An inventory of peralkaline rocks in Queensland for evaluation of REE enrichment potential

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SUMMARY

Highly fractionated peralkaline rocks are globally important sources of rare earth elements and other critical or new economy metals. Such metals are vital for technological advancement and a transition to a clean energy future and are therefore predicted to rise in demand. These are non-traditional commodities in Queensland and it is therefore important to gain a greater understanding of the distribution of peralkaline rocks and the potential for igneous suites to host highly fractionated, enriched components. A critical first step is to compile an inventory of the distribution, geochemistry, mineralogy and geochronology of these rocks.

Rocks units that include peralkaline compositions were emplaced in post orogenic, rifting or plume-related settings during late Triassic or younger magmatic events. These crop out in a broad belt between the Bowen-Mackay area and the southern Border Ranges. They include large A- and I-type plutons, pyroclastic deposits and clusters of smaller rhyolitic to trachytic domes, lavas and shallow intrusions. Three broad age categories are recognised: late Triassic, Cretaceous, and Cenozoic (dominantly Paleogene). Some of the Cretaceous units, and many of the Cenozoic units exhibit enrichment in high field strength and rare earth elements. The Peak Range Volcanics are the most highly enriched but significant potential exists in other units if more thorough sampling can be completed and more highly fractionated rocks found. More detailed geological mapping, combined with expansion of the geochemical, geochronological and isotopic database is required to understand the distribution and crustal-scale controls on peralkaline magmatism.

Key words: Rare earth elements; high field strength elements; new economy metals; peralkaline volcanics; Queensland.

INTRODUCTION

Igneous rocks are important sources of rare earth elements (REE) and other high field strength elements (HSFE) such as Zr, Hf, Nb and Ta (Chakhmouradin and Zaitsev, 2012; Schulz *et al*., 2017; Verplank *et al*., 2014). Demand for these 'critical' or 'new economy' metals is currently met by few deposits but is expected to continue to rise as their importance for technological development and transition to a clean energy future is realised. Development of new economy metal resources may also be influenced by environmental, social, economic and/or political factors (e.g. Weng *et al*., 2015) and they are therefore considered of strategic importance globally.

Of the igneous rocks, carbonatites and peralkaline rocks are considered the most prospective for new economy metal resources. These rock types host known resources globally and within Australia (see Hoatson *et al*., 2011; Schulz *et al*., 2017). Peralkaline rocks are considered favourable because of their relative enrichment in the more valuable heavy REE (HREE). Deposits in Australia include Brockmans (Western Australia) which is hosted in a Paleoproterozoic shallow marine ash flow tuff (Taylor *et al*., 1995) and Toongi (New South Wales) which is hosted in a Jurassic shallow-level trachytic laccolith (Spandler and Morris, 2016). In addition to these known deposits, recent work has shown significant new economy metal enrichment in felsic domes of the Tertiary Peak Range Volcanics in Queensland (Chandler and Spandler, 2020)

The igneous processes leading to economic mineralisation is a rapidly expanding field of research that has seen significant recent developments. Although the origin of peralkaline rocks is debated, most workers propose extensive fractional crystallisation (i.e. >85%) of very low degree partial melts of enriched or metasomatised mantle (e.g. Chandler and Spandler, 2020; Shao *et al*., 2015; Siegel *et al*., 2018; and see Vasyukova and Williams-Jones, 2020). On a regional scale, such circumstances are commonly associated with rifting or mantle plumes in intracontinental settings. Extensive fractional crystallisation is a critical aspect of generating economic mineralisation but late-stage hydrothermal alteration can also be important for redistribution/concentration of elements and favourable changes to ore mineralogy (van de Ven *et al*., 2019; Vasyukova and Williams-Jones, 2020). Intense weathering of enriched igneous rocks under tropical or sub-tropical conditions is also an important secondary process in the redistribution of REE and other new economy metals (e.g. Li *et al*., 2017). Regolith-hosted deposits have additional advantages in ease of mining and extraction and are important sources of these elements (Cocker, 2014).

REE and other new economy metals are non-traditional commodities and our current knowledge of the distribution of favourable lithologies and potential for economic deposits is limited. In order to keep up with the rising demand and increased exploration for these metals, it is clear that governments require a better understanding of the distribution of peralkaline rocks and the potential for igneous suites to host highly fractionated magmas. This knowledge will assist mineral exploration and, importantly, help with land use planning. Traditionally, these rock types have not been considered as having high economic potential and it is now important that peralkaline rocks and new economy metal potential be considered in land use decisions. In addition, it is important to gain a better understanding of the origin of these rocks in the context of the geological development of eastern Australia. This will aid exploration targeting on a regional scale by providing input for mineral systems models. The inventory of peralkaline rocks in Queensland is a compilation of all known information and is an important first step in evaluating the potential for primary or secondary enrichment.

METHOD

Eastern Queensland has experienced episodes of rifting and plume magmatism in post-orogenic or anorogenic settings favourable for the production of peralkaline magmas since the late Triassic. For the purposes of the inventory, we have therefore compiled the following data and information for late Triassic and younger felsic igneous rocks in Queensland: 1) spatial distribution, 2) lithology and mineralogy, and 3) geochemistry, geochronology and isotopic data. Sources include detailed geological mapping (Geological Survey of Queensland, 2018) and associated reports (e.g. Murray *et al*., 2012; Withnall *et al*., 2009), published papers, theses, internal databases and our own recent work (a full list of references for geochemical data plotted below can be obtained from the author upon request).

Although known peralkaline rocks comprise a very small component of late Triassic and younger igneous suites, we compiled full datasets from rocks in this age range in order to: 1) assess trends across the compositional spectrum, 2) evaluate the potential for suites to host peralkaline and/or highly fractionated, REE-enriched rocks, and 3) identify areas that require more data. Here we present some preliminary insights from the volcanic and shallow-level intrusions while compilation for larger intrusions is on-going.

INSIGHTS FROM THE COMPILATION

Felsic igneous rocks of late Triassic and younger age are distributed along a broad belt stretching > 650 km between the Bowen region north of Mackay and the southern Border Ranges (Figure 1). They include large A- and I-type plutons and extensive pyroclastic units as well as clusters of smaller rhyolitic to trachytic domes, lavas and shallow intrusions. Some are well-known but the majority have very little geochemistry (particularly REE data), geochronology or detailed mapping available for study. Three main age groups are recognised: late Triassic, with ages of ca. 225 to 230 Ma, Cretaceous (dominantly early Cretaceous ca 120-105 Ma, with sub-ordinate late Cretaceous ca 75 Ma), and Cenozoic (dominantly Paleogene) with a progression of ages from ca 35 to ca 23 Ma.

Late Triassic igneous units are voluminous but mainly restricted central areas (Figure 1). These units were emplaced during a transitional period following the cessation of subduction-related magmatism in this area (Purdy *et al*., 2012). The most extensive units are associated with large caldera complexes (e.g. Agnes Water Volcanics; Aranbanga Volcanic Group) that have associated, late-stage (resurgent) intrusions. Rock types are dominated by voluminous rhyolitic ignimbrites, lavas, domes and associated autoclastic deposits.

Late Triassic volcanic rocks span the basalt to rhyolite compositional spectrum and alkali content is relatively low (Figure 2a). Parts of some units reach peralkaline compositions at high SiO_2 content (Figure 2b) but overall, HSFE and REE contents are low (Figure 3). In general terms, the western-most units (Winterbourne Volcanics and parts of the Aranbanga Volcanic Group) are more peralkaline and include samples with higher Zr (up to ca 1000 ppm) and total REE (up to ca 375 ppm) At higher degrees of fractionation (i.e. SiO_2 content or Rb/Sr ratio) separation between high and low Zr groups is observed, suggesting that at least some magmas may have progressed along a fraction pathway in which zircon crystallisation was supressed. At even higher degrees of fractionation, such magmas may become more strongly enriched in HSFE and REE.

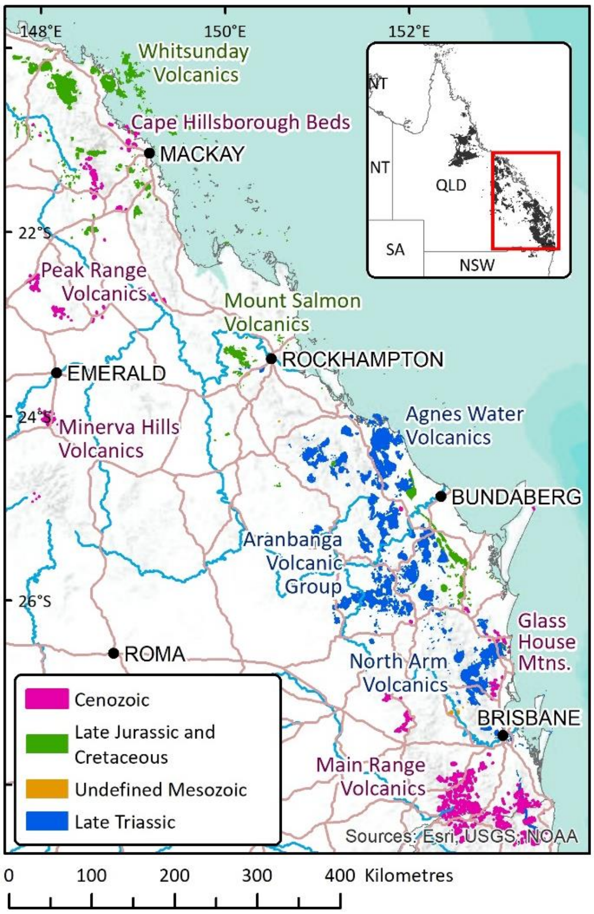

Figure 1. Distribution of felsic igneous rocks of late Triassic or younger age in Queensland. Major units are labelled and coloured by age grouping.

Cretaceous igneous rocks primarily occur in northern areas and are most abundant in the Bowen-Mackay area (Figure 1). They are dominated by rocks emplaced during the early Cretaceous as part of the Whitsunday Large Igneous Province and associated continental rifting (Bryan *et al.*, 2012). The northern-most unit (Whitsunday Volcanics) is well-described (Bryan *et al*., 2000) and dominantly comprises welded dacitic and rhyolitic ignimbrites emplaced in both intra- and extra-caldera environments intercalated with basaltic and silicic lavas. Cretaceous units farther south include trachytic and rhyolitic flows, tuffs and breccias of the Mount Salmon and Wycarbah Volcanics west of Rochampton and prominent trachytic and rhyolitic domes of the Mount Hedlow Trachyte east of Rockhampton. The latter is one of few late Cretaceous units, being emplaced at ca 75 Ma (Cohen, 2007). Another significant component of the Cretaceous group is shallow-level intrusions interspersed in and adjacent to the Bowen Basin. The Mount Ramsay Trachyte is a prominent example and forms a tabular, moderately dipping sill of medium- to coarse-grained syenite with an interesting mineralogy comprising k-feldspar, arfvedsonite, aegirine, nepheline, natrolite and analcite.

Major element geochemistry (including relatively low alkali content) of the Whitsunday Volcanics is similar to that of the late Triassic rocks (Figure 2a). Data for other Cretaceous units are less abundant but appear to follow a different trend and include trachytic and phonolitic compositions (Figure 2a). Peralkaline rocks in the Cretaceous age group are restricted to units other than the Whitsunday Volcanics. The Mount Ramsay Trachyte forms a distinct peralkaline group at ca 60-62% SiO_2 (Figure 2b) and some samples from the Mount Salmon Volcanics, Mount Hedlow Trachyte and Mount Cooper Trachyte also plot in this field. Parts of these units are also relatively enriched in HFSE and REE with compositions approaching those of the Peak Range Volcanics (Figure 3). This also distinguishes them from the Whitsunday Volcanics.

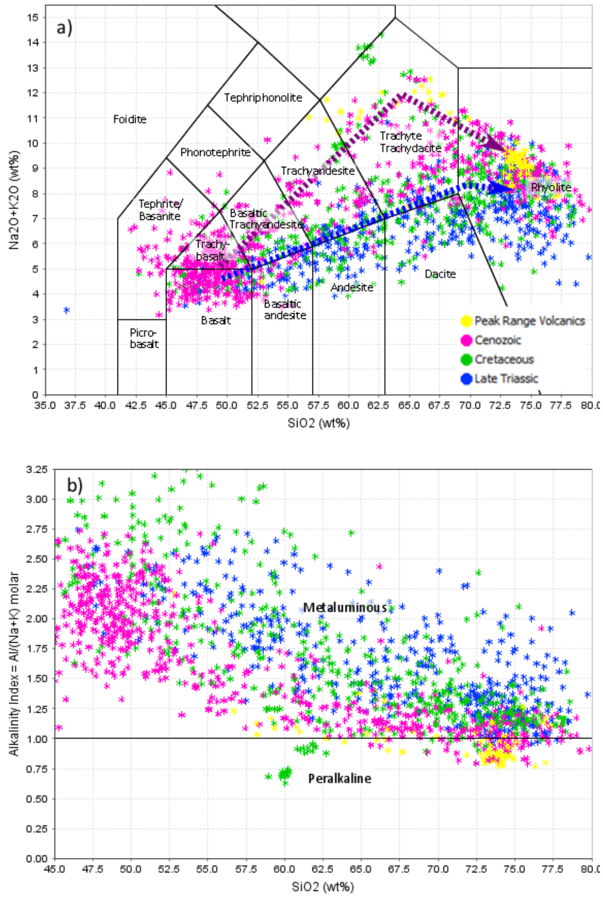

Figure 2. Major element geochemistry of late Triassic and younger volcanic rocks grouped by age. The Cenozoic Peak Range Volcanics are highlighted as a separate group for comparison. a) TAS (Le Maitre *et al*, 1989) showing two main trends, b) Alkalinity index versus SiO_2 (Frost and Frost, 2008).

Cenozoic igneous rocks are laterally extensive in Queensland and are dominated by basaltic lavas. Felsic rocks are more restricted in distribution but occur in scattered localities between Mackay and the southern Border Ranges and as far west as areas around Emerald (Figure 1). These rocks are primarily associated with eroded central volcanoes and exhibit well-defined age progression resulting from movement of the Australian plate over a mantle plume during the Cenozoic (see Cohen *et al*., 2013). Detailed age data for central volcanoes show two trends: one extending from Cape Hillsborough (ca 33 Ma) through Nebo, Peak Range and Springsure to Buckland (ca 27 Ma) and the other extending from Fraser Island (ca 30 Ma) through the Glass House Mountains to the Main Range (ca 24 Ma).

The geology of individual central volcanoes, including the felsic components, is well-described (e.g. see ; Chandler and Spandler, 2020; Cohen, 2007; Cohen *et al*., 2013; Ewart *et al*., 1987; Ewart and Grenfell, 1985; Johnson, 1989; Shao *et al*., 2015). Depending on the level of exposure, felsic components are dominated by either rhyolitic to trachytic domes, tabular flows and associated breccias, or laterally extensive tuffs and ignimbrites. Compositions are heterogeneous with peraluminous and peralkaline rocks occurring in the same suites. Where detailed work and petrogenetic modelling has been completed (e.g. Chandler and Spandler, 2020; Shao *et al*, 2015), peralkaline rocks are generally interpreted as very high degree differentiates (via fractional crystallisation) of mantle melts with peraluminous rocks attributed to crustal contamination.

In some areas (e.g. the Fassifern Valley adjacent to the Main Range Volcanics) significant quantities of shallow-level intrusions are also exposed revealing the complexity of the shallow plumbing systems associated with central volcanoes. Rock types in these areas range from gabbros to syenite.

Significant amounts of geochemical analyses from Cenozoic central volcanoes were completed in the 1980s (e.g. Ewart, 1982; Ewart *et al*., 1985; Grenfell, 1984). More complete analyses have been added more recently for the Glass House Mountains (Shao *et al*., 2015) and Peak Range Volcanics (Chandler and Spandler, 2020). The latter dataset includes analyses from southern bodies and is focussed on one peralkaline dome but data serves as a benchmark for HFSE and REE enriched felsic rocks in this study.

Data from central volcanoes span a wide compositional range and are relatively rich in alkalis. Some data plot along an alkalic trend extending from trachybasalt to trachyte before total alkalis decrease at high SiO_2 content (Figure 2a). Many of the high-silica rocks are peralkaline with the Peak Range Volcanics forming a distinct cluster (Figure 2b). These rocks are also highly enriched in HSFE (e.g. Zr up to ca 5670 ppm) (Figure 3a). While other units appear less enriched (i.e. mostly < 2500ppm Zr) most have not been sampled to the same extent. Moreover, some units (e.g. the Glass House Mountains) include samples with total REE contents that are comparable to the Peak Range Volcanics (Figure 3c). A more thorough sampling program for these units is warranted.

The geochemical similarities (e.g. Figure 4) between the Peak Range Volcanics and samples from the Glass House Mountains is interesting because it contrasts other factors that are thought to influence the distribution and composition of magmatism. The Peak Range Volcanics were emplaced at a major crustal boundary between the Thomson and New England Orogen and coincides with a step in lithospheric thickness (see Chandler and Spandler, 2020) whereas the Glass House Mountains are significantly eastward and remote from any such features. Additionally, available data indicate significantly more juvenile Sm-Nd isotopic compositions for the Peak Range Volcanics relative to the Glass House Mountains (cf. Chandler and Spandler, 2020; Shao *et al*., 2015). Investigation of other controls on the distribution of peralkaline magmatism and HSFE and REE enrichment is clearly required.

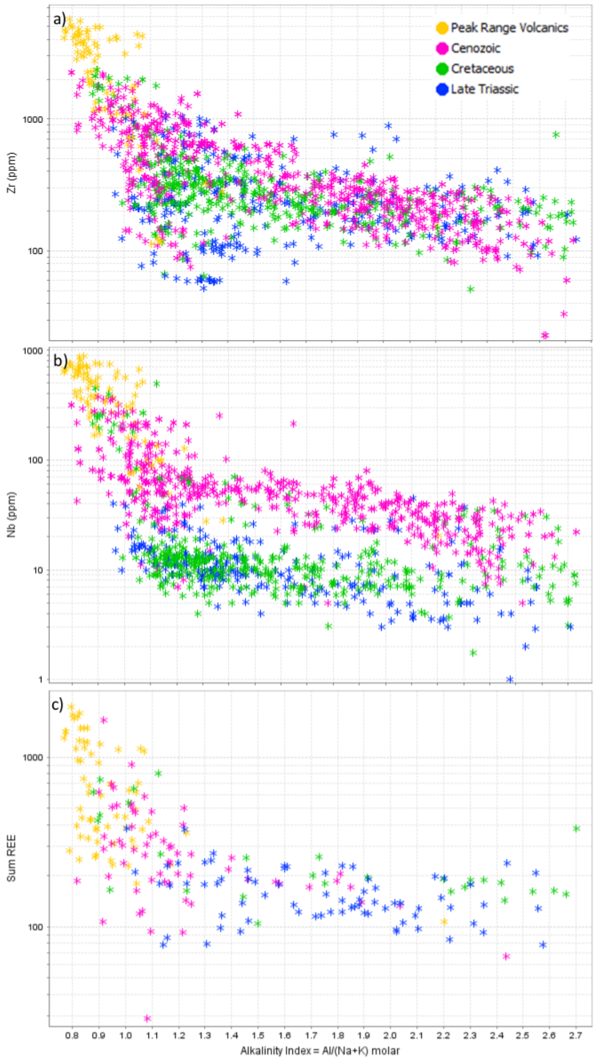

Figure 3. HSFE and sum REE versus Alkalinity Index showing significant differences between age groups. a) Zr content is extreme in some samples from the Peak Range Volcanics, b) Nd clearly distinguishes Cenozoic from late Triassic and Cretaceous volcanics, c) The Peak Range Volcanics, other Cenozoic units and some Cretaceous units (outside of the Whitsunday Volcanics) are rich in REE.

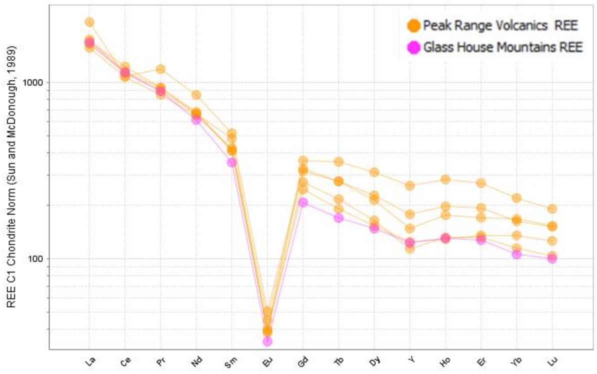

Figure 4. Comparison of chondrite-normalised REE patterns for REE enriched samples from the Peak Range Volcanics (Chandler and Spandler, 2020) and Glass House Mountains (Shao *et al*., 2015).

CONCLUSIONS

Eastern Queensland has experienced episodes of rifting and plume magmatism in post-orogenic or anorogenic settings favourable for the production of peralkaline magmas since the late Triassic. These rocks are distributed in a broad belt between the Bowen-Mackay area and the southern Border Ranges and extending westward to areas around Emerald. Felsic rocks can be divided into distinct late Triassic, Cretaceous and Cenozoic age brackets that are geochemically distinct. Peralkaline rocks are present in each age bracket but are most abundant in the Cenozoic. Enrichment in REE and other critical or new economy metals occurs in the most fractionated Cretaceous units (Mount Salmon Volcanics, Mount Hedlow Trachyte, Mount Ramsay Trachyte) and several Cenozoic units. The Peak Range Volcanics form a distinct, highly enriched group but are effected by sampling bias. Rocks from the Glass House Mountains approach these highly enriched compositions but were emplaced in a different structural/crustal setting. These, and other Cenozoic and Cretaceous units require further sampling and geochemical analysis.

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