less similar degrees. Lanthanum and Nd have average enrichment factors of 11 and 8.1 respectively, while the range for heavy REE (HREE) (Gd–Lu) varies between 6.7 and 8.3.

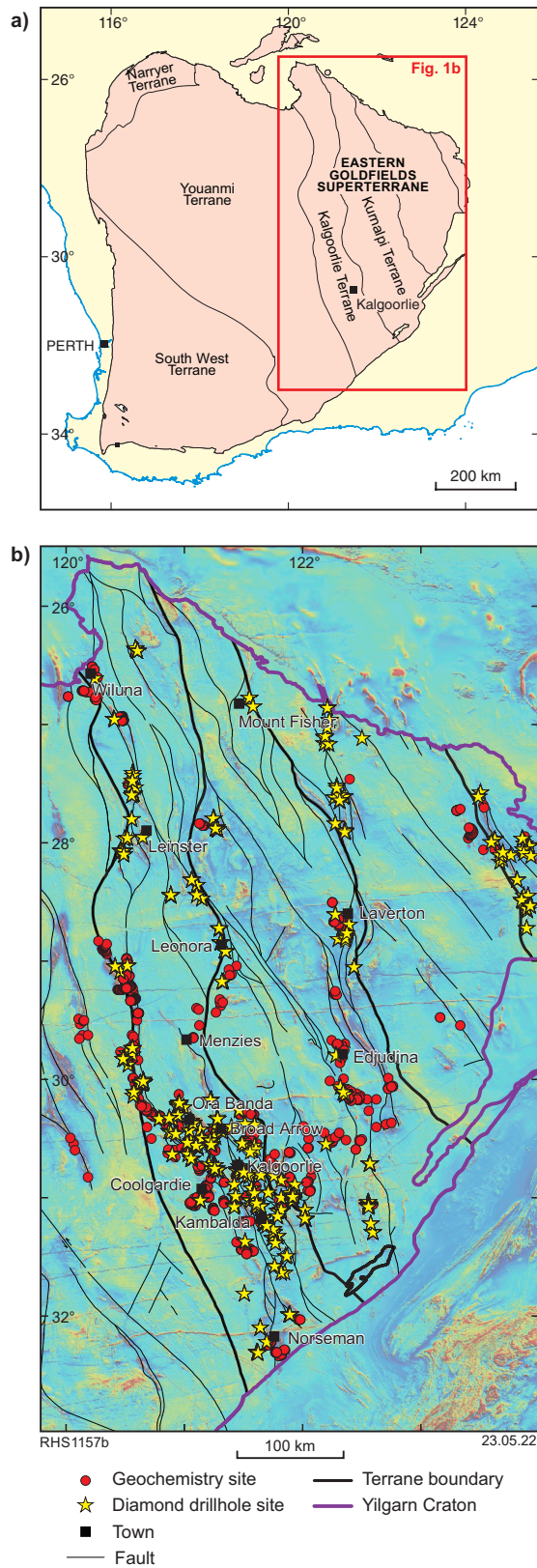


Figure 1. Eastern Goldfields greenstone geochemical barcoding project area overview and sample localities: a) location map of the study area; b) aeromagnetic image of the Eastern Goldfields Superterrane showing the locations of samples used for this study

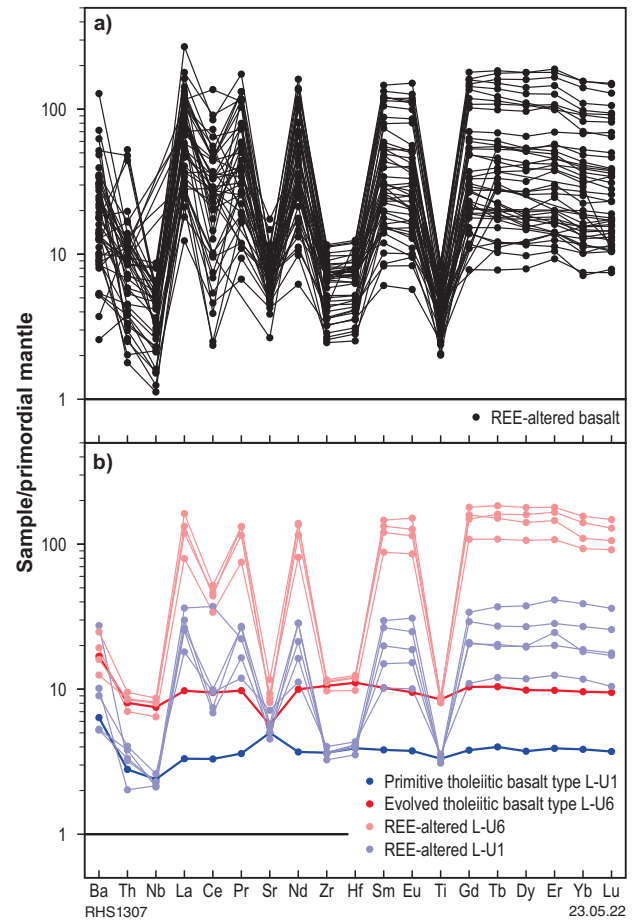


Figure 2. Mantle-normalized trace element diagrams showing, a) the prominent decoupling of HFSE and LILE from the REE; b) that comparisons with unaltered samples of specific basalt types indicates that HFSE, Th and LILE are essentially immobile during this style of alteration, but REE are greatly enriched. (L-U1 and L-U6 refer respectively to primitive and fractionated tholeiites classified as part of the greenstone geochemical barcoding project; Normalization factors after Sun and McDonough, 1989)

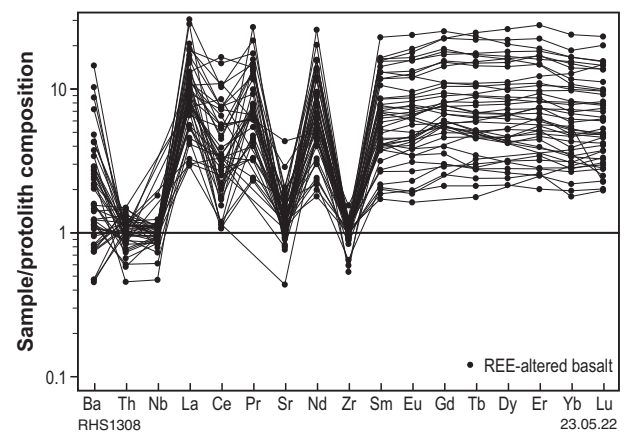


Figure 3. Spider diagram showing the range in enrichment factors for individual trace elements (trace element concentration in a sample normalized against concentrations expected in unaltered basalt of equivalent major element compositions). Except in the case of Ce, which typically shows notable depletions relative to other LREE, the full range of REE are enriched by similar degrees

However, the average for Ce is only ~5. With a geochemical behaviour typically similar to that of the HREE (specifically Ho), Y is also enriched on average by a factor of 10.3. In contrast, average enrichments across the range of HFSE (Ti, Nb, Ta, Zr, Hf), Th and U varies between 0.8 and 1.1 (i.e. little or no change). Deficits in the concentrations of Ce, reflected as significant negative Ce-anomalies on mantle-normalized trace element diagrams suggest the preferential mobility of Ce^{4+} in oxidized alteration fluids.

Maximum enrichment factors exceed 30, and appear positively correlated with the whole-rock P_2O_5 content (Fig. 4). These correlations are particularly strong for Y and the HREE, but significantly weaker for the light REE (LREE). Total enrichments in LREE ($\Sigma LREE = \text{sum of La-Eu}$) reach 687 ppm (average of 230 ppm) and in HREE ($\Sigma HREE = \text{sum of Gd-Lu+Y}$) reach 1428 ppm (average of 396 ppm, ~68% of which is Y). The correlations observed between original P_2O_5 concentration and REE enrichment suggests the REE have been concentrated in, or within the alteration product of, a phosphate mineral. The observation that Th is not enriched along with REE suggests that this phosphate mineral is most likely apatite. Further work is planned to confirm this.

On rare occasions, other rock types collected within the greenstone geochemical barcoding project appear to show similar, although more subdued, REE enrichment patterns to the REE-altered basalts. Hence, it is possible that the manifestation of this style of alteration is not restricted to basaltic rocks. However, if REE enrichment is related to the original P_2O_5 concentration of the rock, as implied by our data, then apart from lamprophyres, sanukitoids and P-rich sedimentary rocks, basalts are the most likely host to significant enrichment.

Regional distribution

Figures 1 and 5 contrast the regional coverage, throughout the Eastern Goldfields Superterrane, of all mafic samples within the greenstone geochemical barcoding project dataset, with the location of REE-altered basalts. The distribution of the REE-altered basalts appears to be strongly correlated with proximity to major, north-northwesterly trending structures – including terrane boundary faults or shear zones. In the northwest of this region, the REE-altered samples concentrate on or near the northern trace of the Ida Fault. We as yet do not have the data to show whether basaltic rock proximal to the southern trace of the Ida Fault exhibits this alteration characteristic; however, there is a strong concentration of REE-altered basalts proximal to and between the Zuleika and Kunanalling Shear Zones.

The absolute concentrations of REE in the REE-altered rocks is variable on a local and regional basis, although there are clusters of high values (Fig. 6). There is a broad correlation between absolute concentrations and the extent to which samples have been enriched over primary (magmatic protolith) concentrations (Fig. 6).

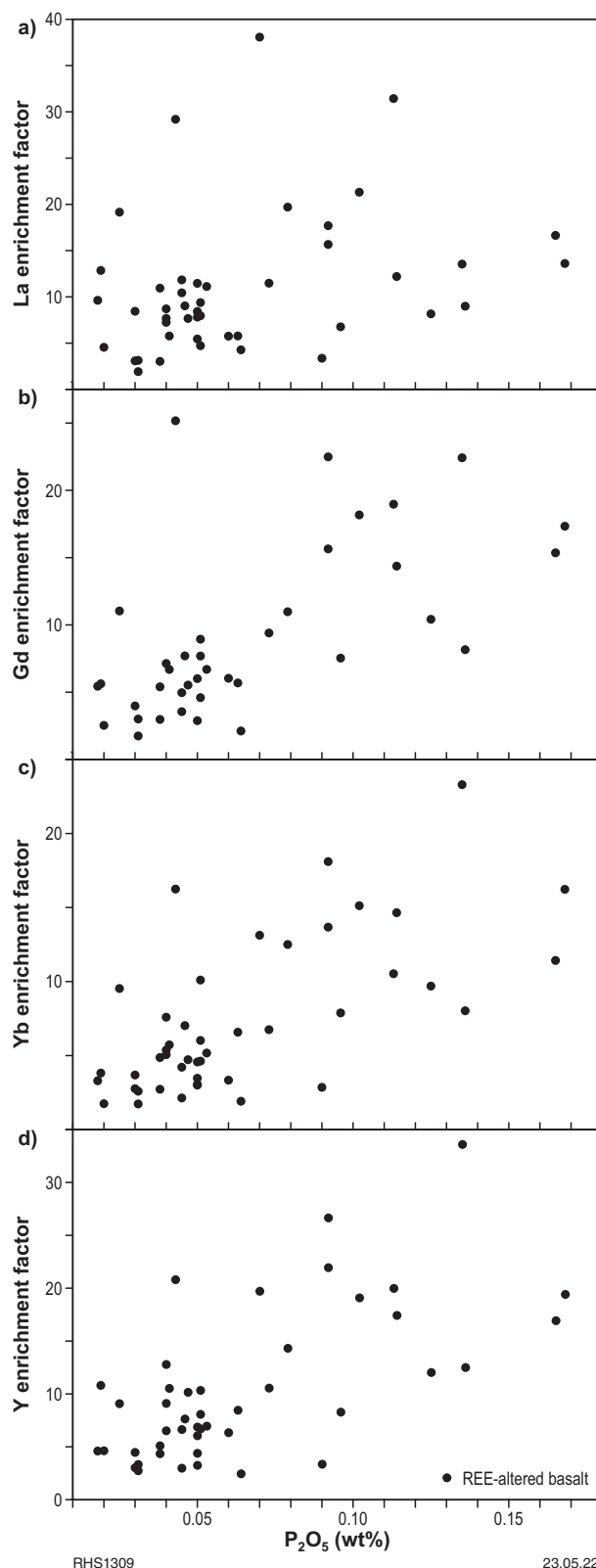


Figure 4. Compositional variation diagrams showing the correlation of enrichment factors for La, Gd, Yb and Y with increasing concentration of P_2O_5 in the altered basalt

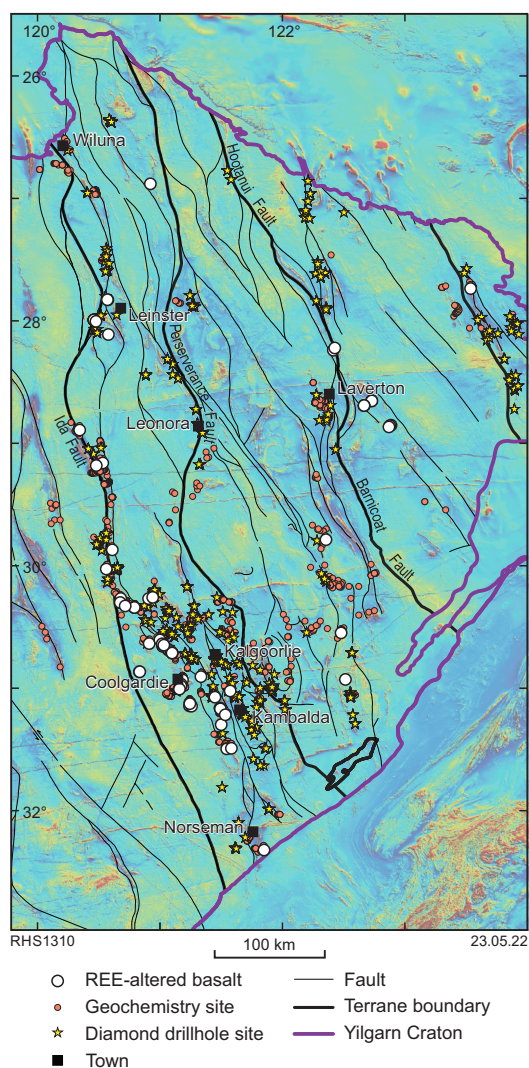


Figure 5. Aeromagnetic image of the Eastern Goldfields Superterrane comparing the location of REE-altered samples and unaltered basalt samples collected for the greenstone geochemical barcoding project

Discussion

Although the greenstone geochemical barcoding project has concentrated on sampling from drillcores, it is notable that all altered samples collected so far have been surface samples. This clearly suggests that alteration is primarily related to recent (Tertiary?) near-surface processes. Attempts are currently underway to determine the timing of alteration. However, surface samples of REE-altered basalts collected from within the Warrunga Shear zone, to the northeast of Agnew, are garnet amphibolites reflecting upper amphibolite conditions reached at c. 2720 Ma (Zibra et al., 2017). Again, REE-altered and unaltered samples occur in close proximity, but analysis of peak metamorphic minerals (garnet and hornblende) in each shows the same compositional distinctions – high REE concentrations and strong decoupling of HFSE from REE in metamorphic minerals in the REE-altered rocks but not in the unaltered rocks. Hence in this case, REE alteration pre-dates metamorphism and, on a regional basis, has occurred on more than one occasion. This might suggest that two of

the more important factors controlling this style of REE enrichment include the scale of the associated structure and the composition of the host (basalt, or perhaps more specifically P-rich basalt). Morris (2018) noted similar REE alteration patterns in regolith samples overlying basalts of the Paleoproterozoic Carson Volcanics adjacent to major structures in the north Kimberley region of Western Australia and attributed them to unusual, structurally controlled hydrothermal alteration of regolith. In the case of the Eastern Goldfields samples, the protolith to the altered material was not extensively weathered – as evidenced by the ‘basaltic’ chemistry reflected in most elements other than the REE. However, the process does appear to be strongly structurally controlled. In the case of the north Kimberley example, it is interesting to note that regolith samples taken in areas distal to the REE-altered samples and their related structures, show the opposite trace element patterns, i.e. HFSE enrichment, REE depletion, positive Ce anomaly. This perhaps suggests the major structures are recirculating fluids earlier involved in surface weathering.

This current study has identified a significant number of occurrences where near surface (and hence, presumably recent) alteration has resulted in significant REE enrichments in basaltic rocks along major crustal structures. However, it is not clear if this is a true reflection of the frequency and/or scale of these alteration processes in the study region, or simply a reflection of the large number of samples collected within the greenstone geochemical barcoding project. We suggest that the latter is not the case since surface samples represent only a very small proportion of the geochemical barcoding dataset.

Weathering of REE-enriched igneous rocks is believed to promote the formation of clay minerals that readily adsorb REE, forming regolith-hosted ion-adsorption deposits. Such deposits are typically low grade, with between 300 and 3500 ppm total REE, but easily mined and effectively processed, and constitute the world’s primary source for HREE (Estrade et al., 2019; Borst et al., 2020). While the enriched REE-altered basalts documented here do not represent a REE resource in their own right, it is possible they represent a favourable protolith for recent regolith-hosted REE accumulations in the region.

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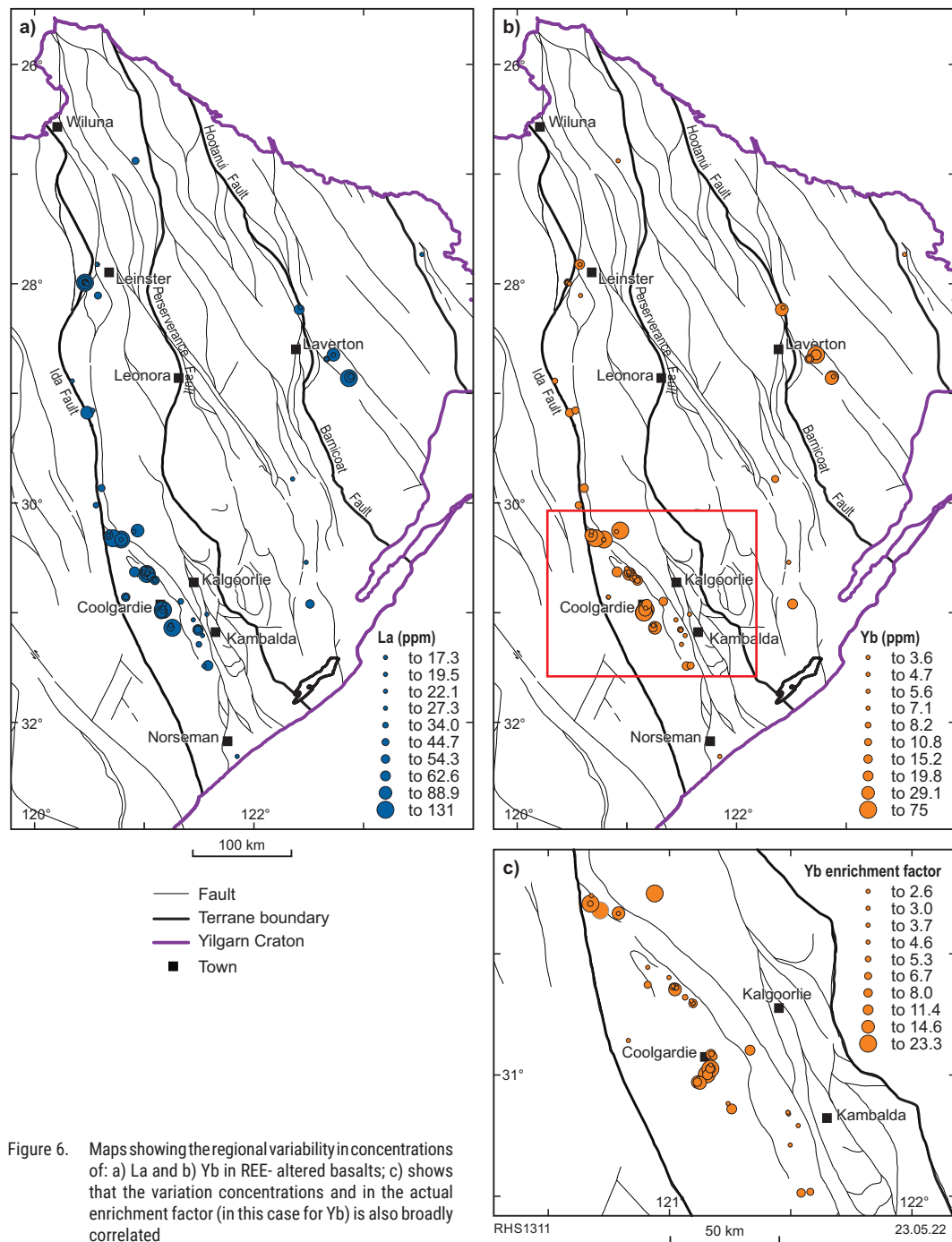


Figure 6. Maps showing the regional variability in concentrations of: a) La and b) Yb in REE-altered basalts; c) shows that the variation concentrations and in the actual enrichment factor (in this case for Yb) is also broadly correlated

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