Pb isotopic domains from the Indian Ocean sector of Antarctica: implications for past Antarctica–India connections.

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Abstract

New feldspar lead isotope compositions of crystalline rocks from the Indian Ocean sector of East Antarctica, in conjunction with the review of data from elsewhere within the continent and from continents formerly adjacent within Gondwana, refine boundaries and evolutionary histories of terranes previously inferred from geological mapping and complimentary isotope studies. Coastal Archaean Vestfold and Napier complexes have overlapping compositions and had Pb isotopes homogenised at 2.5 Ga sourced from or within already fractionated protoliths with high and variable U/Pb. Identical compositions from the Dharwar Craton of India support a correlation with these Antarctic terranes. The Proterozoic-Palaeozoic Rayner Complex and Prydz Belt yield more radiogenic compositions and are broadly similar and strongly suggest these units correlate with parts of the Eastern Ghats Belt of India. A strikingly different signature is evident from the inboard Ruker Complex which yielded unradiogenic compositions. This complex is unlike any unit within India or Australia and suggest that these rocks represent exposures of an Antarctic (Crohn) Craton. Compositions from the enigmatic Rauer Terrane are consistent with a shared early history with the Ruker Complex but with a different post-Archaean evolution.

Introduction

Over its 4.5 billion year history, tectonic and magmatic evolution have ensured that part of the Earth's continental crust has been lost to exhumation and erosion while other parts are buried beneath sedimentary cover or, more recently, ice. In many cases, the only way of learning about these parts of the continental crust is by studying the material eroded from them. Identifying signals in the geochemical or isotope compositions of eroded sediments from parts of the continental crust that have been lost or are hidden is made more complicated in some parts of the world, such as Antarctica, by a lack of information about existing exposures of ancient crust. If we wish to maximise our understanding of the evolution of the continental crust then it is necessary to first fully characterise those parts that we can see.

The Pb isotope composition of feldspar reflects the petrogenesis, crustal age and evolutionary history of its host crystalline rocks and can be utilised to map distinct tectonothermal terranes. Classic example studies come from Precambrian gneisses in the Arabian Shield and the southwest United States (Stacey & Stoeser 1983; Wooden & Mueller 1988). In Antarctica, few feldspar Pb studies exist and these are mostly confined to West Antarctica and the Weddell Sea margin of East Antarctica (Wareham et al. 1998; Mukasa & Dalziel 2000; Millar et al. 2001; Loewy et al. 2011; Flowerdew et al. 2012). These studies showed uniformity in feldspar Pb isotope compositions from West Antarctica, irrespective of rock age, composition or location. In East Antarctica, feldspar Pb isotope compositions are strikingly different and Loewy et al. (2011) infer past Laurentia–Antarctica connections in Coats Land, the first study from East Antarctica to produce tectonically significant conclusions utilising Pb isotopic data.

Demand for a more rigorous and complete characterisation of Pb isotope compositions of feldspar from potential source rocks also comes through the rejuvenation of the application of the Pb compositions of detrital K-feldspar as a provenance tool (Tyrrell et al. 2009; 2010). As a relatively labile phase, K-feldspar is susceptible to breakdown (particularly due to chemical weathering) hence is less likely to survive more than a single sedimentary cycle of erosion, transport, deposition and diagenesis (Gwiazda et al., 1996a, b; Tyrrell et al. 2009). K-feldspar provenance studies are effective, therefore, because they can identify that component of detritus that has likely been derived directly from the source and not via an intermediate sedimentary rock (Tyrrell et al. 2012). The age and chemistry of detrital zircons are commonly used to infer sedimentary provenance, yet unlike feldspar, this resistant mineral is prone to recycling from existing (meta)sedimentary rocks in the source region. Zircon recycling is recognised in Antarctica (Goodge et al. 2010) and feldspar provenance studies have been used here to identify the recycled zircon component (Flowerdew et al. 2012).

This paper extends knowledge of the Pb isotopic characterisation of East Antarctica, by presenting feldspar data from crystalline rocks exposed in the Indian Ocean sector of East Antarctica between approximately 50ºE and 80ºE (Fig. 1). The new and existing (Grew & Manton 1979; Yakovlev et al. 1986; Manton et al. 1992; Mikhalsky et al. 2006a) feldspar Pb isotope data are discussed in the context of the tectonic development of the Indian Ocean sector and are compared with data from other regions of Antarctica and from continents formerly adjacent within Gondwana. The comparison constitutes a review that illustrates the role feldspar Pb data may have in resolving some of the outstanding tectonic questions that surround the identification of exotic terranes and the relative importance of 'Grenville' (1.3-0.9 Ga) versus 'Pan African' (0.6-0.5 Ga) events in the geological history of Antarctica (Fitzsimons 2000, 2003; Goodge et al. 2008; Harley 2003; Will et al. 2009; Boger 2011). These new data further help constrain ongoing detrital feldspar provenance studies which aim to improve our understanding of the sub-glacial Antarctic geology.

Geological evolution Antarctica between Enderby Land and Queen Mary Land

The intermittently exposed geology between Enderby Land and Queen Mary Land comprises a complex collage of Precambrian terranes (see review of Boger 2011; Fig. 1). Three terranes (Napier and Ruker complexes and Vestfold Hills) preserve extensive pristine Archaean protoliths and a further two (Lambert and Rauer terranes) contain minor relics of Archaean crust.

Terranes comprising predominantly pristine Archaean protoliths

The Napier Complex comprises predominantly 3.80–2.80 Ga tonalitic and granitic orthogneisses (Harley & Black 1997; Kelly & Harley 2005) which experienced extreme high-temperature granulite-facies metamorphism (Ellis et al. 1980; Harley & Motoyoshi 2000) at *c*. 2.5 Ga (Kelly & Harley 2005; Carson et al. 2002). This was the last pervasive deformation event to affect the terrane. Similarity between the Napier Complex with Archaean rocks in southern India was first suggested by Grew & Manton (1979) and Grew and Manton (1986). More specific correlation with the Dharwar Craton of India (e.g. Veevers 2009) is supported by recent palaeomagnetic results by Mohanty (2011). Other workers (e.g. Rao & Santosh 2011) highlighted the possibility that the Napier and Dharwar were separated in the Late Archaean and are therefore unrelated.

The Vestfold Hills comprise predominantly 2.5 Ga protoliths, which underwent high-temperature metamorphism shortly after their formation (Black et al. 1991; Harley 1993) and, like the Napier Complex, have also largely evaded later tectonism. The Vestfold Hills too are correlated with the gneisses of Peninsular India, although a correlation with the Singhbhum Craton (Veevers 2009) and regions to the NE of India (e.g. Bangladesh region) is also possible.

The Ruker Complex or consists mostly of Archaean protoliths emplaced at *c.* 3.1–3.2 Ga and 2.8 Ga, and deformed and metamorphosed and amphibolite facies at 2.8 Ga (Mikhalsky et al. 2006b, 2010; Boger et al. 2006). These middle Archaean basement rocks are overlain, and now tectonically interleaved with, Late Archaean metasedimentary (≤ 2.5 Ga) and metavolcanic rocks (Mikhalsky et al. 2001; Phillips et al. 2006). Both the basement and the sedimentary cover rocks were then deformed during the Cambrian, associated with the intrusion of minor granitoids (Mikhalsky et al. 2010). The grade of metamorphism during the Cambrian reworking of the Ruker Complex was not high – mostly greenschist- or lower amphibolite-facies (Phillips et al. 2007a, 2007b). The affinity of the Ruker Complex is unclear. Milkhalsky et al. (2010) correlated the terrane with the Vestfold Hills and by inference also the Indian cratons. Phillips et al. (2006) inferred that both the Rauer Terrane (below) and the Vestfold Hills were proximal to the Ruker Complex on the basis of detrital zircon patterns from the Archaean metasediments, whereas Boger (2011) inferred that no correlative rocks exist outside of Antarctica, instead suggesting that the Ruker Complex represents part of a poorly exposed Antarctic Craton (Crohn Craton), which lies toward the centre of the modern continent. Boger's (2011) interpretation is consistent with that of Harley (2003) and Harley & Kelly (2007), who termed the Ruker Complex as an 'inboard' terrane unrelated in formation and event history to the 'outboard' terranes including the distinct Napier Complex and Vestfold Hills.

Terranes with minor relics of Archaean crust

The Lambert Complex is in sheared contact with the Ruker Complex (Boger et al. 2001). It also has a long geologic history and consists of orthogneissic protoliths that date to *c.* 3.52 Ga (Boger et al. 2008). These are however volumetrically minor with the bulk of the terrane defined by Palaeoproterozoic orthogneisses (2.45–2.10 Ga) and paragneisses (Mikhalsky et al. 2006b, 2010; Corvino et al. 2008; Boger et al. 2008). Both were possibly affected by deformation and metamorphism sometime in the Palaeo-Mesoproterozoic, although episodes at *c.* 0.95 Ga and at *c.* 0.53 Ga are more clearly manifested in the geologic record (Corvino et al. 2008, 2011).

Archaean protoliths of the Rauer Terrane include substantial *c.* 2.84–2.80 Ga, and 3.45 Ga components (Harley et al. 1998; Harley & Kelly, 2007). Interleaved with Mesoproterozoic supracrustal units are 1.3–1.0 Ga felsic and mafic units (Kinny et al. 1993) which intruded during high-temperature metamorphism (Harley 1988, 2003). A subsequent and unrelated phase of Cambrian deformation and metamorphism has interleaved possible Neoproterozoic supracrustal rocks (Kelsey et al. 2008) within the Archaean and Mesoproterozoic gneisses (Harley 2003).

Proterozoic terranes

The Rayner Complex in the northern Prince Charles Mountains includes the Beaver and Fisher terranes (Mikhalsky et al. 2006a and references therein). The Fisher Terrane is a c. 1.40–1.20 Ga predominantly mafic volcanic and plutonic complex (Beliatsky et al. 1994; Kinny et al. 1997) interpreted to represent a calc-alkaline arc (Mikhalsky et al. 2001 and references therein). Amphibolite-facies metamorphism, coeval with minor granitoid intrusion, occurred between 1.2 Ga and 0.95 Ga. The adjacent Beaver Terrane of the North Prince Charles Mountains comprises mainly felsic orthogneisses (McKelvey & Stephenson 1990; Fitzsimons & Harley 1992) which intruded Mesoproterozoic protoliths of uncertain age and origin, between c. 1.07 Ga and 0.91 Ga (Carson et al. 2000; Boger et al. 2000; Mikhalsky et al., this volume), during high grade metamorphism. Other Rayner Complex rocks exposed along Mawson Coast of Kemp Land (Fig. 1) have a experienced a more extreme high-temperature granulite-facies metamorphism (Harley 2003) which occurred between 1.15 Ga and 0.92 Ga (Halpin et al. 2011; Kelly et al. 2002; Carson et al. 2000), during extensive charnockite intrusion. Later Palaeozoic events affecting the Rayner Complex are manifested as minor shear zones and pegmatite emplacement (Grew 1978; Black et al. 1983; Clarke 1988; Carson et al. 2000; Boger et al. 2002). The complex is widely correlated with the Eastern Ghats Belt of east India (e.g. Grew and Manton 1986; Grew et al. 1988; Fitzsimons 2000; Bose et al. 2011).

Excluding the Vestfold Hills and Rauer Terrane (above), most of eastern Prydz Bay comprises felsic and mafic orthogneiss and migmatitic paragneiss, which preserve a basement (Søstrene Orthogneiss) and cover (Brattstrand Paragneiss) relationship (Fitzsimons & Harley 1991; Zhao et al. 1995; Kelsey et al. 2008; Grew et al. 2012). Both sequences, here collectively termed the Prydz Belt, were intensely deformed during high grade Palaeozoic metamorphism (Fitzsimons 1997). The orthogneissic basement rocks, with protolith ages between 1.38 Ga and 1.02 Ga (Liu et al. 2009; Wang et al. 2008) also experienced an earlier period of high–grade deformation and metamorphism between 0.97–0.91 Ga (Liu et al. 2009), whereas the paragneiss cover sequences have a maximum depositional age of c. 1.02 Ga (Grew et al. 2012). Rocks from the Grove Mountains have a similar Palaeozoic metamorphic evolution to coastal Prydz Belt, but Proterozoic protoliths are *c.* 0.92 Ga (Liu et al. 2007) and younger than from coastal Prydz Belt. Although late orogenic Palaeozoic granites are an important component throughout of the Prydz Belt (e.g. Liu et al. 2006) its early history has led many authors to suggest an origin in common with elements of the Rayner Complex (see more details in Mikhalsky et al., this volume). It is unclear how far the Prydz Belt extends beneath the ice. Glacial erratics recovered from the Vestfold Hills and Grove Mountains (Zhao et al. 2007) indicate that rocks, which include Archaean protoliths and sedimentary rocks predominatly derived from Archaean sources, have variably been metamorphosed up to eclogite-facies conditions in the Early Palaeozoic. Exposures at the Queen Mary Coast are either equivalents of those exposed in west Australia or are exotic (Black et al. 1992; Sheraton et al. 1993; Fitzsimons 2003; Boger 2011). Protoliths from the westernmost of the Queen Mary Coast exposures are, however, cut by Palaeozoic intrusions and these intrusions could potentially provide a link with the evolutionary history of the Prydz Belt.

Feldspar Pb isotope data

Pb isotopes in feldspar and their behaviour during metamorphism.

In the following sections we discuss the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ feldspar compositions from crystalline East Antarctic rocks. With time, these ratios increase through the radioactive decay of ^{238}U and ^{235}U to ^{206}Pb and ^{207}Pb, respectively, and because the ^{204}Pb isotope is stable. Episodes of crustal differentiation through magmatism and metamorphism fractionate between the parent and daughter (measured by the

^{238}U/^{204}Pb ratio, μ and the ^{232}Th/^{206}Pb ratio, κ) such that terranes of different age and tectonothermal histories evolve differently in Pb/Pb space. Feldspars normally have very low μ and κ values (e.g. Wooden & Mueller 1988; Bodet & Shärer 2001) and so there is limited radiogenic in-growth once Pb is locked into the crystal at about 700°C (Cherniak, 1995) during magmatic or metamorphic crystallisation. Therefore, feldspar compositions not only provide a snapshot of a particular terranes evolution in Pb/Pb space, but also the ability to reveal aspects of its early history prior to the last equilibration event.

There is some uncertainty regarding the behaviour, and particularly the mobility, of Pb isotopes during high grade metamorphism and anatexis, which may hinder the interpretation of data from such rocks. The Pb isotopic composition of anatectic melts, and thus the feldspar that crystallises from it, is controlled by the relative contributions of Pb from low μ and κ minerals (e.g. feldspar) and high μ and κ accessory phases (e.g. zircon) and their Pb content (Finger and Schiller 2012; Hogan & Sinha 1991). Complete Pb isotope equilibrium is not always achieved (e.g. Chavagnac et al. 2001). Pb isotope heterogeneities can result (e.g. Waight & Lesher 2010) and such studies highlight the need for further research in high grade metamorphic terranes. However, extreme disequilibrium is not commonly reported, in keeping with the concept of broad U enrichment of the upper crust through differentiation processes such as metamorphism and magmatism (Zartman and Doe 1981). This suggests that Pb isotopic tracers can be applied, with caution, in terrane analysis.

Comparison of feldspar Pb isotope compositions from similarly aged rocks can thus highlight similar or contrasting evolution histories and help refine terrane models identified from other geochemical and isotopic techniques. Radioactive decay of ^{232}Th to ^{208}Pb evolution is manifested in the ^{208}Pb/^{204}Pb ratio. Th and U can often fractionate during crustal differentiation and episodes of metamorphism, and consequently record different evolutionary aspects (e.g. Möller et al. 1998). Examples of such fractionation are evident in this study, however, for the majority of rocks the two systems appear to broadly cognate, hence we do not discuss the thorogenic Pb system further. Additionally, distinction between feldspar types is henceforth not made because in this study Pb isotopic compositions do not significantly vary between plagioclase and K feldspar within the same sample.

Samples and methodology

A total of 55 samples were selected for feldspar Pb isotope analysis (Fig. 1). Chosen samples represent the main lithological units which encompass the main intrusive and metamorphic events within each of the terranes from the Indian Ocean sector of Antarctica, and sample details are given in Table 1. Samples were, where possible, also selected with the greatest geographical spread.

Pb isotopic analyses were carried out using a New Wave 193 nm Excimer laser attached to a Thermo Scientific Neptune multicollector ICP-MS, housed at the National Centre for Isotope Geochemistry (NCIG), School of Geological Sciences, University College Dublin, following the analytical procedure outlined by Flowerdew et al. (2012). Data was collected using a faraday cup collector configuration. Corrections for gas blank and isobaric interference of ^{204}Hg on ^{204}Pb were made offline. Sample–standard bracketing was employed to monitor and correct offline for mass bias induced fractionation using ^{203}Tl/^{205}Tl measured in NIST 612 glass, assuming a stepped fractionation between each standard, and using the exponential fractionation laws. Polished sections from each sample were imaged under SEM prior to ablation and the Pb compositions of both K feldspar and plagioclase were analysed (totalling 298 ablations from the 55 samples). Results and further analytical details are given in Table 1.

Results

Pb isotope composition of feldspar from the Indian Ocean sector of Antarctica

Feldspar compositions from orthogneisses within the Napier Complex and Vestfold Hills are similar (Fig. 2). $^{206}Pb/^{204}Pb$ values are typically 15-16 and have $^{207}Pb/^{204}Pb$ values that plot well above the average terrestrial Pb isotope growth curve (Stacey & Kramers 1975), suggesting the terranes were variably enriched in uranium early in their histories. Most samples lie along the 2.5 Ga geochron, indicating that the Pb isotopes were homogenised during high-grade metamorphic events at that time and have remained largely undisturbed since. While there is substantial overlap, the Vestfold and Napier feldspar populations are not identical. Orthogneiss samples from both terranes are mostly indistinguishable, however, some samples from the Crooked Lake gneiss and Grace Lake Granodiorite units in the Vestfold Hills have lower μ values than any from the Napier Complex, and result in lower $^{207}Pb/^{204}Pb$ values. Paragneiss samples from the Napier Complex yield much more radiogenic compositions (sample 49606 yielding $^{206}Pb/^{204}Pb$ values of c. 31) that are unique in all of the Antarctic terranes studied. Grew and Manton (1979) report feldspar with high $^{206}Pb/^{204}Pb$ but low U content, suggesting these ratios are unlikely to have resulted from Pb in-growth. These anomalous Pb compositions were shown by (DePaolo et al. 1982) to reflect a long pre-metamorphic history prior to granulite facies metamorphism at c. 2.5 Ga.

Subtle variations in the Pb isotope data within the Prydz Belt seemingly correlate with lithology and geographical location (Fig. 3). Surprisingly, the orthogneiss basement sample from the Steinnes Peninsula (sample SH0698), which has a c. 1.1 Ga protolith age (Wang et al. 2008), yielded higher $^{206}Pb/^{204}Pb$ values than feldspar hosted in adjacent paragneiss cover (samples SH06115, SH0693 and SH0648), which in turn have slightly lower $^{206}Pb/^{204}Pb$ values than late granitic rocks (samples IF88242 and NRL147). The unradiogenic compositions of the younger cover sequence, compared with the older basement orthogneiss, could be explained by contributions to the Brattstrand Paragneiss from older crustal sources as Grew et al. (2012) suggested for a quartzite unit in the Brattstrand Paragneiss on the basis of zircon Hf-Lu and whole-rock Sm-Nd data. With this rationale, the Pb isotope data would seem to suggest that the undated 'basement' from Hovde Island could belong to the younger cover sequence. The Queen Mary coastal samples and the Grove Mountains samples have $^{206}Pb/^{204}Pb$ values which plot between the basement and cover groups obtained from the Prydz Bay coastal rocks. The Pb isotope signature for these regions together with the Prydz Bay late granitc rocks may represent mixtures of basement and cover Pb isotope reservoirs, and tentatively suggest compositionally similar sequences are extensive across the Prydz Belt.

Feldspars from the Beaver Terrane, part of the Rayner Complex, have Pb compositions that are (just) distinct from the Prydz Belt, with the Rayner Complex rocks having generally higher $^{207}Pb/^{204}Pb$ for similar $^{206}Pb/^{204}Pb$ values (Fig. 2). Additionally, variation in the Pb isotope compositions is observed between the different orthogneiss samples. Sample IF8988 of orthopyroxene-bearing banded orthogneiss yielded the highest $^{206}Pb/^{204}Pb$ values of *c*. 21. Orthogneiss from Amery Peaks (sample IF89326) and Mount Bunt (IF89122) yielded lower $^{206}Pb/^{204}Pb$ values of around 18. The remaining three orthogneiss samples are least radiogenic and form a cluster with ^{206}Pb/^{204}Pb values of *c*. 17.9. The significance of these variations is unclear but a scenario like that from the Prydz Belt is possible, where the Pb isotope compositions of the c.980-990 Ma orthogneisses are derived from mixtures of orthogneiss and paragneiss units is possible.

Samples from the Rauer Terrane fall into two distinct groups. Archaean orthopyroxene-bearing felsic gneiss sample SH88191 forms the first group, which although the gneiss is reworked in Palaeozoic events (Harley & Kelley 2007) it preserves an Archaean Pb composition with low ^{206}Pb/^{204}Pb values <14. The second group come from mapped units with late Mesoproterozoic protolith ages and have populations which broadly overlap those from the Rayner Complex and the Prydz Belt. The Rauer Terrane compositions, like those from the Rayner Complex, yield subtly higher ^{207}Pb/^{204}Pb for similar ^{206}Pb/^{204}Pb values than the Prydz Belt rocks. This pattern is consistent with a derivation from a higher μ Pb isotopic reservoir. Variations in ^{206}Pb/^{204}Pb do not correlate with any mapped unit, so the significance of the array of compositions within the second compositional group is uncertain.

Feldspars from rocks within the Ruker Complex, which have yielded Archaean U-Pb zircon ages, yielded a wide range of Pb isotope compositions, with the majority plotting below or on the Stacey & Kramers (1975) growth curve. Feldspars from granite sample 9828-210 are least radiogenic with ^{206}Pb/^{204}Pb values of *c*. 13. Feldspar from granite sample 9828-190 yields slightly more radiogenic compositions, which lie just below the growth curve with ^{206}Pb/^{204}Pb values of *c*. 13.5. Excluding the least radiogenic sample (9828-210), the remaining data form a best fit errorchron which yields an age of 2.9 ± 0.1 Ga (Fig. 2). This age overlaps the last major phase of magmatism and metamorphism to affect the complex and why the feldspars form the errorchron can be explained as a consequence of in-growth from a starting composition similar to sample 9828-190.

Archaean granite gneiss from the Lambert Complex (sample 9828-337) has feldspar compositions indistinguishable from those from the Ruker Complex, and also lies on the c. 2.9 Ga errorchron. The Palaeoprotoerozoic rocks, which are more representative of the Lambert, differ from the Ruker since they plot above the Stacy & Kramers (1975) and the errorchron and so must have been derived from a higher μ reservoir. The Palaeoproterozoic sample analysed from the Mount Newton (granite sample 48145-2) is a good example of such rocks and confirms the presence of the Lambert Complex west of the Mawson Escarpment. The high ^{206}Pb/^{204}Pb values of between 19 and 20 have corresponding ^{207}Pb/^{204}Pb values which lie close to the 500 Ma geochron indicate Pb isotope equilibration during Palaeozoic metamorphism has affected the Palaeoproterozoic rocks from the Mawson Escarpment.

Discussion and comparison within Gondwana

In Figure 2 the Pb compositions of Antarctic feldspar are compared with those from the major crustal terranes of India and Australia. Although data is lacking from large tracts of the Archaean Indian terranes, compositions from the Vestfold Hills and Napier Complex match those from the Dharwar Craton in India and therefore tentatively support connections for these terranes with cratonic peninsular India (Mohanty 2011). The differences in the Pb isotope compositions indicate that the Vestfold Hills and Napier Complex come from different parts of the craton. Archaean rocks from the Rauer Terrane have feldspar Pb isotope compositions which do not match any known rocks from India and hence reinforce evidence that the Rauer Terrane had a very different evolutionary history to neighbouring Vestfold Hills (Harley 2003; Harley & Kelly 2007).

The re-equilibration of Pb isotope compositions within the Ruker Complex at *c.* 2.9 Ma is consistent with zircon geochronology (Boger et al. 2006), which suggests metamorphism in the late Archaean was the last pervasive high grade event to affect the terrane. The sample which has no apparent Pb in-growth after this late Archaean equilibration (Sample 9828-190) has feldspar compositions which are indistinguishable from the pristine Archaean rock within the Rauer Terrane. Although possibly co-incidental, this similarity could also be used to further tectonic models inferring past Ruker–Rauer connections (Mikhalsky et al. 2010). More speculatively, but perhaps more importantly, on the basis of the dissimilarity of feldspar compositions with those from the Yilgarn Craton of west Australia (Qiu & McNaughton 1999), it can be argued that the Ruker Complex is not a fragment of Australia left behind during its separation from India in the earliest Proterozoic. Instead, the feldspars from the Ruker Complex that have low U contents, and so have not suffered from isotopic in-growth, have unique Pb compositions, providing evidence that these rocks represent part of an Archaean or Crohn craton, as was proposed by Boger (2011). Although the Rauer Terrane has some feldspar with compositions that overlap with those from the Yilgarn Craton (Fig. 2), any Australian correlation remains highly speculative until more data are available both from pristine Archaean Rauer Terrane rocks and from possible Indian correlatives.

Despite re-equilibration of the Palaeoproterozoic Lambert Complex samples during the Palaeozoic, their derivation from high-μ reservoirs lends support for models that indicate the Lambert Complex has a different evolutionary history to the Ruker Complex (Boger et al. 2001; 2008; Corvino & Henjes-Kunst, 2007; Corvino et al. 2008). The volumetrically small Archaean elements within the Lambert Complex may indicate that the Ruker and Lambert complexes were interleaved, either in the Palaeozoic or in the Proterozoic.

The rocks from the Rayner Complex mostly have feldspar Pb compositions which overlap those from Domain 3 from the Eastern Ghats Belt of India (Rickers et al. 2001). We view such a strong similarity as verification that these two regions share similar protoliths and have a common evolutionary history, as has previously been suggested on the basis of field and petrographic observations, and from other isotope and geochemical indicators (Fitzsimons 2000). Samples which overlap Domain 2 from the Eastern Ghats Belt of India (Fig. 2) could result from a combination of small degrees of in-growth or from re-homogenisation during the Palaeozoic. Direct correlations of Domain 2 of the Eastern Ghats Belt with rocks from the Pyrdz Bay region could, therefore, be misleading and we do not pursue this argument further.

Compositions from the Prydz Belt are just distinguishable from the Beaver Terrane of the Rayner Complex (generally less radiogenic and lower μ in the Prydz Belt), so the proposed simple model that the Prydz Belt represents protoliths of the Rayner Complex more strongly reworked during Cambrian orogeny (Grew et al. 2012) is not, in general, compatible with the Pb isotope data. For the Fisher Terrane, feldspar Pb isotopic values plot below the Stacey & Kramers (1975) curve. This is consistent with models for their origin within a juvenile intra-oceanic to continental margin arc (Mikhalsky et al. 2001 and this volume).

Terranes from elsewhere in Antarctica have, in general, Pb isotope compositions that are broadly different to those from the Indian Ocean sector (Fig. 4). Compositions outside of the Indian Ocean sector tend to plot on or below the Stacey & Kramers (1975) terrestrial Pb evolution curve, whereas those within the region, with the exception of the Fisher Terrane and Ruker Complex, plot above it. Markedly different, are the feldspar compositions from West Antarctica, which have $^{206}Pb/^{204}Pb$ values of *c*. 18.7 and lie close to the evolution curve (Mukasa & Dalziel 2000; Millar et al. 2001; Flowerdew et al. 2012). This is a reflection of the younger protolith ages for the majority of the West Antarctic accreted terranes and makes them readily distinguishable from all of the East Antarctica terranes (Flowerdew et al. 2012). Mesoproterozoic and Neoproterozoic to early Palaeozoic comparisons are more relevant because of the potential insights they may provide to East Antarctic evolution. Late Mesoproterozoic protoliths in the Maud Belt (Jacobs et al. 1998) of central and western Dronning Maud Land (Fig. 1) formed in an Andean-style arc that developed along the margin of the Kaapvaal Craton of Africa (e.g. Bisnath et al. 2006) and its extension into Antarctica as the Grunehogna terrane (Marschall et al. 2010). The Maud Belt has feldspar compositions from western Dronning Maud Land (Flowerdew et al. 2012) and the Sør Rondane Mountains (Grew et al. 1992) that have lower $^{207}Pb/^{204}Pb$ values at a similar $^{206}Pb/^{204}Pb$ ratio when compared to feldspar from late Mesoproterozoic to early Neoproterozoic rocks from the Indian Ocean sector (Fig. 4). A similar pattern in feldspar composition from these two regions is evident from rocks which have independently determined as Cambrian in age. Until feldspar Pb data are available from this area, it can be assumed the rocks from central Dronning Maud Land will have similar feldspar compositions, as is recorded at either side. Such a distinction between the African-Antarctic rocks (Dronning Maud Land) from Indian-Antarctic (Indian Ocean sector) could be used as further evidence for a separate origin and evolution of these two regions, and could in the future be used as a method for recognising and constraining any extensions of the orogenic belts through the centre of Antarctica (Boger 2011).

The Pb isotope compositions of feldspar from the Maud Belt (Flowerdew et al. 2012; Wareham et al. 1998) are indistinguishable from those from late Mesoproterozoic volcanic rocks from Coats Land reported by Loewy et al. (2011) and Flowerdew et al. (2011). Superficially, this suggests that the Pb data cannot be used to distinguish between the African-Antarctic Maud Belt and the possible Laurentian Coats Land rocks, as was originally suggested by Loewy et al. (2011). A Laurentian connection may, in fact, still be valid although this conclusion is not completely clear on the basis of Pb isotope data alone. As a note of caution, the low-μ values of the possible Laurentian Coats Land Block, the Maud Belt and the low-μ feldspar from exposures of the Antarctic Crohn Craton in the Indian Ocean sector are not distinct but are inferred to reflect different Pb evolution histories that converged on the same end-point.

The possibility that the Gawler Craton extends from Australia through Antarctica to the Shackleton Range (Will et al. 2009; Goodge & Finn 2010) may also be assessed by feldspar Pb-isotope compositions when further data are collected. Palaeoproterozoic gneisses from the Read Mountains in the Shackleton Range plot on the Stacey & Kramers (1975) curve (Flowerdew et al. 2012; Will et al. 2010). Thus, comparison with compositions from Laurentia could be used to test the models for past connections of East Antarctica with Laurentia in the central Transantarctic Mountains (Goodge et al. 2008, 2010) when feldspar Pb isotope data from the central Transantarctic Mountains become available.

Concluding remarks

Pb isotope compositions of feldspar from the inboard Archaean Ruker Complex are distinct from the coastal Archaean terranes of the Vestfold Hills and Napier Complex. The Vestfold and Napier compositions overlap those from the Dharwar craton of India and allow for these Antarctic terranes to have shared evolutionary histories with different parts of cratonic India. The compositions from Archaean components of the Rauer Terrane are consistent with a shared early history with the Ruker Complex, which have feldspar Pb isotope compositions unlike any from continents formerly adjacent within Gondwana. Both regions, the Ruker and the Rauer, may represent exposures of an Antarctic craton that has greater, currently unexposed, extent beneath the East Antarctic Ice Sheet.

The Beaver Terrane of the Rayner Complex, the Prydz Belt and elements of the Rauer Terrane have subtly different feldspar compositions but all of which broadly overlap those from Domain 3 (Rickers et al. 2001) within the Eastern Ghats of India. It is possible, therefore that these regions broadly share common protoliths and a common evolutionary history and thus are correlatives. The Fisher Terrane, however, has very different compositions, in line with an origin as a juvenile oceanic arc, which highlights the complex tectonic and terrane amalgamation history that is preserved in this region of Antarctica.

The varied isotopic compositions of feldspar from the terranes in the Indian Ocean sector highlight the potential effectiveness of Pb isotopes in detrital feldspar as a provenance tool from this sector of Antarctica.

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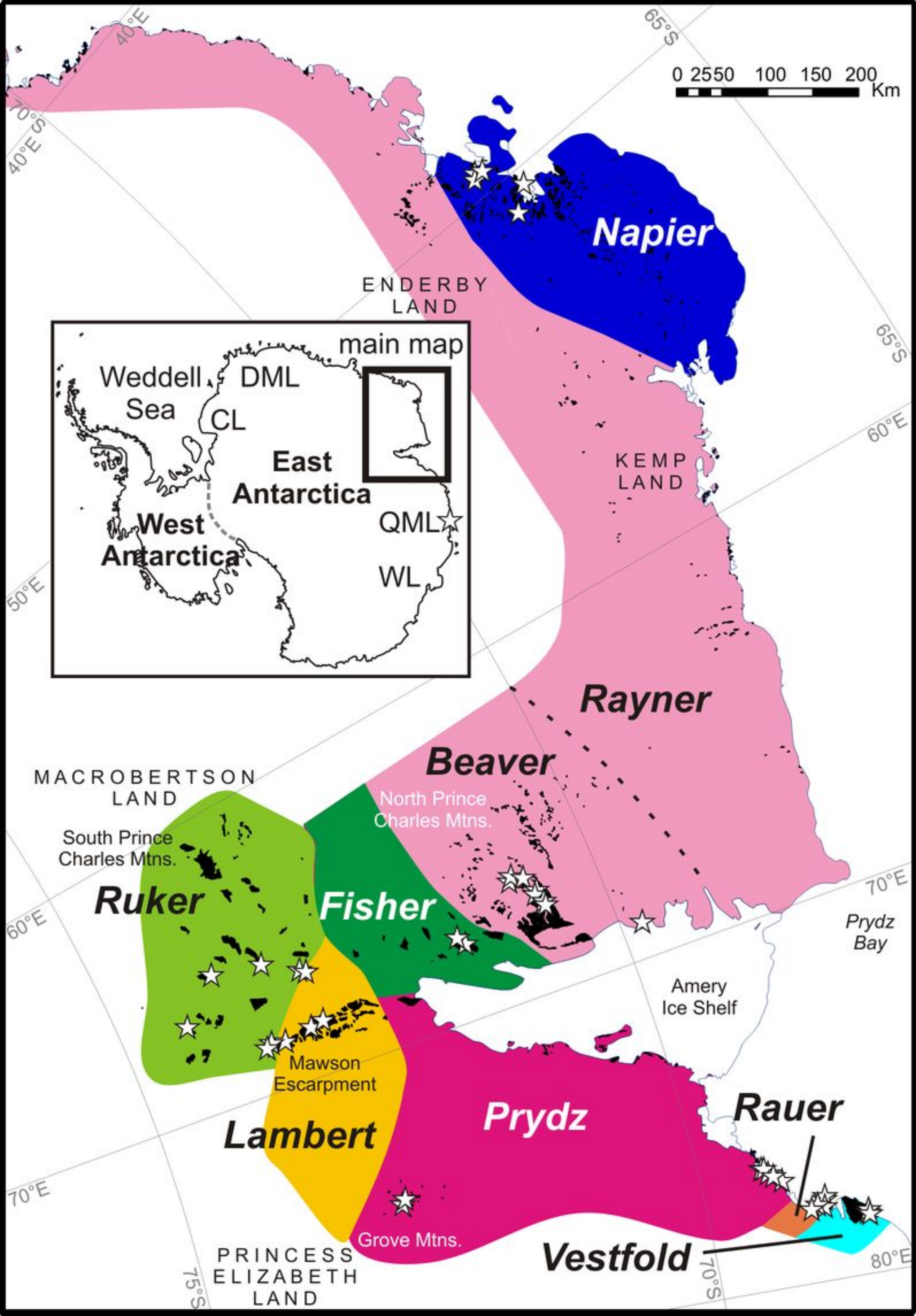
Figure Captions

Figure 1. Sketch geological terrane map for the Indian Ocean sector of East Antarctica. Inset shows location of main map, CL = Coats Land, DML = Dronning Maud Land, QML = Queen Mary Land, WL = Wilkes Land. Grey dashed line indicates geographical boundary between East and West Antarctica. White stars show the localities of samples which feldspar Pb isotope compositions were determined as part of this study. The dashed line separates the Beaver Terrane from the undifferentiated parts of the Rayner Complex.

Figure 2. Feldspar Pb compositions from the Indian Ocean sector of Antarctica. Colour schemes represent craton affinity and correlations. Fields for feldspar compositions from the Dharwar and Singhbhum cratons of India (pale grey labelled with black text) and Yilgarn craton of Australia (grey labelled with black text) are shown for comparison (data from Rickers et al. 2001; Krogstad et al. 1995; Meen et al. 1992; Qiu & McNaughton 1999; Négrel et al 2010). Fields without shading represent feldspar compositions from the Eastern Ghats belt of India (data from Mezger & Cosca 1999; Rickers et al. 2001; Upadhyay et al. 2006a, 2006b, labelled with grey text where abbreviation are as follows: D1 = Domain 1, D2 = Domain 2, D3 = Domain 3 and WA = western alkaline rocks) with the exception of Domain 3 of the Eastern Ghats, defined by Rickers et al. (2001), which is shaded yellow. Compositions from Domain 4 Rickers et al. (2001) are not shown. Blue evolution curve is the terrestrial crustal curve of Stacy & Kramers (1975) grey lines show geochrons for 2500 Ma, 1000 Ma and 500 Ma. Dashed line is the reference line for compositions from the Runker Terrane. Inset top right shows detail of compositions with $^{206}Pb/^{204}Pb$ between 17 and 19. Inset top left shows a Gondwana reconstruction after Powell et al. (1988) showing the proximity of the Antarctic terranes with those in India.

Figure 3. Feldspar Pb compositions from the Prydz Belt. Solid diamonds = Steinnes basement, grey diamonds = Hovde possible basement, grey circles = Brattstrand paragneiss cover, open triangles = late granites, crosses = Grove mountains, and plusses = Mirnyi Station.

Figure 4. Sketch map of Antarctica showing gross feldspar Pb isotope domains. The extents of the fields are guided by other geological, geochemical and geophysical as well as feldspar Pb isotope data. The fields for Archaean to Mid Mesoproterozoic rocks are plotted below left, fields for Late Mesoproterozoic and younger rocks are plotted below right. Colour schemes represent craton affinity and correlations. Blue colours with India, yellow colours with Africa, pink colours with Australia, red with Laurentia whereas green colours represent domains that are unique to Antarctica. Data outside of the Indian Ocean sector are for West Antarctica from Flowerdew et al. (2011), Millar et al. (2001), Mukasa & Dalziel (2000), for Coats Land from Flowerdew et al. (2011), Loewy et al. (2011), Wareham et al. (1998) for the Read and Pensacola Mountains from Flowerdew et al. (2011) and for the Maud Belt from Flowerdew et al. (2011) and Grew et al. (1992). Abbreviations: CL = Coats Land, FT = Fisher Terrane, GC = Grunehogna Craton, LT = Lambert Terrane, MP = Maud Province, NC = Napier Complex, PB = Prydz Belt, PM = Pensacola Mountains, RC = Rayner Complex, RT = Rauer Terrane, RM = Read Mountains, RU = Ruker Complex, VH = Vestfold Hills, WA = West Antarctica.



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CL
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QML
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KEMP
LAND
Rayner
Beaver
MACROBERTSON
LAND
North Prince
Charles Mtns.
South Prince
Charles Mtns.
Ruker
Fisher
Prydz
Bay
Amery
Ice Shelf
Mawson
Escarpment
Lambert
Prydz
Rauer
Vestfold
Grove Mtns.
PRINCESS
ELIZABETH
LAND
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60°E
70°E
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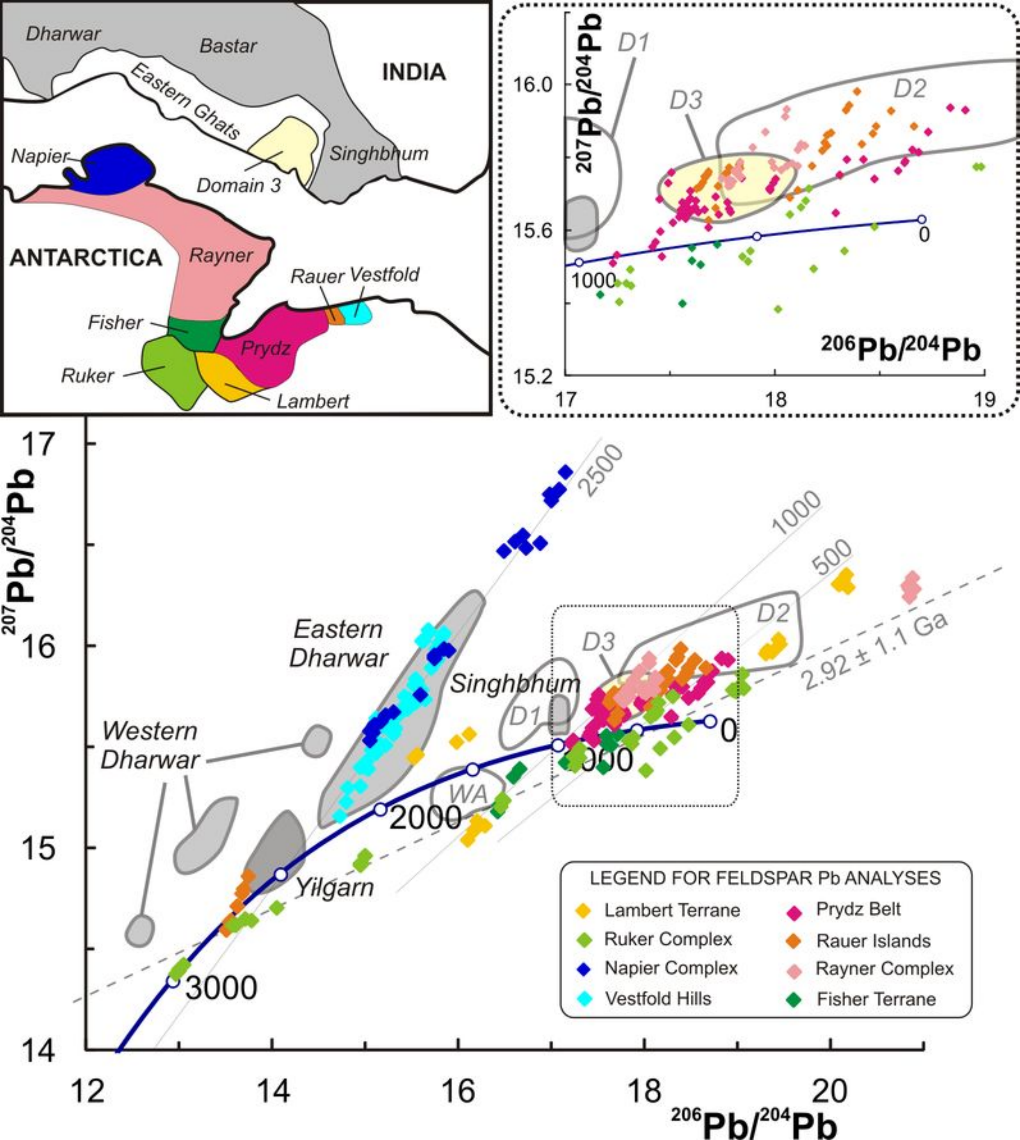
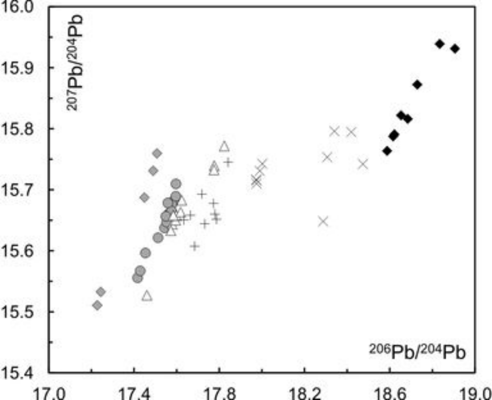
65°S
70°S
75°S



Dharwar
Bastar
INDIA
Eastern Ghats
Singhbhum
Napier
Domain 3
ANTARCTICA
Rayner
Rauer
Vestfold
Fisher
Prydz
Ruker
Lambert
D1
D2
D3
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
1000
0
2500
500
Eastern Dharwar
Western Dharwar
Singhbhum
WA
Yilgarn
2000
3000
2.92 ± 1.1 Ga
LEGEND FOR FELDSPAR Pb ANALYSES
Lambert Terrane
Ruker Complex
Napier Complex
Vestfold Hills
Prydz Belt
Rauer Islands
Rayner Complex
Fisher Terrane



16.0
15.9
15.8
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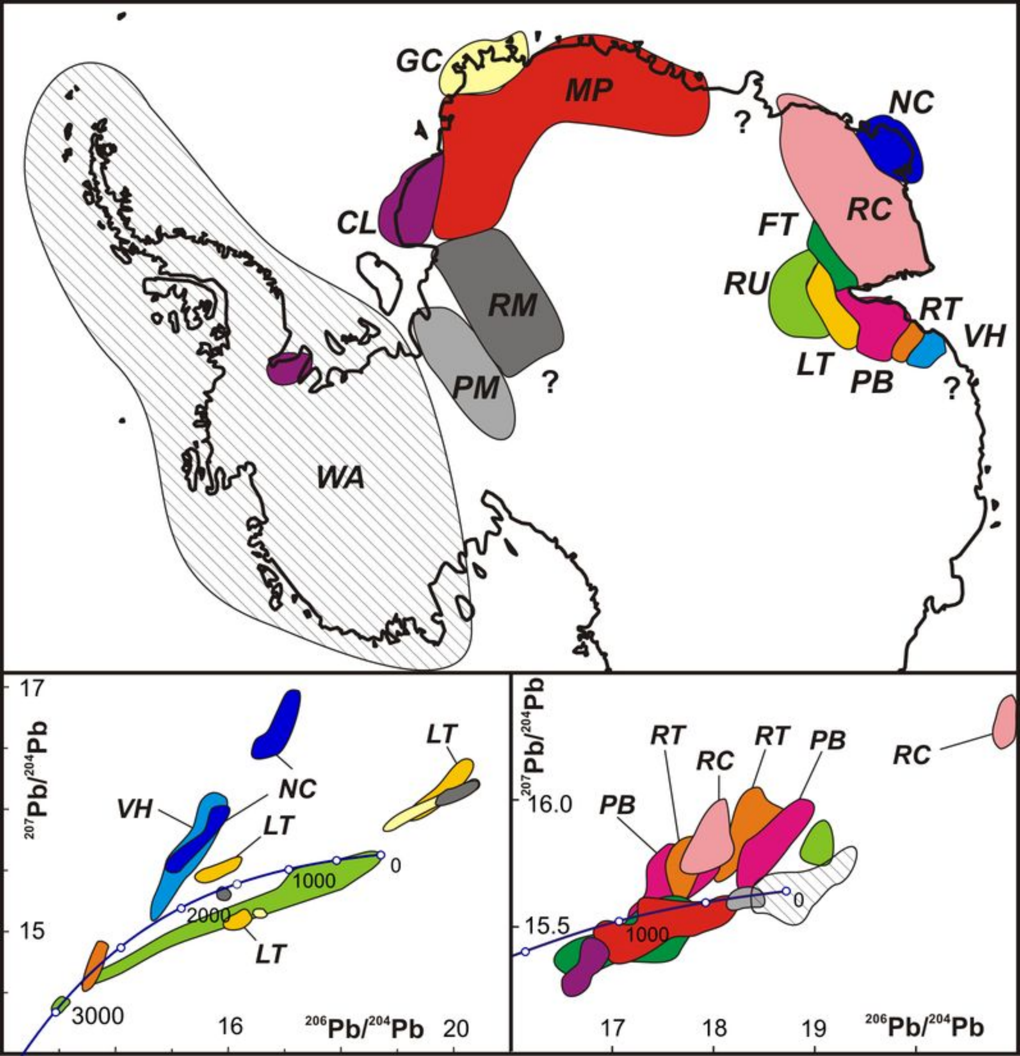
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$



GC
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