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Two distinct origins for Archean greenstone belts

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ABSTRACT

Applying the Th/Yb–Nb/Yb plot of Pearce (2008) to the well-studied Archean greenstone sequences of Western Australia shows that individual volcanic sequences evolved through one of two distinct processes reflecting different modes of crust–mantle interaction. In the Yilgarn Craton, the volcanic stratigraphy of the 2.99–2.71 Ga Youanmi Terrane mainly evolved through processes leading to Th/Yb–Nb/Yb trends with a narrow range of Th/Nb ('constant-Th/Nb' greenstones). In contrast, the 2.71–2.66 Ga volcanic stratigraphy of the Eastern Goldfields Superterrane evolved through processes leading to Th/Yb–Nb/Yb trends showing a continuous range in Th/Nb ('variable-Th/Nb' greenstones). Greenstone sequences of the Pilbara Craton show a similar evolution, with constant-Th/Nb greenstone evolution between 3.13 and 2.95 Ga and variable-Th/Nb greenstone evolution between 3.49 and 3.23 Ga and between 2.77 and 2.68 Ga. The variable-Th/Nb trends dominate greenstone sequences in Australia and worldwide, and are temporally associated with peaks in granite magmatism, which promoted crustal preservation. The increasing Th/Nb in basalts correlates with decreasing $\varepsilon_{\mathrm{Nd}}$, reflecting variable amounts of crustal assimilation during emplacement of mantle-derived magmas. These greenstones are typically accompanied in the early stages by komatiite, and can probably be linked to mantle plume activity. Thus, regions such as the Eastern Goldfields Superterrane simply developed as plume-related rifts over existing granite–greenstone crust – in this case the Youanmi Terrane. Their Th/Nb trends are difficult to reconcile with modern-style subduction processes. The constant-Th/Nb trends may reflect derivation from a mantle source already with a high and constant Th/Nb ratio. This, and a lithological association including boninite-like lavas, basalts, and calc-alkaline andesites, all within a narrow Th/Nb range, resembles compositions typical of modern-style subduction settings. These greenstones are very rare, and were probably only preserved when fortuitously stabilised by granitic magmatism related to the evolution of later variable-Th/Nb greenstones. The rarity of constant-Th/Nb trends suggests that either processes forming them never dominated Archean greenstone evolution, or that such greenstones simply were rarely preserved. Metamorphic mobility of Th renders the Th/Yb–Nb/Yb plot inappropriate for interpreting Eoarchean greenstone units worldwide. Nevertheless, such sequences appear dominated by volcanic rocks that, in modern settings, reflect only the embryonic or initiation stages of subduction. They probably record subduction failure rather than anything resembling modern-style subduction.

1. Introduction

Archean greenstone sequences are typically dominated by subaqueously-erupted basalts, with locally abundant komatiite, andesitic to dacitic volcanic and volcaniclastic units, and fine-grained sedimentary rocks such as chert and banded iron-formation (BIF). These supracrustal sequences typically form structurally attenuated belts partially to totally enclosed by granitic rocks ('granite' and 'granitic' are used here in a general sense to include both high-K compositions and rocks within the tonalite–trondhjemite–granodiorite series).

Discussion on the origins of greenstone sequences, and of Archean crust in general, has historically been polarised between views advocating subduction–accretion processes like those occurring at modern convergent plate margins (e.g. Barley et al., 1984;

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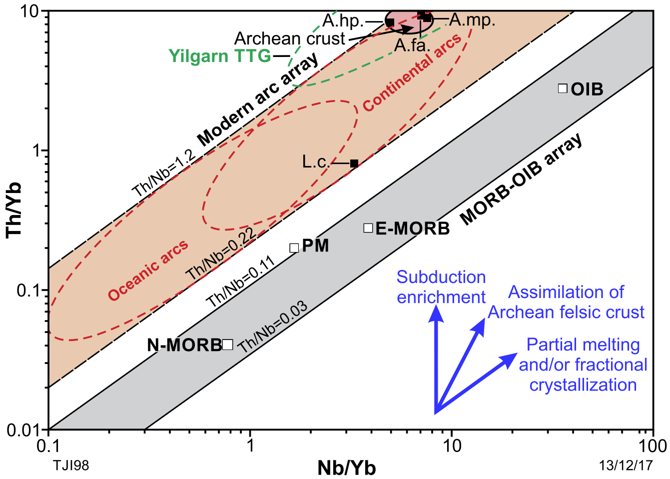

Fig. 1. The Th/Yb–Nb/Yb plot of Pearce (2008) showing main fields as well as composition vectors expected during subduction enrichment of a mantle source, partial melting and crustal assimilation (modified after Pearce, 2008) [values for various mantle reservoirs are from Sun and McDonough, 1989; value for lower continental crust (L.c.) is from Rudnick and Gao, 2003; field for Archean crust encompasses Archean felsic average (A.fa.) from Pearce, 2008, and average high-pressure (A.hp.) and medium-pressure (A.mp.) TTG from the compilation of Moyen, 2011]. The Yilgarn TTG field encompasses >90% of TTG from the Yilgarn Craton with Th/Yb < 10.

Condie, 2005), and non-uniformitarian models advocating an early Earth that remained too hot for modern-style convergent margin processes, but where vertical accretion, perhaps dominated by the effects of mantle-plumes, dominated (e.g. Hamilton, 2003; Stern, 2008; Bédard, 2006, 2017; Bédard et al., 2013; Campbell and Hill, 1988).

A geochemical approach to this debate has been to compare the geochemistry of basaltic and intermediate rocks in greenstone belts with geochemical proxies of modern subduction processes (e.g. Condie, 2005; Pearce, 2008). However, whereas many such proxies identify a 'crustal' signature in the bulk source of many Archean magmas, they cannot uniquely identify the stage in magmatic history at which that signature was added to mantle-derived magmas. This is a critical failure, since central to the whole debate is whether crustal components were added to a mantle source region prior to melting, or were later acquired by mantle-derived magmas during their emplacement within the crust. However, the Th/Yb–Nb/Yb (and similar) plot of Pearce (2008) offers a simple diagnostic means of interpreting how mantle-derived magmas and crust may have interacted. On this plot (Fig. 1), magma batches formed from Th-enriched subduction-modified mantle show extended trends at high and relatively constant Th/Nb ratios typically within a broad field (a modern arc-array) above but parallel with the modern mantle-array. These 'constant-Th/Nb' trends can be interpreted to reflect varying degrees of melting of a subduction-modified source and subsequent fractional crystallisation. In contrast, progressive, or variable, incorporation of crust into mantle-derived magma produces steeper trends with increasing Th/Nb ratios lying between the mantle source composition and a crustal contaminant. These 'variable-Th/Nb' trends are thus dominated by a variety of mixing processes (e.g. assimilation-fractional crystallisation, bulk mixing). Application of this plot to Archean basaltic and andesitic rocks has provided contrasting interpretations with, on the one hand, the view that nearly all Archean greenstone sequence are subduction/accretion related ophiolites (Furnes et al., 2015) and, on the other hand, the view that many Archean greenstones show compositional variations that cannot be used to infer a subduction-modified source (Pearce, 2008; Barnes et al., 2012).

We use the Th/Yb–Nb/Yb plot to interrogate an extensive dataset of ∼2200 high-quality geochemical data from basaltic and intermediate volcanic rocks in greenstone belts of the Western Australian Yilgarn Craton and compare the results to a similar treatment of greenstone belts from the Pilbara Craton, to the north. Only analyses containing trace element data determined by ICP-MS are considered. The majority of these samples have been collected by, and analysed for, the Geological Survey of Western Australia (see Supplementary Appendix 1). Other data sources are given in Barnes et al. (2012). The dataset was screened to remove analyses with MgO $\geq$ 18 wt% (anhydrous) to exclude komatiites, which are widely regarded as plume-related. No silica filter was applied, although analyses with $SiO_2 \geq 63$ wt% are distinguished (open symbols on most figures) from lower silica samples (basalt to andesite – closed symbols on most figures). Less significance is placed on the high-silica rocks because saturation in accessory phases in high-silica magmas potentially adds additional and less-predictable influences on compositional trends, and because such samples may, in any case, be direct crustal melts. Our data analysis reveals clear and systematic distinctions between greenstone belts of different age, geographic location and lithological assemblage. Within the caveat that our study deals only with greenstone chemistry, we suggest that the results discussed here require a reinterpretation of the geological evolution of the Yilgarn Craton and have implications for greenstone evolution throughout the Archean globally.

2. Geological setting

2.1. Yilgarn Craton

Greenstone belts of the Meso- to Neoarchean Yilgarn Craton have been divided between seven terranes based on distinct sedimentary and magmatic characteristics, geochemistry, and age (Cassidy et al., 2006) (Fig. 2a). We concentrate here on the two regions of the Yilgarn Craton for which extensive sets of high-quality geochemical data exist, and for which a reasonably detailed stratigraphy has been established. These regions include the Kalgoorlie and Kurnalpi Terranes forming the western portion of the Eastern Goldfields Superterrane (EGST) and the Murchison Domain forming the western part of the Youanmi Terrane. The EGST is further subdivided into tectonostratigraphic domains (Cassidy et al., 2006), but we refer here instead to geographically constrained greenstone belts (Fig. 2a).

The Youanmi Terrane also includes the Southern Cross Domain, which separates the Murchison Domain from the EGST. Both domains include older greenstone stratigraphy, comprising poorly exposed 2.99–2.85 Ga and 2.82–2.74 Ga sequences dominated by basaltic and high-Mg basaltic rocks with subordinate felsic volcanic rocks, interlayered with BIF. Komatiite is rare in the north (e.g. Chen et al., 2005), but forms a significant undated component in the southern part of the Southern Cross Domain (Perring et al., 1996). These early (2.99–2.74 Ga) greenstones are unconformably overlain by 2.73–2.71 Ga greenstones locally dominated by fine to coarse clastic rocks and felsic volcanic rocks, but also locally including basaltic and high-Mg basaltic units. The better exposed 2.82–2.71 Ga stratigraphy of the Murchison Domain includes the Norie Group and overlying Polelle Group, unconformably overlain by the Glen Group (Van Kranendonk and Ivanic, 2009; Van Kranendonk et al., 2013). There is considerably less stratigraphic and age control on greenstones in the Southern Cross Domain, although it appears to show many lithological similarities to the Murchison Domain.

Greenstones of the EGST range in age from 2.71 to 2.66 Ga, although in very rare instances there is evidence for remnants of older successions. Such older remnants apparently underly-