Geochemistry and tectonic setting of basalts from the Eastern Goldfields Superterrane

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A database of more than 650 whole rock analyses on basaltic rocks from the Eastern Goldfields Superterrane has been compiled from the literature and from public-domain datasets. The data falls into three distinct geochemical categories: a High-Th Siliceous Basalt group, a Low-Th Basalt group and an Intermediate-Th Basalt group. The Low-Th Basalt group shows SiO_2 values between 50 and 53 wt%; Al_2O_3 around 15 wt%; elevated Cr and Ni; MgO mostly between 5.5 and 8 wt%; and flat REE–HFSE patterns with slight depletion in Th and minor positive and negative Nb anomalies. The High-Th Siliceous Basalt group has high SiO_2, commonly >54 wt%; MgO between 6 and 9 wt% with higher values reflecting presence of accumulated olivine or pyroxene; low Fe and Ti compared with Low-Th Basalt group; depleted Ni for given Mg#; enriched LREE and Th, combined with strongly negative Nb anomalies and mantle-like Zr/Nb, Nb/Y, Al/Ti and HREE ratios. The Intermediate-Th Basalt group is intermediate between these two end members in almost all respects. All three groups are represented across the entire Eastern Goldfields Superterrane.

The most widespread group, the Low-Th Basalt, is remarkably homogeneous across terranes and domains. It is interpreted as the Archean analogue of plume-head related Large Igneous Province basalts, showing a close match to flood basalts associated with late-stage continental rifting. The High-Th Siliceous Basalt group displays a distinctive geochemical signature, which is evidently unique to Archean greenstone terranes. Derivation by contamination during fractionation of komatiites, probably deep in the crust, and followed by mid-crustal homogenisation in magma chambers, is the most likely hypothesis.

Basalts with characteristic island arc signatures such as Nb depletion and low Ni and Cr contents have not been recorded in the Eastern Goldfields Superterrane. This poses a significant challenge to uniformitarian models, which attempt to explain the evolution of the entire east Yilgarn craton in terms of modern arc accretion tectonics.

Distribution of mafic and ultramafic mafic magmatism across the superterrane at *ca* 2700 Ma can be explained by emplacement of a major driving plume under the “lid” of the Youanmi Craton. The keel of thickened, buoyant lithosphere under the archon diverted the plume head towards the craton margin, where it induced continental rifting. Voluminous eruption of plume-tail komatiite was concentrated and focused through this zone of rifting along the eastern margin of the Youanmi craton in the Kalgoorlie Terrane, while plume-head basalts and less voluminous komatiites were erupted over a much wider area.

Keywords: Archean, basalt, komatiite, mantle plume, Yilgarn, geochemistry, tectonics

INTRODUCTION

The nature of Archean geodynamic processes is a subject of major debate, both in terms of whole Earth tectonics as well as for individual cratons and terranes[1]. The main point of controversy has been whether plate tectonics operated in the Archean in anything approaching its modern form. This debate is fuelled, in part, by the fact that Archean granite–greenstone terrains have elements that are both common to modern active continental margins, e.g. widespread mafic to felsic volcanism with calc-alkaline and adakitic components (Barley *et al.* 2008; Polat *et al.* 2008; Wyman *et al.* 2008), large-scale strike-slip structures, and abundant granitoids (Champion & Sheraton 1997; Czarnota *et al.* 2010); but also elements that are distinctly different from their proposed modern counterparts, e.g. komatiites and other manifestations of plume volcanism (Campbell & Hill 1988), predominantly low-pressure metamorphism (Brown 2008), lack of accretionary prisms and scarcity of andesites (Hamilton 1998, 2003). The controversy is fuelled by a shortage of constraining data from some cratons, allowing a wide range of plausible inferences to be made from limited information, and by the different emphasis some workers place on some aspects of the geology at the expense of others.

Nowhere is the debate regarding the style of Archean tectonics more extreme than for the eastern Yilgarn Craton of Western Australia, where two substantially different types of model have been applied:

1. Partial melting of the mantle in extensional settings such as intracratonic rifting that involves lithospheric extension initiated by a thermal anomaly in the mantle (Archibald *et al.* 1978, 1981; Groves & Batt 1984; Hallberg & Giles 1986; Campbell & Hill 1988; Hammond & Nisbet 1993; Passchier 1995). This thermal anomaly has been ascribed to a mantle plume, and prolonged development of volcanic sequences and granites to the conductive relaxation of the associated thermal anomaly (Campbell & Hill 1988).
2. Convergent plate margin (subduction-related) tectonic settings involving magmatism in an arc and related extensional basin settings based on comparisons with well-documented Phanerozoic convergent margins (Barley *et al.* 1989, 2008; Drummond & Defiant 1990; Swager *et al.* 1992; Morris & Witt 1997; Kositcin *et al.* 2008).

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[1] Note that in this paper terrane is used to denote pieces of crust with distinct geological histories, whereas terrain is used to denote a geological area without any tectonic inference

Poor exposure over large parts of the craton has partly been responsible for the development of these radically different models, and a limited amount of geochemical and geochronological data has also played a part. This is particularly true for those models developed prior to a rapid expansion of geochemical, geophysical and isotopic data over the last twenty years. Currently, most workers agree that some form of arc-accretion tectonics was responsible for the growth of the eastern half of the craton, known as the Eastern Goldfields Superterrane (Morris & Witt 1997; Cassidy *et al.* 2006; Barley *et al.* 2008; Czarnota *et al.* 2010). These models are principally based on the following pieces of evidence:

1. parts of the stratigraphy of volcanic successions and geochemistry of felsic volcanic rocks changes abruptly across the strike of late tectonic strike-slip shear zones;
2. some intermediate to felsic volcanic successions have calc-alkaline, arc-like geochemical signatures;
3. the late stage of volcanism was accompanied by the craton-wide emplacement of calc-alkaline (high-Ca) granites, interpreted as the products of subduction zone-related arc-type magmatism;
4. Sm–Nd model age maps of the craton (Champion & Cassidy 2007) show a distinct younger (more juvenile) composition for rocks of the Eastern Goldfields Superterrane than terranes to the west of the Ida Fault (an inferred terrane boundary); and
5. late-tectonic clastic basins that are fault-bounded against inferred terrane boundaries and have similarities with modern foreland basins (Krapez *et al.* 2000).

All of the arc-accretion models of formation for the Eastern Goldfields Superterrane tend to skirt around one salient fact, however: the proposed different terranes all have a common early history of mafic–ultramafic volcanism, much of which has characteristics strongly suggesting derivation from mantle plumes (Campbell *et al.* 1989; Lesher & Arndt 1995). This would imply extensive interaction of plumes with arcs, a model that has been popular in the Archean literature particularly on the Superior province (Wyman & Hollings 1998; Hollings & Wyman 1999; Hollings *et al.* 1999; Wyman 1999), but which is at odds with observations in the modern Earth. Active mantle plumes and arcs nowadays have a strongly antithetic relationship, with plumes being located either within plates, or at mid-ocean ridges such as Iceland (Campbell 2007). Plume products may be juxtaposed with arc volcanisms due to tectonic impingement of oceanic plateaus on convergent margins, such as the Caribbean–Columbian Plateau (Kerr *et al.* 2002), but simultaneous eruption of arc and plume magmas in the same place is virtually unknown in modern settings.

Two questions are central to the interpretation of Archean crustal evolution in the East Yilgarn Craton:

1. To what extent do the volcanic assemblages in the Eastern Goldfields Superterrane geochemically resemble modern arc and plume rocks?
2. How do the spatial and temporal relationships of different volcanic rock types in the Eastern Goldfields Superterrane resemble those seen in modern tectonic environments?

In this contribution, we focus on the major and trace element compositions of the basaltic component of the Eastern Goldfields Superterrane volcanic assemblage, with the objectives of defining the major geochemical groupings, and finding the best match between these groupings and those found in the Phanerozoic record.

Archean basalts

A large number of previous papers deal with the geochemistry of Archean basalts (Arndt & Nesbitt 1982; Arndt & Jenner 1986; Arndt 1991; Lesher & Arndt 1995; Hollings *et al.* 1999; Kerrich *et al.* 1999a, b; Polat *et al.* 1999; Hollings & Kerrich 2000, 2006; Polat & Kerrich 2001, 2002; Kerrich & Xie 2002; Manikyamba *et al.* 2004; Pearce 2008), and several deal specifically with the Eastern Goldfields Superterrane (Redman & Keays 1985; Arndt & Lesher 1992; Lesher & Arndt 1995; Said & Kerrich 2009, 2010a, b; Said *et al.* 2010, 2011). All of the published Eastern Goldfields Superterrane studies are restricted to the Kambalda Formation in the southern portion of the Kalgoorlie Terrane. In recent years, a large body of high quality geochemical data across the entire Eastern Goldfields Superterrane has become available in the peer-reviewed literature, in public-domain databases and from a number of previously unpublished site-specific studies. The approach taken here is to compile all of these data sets, and conduct a rigorous comparison with modern environments based on the vast and comprehensive University of Mainz GeoRoc database at < http://georoc.mpch-mainz.gwdg.de/georoc/> (Sarbas 2008). To a degree this approach follows on from previous classification systems which attempt to diagnose tectonic environments based on high field strength element combinations such as Ti–Zr–Y and Nb–Th–Zr (Pearce & Cann 1973; Meschede 1986; Agrawal *et al.* 2008; Pearce 2008). This study has taken the more probabilistic approach of comparing Eastern Goldfields Superterrane data populations with data density clouds for different Phanerozoic environments, using a variety of robust, alteration-resistant elements.

Data Sources and methodology

The Eastern Goldfields Superterrane data set is taken from a number of published sources cited above, from the large public-domain database released as the final report of Australian Minerals Industry Association project P763 (Barley *et al.* 2006), and from a number of previously unpublished CSIRO studies. Data sources and localities are summarised in the Appendix, Table A1.

In the case of the GeoRoc data, as with any very large data compilation, there are difficulties and uncertainties associated with data quality, and variable precision of different analytical techniques with time, particularly for elements such as Nb and Th present at low ppm or sub ppm levels. The approach taken here is to restrict the dataset to analyses published since 1999, where data are reported for Th, Nb, Zr and most of the REE group, and also to eliminate suspected low precision data based on reporting intervals (e.g. analyses where Th and Nb are reported at intervals of 0.5 ppm or more are rejected). Some individual analyses with highly erratic REE–HFSE patterns on multi-element spidergrams have been discarded. Numbers of “surviving” analyses in each of the main tectonic categories – island arcs, oceanic plateaus – along with estimated number of sites are given in the Appendix, Table A2. Given the vast number of citations (well over a thousand) and data sources involved we have not attempted to identify or credit them all, and the reader is referred to the GeoRoc website for further details.

In the case of the Eastern Goldfields Superterrane data set, individual basalt and basaltic andesite samples have been selected from a larger compilation of all publically available geochemical data on Eastern Goldfields Superterrane greenstones, based on the following geochemical criteria to discriminate essentially basaltic compositions: SiO_2 between 46 and 56 wt%; Al_2O_3 between 10 and 20 wt%; MgO between 3 and 15 wt%; FeO between 5 and 20 wt%; $Na_2O + K_2O$ <5 wt%; TiO_2 less than 1.75 (to eliminate rocks with accumulated Ti-rich oxide phases) and reported analyses for Th, Nb, Zr, Y and REE, subject to the same considerations as the GeoRoc data, giving a total of 612 individual samples. (A few additional samples are included which do not satisfy all these criteria but which contain high-quality PGE data). There is a concentration of data from the southern Kalgoorlie Terrane, but data are distributed over most of the exposed are of the Eastern Goldfields Superterrane. The data set includes outcrop and drill core samples, and includes both intrusive and extrusive facies. Mafic intrusive bodies outside greenstone belts are excluded.

The choice of elements and ratios used in the following comparisons is based on two main criteria: relative immobility during the pervasive alteration, which affects almost all Eastern Goldfields Superterrane greenstone rocks; and relative invariance of element ratios during simple low-pressure crystal fractionation processes. Particular incompatible trace element ratio–ratio plots, such as Zr/Nb *vs* Nb/Th, Th/Yb *vs* Nb/Yb, Nb/Y *vs* Zr/Y and Gd/Yb *vs* La/Sm, have been widely used in studies of mafic volcanic petrogenesis in Archean and younger rocks, e.g. (Meschede 1986; Kerrich *et al.* 1999a; Condie 2003, 2005; Pearce 2008), and these are employed here. Oversimplifying somewhat, Zr/Nb and Nb/Yb are proxies for subduction related processes involving retention of Nb in the source during slab melting (Condie 2003, 2005); La/Sm and Th/Nb are indicative of input of “continental” components, either introduced into mantle sources or assimilated during assimilation and fractional crystallisation (AFC) processing; and Gd/Yb and (with reservations) Al/Ti are proxies for depth of melting and presence or absence of garnet in source regions (Arth *et al.* 1977; Herzberg & Ohtani 1988; Herzberg & Ohara 1998). The magnesium number, molar % Mg/(Mg+Fe), is used as a proxy for degree of fractionation, in preference to MgO, for the reason that MgO ceases to vary monotonically with fractional crystallisation in plagioclase-saturated systems.

Eastern Goldfields Superterrane stratigraphy

The sample distribution across the EGS is shown in Figure 1, and representative stratigraphic columns with ages for the three sampled terranes, Kalgorlie, Kurnalpi and Burtville, in Figure 2. Sampling is biased towards the Kalgoorlie terrane (310 samples) as compared with the Kurnalpi (264) and Burtville (44) terranes. Kalgoorlie terrane samples are predominantly from the 2710–2695 Ma Kambalda sequence. Kurnalpi sampling is dominated by basalts from the 2710–2680 Ma sequence (Welcome Well, Murrin Murrin, Melita) associated with abundant andesitic, dacitic and rhyolitic volcanism (Barley *et al.* 2006). Burtville samples are predominantly from the *ca* 2800 Ma Duketon Domain. Hence the Kalgoorlie and Kurnalpi sample sets (and the Agnew–Wiluna and Gindalbie subdivisions of Kalgorlie and Kurnalpi, respectively) are age-equivalent over an interval of 10–20 Ma, while the Burtville dataset is about 100 Ma older (Pawley *et al.* 2012).

EASTERN GOLDFIELDS SUPERTERRANE MAFIC ASSOCIATIONS

Major, minor and trace element compositions of the entire Eastern Goldfields mafic data set are plotted in Figure 3, subdivided by terrane. The data set defines a wide range in major element compositions, particularly in SiO_2, but includes a number of distinct groupings, which form the basis for much of the following discussion. Broadly, Al_2O_3 and TiO_2 show expected negative correlations, and Ni and Cr positive correlations with Mg#. Incompatible element ratios, incorporating REE and high field-strength elements (HFSE) define linear arrays, compared with idealised fields and mantle source components from Condie (2005) and Pearce (2008) in Figure 3 (I, j) (All normalising factors for trace element ratios in this paper are based on the primitive mantle estimate of McDonough & Sun 1995).

Based in part on previous stratigraphic and geochemical studies (Redman & Keays 1985; Lesher & Arndt 1995; Said & Kerrich 2010a; Said *et al.* 2010) and on clustering within the dataset, the Eastern Goldfields Superterrane mafic array is divided into three distinct groups: Low-Th Basalts (LTB), High-Th Siliceous Basalts (HTSB) and Intermediate Th basalts (ITB). (The term “group” rather than “suite” is preferred, as “suite” presupposes a petrogenetic relationship that should not be assumed at the outset). These groups are represented by “type” stratigraphic units in the southern Kalgoorlie Terrane: respectively, the Lunnon Basalt, the Paringa basalt (excluding the low-Si Paringa component identified by Said & Kerrich 2009) and the Devon Consols Basalt (Archibald *et al.* 1978; Lesher & Arndt 1995). The groups are defined primarily on the basis of ratios of highly incompatible elements to moderately incompatible Ti.

Particularly clear distinctions and consistent clusters of ratios are observed on plots of Th, Nb, Zr and La *vs* TiO_2 (Figure 4). Also shown on Figure 4 are data from Said & Kerrich (2010b) for samples from “type localities” of the Paringa, Lunnon and Devon Consols basalts in the southern Kalgoorlie Terrane, identified by the stratigraphic unit. Strong correlations and distinctive trace element ratios are observed within each group. The groups are defined by the value of Th/Ti, with the additional proviso of inclusion of all samples from the type locality units.

No stratigraphic correlation is implied by this scheme; all three groupings are present throughout the Eastern Goldfields Superterrane, in units of different ages (Figure 2). In addition, a fourth group, komatiitic basalts (KB), falls within the set of geochemical criteria used to extract “basaltic” compositions from the Eastern Goldfields Superterrane database. This group is defined by a combination of geochemistry (Al/Ti ratio 0.75–1.1, and MgO content 10–18 wt%) and location within known sequences of true komatiites; by using this terminology we do not intend to exclude the possibility that the other groups may or may not have komatiitic as opposed to tholeiitic affinities. The widely used term “siliceous high-magnesian basalt” (Redman & Keays 1985; Barnes 1989; Sun *et al.* 1989) is avoided, at least for now, on the grounds that the Low-Th Basalt, High-Th Siliceous Basalt and Intermediate-Th Basalt groups have a wide range of overlapping MgO, and also that MgO content may be greatly influenced by the presence of phenocryst or cumulus olivine or pyroxene.

Geochemical characteristics of the different groups are evident in Figure 5, where the same dataset plotted in Figure 3 is recast according to group rather than location. The comparison of the groups with the GeoROC data clouds plotted in Figure 5 are discussed in detail below, and the following sections describe the essential features of the individual groups.

Low-Th Basalt group.

The Low-Th Basalt group occurs across all terranes, and includes samples ranging from as old as 2960 Ma in the Burtville terrane (Hall, pers. comm. 2011) to 2705–2690 Ma in the Kalgorlie and Kurnalpi terranes. Low-Th Basalts in their best-known locality, the Lunnon Basalt between Kalgoorlie and Kambalda, consists primarily of non-vesicular aphyric pillow basalts with massive sheet flows. It is interpreted as forming in submarine mafic plains facies on pre-existing continental crust (Arndt *et al.* 2008), and forms the substrate to the extensive Kambalda Komatiite unit. Rocks of this geochemical affinity are found throughout the entire southern half of the Kalgoorlie Terrane, encompassing both extrusive and high-level intrusive settings, and compositional equivalents are widespread across the entire Eastern Goldfields Superterrane, commonly but not exclusively associated with komatiites (Fig. 1).

The group extends over a wide range of major element compositions, attributable largely to low-pressure crystal fractionation, but has a tightly constrained range of incompatible trace element ratios. A large part of the range in Low-Th Basalt compositions can be attributed to low-pressure crystal fractionation process, generating anomalously Mg-rich and Ti-rich cumulates.

The general features of the Low-Th Basalt group can be summarised as follows: a typical tholeiitic Fe-enrichment trend at SiO_2 values between 50 and 53 wt%; moderate Al_2O_3 around 15 wt%; distinctly elevated Cr and Ni; MgO mostly between 5.5 and 8 wt%; and flat REE–HFSE patterns with slight depletion in Th and very minor positive and negative Nb anomalies (Figure 6). These are typical features of extensive sequences of Archean tholeiites reported in greenstone belts elsewhere, particularly in the Superior Province (Kerrich *et al.* 1999a; Hollings & Kerrich 2006).

The spatial variability of Low-Th Basalt group rocks across the entire Eastern Goldfields Superterrane at around 2.7 Ga is shown in Figure 7, where samples are subdivided according to the terrane–domain–belt subdivision shown in Figure 1 with some specific localities broken out. Only those samples from the 2710–2690 age ranges within the Kalgoorlie and Kurnalpi Terrane are shown. The most notable characteristic is the remarkable spatial consistency and lack of systematic variation, with some minor exceptions. The Kalgoorlie Terrane data set has a systematically slightly higher, although overlapping, population of Gd/Yb_n and La/Sm_n values compared with the Kurnalpi Terrane. The Kurnalpi Terrane contains a slightly higher proportion of low $(Nb/La)_n$ samples. The lack of high Mg# samples in the Gindalbie domain may be down to the very limited extent of sampling.

Considering also the older Burtville Terrane sequence plotted in Figure 3, the conclusion is that the Low-Th Basalt Group represents a characteristic and restricted range of magma compositions erupted over extensive areas at two (at least) distinct periods around 2710–2700 Ma and 2800–2790 Ma.

High-Th Siliceous Basalt group

The High-Th Siliceous Basalt group is characterised by the Paringa Basalt, which in its type area between Kalgoorlie and Kambalda forms the upper part of the Upper Basalt Unit (Figure 2). Here it comprises a mix of pillows and massive flows, some of which are thick and internally differentiated (Lesher 1983). Lavas commonly show characteristic variolitic textures, generally interpreted as devitrification-related spherulites (Hanski 1993; Fowler *et al.* 2002). Pyroxene micro-spinifex textures and glomerophyric olivine are common (Said & Kerrich 2009). High-Th Siliceous Basalt group rocks also form distinctly layered shallow sills with pyroxene-rich lower cumulate layers and leucogabbro upper layers, including the Mt Monger sills (Williams 1971), the Defiance Dolerite (Lesher & Arndt 1995), the Vivien Dolerite in the Agnew–Lawlers area (Figure 1) (unpublished data) and probably the Mt Thirsty and Ora Banda sills, both of which contain broad zones of anomalously elevated Pt and Pd within pyroxenitic cumulates (Barnes & Hill 1991). Geochemically equivalent rocks are relatively uncommon but occur in a number of localities across the Eastern Goldfields Superterrane (Figure 1).

The group spans a range of major element compositions from high-silica basalts to magnesian andesites, and like the Low-Th Basalt group includes a component of fractionates and cumulates from shallow-level sills. The general characteristics are high SiO_2, commonly >54 wt%; MgO between 6 and 9 wt% with higher values reflecting presence of accumulated olivine or pyroxene; relatively low Fe and Ti compared with Low-Th Basalt group; distinctly depleted Ni for given Mg#, not matched by depletion in Cr; strongly enriched LREE and Th, combined with strongly negative Nb anomalies and mantle-like Zr/Nb, Nb/Y and HREE slope (Figures 4, 5). HFSE ratios are very strongly clustered despite a wide range in Mg#, Cr and Ni. Among the higher Mg# rocks, most are strongly Cr enriched with weakly enriched Ni, consistent with the presence of accumulated pyroxene in the lower portions of differentiated sills or flows. These major element compositions broadly overlap the komatiitic basalt group, but differ markedly in their Th–LREE characteristics.

A further distinctive feature of the High-Th Siliceous Basalt group is a highly consistent, mantle-like value for $(Al/Ti)_n$ (Figure 8), in all but a small subset of samples that has restricted $(Th/Ti)_n$ (between 9–14), and widely variable $(Al/Ti)_n$ (1.2– 3.0) that can be explained as plagioclase cumulates in layered sills. The narrow range in $(Al/Ti)_n$ ratio in the main cluster is identical to that considered to be distinctive for Munro-type komatiites as typical of the Eastern Goldfields Superterrane; i.e. high degree partial melts that left no aluminous phases in their melt residue.

High-Th Siliceous Basalt group rocks have characteristically undepleted Pt and Pd contents across their range of Mg#, as noted by Redman & Keays (1985) and Said *et al.* (2011). This magma group was evidently never sulfide-saturated. However, it should be pointed out that more fractionated, low Mg# equivalents to more fractionated, PGE-depleted components of the Low-Th Basalt suit have not been analysed for PGEs.

Intermediate-Th Basalt group

The Intermediate-Th Basalt group appears to be transitional between the Low-Th Basalt and High-Th Siliceous Basalt in almost every respect (Figures 4–6): major element chemistry, highly incompatible element contents and ratios including depth of Nb anomalies, PGE contents, and Ni and Cr contents. The only possible exception to this principal is in the HREE, where the Intermediate-Th Basalt group has almost identical ratios and abundances to Low-Th Basalt, but distinctly higher abundances than High-Th Siliceous Basalt (Figure 6b), a feature which may be attributable to the higher abundance of cumulate rocks in the High-Th Siliceous Basalt group.

Spatial and temporal distribution of the Eastern Goldfields Superterrane mafic–ultramafic volcanic groups

The spatial distribution of the three mafic groups, along with the outcrop pattern of komatiites (Barnes & Fiorentini 2011), is shown on Figure 1. Within the limitations of available sampling, it is evident that all three groups are present in most if not all of the major terrane, domain and belt subdivisions of the Eastern Goldfields Superterrane, including the two main age groupings of *ca* 2.7 Ga in both the Kalgoorlie and Kurnalpi terranes, and in the *ca* 2.8 Ga Burtville terrane sequence. The assemblage of komatiites and Low-Th Basalts of the *ca* 2.7 Ga age grouping spans the boundary between the Kalgoorlie and Kurnalpi terranes.

Comparison of Eastern Goldfields Superterrane groups with Phanerozoic basalts

Two different approaches have been taken to make multivariate comparisons between the Eastern Goldfields Superterrane groups and possible Phanerozoic analogues. The first is to compare a variety of X–Y scatter diagrams with data-clouds from specific environments obtained from the filtered and quality-controlled subset GeoRoc database. The second approach, which can be thought of as "data fishing", is to interrogate the entire GeoRoc database including all sampled tectonic settings (MORBs, OIBs, IABs, LIPS etc.) for geochemically similar samples using the critical ranges of geochemical properties, which define the main mass of Low-Th Basalt and High-Th Siliceous Basalt samples.

The data-cloud approach incorporates discriminants used by previous studies attempting to assign tectonic settings to rocks of uncertain affinity (e.g. Pearce & Cann 1973; Kerrich & Wyman 1997; Condie 2003) but recognises that the boundaries between data fields are fuzzy at best. Certain categories such as MORB, OIB and back-arc basalts have distinctive n-dimensional data clouds, but broad areas of overlap. The data-cloud approach is applied here to the previously identified candidates for tectonic setting of Eastern Goldfields Superterrane greenstones: plume-related oceanic plateaus; and arc settings, both continental and intra-oceanic.

Comparison with oceanic plateaus

The geochemical plots for the entire Eastern Goldfields Superterrane mafic group are compared in Figure 5 with data density contours on GeoRoc data for 469 samples of Phanerozoic oceanic plateau basalts. (The blue contour outlines 70% of the data, and the yellow contour about 50%). The match with the Low-Th Basalt group is generally strong, particularly for the following: Mg# *vs* Al_2O_3, FeO and TiO_2; $(Gd/Yb)_n$ *vs* $(La/Sm)_n$ (i.e. shape of the REE profile); and the relative proportions of the HFSE Zr, Nb, Th and Y, elements that have been widely used as discriminators of tectonic setting (Meschede 1986; Condie 2003; Agrawal *et al.* 2008; Pearce 2008). The Nb/Yb ratios in the Low-Th Basalt group are slightly low, although the range of $(Nb/Th)_n$ is similar to the plateau dataset; all these ratios are close to mantle values. Silica contents in the Low-Th Basalt group are slightly high, and Cr and Ni contents are typically 50% higher for the same Mg#, a distinctive characteristic of Archean basalt groups noted by Arndt (1991). The High-Th Siliceous Basalt dataset falls almost entirely outside the 70^{th} percentile field for oceanic plateaus. The Low-Th group overlaps with the main data concentration for oceanic plateaus on the Th/Yb–Nb/Yb plot (Figure 5i), although slightly oblique to the plateau trend.

Comparison with intra-oceanic island arcs (including back-arc basins)

A group of geochemical plots for the entire Eastern Goldfields Superterrane mafic group is shown in Figure 9 compared with data density contours on GeoRoc data for 278 samples of Phanerozoic intra-oceanic island arcs and back arc basins. The match for Low-Th Basalt group rocks is much poorer for almost all elements and ratios except for SiO_2 and TiO_2 relative to Mg#. REE patterns and $(La/Sm)_n$–$(Gd/Yb)_n$ are a reasonable match, but the Low-Th Basalt group lacks the more severe LREE depletion evident in much of the arc dataset. The Low-Th Basalt group is also markedly enriched in Ni and Cr in comparison to the arc data. Most strikingly, the arc group contains a very strong and pervasive signal of Nb depletion evident in $(Nb/Yb)_n$ which is entirely lacking in the Low-Th Basalt group. Insofar as this Nb depletion signature is the characteristic geochemical signature of modern island arcs, this comparison indicates a lack of evidence for island arc basalts in the Eastern Goldfields Superterrane data set.

This conclusion also extends to the High-Th Siliceous Basalt group. While there is some very limited overlap for some major elements, the High-Th Siliceous Basalt group defines an entirely separate region of compositional space from the arc fields in the compatible and incompatible trace elements.

Comparison with continental arcs

It is widely accepted that much if not all of the Eastern Goldfields Superterrane volcanic assemblage was erupted through pre-existing continental crust, so it is important to consider comparisons between the Eastern Goldfields Superterrane basalt assemblage and Phanerozoic continental arcs. The dataset in Figure 10 includes a variety of Andean-style arc settings (Central Andean Belt, Cascades, Mexican and Central American volcanic belts) along with rifted continental margin arcs and marginal basins (e.g. Kamchatka, Philippines – see Appendix for full listing).

Some overlap exists between Low-Th Basalt group basalts and the continental arc dataset for trace elements, insofar as the relatively tight Low-Th array overlaps with the end of a larger arc array in $(Gd/Yb)_n$–$(La/Sm)_n$, and $(Zr/Nb)_n$–$(Nb/Th)_n$. However, $(Nb/La)_n$–$(La/Sm)_n$ fields are significantly different, and the Low-Th Basalt group lacks the distinctive correlation between $(Gd/Yb)_n$–$(La/Sm)_n$ (i.e. uniform downward slope from La to Yb) seen in the arc group. Large differences are evident in major element and compatible element trends, particularly in Al_2O_3, where Low-Th Basalt compositions are much less aluminous for given Mg#. Low-Th group samples are also significantly enriched in FeO, Ni and Cr for given Mg# than continental arc basalts. High-Th Siliceous Basalt samples show more overlap in some major element characteristics, but are even more depleted in Al_2O_3, and show no overlap at all in REE space.

Data Fishing: the Low-Th Basalt group

Results of interrogation of the full GeoRoc data set for Low-Th Basalt-like geochemical parameters are listed in Table 1 along with original data sources, and plotted in Figure 11. It should be emphasised that this data search takes in the entire population of terrestrial basalts from all tectonic environments including oceanic and continental arcs, oceanic and continental large igneous provinces (LIPs), continental rifts, MORBs and OIBs.

The best match in a Cenozoic environment is a group of plume-related tholeiites from the seaward-dipping reflectors on the eastern continental margin of Greenland. These rocks represent the impingement of the North Atlantic LIP plume on the rifting continental margin of the Proto-Atlantic. The match is close for all the critical parameters, the main difference being the universal one that the Low-Th Basalt group basalts have higher Ni (and Cr, not shown) for the same Mg#.

Basalts from the Caribbean–Columbian Plateau – Serrania de Baudo in Colombia, and the Nicoya Complex in Costa Rica – are the next best fit, particularly for REE and major elements, differing from Low-Th Basalt group in having lower Ni, but also larger positive Nb anomalies The Colombian locality is significant in view of the presence of the only known Phanerozoic komatiites at Gorgona Island off the Colombian Coast; these are also considered to be part of the Caribbean–Columbian Plateau (Storey *et al.* 1991). The Gorgona komatiites have extremely depleted trace element chemistry, implying that the observed high Nb/Th in the basalts may reflect this characteristic of the plume source.

Basalts from the Ontong-Java oceanic plateau match well for major elements, but differ in having slightly lower Ni and SiO_2, and slightly higher $(Gd/Yb)_n$. Matches were also found in some Icelandic plume-related basalts, from the Theistaraykir volcanic field in the northern Iceland rift zone; these are the only examples of matches within an ocean island environment, which in this case is part of the same plume which gave rise to the east Greenland LIP.

It is noteworthy that no arc samples of either continental or oceanic affinity are recorded among the "lookalike" population. Without exception, all the matches are from plume related basalts.

Data fishing: the High-Th Siliceous Basalt group

A similar approach for High-Th Siliceous Basalt group compositions was considerably less successful in finding Phanerozoic analogues (Table 2). Applying a strict set of parameters based on the observed limited range of REE and HFSE ratios found one single match in the entire Georoc database: a magnesian andesite from Antofalla in the Central Andean Volcanic Zone. Expanding the search ranges to considerably less restrictive ranges of $(La/Sm)_n$, resulted in 55 hits, which are plotted in Figure 12.

The highest number of matches was found in a group of anomalously Si-enriched, HREE- and Nb-depleted rocks from the Jurassic flood basalt sequence in Dronning Maud Land, Antarctica (Wittenbrink 1997), but these differ in several respects: lower silica (Figure 12a), distinctly higher TiO_2 (Figure 12b), higher total alkalies (Figure 12d), and markedly higher and (Gd/Yb)n and slightly higher Th/Yb ratios at given Nb/Yb ratios (Figure 12e, f). Where the search space is narrowed down to reflect the distinctly low-Ti character of the High-Th Siliceous Basalt group, a few approximate matches are found in a small handful of widely scattered individual samples from a variety of continental and oceanic localities: the Central Andean Volcanic Zone, the Central American Volcanic Arc, the Alaska Peninsula and Aleutian Arc, Kamchatka, the Mexican volcanic belt, the new Hebrides Arc and the Izu Bonin Arc. However, all of these samples differ in some important respects, primarily in having higher $(Gd/Yb)_n$ (Figure 12e) and higher total alkalies (Figure 12d).

This analysis leads to the conclusion that the High-Th Siliceous Basalt group rocks are unique, and no direct Phanerozoic analogues exist. Coupled with their distinctive komatiite-like Al/Ti ratios, this suggests a direct connection between the High-Th Siliceous Basalt group and komatiites, proposed by numerous studies (Redman & Keays 1985; Barnes 1989; Sun *et al.* 1989; Lesher & Arndt 1995) but rejected by Said & Kerrich (2009).

DISCUSSION

Armed with these observations, it is possible to draw some conclusions about the mafic volcanic component of the Eastern Goldfields Superterrane. This provides some constraints on models for tectonic evolution.

Petrogenesis of the Low-Th Basalt group

The Low-Th Basalt group is the Archean analogue of Phanerozoic LIP basalts, and can be confidently interpreted as the product of a mantle plume or plumes, consistent with previous interpretations cited above, and in common with other Archean flood basalt groups from the Superior Province (Kerrich *et al.* 1999a), the Dharwar Craton (Manikyamba *et al.* 2004) and elsewhere. Considering only the younger *ca* 2.7 Ga components, the Low-Th Basalt group has all of the hallmarks of impingement of a plume head LIP on the lithosphere: very widespread eruption of highly homogenous mafic magma. This is entirely consistent with the close association (at least in the Kalgoorlie Terrane) between Low-Th Basalt group basalts and komatiites. The Campbell *et al.* (1989) "heads and tails" model provides a robust explanation, and also explains the distinctive feature of Low-Th Basalt group basalts, their anomalously high Ni and Cr contents. As originally suggested by Arndt (1991), this is a consequence of the Cr, Ni rich komatiite component mixed into the plume head.

The closest match among Phanerozoic plume basalts to the Low-Th Basalt group are not oceanic plateaus, but rather the East Greenland plume basalts (seaward dipping reflectors) associated with the North Atlantic LIP and the early opening of the North Atlantic (Fitton *et al.* 1998, 2000). Bearing in mind the extent of the Low-Th Basalt group across the entire eastern half of the east Yilgarn craton, this provides supporting evidence in favour of a cratonic rift setting for the Eastern Goldfields Superterrane.

Both end-member groups, Low-Th Basalt and High-Th Siliceous Basalt, are entirely unlike anything seen in modern island arcs. The distinctive features of modern arc basalts, i.e. the strongly negative Nb anomalies coupled with generally flat to slightly depleted incompatible element patterns, low FeO and high Al_2O_3 for a given Mg# and low Ni and Cr, are almost entirely absent from the record of Eastern Goldfields Superterrane mafic magmatism. This could be explained away on the basis of different thermal conditions of subduction in the Archean; for example different thermal regimes owing to overall higher ambient mantle temperatures could affect the thermal stability of rutile, the phase generally considered to be responsible for retention of Nb during slab melting. However, Nb is not the only difference, as is evident from Figures 5, 9 and 10; in almost all aspects of major and trace element chemistry – SiO_2, Ni, Cr, and HFSE – the Low-Th Basalt group differs crucially from arc basalts and much more closely resembles plume derived basalts associated with continental breakup.

Petrogenesis of the High-Th Siliceous Basalt group

Although a very small number of modern continental arc samples bear a passing resemblance to High-Th Siliceous Basalt group rocks, other equally similar analogues (none of which are particularly close) also come from plume-related LIPs. The most similar examples are interpreted as continental flood tholeiites contaminated by crustal melts (e.g. Luttinen & Furnes 2000).

The High-Th Siliceous Basalt group, or more strictly the Paringa Basalt type unit, has been assigned to a category of magmas called siliceous high-Mg basalts, a category which has also been taken to include some of the proposed parental magmas to the Bushveld Complex (Hatton & Sharpe 1989). Broadly these have SiO_2 >52 wt% and as high as 58 wt%, MgO ~8–15 wt%, enriched LREE and Th over HREE and Nb, and undepleted Pt and Pd (Redman & Keays 1985; Barnes 1989; Sun *et al.* 1989; Lesher & Arndt 1995; Said & Kerrich 2009; Said *et al.* 2011). Assigning the High-Th Siliceous Basalt group to this category is subject to some uncertainties: in particular, many samples from the Paringa Basalt contain accumulated olivine or pyroxene phenocrysts that result in elevated MgO contents. Leaving this aside, the suggestion has been made that magmas with affinities to High-Th Siliceous Basalts could be an Archean analogue to modern boninites (Hatton & Sharpe 1989; Polat *et al.* 2002), although not necessarily related to subduction (Smithies 2002). This comparison has been considered in detail and rejected by Said & Kerrich (2009) on several detailed lines of evidence: contrasting FeO contents, lack of evidence for high primary water contents, contrasting REE patterns and distinctly different Al/Ti and Ti/Zr ratios. It suffices to add here that no matches to modern boninites were found using geochemical matching parameters considerably less stringent than those listed in Table 2.

On this evidence, the High-Th Siliceous Basalt magmas are not boninites and have no Phanerozoic analogues, or at least none that have been sampled. Like komatiites, High-Th Siliceous Basalt magmas appear to be characteristic of the Archean. This leads back to the question of whether the High-Th Siliceous Basalt group is derived by combined fractionation and contamination of komatiites, the standard interpretation of siliceous high-Mg basalts (Huppert & Sparks 1985; Barnes 1989; Sun *et al.* 1989; Lesher & Arndt 1995). Evidence for this has been a close spatial association with komatiites, evident in Figure 1, and a match of High-Th Siliceous Basalt compositions to modelled AFC fraction trends. Added to this is the evidence of the tightly-clustered, komatiite-like Al/Ti and Zr/Nb ratios of the High-Th Siliceous Basalt group. However, this conclusion has been challenged in recent years.

Bateman *et al.* (2001) argued for an origin of the Paringa Basalt by deep melting in the plume leaving residual garnet, but the distinctive Al- and HREE-depletion signals of this process, as seen in Al-depleted komatiites elsewhere (Arndt *et al.* 2008), are not evident in the High-Th Siliceous Basalt data (Fig. 8). The $(Al/Ti)_n$ ratios and $(Gd/Yb)_n$ ratios are typically close to mantle values, precluding extensive garnet involvement.

Said & Kerrich (2009) modelled an AFC process involving a Kambalda Komatiite starting liquid and an average continental crust contaminant, and obtained good approximations to the Paringa Basalt compositional array for 25–30% contamination, coupled with 35–40% fractionation, mostly of olivine. However, despite this match these authors rejected such an origin on a number of grounds, principally:

1. a lack of potential granitic contaminant with appropriate Nd isotopic signatures to account for the observed isotopic composition of the Paringa Basalt; coupled with a poor match between AFC model trends and known potential upper crustal contaminants such as the Black Flag Beds;
2. a general uniformity of trace element ratios indicative of contamination, such as Nb/Th and La/Sm, and a lack of correlation between these element ratios and total Th or LRE content, and whole rock Mg#;
3. lack of PGE depletion; and
4. age relationships – the Paringa basalt is thought to be approximately ten million years younger than the komatiites (Nelson 1997).

We consider these arguments are not sufficiently robust to justify discarding the hypothesis. Leaving the final point for now, they are considered in reverse order.

It is well established that komatiites arrive in the crust substantially S-undersaturated, as a result of the high degree of melting and negative pressure-dependency of S-saturation (Lesher 1989; Mavrogenes & O'Neill 1999; Fiorentini *et al.* 2010a). Simple addition of a siliceous contaminant and associated drop in temperature does indeed lower the S solubility, but also (unless the contaminant itself is S-enriched) dilutes the S content of the original melt; the net effect is that it is very hard to drive a komatiite melt to S saturation by AFC alone (Li & Ripley 2005, 2009).

Considering the lack of correlation between, for example, Th/Nb and total Th, this argument neglects the effects of low-pressure, high-level fractionation and crystal accumulation, which may be superimposed upon AFC processes that took place deeper in the crust. Addition or subtraction of olivine or pyroxene results in a change in whole-rock Th or La without changing any of the incompatible element ratios. A correlation between Th and Th/Nb would only be expected if all the chemical variance in the rock group occurs as the result of a single AFC episode with no subsequent crystal–liquid fractionation, and if all the samples represented liquid compositions. Given that the High-Th Siliceous Basalt group is known to contain differentiated high-level layered flows and sills, simple fractionation and accumulation are likely be important effects, and hence the lack of correlation is not a robust argument.

The isotopic argument depends on knowledge of potential contaminants. Said & Kerrich (2009) claim that the regional granite population of the Eastern Goldfields Superterrane has a range of ε_{Nd} distinctly above that of the Paringa Basalt. However, the existence of continental crust with a range of ages beneath Kambalda has been established on a range of isotopic evidence (Compston *et al.* 1986; Champion & Cassidy 2007). The range of variability within potential contaminants is too wide to constrain the argument.

The striking coherence of trace element ratios in the High-Th Siliceous Basalt group, evident in Figure 4 and noted by Said & Kerrich (2009), is difficult to explain by AFC processes, particularly if the process is a complex one with multiple contaminants of differing composition, as is likely. AFC processes would be expected to scatter trace element ratios. A possible way around this problem for a model involving crustal contamination of komatiites is to invoke a two-stage process. The initial AFC evolution may have occurred in deep-seated lower crustal magma chambers, accompanied by wholesale convection-driven homogenisation of the resulting magmas. Subsequent emplacement and eruption involved further homogenisation in mid- or upper-crustal magma chambers, accompanied by low-pressure crystal fractionation with little contamination, causing a range in LREE and HFSE contents without greatly modifying the trace element ratios. If the AFC process happened deep in the crust, then the contaminant composition is essentially unknown, and numerical models can neither prove nor disprove the hypothesis. Considering trace element ratios unaffected by low pressure fractionation processes, such as Nb/Yb, Th/Yb etc (Figure 3i), the east Yilgarn basalt population as a whole defines a trend parallel to that expected for contamination by average continental crust, with the High-Th Siliceous Basalt group at the most contaminated end of the trend.

The operation of contamination processes within the komatiites themselves is indicated by the presence of zircon xenocrysts in the komatiites with ages ranging from 3.5 to 2.8 Ga (Compston *et al.* 1986), and by extensive evidence for contamination at high crustal levels in komatiite channels associated with nickel deposits (Barnes *et al.* 1995, 2004, 2007; Lesher *et al.* 2001; Dowling *et al.* 2004; Fiorentini *et al.* 2010b). Given this evidence, it is likely that komatiites assimilated their wall rocks at multiple crustal levels during ascent.

This leaves the age relationship, which is the most persuasive argument against a komatiite-related model. The current view of komatiite in the Kalgoorlie Terrane is that they were erupted over a short time span, probably less than 5 million years, over the entire length of the belt, in a plume-head LIP event, and the Paringa Basalt is about ten million years younger (Nelson 1997, 1998). However, the situation may be more complex. A number of mafic sills, most notably the Golden Mile Dolerite, have distinctly Low-Th Basalt group affinity, but intrude the Black Flag Beds at 2680 ± 9 Ma, making them younger than the Paringa Basalt. This implies that plume activity was continuing, at least in the southern Kalgoorlie Terrane, through Paringa Basalt time and later. Either plume head magmatism in the late Archean continued for a longer period than counterparts in the Phanerozoic, or this particular piece of crust was still interacting with the plume head over the entire period. This is likely; the plume head represents a very large thermal anomaly trapped beneath an initially cool lithospheric lid, and this anomaly would be expected to remain capable of generating mafic melts over tens of millions of years (Campbell & Hill 1988). Periodic rifting and thinning of overlying lithosphere could give rise to multiple cycles of plume head melting. Alternatively, the plume activity following the initial basalt and komatiite outpouring may reflect the ongoing input from the plume tail, which in Phanerozoic plumes characteristically outlasts the very short (1–2 Ma) plume-head LIP event by tens to hundreds of millions of years (Campbell 2007).

The simplest consistent hypothesis for the origin of the High-Th Siliceous Basalt group remains deep-crustal contamination of komatiites, followed by homogenisation in deep-crustal or mid-crustal magma chambers, and further modification by low-pressure fractional crystallisation. There is no obvious way to discriminate geochemically or isotopically between deep AFC-style contamination of komatiite melts by older continental crust, and Said & Kerrich's (2009) model of mixing of a subduction-derived older continental source into the plume head. Plume heterogeneity of the type required by a source model is well established in modern settings. Consideration of the details of the geochemistry, and particularly the komatiite-like Al/Ti ratios of the High-Th Siliceous Basalt group, makes the contamination scenario more plausible. Derivation of High-Th Siliceous Basalt group basalts by source enrichment cannot be disproved, but leaves some important observations unexplained.

If the contaminated komatiite model is correct, then it provides a simple explanation for the lack of Phanerozoic analogues to High-Th Siliceous Basalt group magmas: the lack of komatiite production in cooler Phanerozoic plumes. If the second model applies, then an explanation is required for why Paringa-like compositions are evidently completely absent from the Phanerozoic record, where input of subducted continental material into plume sources is generally accepted as a widespread process to account for the enriched nature of OIB plumes (Campbell & Griffiths 1992; Hart *et al.* 1992; Hoffman 1997).

Petrogenesis of the Intermediate-Th Basalt Group

The Intermediate-Th Basalt group is evidently as widespread as the Low-Th Basalt group, and similarly shows no discernible spatial variability in composition. In terms of the characteristic trace element ratios such as Th/Ti, Nb/Ti and Nb/La that characterise the Low-Th Basalt and High-Th Siliceous Basalt groups, the Intermediate Thorium Basalt group shows an almost continuous variation between these end members, and on plots such as Th/Yb *vs* Nb/Yb falls in the middle of striking linear trends between the two end members. This linear trend is parallel to that expected for contamination by continental crust, but the variability in Al/Ti ratio is similar to that seen in the Low-Th Basalt group and wider than that in the main cluster of High-Th Siliceous Basalts. This leads to a preferred interpretation of origin by variable degrees of deep crustal contamination of Low-Th Basalt group basalts.

Significance for tectonic models of the Eastern Goldfields Superterrane

Modern Low-Th Basalt group analogues are exclusively plume related. The characteristic plume-head assemblage of Low-Th Basalt group basalts and komatiites extends across the entire Eastern Goldfields Superterrane, particularly in the 2.7 Ga rocks, which constitute the bulk of the greenstone package.

Current arc-accretion models suggest that the mafic–ultramafic magmas were emplaced into a back-arc setting, behind the coeval Kurnalpi arc, where volcanic assemblages include rocks that bear a close petrographic and geochemical similarity to modern calc-alkaline andesite arc rocks (Barley *et al.* 2008). However, there is no evidence in the Kurnalpi Terrane or anywhere else in the Eastern Goldfields Superterrane for basaltic rocks with the characteristic Nb-depleted, low-Ni, low-Cr signal of island arc basalts, and the low-Th basalt populations from the Kalgoorlie and Kurnalpi Terranes are essentially indistinguishable from one another (Fig. 3). The arc model for the Kurnalpi Terrane then turns on the question of whether the Kurnalpi andesites can only be formed in calc-alkaline arcs, and not by AFC processes from plume basalts. This is a question that requires further examination, but which can partly be answered by investigation of Phanerozoic and even some other Archean analogues, which show that calc-alkaline felsic magmas are not exclusive to arc settings (e.g. Hooper *et al.* 2002; Willbold *et al.* 2009; Leclerc *et al.* 2011).

Current models of arc accretion based primarily on subduction processes (Barley *et al.* 2008; Czarnota *et al.* 2010) acknowledge the existence of early plume magmatism, but do not come to grips with the scale of the problem. Scale is in fact the problem: the cartoon cross sections of Czarnota *et al.* (2010) show the presence of a hypothetical plume component in a back-arc rift above a down-going slab, occupying a zone about 50 km wide and 100–200 km deep. The plume head anomalies, which are responsible for modern LIP volcanism, are at least an order of magnitude wider than this; typical LIP provinces represent plume head melting over areas of the orders of millions of square km, and typically 2000–2500 km across (Campbell & Griffiths 1990; Self *et al.* 1997; Coffin & Eldholm 2000; Kerr *et al.* 2000; Ernst 2007a, b). Models involving mantle plumes in Archean back arc settings are at the wrong scale by at least an order of magnitude, if not two.

Examples of plume magmatism impinging on arc settings in the modern Earth are rare. Falloon *et al.* (2007) detected enriched (EMI, EMII, HIMU) plume components among a complex mixture of sources in back-arc basalts from the Lau Basin in the southwest Pacific, but this is distinct from the entirely plume-dominated signal seen in the Low-Th Basalt group in that characteristic arc basalt signals are also present in the Lau Basin. A number of examples exist of older continental plateaus or ocean islands drifting into convergent margins and interacting with subduction zones, e.g. the Galapagos plume track and the southern Central American arc (Gazel *et al.* 2011), and the Caribbean Plateau and neighbouring arc systems (White *et al.* 1999), but this is fundamentally different from the models proposed for the Eastern Goldfields Superterrane.

The alternative is that the essential first stage in development of the Eastern Goldfields Superterrane is a major plume-driven continental rifting event, on the lines envisaged by Campbell & Hill (1988). Plume impingement on the craton drives continental rifting, controlled by the location of pre-existing sutures (Hill 1991). The magmatic cycle begins with eruption of plume products onto a pre-existing crust of calk-alkaline affinity, followed by development of calc-alkaline-like volcanic assemblages developed in local areas of foundering of dense hydrated mafic crust. Further development of this argument awaits detailed consideration of the geochemistry of the felsic and intermediate rocks across the Eastern Goldfields Superterrane.

Distribution of komatiites and plume-head basalts

Komatiites and Low-Th Basalt group basalts share a very similar distribution across the Eastern Goldfields Superterrane (Figure 1). Whereas the Low-Th Basalt group evidently shows no compositional variation across the entire Eastern Goldfields Superterrane, the same is not true of komatiites. The komatiite assemblage at *ca* 2.70 Ga shows a general decrease in proportion of extremely olivine-rich, very high MgO cumulate rocks eastward from the Kalgoorlie terrane, although there is no evidence for systematic change in the MgO content of the komatiite magmas themselves. The most highly magnesian rocks, restricted to the Kalgoorlie terrane are olivine adcumulates, formed in high-flux flow conduits, which host most of the major nickel sulfide deposits, and mark the locus of maximum emplacement rate of primitive komatiite magmas (Barnes & Fiorentini 2012). Furthermore, this belt of high-flux komatiites and its associated ores is spatially related to the edge of the Youanmi Terrane "archon", a block of older cratonised crust defined by the isotopic signal of source rocks to the granitoids (Champion & Cassidy 2007; Begg *et al.* 2010). This relationship, common to many of the world's major nickel sulfide provinces, is attributed by Begg *et al.* (2010) to emplacement of a mantle plume under the archon, and consequent localisation of flow of the plume head to give rise to maximum melting beneath the thinner lithosphere around the edges. Significantly, plume-derived komatiitic volcanism of the same age has also been recognised in the northwestern Youanmi Terrane, indicating the widespread development of the plume head under the Youanmi archon at this time (Van Kranendonk *et al.* in press).

We propose this framework as a plausible explanation for the distribution of Eastern Goldfields Superterrane komatiites and basalt groups (Figure 13). The plume is initially emplaced with its axis somewhere beneath the eastern portion of the Youanmi archon, and flow-lines are deflected towards the archon margin by the sloping base of the lithosphere (Sleep *et al.* 2002; Begg *et al.* 2010). Melting in the plume tail is primarily focused beneath the eastern-rifted margin of the craton, giving rise to a linear belt of komatiites and associated contaminated High-Th Siliceous Basalt derivatives concentrated within the Kalgoorlie Terrane. This interpretation has the Kalgoorlie Terrane komatiite–basalt assemblage as the Archean counterpart of the East Greenland seaward-dipping reflector basalt sequence (Fitton *et al.* 2000; Campbell 2007).

This phase of plume emplacement and tectonism corresponds to the D_0 extension event that is now recognised as the first craton-wide deformation preserved in the Eastern Goldfields Superterrane (Hammond & Nisbet 1993; Swager & Nelson, 1997; Blewett & Czarnota 2007; Czarnota *et al.* 2010). High heat flux associated with the most voluminous and high-flux komatiites, those marked by the olivine adcumulate bodies of the Agnew–Wiluna belt, gives rise to partial melting of older mafic lower crustal material, forming tonalite-trondjhemite-granodiorite (TTG)-type felsic volcanic rocks which were simultaneously erupted with komatiites along much of the northern half of the Kalgoorlie Terrane. These locations of bimodal felsic–komatiitic volcanism are associated with major nickel sulfide deposits at Perseverance, Mt Keith and Black Swan (Dowling *et al.* 2004; Barnes *et al.* 2011).

The plume head extends much further to the east (Figure 13c, d), and is manifest as widespread eruption of Low-Th Basalt group basalts. Slightly deeper melting of the plume head to the west under the craton margin accounts for the slightly higher $(Gd/Yb)_n$ values in the Low-Th Basalt group in the Kalgoorlie Terrane. The flood basalts are locally overlain by the distal portions of extensive komatiite flow fields (Hill *et al.* 1995), originating in and flowing from the Kalgoorlie Terrane.

Two hypotheses are open for consideration for the origin of the Kurnalpi andesite assemblage, which according to dating reported by Czarnota *et al.* (2010) (Figure 2) both pre-dates and post-dates the main *ca* 2705 Ma peak age of plume volcanism: as a pre-existing calc-alkaline subduction-related arc into which the Low-Th Basalt group + komatiite plateau drifted; or as a product of contamination of Low-Th Basalt group basalt with TTG-type granitoid. Resolution of this issue, and further consideration of the degree of affinity between the Kurnalpi andesites and modern arc volcanism, requires detailed consideration of local stratigraphic and volcanological relationships and consideration of possible fractionation–assimilation models.

CONCLUSIONS

The Low-Th Basalt group basalts are typical Ni, Cr-enriched Archean flood tholeiites, representing plume-head volcanism formed in close association with komatiites. The main *ca* 2705 Ma sequence formed a Large Igneous Province, which extended across much of the exposed area of the Eastern Goldfields Superterrane with no discernible lateral variation in composition.

The closest match among Phanerozoic plume basalts to the Low-Th Basalt group are the East Greenland plume basalts associated with the North Atlantic LIP and the early opening of the North Atlantic. This provides supporting evidence in favour of a plume-driven cratonic rift setting for the Eastern Goldfields Superterrane.

The High-Th Siliceous Basalt group represents a distinctive Si- and LILE-enriched, HFSE-depleted geochemical signature, which is evidently unique to Archean greenstone terranes. No direct matches are found in Phanerozoic rocks from any setting, although passing similarities are seen in rare samples from some plume settings and in some continental arcs. High-Th Siliceous Basalt group rocks are found associated with komatiites in most terranes and domains. They are not restricted to the Kalgoorlie Terrane. Derivation by contamination during fractionation of komatiites, probably deep in the crust, and followed by mid-crustal homogenisation in magma chambers, remains the most likely hypothesis.

The Intermediate-Th Basalt group is intermediate between Low-Th Basalt and High-Th Siliceous Basalt end-members, and falls on linear trends between the two groups on trace element ratio plots. The spatial distribution of Intermediate-Th Basalt is almost as widespread as that of Low-Th Basalt group basalt. The petrogenesis of these magmas remains unclear, but the preferred model involves varying degrees of crustal contamination of Low-Th Basalt group basalt sourced from the plume head.

Basalts with characteristic island arc signatures such as Nb depletion and low Ni and Cr contents are absent, or at least have not been sampled. This poses a significant challenge to uniformitarian models, which attempt to explain the evolution of the entire east Yilgarn craton purely in terms of modern arc accretion tectonics (see also Smithies *et al.* 2007).

Distribution of mafic and ultramafic mafic magmatism across the superterrane at *ca* 2705 Ma can be explained by emplacement of a major driving plume under the “lid” of the Youanmi Craton. The base of thickened, buoyant lithosphere under the archon diverted flow-lines within the plume towards the archon margin. Arrival of the plume head, possibly under an original suture or zone of weakness at the archon margin, produced extension and continental rifting. Voluminous eruption of plume-tail komatiite was concentrated and focused along the eastern margin of the Youanmi craton in what became the Kalgoorlie Terrane, while plume-head basalts were erupted over a much wider area. The patchy distribution of komatiites, generally lacking in thick cumulate-filled conduit facies, across the eastern portions of the Eastern Goldfields Superterrane can be accounted for by generally eastward flow of extensive komatiite flow fields sourced from eruption sites in the Kalgoorlie Terrane.

This model is broadly along the lines of that proposed by Campbell & Hill (1988), and does not entirely preclude the possibility of arc development and subsequent accretion outboard from the archon margin. However, the uniform plume character of the mafic–ultramafic association, and the scarcity of demonstrably arc-related mafic magmatism, argue strongly that the mafic component of the Eastern Goldfields Superterrane is not related to subduction processes. This provides an important constraint for holistic models of Eastern Goldfields Superterrane evolution.

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Table 1 Results of interrogation of GeoRoc database for Low-Th Basalt-like geochemical characteristics. Search parameters (left) and matches in GeoRoc database (right).

Table 2 Results of interrogation of GeoRoc database for High-Th Siliceous Basalt-like geochemical characteristics. Search parameters (left) and matches in GeoRoc database (right).

Appendix – data sources

Table A1 Sources of Eastern Goldfields data – localities, references and numbers of samples. Coordinates in Australian Map Grid zone 51.

Table A2 Summary of GeoROC database sources.

Criteria for selection of analyses: “Basaltic” samples defined by SiO_2 >45 and <58 wt%; Al_2O_3 >9 and <20; MgO >3 and <18; FeO >5 and <18. Requires analyses for the following elements: Th, Nb, Zr, Y, La, Sm, Nd, Gd, Yb, reporting intervals <0.5 ppm, analyses published since 1999. Table shows number of sampled localities, and number of samples per locality, for each major tectonic subdivision. Full details on data sources available from GeoRoc website, < http://georoc.mpch-mainz.gwdg.de/georoc/> (Sarbas 2008).

FIGURE CAPTIONS

Figure 1 Location map with major terrane/domain subdivisions and samples showing subdivision into geochemical types

Figure 2 Simplified stratigraphic columns for the various terranes of the Eastern Goldfields Superterrane.

Figure 3 Eastern Goldfields Superterrane basalt data subdivided by terrane. Subscript n indicates normalisation to McDonough & Sun (1995) primitive magma composition. Trace element ratio–ratio diagram (I) after Pearce (2008); diagonal lines enclose mid-ocean ridge basalt (MORB)-ocean island Basalt (OIB) mantle source array; ARC field encloses Cenozoic ocean island basalts. Vector C indicates effect of contamination with average upper continental crust. Trace element ratio–ratio diagram (J) after Condie (2005); open black symbols indicate idealised mantle source components, DEP = depleted mantle, REC = recycled subducted component, EN = enriched mantle, PM = primitive mantle, UC = upper continental crust. Element ratios in I and J are not mantle normalised. In this and following diagrams major element oxides are plotted in wt%, Ni and Cr in ppm.

Figure 4 Trace elements *vs* TiO_2, and TiO_2 and Th/Ti *vs* Mg# (molar MgO/[MgO + FeO]), for the entire Eastern Goldfields Superterrane basalt dataset. Closed symbols indicate samples of Low-Th Basalt, Intermediate Th-Basalt and High-Th Siliceous Basalt from the specific Lunnon, Devon Consols and Paringa Basalt stratigraphic units in the southern Kalgoorlie Terrane.

Figure 5 Eastern Goldfields Superterrane basalt data plotted by geochemical group. Contoured data clouds are shown for intra-oceanic island arcs and back arc basins from the GeoRoc database. The blue contour outlines 70% of the data, and the yellow contour about 50%.

Figure 6 Multi-element variation diagrams for Eastern Goldfields Superterrane basalt groups. Median, 25th percentile and 75th percentile for each element for each group.

Figure 7 Variability within Low-Th Basalt group rocks only, within different terranes and selected specific localities of the Eastern Goldfields Superterrane.

Figure 8 Mantle normalised ratios Th/Ti *vs* Al/Ti for Eastern Goldfields Superterrane basalts

Figure 9 Comparison of Eastern Goldfields Superterrane basalt data with data clouds for intra-oceanic island arcs and back arc basins from the GeoRoc database.

Figure 10 Comparison of Eastern Goldfields Superterrane basalt data with data clouds for continental arcs and marginal basins from the GeoRoc database

Figure 11 Phanerozoic basalts with Low-Th Basalt-like characteristics, by locality, compared with data density clouds on Eastern Goldfields Superterrane Low-Th Basalt group basalts. Search parameters listed in Table 1.

Figure 12 Phanerozoic basalts with High-Th Siliceous Basalt-like characteristics, by locality, compared with data points on Eastern Goldfields Superterrane HTSB group basalts. Search parameters listed in Table 2, Search 2. “Arc Other” includes one or two samples each from the Alaska Peninsula and Aleutian Arc, Kamchatka, the Mexican volcanic belt, the new Hebrides Arc and the Izu-Bonin Arc.

Figure 13 Cartoon for early stages of *ca* 2700 Ma Eastern Goldfields Superterrane greenstone development. (a) Starting plume ascending beneath the Youanmi archon, within few hundred km of original suture with more juvenile eastern Goldfields craton. Plume head is mixture of high-T tail (generating komatiite melts) and entrained ambient mantle (Campbell *et al.* 1989; Griffiths & Campbell 1990). (b) Impingement and flattening of plume head beneath lithosphere, onset of generation of continental rifting centred on original suture, and onset of komatiite and low-Th basalt production. (c) Maximum melt production occurs beneath Youanmi craton margin, controlled by flow of plume along sloping base of craton margin (Begg *et al.* 2010), focusing of predominant flux of komatiite plume-tail melt at craton margin. (d) Plan view of time-frame (c) – widespread eruption of komatiite, Low-Th Basalt (LTT) and associated tonalite-trondjhemite-granodiorite series (TTG) crustal melt products along Kalgoorlie terrane, controlled by presence of inherited through-going trans-lithospheric structures. Low-Th Basalt and less voluminous komatiite eruptions extend ~1000 km east of original plume axis; distal komatiite facies also forming in extensive komatiite flow fields originating in or near the Kalgorlie terrane.