Magmatism of the Weddell Sea rift system in Antarctica: Implications for the age and mechanism of rifting and early stage Gondwana breakup

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ABSTRACT

Thick (~800 m) basaltic successions from the eastern Antarctic Peninsula have been dated in the interval 180 – 177 Ma and preserve a transition from a continental margin arc to a back-arc extensional setting. Amygdaloidal basalts from the Black Coast region of the eastern margin of the Antarctic Peninsula represent a rare onshore example of magmatism associated with back-arc extension that defines the early phase of Weddell Sea rifting and magmatism, and Gondwana breakup. The early phase of extension in the Weddell Sea rift system has previously been interpreted to be related to back-arc basin development with associated magnetic anomalies attributed to mafic-intermediate magmatism, but with no clearly defined evidence of back-arc magmatism. The analysis provided here identifies the first geochemical evidence of a transition from arc-like basalts to the development of depleted back-arc basin basalts in the interval 180 – 177 Ma. The exposed Black Coast basaltic successions are interpreted to form a minor component of magmatism that is also defined by onshore sub-ice magnetic anomalies, as well as the extensive magnetic anomalies of the southern Weddell Sea. Back-arc magmatism is also preserved on the Falkland Plateau where intrusions postdating 180 Ma are associated with early phase rifting in the Weddell Sea rift system. Back-arc extension was probably short-lived and had ceased by the time the northern Weddell Sea magmatism was emplaced (<175 Ma) and certainly by 171 Ma, when an episode of silicic magmatism was widespread along the eastern Antarctic Peninsula. Previous attempts to correlate mafic magmatism from the eastern Antarctic Peninsula to the Ferrar large igneous province, or, as part of a bimodal association with the Chon Aike silicic province are both dismissed based on age and geochemical criteria.

Keywords: Gondwana; back-arc extension; basalts; Ferrar; large igneous province

1. Introduction

The evolution of the Weddell Sea rift system (WSRS) is closely linked with the emplacement of the Karoo-Ferrar large igneous province (LIP), the early breakup of Gondwana, and the translation and rotation of micro-continental blocks that formed West Antarctica (Schopf, 1969). The WSRS developed on the continental lithosphere of Antarctica (Leat et al., 2018) and interpretation of aeromagnetic geophysical data (Ferris et al., 2000; Jordan et al., 2013, 2017) and seismic data (Jokat and Herter, 2016) indicates that large parts of the present day Weddell Sea are underlain by mafic intrusions/lavas. The magmatism of the WSRS has been attributed to an offshore extension of the Early Jurassic Ferrar LIP (Storey et al., 1996), magmatism associated with rifting during the early stages of Gondwana breakup (e.g. Martin, 2007) or a failed Jurassic ocean basin (Jokat and Herter, 2016). Two separate episodes of Weddell Sea extension and magmatism have been identified by several authors (e.g. König and Jokat, 2006; Jordan et al.,2017); an early stage east-west rifting episode potentially linked to back-arc extension and a later stage north-south rifting episode associated with the separation of Antarctica and Africa.

This paper investigates the petrogenesis and tectonic setting of thick (500 – 800 m) successions of Early Jurassic basaltic volcanic rocks from the eastern Antarctic Peninsula and how they relate to early stage extension as part of the WSRS. We shall evaluate if the basaltic magmatism is related to back-arc rifting associated with the Antarctic Peninsula continental margin and how this relates to Weddell Sea rifting, or whether the mafic magmatism is more closely related to the Ferrar LIP.

2. Weddell Sea Rift System

2.1 Overview

The Weddell Sea and embayment is bounded by the Antarctic Peninsula, East Antarctica and the smaller crustal blocks of Haag Nunataks and the Ellsworth-Whitmore Mountains to the south (Fig. 1). The precise position of these microcontinental crustal blocks in the developing Weddell Sea prior to and during fragmentation of the Gondwana supercontinent are still not resolved (e.g. Dalziel, 2013; Jordan et al., 2017; Jokat and Herter, 2016), particularly their translation and rotation. Based on geological and paleomagnetic data the crustal blocks are suggested to be translated from a pre-breakup position towards the Natal Embayment between East Antarctica and South Africa (Dalziel 2013, Randall and MacNiocaill 2004). Alternatively, models suggesting far more limited rotation and translation are interpreted from geophysical investigations of the WSRS area, which do not exhibit any tectonic evidence for a far-traveled block (Studinger and Miller, 1999; Jokat and Herter 2016; Jordan et al., 2017). The motion of the Haag Nunataks and Ellsworth-Whitmore Mountains crustal blocks are key to understanding the evolution of West Antarctica and the WSRS as their movement involved interaction with the WSRS, but the mechanism of this relationship is poorly understood. Jordan et al. (2013) interpreted the WSRS to be 400 – 600 km in width along most of its 900 km length, but widening towards the north where there is a transition from thinned continental crust to oceanic crust of the Weddell Sea embayment (King, 2000). Seismic refraction data along the front of the Filchner-Ronnie Ice Shelf identifies a zone of ~20 km thick crust overlain by 12 – 15 km of sediments (Leitchenkov and Kudryavtzev, 1997; Jokat and Herter, 2016), interpreted to reflect anomalously thick oceanic crust or highly attenuated, underplated and intruded transitional continental crust (Jokat and Herter, 2016). These seismic estimates of crustal thickness are consistent with regional estimates from gravity data of <30 km from GRACE satellite data (Block et al., 2009), and 27 – 29 km from marine and terrestrial gravity data (Studinger and Miller 1999).

Jordan et al. (2017) divided the WSRS into two distinct provinces identified by their differently trending magnetic anomalies (Fig. 3a). The Northern Weddell magnetic province (NWMP) is characterized by magnetic anomalies with a prominent NE-SW trend (Fig. 3b). A Southern Weddell magnetic province (SWMP) which is situated between the Haag Nunataks crustal block and the

Explora Anomaly (Fig. 3b) has magnetic anomalies with a dominant N-S trend. Jordan et al. (2017) interpreted the SWMP to predate the NWMP on the basis of cross-cutting trends. They suggested that the SWMP related to Early Jurassic east-west extension in the WSRS that may have been linked to back-arc extension along the Antarctic Peninsula margin. Nevertheless, they were unable to identify any clear evidence for back-arc related magmatism. The NE-SW trending NWMP is characterized by a fault splay magnetic fabric. This has been interpreted to be related to the separation of East Antarctica and Africa (Jordan et al., 2017), although a component of approximately N-S rifting between the Antarctic Peninsula and East Antarctica is suggested from seismic data (Jokat and Herter 2016), and is required if the Antarctic Peninsula was in its current location. The nature of the crust in the NWMP is not resolved by potential field data, but the highly extended transitional continental, or anomalously thick oceanic crust, observed in seismic refraction data (Jokat and Herter 2016) is consistent with the NWMP having undergone significant extension and rifting. The higher amplitude of the observed magnetic anomalies, relative to the SWMP region, may reflect the more magmatic and closer to oceanic character of this region.

2.2 Age of rifting

The age of rifting of the WSRS has not been dated directly, but is considered to be Early – Middle Jurassic in age, overlapping with the early stages of Gondwana breakup (Storey et al., 1988; König and Jokat, 2006; Martin, 2007; Dalziel, 2013; Jordan et al., 2017; Leat et al., 2018). Jordan et al. (2017) interpreted the east-west rifting of the SWMP to be related to back-arc extension along the Antarctic Peninsula margin. They suggested that this extension was accommodated along the geophysically identified Pagano shear zone on the Ellsworth-Whitmore Mountains block to the south (Fig. 3b). The Pagano shear zone is interpreted to be a left lateral transtensional structure (Jordan et al., 2013) with ~500 km of displacement (Jordan et al., 2017). Movement on the shear zone has been dated at ~175 Ma, based on the age of Early Jurassic syn-deformational plutons that were emplaced in the interval 178 – 174 Ma (Lee et al., 2012; Jordan et al., 2013; Craddock et al., 2017; Leat et al., 2018). The Pagano Nunatak granite (Fig. 1; 174.62 ± 0.16 Ma; Craddock et al., 2017) was emplaced in a releasing bend of the Pagano shear zone near the margin of the Ellsworth-Whitmore Mountains block, implying that the shear zone was active at this time. Other associated granites at Pirrit Hills (178.0 ± 3.5 Ma; Leat et al., 2018), Nash Hills (177.44 ± 0.04 Ma; Craddock et al., 2017) and Linck Nunatak (174.382 ± 0.26 Ma; Craddock et al., 2017) do not show any direct evidence of emplacement into an active shear zone and are adjudged to have been emplaced within the more coherent Ellsworth-Whitmore Mountains crustal block (Jordan et al., 2013; Leat et al., 2018). If motion on the Pagano shear zone was related to east-west extension as part of the SWMP (Jordan et al., 2017) then the deformed granitoid emplacement age from Pagano Nunatak (174.6 ± 0.2 Ma) should provide a reliable chronometer for the initial phase of Weddell Sea rifting and the early stages of Gondwana breakup.

Storey et al. (1988) and Leat et al. (2018) considered that lithospheric extension in the WSRS led to extensive mafic magmatism, which allowed the development of a thickened lower crustal underplate, providing heat for crustal anataxis and the emplacement of the Pagano shear zone granites.

Dating the age of rifting that led to the development of the NWMP is more difficult as there are no clear onshore examples of magmatic or tectonic activity associated with the broadly northwest-southeast extension. Cross-cutting relationships of magnetic fabrics indicate the NWMP postdates the ~175 Ma extension of the SWMP (Jordan et al., 2017), whilst rifting of the NWMP is likely to have predated the development of true oceanic crust in the Weddell Sea embayment.

Identifying the age of oceanic crust in the Weddell Sea is complicated because of slow spreading rates, which makes identifying magnetic anomaly ages difficult. König and Jokat (2006) interpreted the first true ocean floor in the southern Weddell Sea to have been created at ~147 Ma (M19/M20 chron) following approximately 20 Myr of stretching and rifting in the WSRS. Although Jokat and Herter (2016) suggested that the maximum age of oceanic crust could be ~160 Ma. If the ~147 Ma age is correct for the earliest oceanic spreading, the rifting that led to the development of the NWMP is interpreted to have taken place in the interval 175 – 147 Ma. Mueller and Jokat (2019) have investigated magnetic spreading anomalies constraining oceanization in the Africa-Antarctica corridor and have identified anomalies as old as 164 Ma, but these ages may not continue in to the Weddell Sea sector.

2.3 Summary of WSRS events

Extension in the Weddell Sea sector of Antarctica was a critical episode in the early stages of Gondwana breakup and records evidence of rifting between East and West Antarctica and separation of Antarctica from Africa and South America. It also played a pivotal role in the distribution of smaller crustal blocks during breakup and West Antarctica assembly.

The geology of the present day Weddell Sea has been influenced by five key events during the early stages of Gondwana breakup:

i) *The emplacement of the Karoo-Ferrar LIP at 183 ± 1 Ma (*U-Pb ages: *Svensen et al., 2012; Burgess et al., 2015).* This major magmatic event is thought to have been related to early-formed rift structures associated with the first stages of Gondwana breakup, both between Africa and Antarctica, and in the Weddell Sea embayment (Elliot and Fleming, 2000). The magmatism may be related to the Filchner rift and Explora magnetic anomalies (Fig. 3), which are interpreted to be the oldest structures identified in the southern Weddell Sea (Ferris et al., 2000).

ii) *Early Jurassic (~180 – 175 Ma) rifting leading to the SWMP.* This episode of east-west extension and magmatism was one of the earliest phases of Gondwana breakup in the Weddell Sea sector and has been linked to back-arc basin extension of the Antarctic Peninsula associated with slab roll-back and trench retreat. Movement associated with east-west extension of the SWMP was accommodated along the Pagano shear zone (Jordan et al., 2017).

iii) *Middle – Late Jurassic rifting of the NWMP is related to the early stages of separation of East Antarctica and South America.* NE-SW trending magnetic anomalies, semi-parallel to the Explora Anomaly (Fig. 3), record magmatism associated with crustal thinning. This episode of extension postdates the SWMP.

iv) *Development of oceanic crust in the northern Weddell Sea embayment.* Developed as a result of seafloor spreading that initiated at ~147 Ma and accelerated through the Cretaceous as rifting between Antarctica and South America continued and led to the development of the Rocas Verdes marginal basin (Mukasa and Dalziel, 1996).

v) *Subduction of Weddell Sea oceanic crust at the active margin with the emerging Scotia Plate.* The subduction zone would have developed to the south and east of the present day South Scotia Ridge and led to the subduction of the northern flank of the Weddell Sea oceanic crust (Barker, 2001).

2.4 Role of crustal blocks in the developing Weddell Sea

The WSRS is closely associated with the translation and potential rotation of the microcontinental blocks of Haag Nunataks and Ellsworth-Whitmore Mountains (e.g. Jordan et al., 2017; Dalziel, 2013). The crustal blocks translated and rotated from their pre-breakup position in the Natal Embayment (Fig. 2) between East Antarctica and South Africa (Adie, 1952; Schopf, 1969; Dalziel and Elliot, 1982; Grunow et al., 1987; Curtis and Storey, 1996). Jordan et al. (2017) interpreted the Haag Nunataks and Ellsworth-Whitmore microcontinents to be a composite crustal block whose movement was associated with extension in the WSRS during the breakup of Gondwana.

3. Influence of the Ferrar LIP on Weddell Sea rift magmatism

3.1 Background

The Ferrar LIP extends along the length of the Transantarctic Mountains from the Theron Mountains to northern Victoria Land (Fig. 1; Elliot et al., 1999). Magmatism of the Ferrar LIP has also been recognized from southeast Australia (Hergt et al., 2001), New Zealand (Mortimer, 1995), southern Africa (Riley et al., 2006) and potentially the Falkland Islands (Hole et al., 2016). The total length of the Ferrar LIP is over 4000 km and outcrops mostly as extensive sill complexes, often with thicknesses of up to 200 m (Elliot and Fleming, 2000). Chemical homogeneity over large distances of the Ferrar LIP has led Fleming et al. (1997) and Leat (2008) to advocate the long distance transport of Ferrar magmas.

The Dufek Massif and Forrestal Range layered mafic intrusion (Fig. 1) has an estimated volume of ~6600 km^3 (Ferris et al., 1998) and has been interpreted to form part of the Ferrar LIP and may represent one of the point sources for the long distance transport of magmas via a network of sills or dykes (Leat, 2008).

The Ferrar LIP lavas and sills are predominantly low-Ti tholeiites and have been dated by several workers (Fleming et al., 1997), but often with concerns over the accuracy of the $^{40}Ar/^{39}Ar$ geochronology (Riley and Knight, 2001). Recent, high precision dating by Burgess et al. (2015) have resolved the geochronology from large areas of the Ferrar LIP into the narrow time interval, 183.2 – 182.8 ± 0.2 Ma. The Dufek layered mafic intrusion has also been dated by Burgess et al. (2015) and yielded a $^{206}Pb/^{238}U$ age of 182.7 ± 0.1 Ma, consistent with the U-Pb age of 182.7 ± 0.4 Ma determined by Minor and Mukasa (1997).

3.2 Gondwana breakup magmatism and the Weddell Sea rift

The coincidence in age between magmatism of the Karoo (182 ± 2 Ma; Svensen et al., 2012) and the Ferrar (183 ± 1 Ma; Burgess et al., 2015) magmatic provinces, and the early stages of Gondwana breakup and Weddell Sea rifting have led several authors (e.g. Storey et al., 1996) to propose an extension of LIP magmatism into the Weddell Sea region. Several authors (e.g. Ferris et al.,2000; Elliot and Fleming, 2000; König and Jokat, 2006; Jokat and Herter, 2016 interpreted the WSRS to be a failed arm of the Jurassic triple junction that formed above a mantle plume which led to LIP emplacement (Elliot and Fleming, 2000; Storey et al., 2013). The Explora Anomaly of the coastal margin of East Antarctica (Fig. 3b) is also interpreted to be related to breakup magmatism at ~183 Ma (Jourdan et al., 2005), whilst Jordan et al. (2017) suggested the parallel trending NWMP could also be related to Karoo-Ferrar magmatism.

Karoo-Ferrar magmatism recorded from KwaZulu Natal (182 – 176 Ma; Riley et al., 2006), the Falkland Islands (182 – 179 Ma; Hole et al., 2016) and the orientation of the magnetic anomalies of the NWMP may indicate an expression of Karoo-Ferrar magmatism that extends across this region of pre-breakup Gondwana (Fig. 2), with an extension onto the eastern Antarctic Peninsula (Fig. 4). However, establishing any clear correlation between Karoo-Ferrar LIP magmatism and Weddell Sea magmatism is complicated by the absence of any precise age control on Weddell Sea rift-related magnetic anomalies of the NWMP, although the broader age range of magmatism (182 – 176 Ma) from KwaZulu Natal (Riley et al., 2006) and the Falkland Islands (Hole et al., 2016) is perhaps more conducive of a link to the NWMP. However by understanding the petrogenesis and tectonic setting of the basaltic magmatism on the eastern Antarctic Peninsula it is possible to resolve how widespread Karoo-Ferrar magmatism was in the WSRS.

4. Antarctic Peninsula magmatism

4.1 Geology of the Antarctic Peninsula

The Antarctic Peninsula has been interpreted as an accretionary continental arc of the Gondwanan margin, which developed on Paleozoic basement during Mesozoic subduction (Suarez, 1976). Vaughan and Storey (2000) reinterpreted the geology of the Antarctic Peninsula as an amalgamation of para-autochthnous and allocthonous terranes which accreted onto the Gondwana margin. More recently, Burton-Johnson and Riley (2015) have suggested a tectonic model involving in situ continental arc development and have rejected an accreted terrane hypothesis.

The geology of the eastern margin of the Antarctic Peninsula is dominated by Early – Middle Jurassic silicic volcanic rocks (Pankhurst et al., 2000; Riley et al., 2001), which are closely associated with granitoid plutonic rocks (Riley and Leat, 1999), thick (~1 km) sequences of Jurassic terrestrial sedimentary rocks deposited in a back-arc basin (Hunter et al., 2005) and significant basaltic units (Wever and Storey, 1992; Riley et al., 2016). These Jurassic sequences are thought to overlie metamorphic and plutonic rocks of Paleozoic age based on broadly distributed isolated outcrops (e.g. Riley et al., 2012).

4.2 Basaltic lava successions

Basaltic lavas and mafic greenstones crop out at multiple localities along the eastern margin of the Antarctic Peninsula and have been described by Wever and Storey (1992) and Riley et al. (2003, 2016) from Jason Peninsula and the Black Coast-Lassiter Coast region of eastern Palmer Land (Fig. 1).

The greatest observed thicknesses of Jurassic basaltic lavas on the eastern Antarctic Peninsula (Fig. 1) occur at the Eland Mountains (>800 m thickness) and Kamenev Nunataks (>500 m) where weakly porphyritic, deformed amygdaloidal metabasalts crop out (Fig. 5). The unit at Eland Mountains has been described by Riley et al. (2016) and was interpreted as a succession of basaltic lava flow units. The lavas are metamorphosed to greenschist facies and contain leucocratic amygdales, which are ovoid - irregular in form. The basaltic groundmass is characterized by abundant plagioclase and actinolite, with minor epidote and titanite. The lavas are punctuated by several fine grained, cream-grey coloured felsic units, which are typically 1 – 2 m in thickness and were emplaced contemporaneously with the basaltic lavas. These felsic units have been dated by Riley et al. (2016) at 180.2 ± 0.7 and 177.6 ± 1.0 Ma and provide an age for the entire basaltic succession at 178 ± 2 Ma. This age is broadly coincident with the age of the basaltic lavas from Jason Peninsula (main phase 176 – 174 Ma; Riley et al., 2003) and the age of basaltic lavas from the Sweeney Formation further south, which were interpreted to be younger than 183 Ma based on detrital zircon ages from associated metasedimentary rocks (Hunter et al., 2006). Therefore, a significant pulse of basaltic magmatism within the age range, 183 – 176 Ma, with a probable age of ~178 Ma is widespread along the eastern margin of the Antarctic Peninsula.

Previous workers (e.g. Riley et al., 2003) have attempted to correlate the Early Jurassic basaltic magmatism with the extensive silicic volcanism of the region (Riley et al., 2001, 2010). However, silicic volcanism occurred in two distinct pulses on the Antarctic Peninsula at ~184 – 183 Ma and 171 – 168 Ma (Pankhurst et al., 2000; Hunter et al., 2006; Riley et al., 2010), so it is difficult to include the episode of basaltic magmatism at ~178 Ma into either of these events and a distinct tectonic environment is now favoured.

4.3 Evidence of mafic magmatism from geophysical data

McGibbon and Wever (1991) identified a series of north-south trending magnetic anomalies across eastern Palmer Land, from the Black Coast towards the Filchner-Ronne Ice Shelf (Fig. 1). Using the magnetic susceptibilities recorded by McGibbon and Garrett (1987), McGibbon and Wever (1991) were able to interpret that the north-south trending magnetic anomalies (Fig. 3b) could only be the result of either gabbroic rocks or amygdaloidal basalts of the known lithologies that outcrop on the adjacent eastern Antarctic Peninsula. The basaltic lava/gabbroic bodies that occur in the coast parallel north-south trending zone are likely to have had a strong tectonic control on their emplacement, potentially as a result of east-west extension. They are likely to represent a significant offshore and sub-ice extension of the basaltic rocks identified from Eland Mountains-Kamenev Nunatak.

5. Geochemistry

5.1 Previous work

Riley et al. (2003, 2016) and Wever and Storey (1992) investigated the geochemistry of the basaltic units from Eland Mountains, Kamenev Nunatak and Jason Peninsula (Fig. 1). These mafic rocks from the eastern Antarctic Peninsula exhibit only a moderate degree of variation; the Eland Mountains succession are overwhelmingly transitional basalts akin to the Group III basalts from the Black Coast (Wever and Storey, 1992). The lavas from Kamenev Nunatak are calc-alkaline and more intermediate in composition, akin to the basaltic andesites from Jason Peninsula (Riley et al., 2003). The Th/Yb vs. Nb/Yb plot (Fig. 6) which uses trace elements that are likely to have been immobile during alteration and metamorphism is a useful diagram to illustrate the influence of subduction-modified components relative to MORB-OIB compositions. A subset of Eland Mountains and Kamenev Nunatak basaltic lavas are close in composition to the basaltic andesites of the Ferrar LIP and have relatively high Th/Yb with respect to MORB-OIB, typical of compositions from continental margin arcs. This attribute is even more marked in the intermediate rocks of Jason Peninsula which have the highest Th/Yb ratios (~5). The field defined by the Black Coast Cretaceous dykes (Leat et al., 2002) is used to represent mafic magmas derived from subduction-modified lithospheric mantle in the Antarctic Peninsula and overlaps with the most enriched rocks of the Eland Mountains-Kamenev Nunatak succession.

5.2 Analytical techniques

Five basaltic samples from Eland Mountains, Kamenev Nunatak and the nearby Leininger Peak (Fig. 1) have been analysed for their Sr-Nd isotope values (Table 1). Sr and Nd isotope compositions were measured at the British Geological Survey (Keyworth, UK) where samples were dissolved using standard HF/HNO_3 methods. Sr and bulk REE were separated using Dowex AG50 cation exchange columns, and Nd was subsequently extracted using LN-Spec columns. Sr fractions were loaded onto outgassed single Re filaments using a TaO activator solution, and analysed in a Thermo-Electron Triton mass spectrometer in multi-dynamic mode. Data are normalised to $^{86}Sr/^{88}Sr = 0.1194$. Results are quoted relative to a value of 0.710250 for the NBS987 standard. Nd fractions were loaded onto one side of an outgassed double Re filament assembly, and analysed in a Thermo Scientific Triton mass spectrometer in multi-dynamic mode. Data are normalised to $^{146}Nd/^{144}Nd = 0.7219$. Results are quoted relative to a value of 0.512115 for the JNd-i standard.

5.3 Interpretation

Analysis of the geochemistry of basaltic rocks from the eastern Antarctic Peninsula illustrates that more than half of the analysed samples (Wever and Storey, 1992; Riley et al., 2016; this study) from the Eland Mountains-Kamenev Nunatak succession plot at much more depleted compositions close to the MORB array, and overlap in Nb/Yb with N-MORB. The compositions of these samples is consistent with a sub-lithospheric MORB-like source mantle, perhaps melting in an extensional setting. The modest increase in Th/Nb relative to N-MORB suggests a back-arc setting (Pearce and Stern, 2006). The amygdaloidal basaltic rocks from the Hjort Formation (Wever and Storey, 1992) and the Sweeney Formation (Hunter et al., 2006) also overlap with the more depleted basaltic rocks from Eland Mountains-Kamenev Nunatak, also supporting a possible back-arc extensional setting.

The plot of Ba/Nb vs. Th/Nb (Fig. 7) is a useful discriminant to understand the relative contribution of different source components in arc and back-arc extensional settings. Ba/Nb is a proxy for the contribution from the arc, whilst Th/Nb provides a proxy for a deeper contribution. A diagonal vector reflects both Th and Ba enrichment, whilst the vertical vector reflects only Ba shallow enrichment (Pearce and Stern, 2006). Caution has to be exercised using Ba as a discriminant, given its mobility, so the least altered rocks have been selected for analysis. A subset of the lavas from the Eland Mountains succession closely follow the deep component vector, typical of a back-arc extensional setting and are the samples that plot at depleted compositions in Fig. 6. The Cretaceous dykes of the Antarctic Peninsula (Leat et al., 2002) follow the shallow enrichment vertical vector and represent the geochemical characteristics of the Antarctic Peninsula magmatic arc. The lavas from Jason Peninsula are distinct to both the Antarctic Peninsula arc dykes and the Eland Mountains-Kamenev Nunatak and may reflect emplacement in a developing extensional setting that isn't apparent in Fig. 6. The basaltic rocks from the Hjort Formation and Sweeney Formation are also close to the deep component vectors indicating a potential back-arc extensional setting as suggested in Fig. 6. Rare earth element (REE) values also demonstrate the relatively depleted characteristics of a subset of basaltic rocks from Eland Mountains and the Sweeney Formation, in comparison to the Black Coast Cretaceous dykes and the basaltic andesites from Jason Peninsula (Fig. 8). The Eland Mountains and Sweeney Formation basalts have relatively flat REE profiles, indicating derivation from a more depleted source, in comparison to the strongly enriched REE profiles from Jason Peninsula and the Cretaceous dykes, which are typical of derivation from a subduction-modified source.

The newly acquired dataset is plotted alongside Sr-Nd data (Fig. 9) from other Black Coast basaltic rocks (Wever and Storey, 1992). Also plotted are the field of mafic rocks from the Ferrar LIP (Fleming et al., 1995; Molzahn et al., 1996) and potentially related magmatism from the Falkland Islands (Hole et al., 2016) and KwaZulu Natal (Riley et al., 2006). The limited isotopic dataset from the Eland Mountains-Kamenev Nunatak region exhibit a broad range in both $^{87}Sr/^{86}Sr_i$ values (0.7055 – 0.7120) and εNd_i (-1.5 to -5.5). The range in isotopic values broadly overlaps with the range displayed by the Karoo-Ferrar related dyke suites from the Falkland Island (Hole et al., 2016) and KwaZulu Natal (Riley et al., 2006), which overlap in age with the eastern Antarctic Peninsula lava successions (~178 Ma).

The Cretaceous dykes from the Black Coast region overlap in composition with the Jason Peninsula basalts and some of the Eland Mountains basalts. However, generally the Sr-Nd data fail to identify a subset of more depleted compositions from the Eland Mountains-Kamenev Nunatak successions that is observed in the trace element data.

6. Discussion

Weddell Sea rift magmatism during the Early – Middle Jurassic is likely to be related to three broadly contemporaneous magmatic/tectonic processes:

i) The emplacement of the Ferrar LIP and its potential correlatives in KwaZulu Natal and the Falkland Islands in the interval 183 – 176 Ma.

ii) The emplacement of the southern Weddell magnetic province (SWMP) at 180 – 175 Ma, which is potentially linked to back-arc basin extension of the Antarctic Peninsula continental margin arc and strike-slip movement along the Pagano shear zone.

iii) Magmatism associated with the emplacement of the northern Weddell magnetic province (NWMP) after at least 175 Ma and any potential Falkland Islands-KwaZulu Natal link.

It is likely that mafic magmas were emplaced in the WSRS during all three of these events (Jordan et al., 2013; Jordan et al., 2017; Leat et al., 2018). While the compositions of the Ferrar magmatism are well known, there are no known outcrops or samples from the magmas forming the two magnetic provinces in the WSRS.

6.1 Links to the Ferrar large igneous province

Wever and Storey (1992) investigated a broad range of mafic greenstones (Hjort Formation) from the Black Cost region of the eastern Antarctic Peninsula and divided them into three distinct groups.

They highlighted that the most isotopically enriched rocks (Group III) of the Black Coast basaltic successions were akin to the low-Ti tholeiites of the Ferrar LIP. However, their interpretation was based on a small sample set with limited geochemical data and no geochronological control. The age data and geochemistry interpreted here and presented in Riley et al. (2016) also make it tempting to suggest a potential correlation between the eastern Antarctic Peninsula successions and the Ferrar LIP as geochemical characteristics of part of the Eland Mountains-Kamenev Nunatak successions overlap with the dominant Mount Fazio chemical rock type of the Ferrar LIP (Fig. 6). Also, the presence of magnetic anomalies in the southern Weddell Sea are consistent with mafic-intermediate sills or lavas (Jordan et al., 2017) and could partly represent an extension of the Ferrar LIP toward the Antarctic Peninsula margin.

Although the age of the Eland Mountains-Kamenev Nunatak (Black Coast) successions, at 180 – 177 Ma, is ~3 – 6 Myr younger than the main phase of Ferrar LIP magmatism (Burgess et al., 2015), the Black Coast basalts could represent the final phase of magmatism on the periphery of a more extensive province. The pre-breakup reconstruction of Gondwana at 180 Ma (Fig. 2) places the Black Coast region an equivalent distance from the proposed plume centre as the Transantarctic Mountains. The long-distance transport of Ferrar magmas described by Leat (2008) indicates that extension of the Ferrar LIP into the Black Coast region is potentially feasible. The caveat to any Ferrar LIP-Black Coast association is that although there is good geochemical agreement between some eastern Antarctic Peninsula basaltic successions, overwhelmingly there are clear geochemical differences to the more depleted units from Eland Mountains-Kamenev Nunatak, Hjort Formation and Sweeney Formation (Riley et al., 2016). Although the thicker successions (~800 m) at Eland Mountains-Kamenev Nunatak are the most likely candidates for any Antarctic Peninsula expression of the Ferrar LIP, an age discrepancy of ~5 Myr between the Ferrar LIP (183 ± 1 Ma; Burgess et al., 2015) and the Eland Mountains succession (178 ± 2 Ma; Riley et al., 2016), combined with a depleted geochemical signature for the main part of the succession is considered to make such a correlation unlikely.

Other potential distal correlatives of the Ferrar LIP include basaltic/dolerite dyke swarms that crop out in KwaZulu Natal in southern Africa (Riley et al., 2006) and the Falkland Islands (Hole et al., 2016). Both Riley et al. (2006) and Hole et al. (2016) dated the dyke swarms in the interval 182 – 176 Ma and suggested the compositions were transitional between Karoo and Ferrar LIP magma types, and akin to those of the Theron Mountains of Antarctica (Fig. 1; Brewer et al., 1992). Pre-breakup reconstructions of Gondwana at 180 Ma place the Falkland Islands, KwaZulu Natal and the Theron Mountains in adjacent locations at the junction of the Karoo and Ferrar LIPs (Fig. 2). Extrapolating this association to include the eastern Antarctic Peninsula basaltic successions, despite some overlap in chronology (with Falkland Islands and KwaZulu Natal) is however, tectonically unlikely and not supported by the geochemistry. Hence, a direct correlation between Early Jurassic Antarctic Peninsula basaltic magmatism and the Ferrar LIP (including KwaZulu Natal-Falkland Islands) is not supported.

6.2 Association with the Southern Weddell magnetic province (SWMP)

The magnetic anomalies of the SWMP are less magnetic than the anomalies of the NWMP and are interpreted to represent a mix of mafic and intermediate-silicic intrusions or lavas (Jordan et al., 2017). The SWMP anomalies trend NW-SE and Jordan et al. (2017) suggested they relate to broadly east-west rifting in a back-arc basin setting of the Antarctic Peninsula. Back-arc extension has been indirectly dated at ~175 Ma based on the dating of granitoid bodies (Leat et al., 2018) emplaced into the active Pagano shear zone of the Ellsworth Mountains (Fig. 3b). Movement along the Pagano shear zone accommodated motion associated with the back-arc extension, hence the contemporaneous emplacement and deformation of the Pagano Nunatak shear zone granite (174.62 ± 0.16 Ma; Craddock et al., 2017) dates a period of major extension.

The basaltic successions from Eland Mountains-Kamenev Nunatak have an age essentially coincident with extension (178 ± 2 Ma; Riley et al., 2016) and geochemical characteristics that are consistent with a transition from arc-related basalts to back-arc basin basalts from a deeper, more depleted source. Magmatism of this developing back-arc basin, related to east-west extension is preserved in minor north-south magnetic anomalies identified close to the Antarctic Peninsula margin (McGibbon and Wever (1991), Ferris et al., 2002) and also by the magnetic fabric of the SWMP, although this has been largely overprinted by the later NWMP adjacent to the Black Coast (Fig. 3b). The basaltic successions from the eastern Antarctic Peninsula lack a clear 'arc' affinity that is typical of other basaltic successions of the Antarctic Peninsula (Leat et al., 2002) and are also distinct in their greater thickness (~800 m) and field characteristics (multiple, amygdaloidal flow units). The Eland Mountains-Kamenev Nunatak successions have a stratigraphically lower age of 180.2 ± 0.7 Ma and an upper age of 177.6 ± 1.0 Ma and geochemically record the transition to true back-arc basin basalts. An Early Jurassic back-arc basin setting is also supported by facies analysis of >4 km thickness of sedimentary rocks of the Latady Group, which were deposited in the developing Latady Basin (Hunter and Cantrill, 2006).

The interpretation of geophysical data from the Falkland Plateau (Schimschal and Jokat, 2019) indicates that the Falkland Plateau basin consists of up to 20 km of thick oceanic crust, which is related to an extensional back-arc setting. In their model, Schimschal and Jokat (2019) suggest rifting was initiated at ~178 Ma after the emplacement of the Karoo-Ferrar dyke swarms on the Falkland Islands (Hole et al., 2016).

Therefore, several lines of evidence strongly point to an extensional back-arc regime at ~178 Ma in the proto-Weddell Sea; a tectonic setting which marked the initial phase of Weddell Sea opening and one of the earliest phases of Gondwana breakup. The tectonic interpretations of Jordan et al. (2017) and Schimschal and Jokat (2019) both indicate that east-west extension was underway at ~178 Ma, whilst onshore magmatism described by McGibbon and Wever (1991), Wever and Storey (1992), Riley et al. (2016) and this study also indicate rift-related magmatism at ~178 Ma.

Geochemically, the back-arc basin basalts of the Eland Mountains-Kamenev Nunatak successions show a source that changed from an arc-influenced setting to a more depleted, asthenospheric-like source as the back-arc basin developed. This transition occurred in the interval 180 – 177 Ma and likely reflects the early stages of back-arc basin development and the onset of east-west extension in the adjacent Weddell Sea. Back-arc related extension continued until at least ~175 Ma based on the age of the Pagano Nunatak granite and was likely to have ceased at the time of onset of extensive silicic volcanism at ~171 Ma.

It is also significant that the SWMP is less magnetic than the NWMP (Jordan et al., 2017) and likely reflects a mix of mafic-intermediate lavas which is consistent with the successions identified on the Black Coast (Wever and Storey, 1992; McGibbon and Wever, 1991; Riley et al., 2016). The coast parallel magnetic anomalies of the SWMP are no longer clearly preserved adjacent to the Black Coast, as they have been overprinted by the later stage NWMP (Fig. 4). However, N-S magnetic trends identified by Ferris et al., 2002 in the black coat region could reflect back arc extension.

6.3 Association with the Northern Weddell magnetic province (NWMP)

The Northern Weddell magnetic province (NWMP) is a complex array of lineations with a dominant NE-SW trend (Fig. 3b) attributed to extensional tectonics (Jokat and Herter, 2016; Jordan et al., 2017). The magnetic anomalies of the NWMP are adjacent to the Eland Mountains-Kamenev Nunatak basaltic successions (Fig. 3b) and the magnetic anomalies are interpreted to represent mafic intrusions/lavas that were the precursor to the onset of seafloor spreading in the Weddell Sea. The NWMP extension postdated the SWMP but was possibly coincident with the later separation of the Falkland Plateau from the Weddell Sea rift region (Ferris et al., 2000).

If the Eland Mountains-Kamenev Nunatak basaltic successions do represent an onshore expression of the magmatism associated with extension of the NWMP then the timing is critical. Extension in the NWMP has been interpreted by Jordan et al. (2017) to have likely taken place after extension in the SWMP at ~178 Ma. However, given that movement on the Pagano Shear Zone was still ongoing at ~175 Ma, which is linked to the emplacement of the SWMP, it implies that extension in the NWMP must postdate 175 Ma. There is no geochemical control on the offshore magmatism associated with the NWMP to correlate with the basaltic successions from Eland Mountains-Kamenev Nunatak. The identification of north-south trending magnetic anomalies by McGibbon and Wever (1991) that are likely to reflect an extension of the Eland Mountains-Kamenev Nunatak succession indicate that an association with the NE-SW trending magnetic anomalies of the NWMP is unlikely even though they are adjacent in present day configurations.

Jordan et al. (2017) also suggested that the NWMP could represent a transtensional setting associated with a later stage Gondwana configuration, in which case the eastern Antarctic Peninsula basalts would very likely predate such a tectonic setting and make any association with the NWMP unlikely. Also, the NWMP is characterized by more strongly magnetic anomalies indicating mafic intrusions, unlike the mafic-intermediate compositions of the Black Coast successions.

In summary, the chronology of events make any association between the Black Coast basaltic successions and the NWMP unlikely on the basis that the NWMP postdates the emplacement of the SWMP and that the basaltic successions are related to an extensional regime that continued until ~175 Ma.

7. Conclusions

- The Weddell Sea rift system has developed on continental lithosphere and is underlain by extensive mafic lavas and/or intrusions that have been attributed to rift-related magmatism or a continuation of the Ferrar LIP into the proto Weddell Sea (Jordan et al., 2017).

- A thick (~800 m) succession of basaltic-basaltic andesite lavas from the eastern Antarctic Peninsula are adjacent to the Weddell Sea margin and provide a rare onshore example of magmatism related to the tectonic history of the Weddell Sea.

- The lava successions were emplaced into a developing back-arc extensional setting in the interval 180 – 177 Ma and exhibit a trend from arc-like basalts of a continental margin setting to a more depleted, deeper-seated source, typical of back-arc basin basalts.

- Offshore magnetic anomalies have been attributed to east-west extension dated at ~175 Ma and are interpreted to have developed in a back-arc extensional setting.

- Further evidence for back-arc related magmatism at ~178 Ma is interpreted from the Falkland Plateau region (Schimschal and Jokat, 2019).The first phase of Weddell Sea extension and rifting is therefore related to Early Jurassic back-arc extension along the Antarctic Peninsula continental margin associated with recognized Early Jurassic subduction (Riley et al., 2017). Any potential correlation between the basaltic successions of the Black Coast and the extensive basaltic lavas and sills of the Ferrar large igneous province are discounted on the basis of a ~5 Myr age discrepancy and geochemical differences.

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Figure 1: Map of Antarctica showing the key localities in the Weddell Sea sector of Antarctica. JP; Jason Peninsula; EM: Eland Mountains; KN: Kamenev Nunatak; LP: Leininger Peak; HN: Haag Nunataks; EWM: Ellsworth-Whitmore Mountains; FRIS: Filchner-Ronne Ice Shelf; BI: Berkner Island.

Figure 2: Regional Gondwana reconstruction at 180 Ma from Jordan et al. (2017). The pre-breakup positions of the Haag Nunataks-Ellsworth Whitmore Mountains blocks are shown adjacent to the Falkland Islands block in the Natal Embayment. AP: Antarctic Peninsula; FI: Falkland Islands; TI: Thurston Island; NE: Natal Embayment; MBL: Marie Byrd Land; KZN: KwaZulu Natal; Tas: Tasmania. This reconstruction is adapted from Jordan et al. (2017) and Jokat and Herter (2016) and the proto-Pacific margin configuration of crustal blocks cannot be considered definitive.

Figure 3: Aeromagnetic data and identified structural trends across the Weddell Sea Rift System (Jordan et al., 2017). a) Aeromagnetic data compilation. b) Inferred magnetic lineations from the aeromagnetic data highlighting the distinct trend of the NWMP and SWMP regions. The sub-ice magnetic lineations of McGibbon and Garrett (1987) are shown along the Black Coast. AP: Antarctic Peninsula; OA: Orion Anomaly; EA: Explora Anomaly; FR: Filchner Rift; DI: Dufek Intrusion; PSZ: Pagano shear zone; EWM: Ellsworth-Whitmore Mountains.

Figure 4: Schematic diagram illustrating the proposed two-phase development of the NWMP and SWMP (Jordan et al. (2017). a) Back-arc extension at ~178 Ma led to the development of the N-S oriented structures of the SWMP. The onshore expression of back-arc magmatism is highlighted by the star on the Black Coast. Movement associated with back-arc extension was accommodated along the Pagano shear zone (PSZ). b) Development of the NWMP took place after 174 Ma and was associated with broadly N-S extension associated with the breakup of East Antarctica and Africa.

Figure 5: Weakly deformed amygdaloidal basalts from the Eland Mountains. N10.123.1 [70.6653 S, 062.7750 W].

Figure 6: Variations in Th/Yb vs. Nb/Yb for mafic rocks from the eastern Antarctic Peninsula relative to the MORB-OIB array (Pearce and Peate, 1995). The Eland Mountains-Kamenev Nunatak analyses are from Riley et al. (2016), Hjort Formation (Wever and Storey, 1992), Jason Peninsula (Riley et al., 2003). Cretaceous dykes from the Black Coast represent arc-modified lithosphere of the eastern Antarctic Peninsula (Leat et al., 2002). Average Ferrar MFCT (Mount Fazio chemical type) is from Molzahn et al. (1996).

Figure 7: Plot of Ba/Nb vs. Th/Nb to investigate the relative roles of shallow and deep subduction components in a back-arc extensional setting (Pearce and Stern, 2006). Ba/Nb is the proxy for total subduction input and Th/Nb represents the proxy for deep subduction input. The deep component is highlighted by the diagonal vector and the shallow component is a vertical vector. Back-arc basin basalts will follow the deep component vector (e.g. Eland Mountains and Sweeney Formation basalts; Riley et al., 2016; Hunter et al., 2006) and the continental margin arc basalts will follow the vertical vector (e.g. Cretaceous Black Coast basalts; Leat et al., 2002).

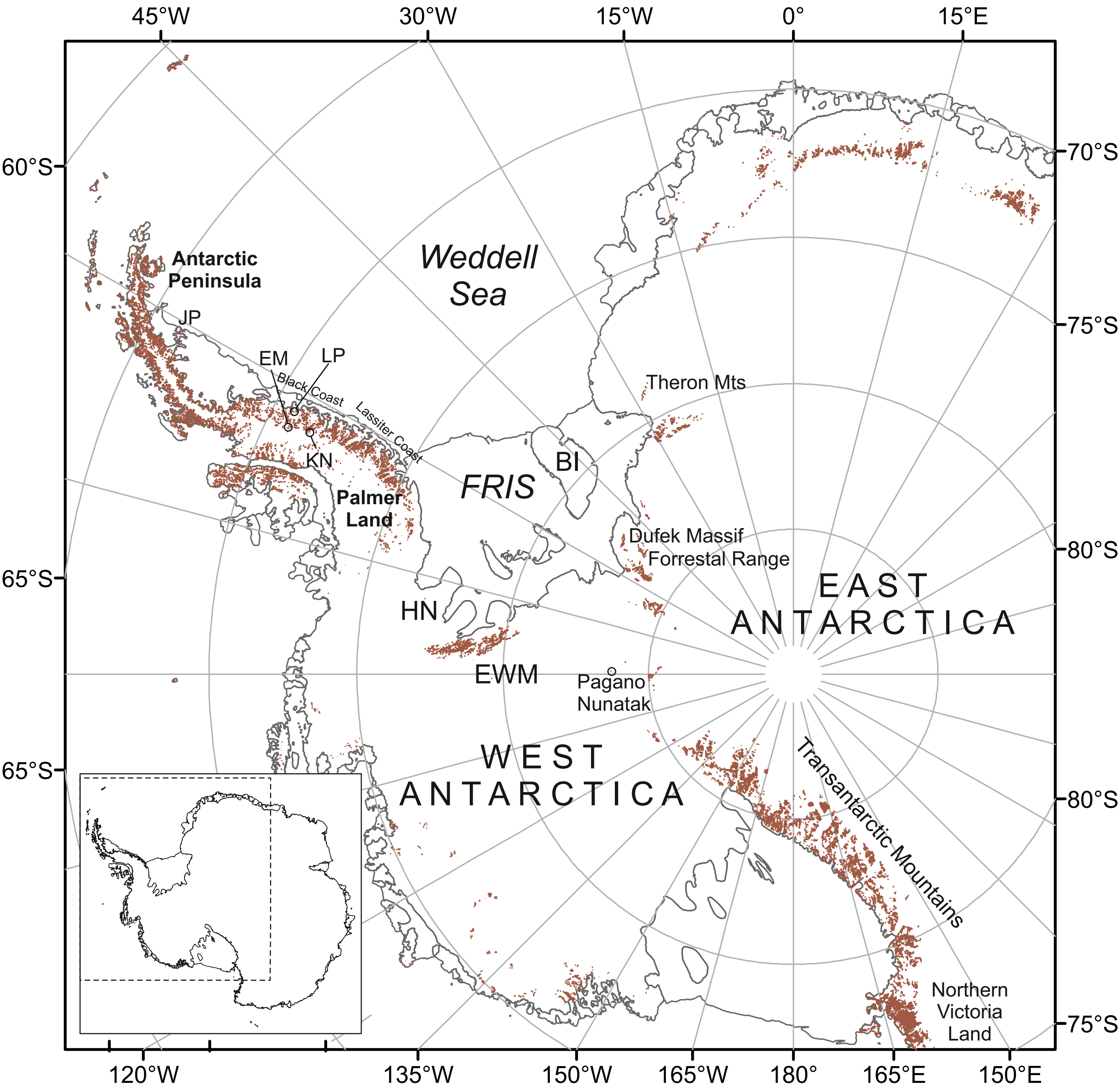
Figure 8: Chondrite (Nakamura, 1974) normalized REE diagrams for the basaltic successions from the east coast of the Antarctic Peninsula. Light REE enriched abundances from Jason Peninsula (Riley et al., 2003) and the Cretaceous Black Coast dykes (Leat et al., 2002) are shown relative to the more depleted compositions from the Sweeney Formation (shaded area; Hunter et al., 2006) and the Eland Mountains succession (line data; Riley et al., 2016).

Figure 9: $^{87}Sr/^{86}Sr_i$ vs. εNd_i for magmatic rocks from the eastern Antarctic Peninsula, shown in comparison to data fields from the Ferrar LIP, Falkland Islands (Hole et al., 2017). KwaZulu Natal (Riley et al., 2006). Data sources: Eland Mountains-Kamenev Nunatak (Wever and Storey, 1992; this study); Sweeney Formation (Hunter et al. 2006); Jason Peninsula (Riley et al. 2003); Cretaceous Black Coast dykes (Leat et al. 2002); Karoo (Riley et al., 2005). KZN: KwaZulu Natal; PST: Port Sussex type; DIT: Dyke Island type; MFCT: Mount Fazio chemical type.

Table 1: Sr-Nd isotope geochemistry

Sample	Location	Age	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$^{143}Nd/^{144}Nd_i$	eps(Nd)	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr_i$
N10.227.1	Leininger Peak	178	4.90	18.55	0.1596	0.512485	0.512297	-2.1	79.6	50.8	4.54	0.716883	0.70545
N10.436.3	Leininger Peak	178	4.57	21.39	0.1292	0.512392	0.512240	-3.2	76.6	189.9	1.17	0.709828	0.70689
N10.6.1	Eland Mountains	178	3.48	12.93	0.1625	0.512520	0.512329	-1.5	13.9	368.4	0.11	0.707434	0.70716
R.4144.5	Kamenev Nunatak	178	3.83	16.62	0.1393	0.512289	0.512125	-5.5	39.3	137.6	0.83	0.714025	0.71194
R.4291.2	Hjort Fm (III)	178	4.01	15.06	0.1609	0.512347	0.512154	-5.0	35	149	0.68	0.710752	0.70904

Rb-Sr and Sm-Nd isotope analyses were performed at NIGL, Keyworth, UK.



45°W
30°W
15°W
0°
15°E
60°S
70°S
75°S
80°S
65°S
80°S
65°S
80°S
75°S
120°W
135°W
150°W
165°W
180°
165°E
150°E
Antarctic
Peninsula
JP
EM
LP
Black Coast
Lassiter Coast
KN
Palmer
Land
Weddell
Sea
FRIS
BI
Theron Mts
Dufek Massif
Forrestal Range
EAST
ANTARCTICA
HN
EWM
Pagano
Nunatak
WEST
ANTARCTICA
Transantarctic Mountains
Northern
Victoria
Land

Figure 1

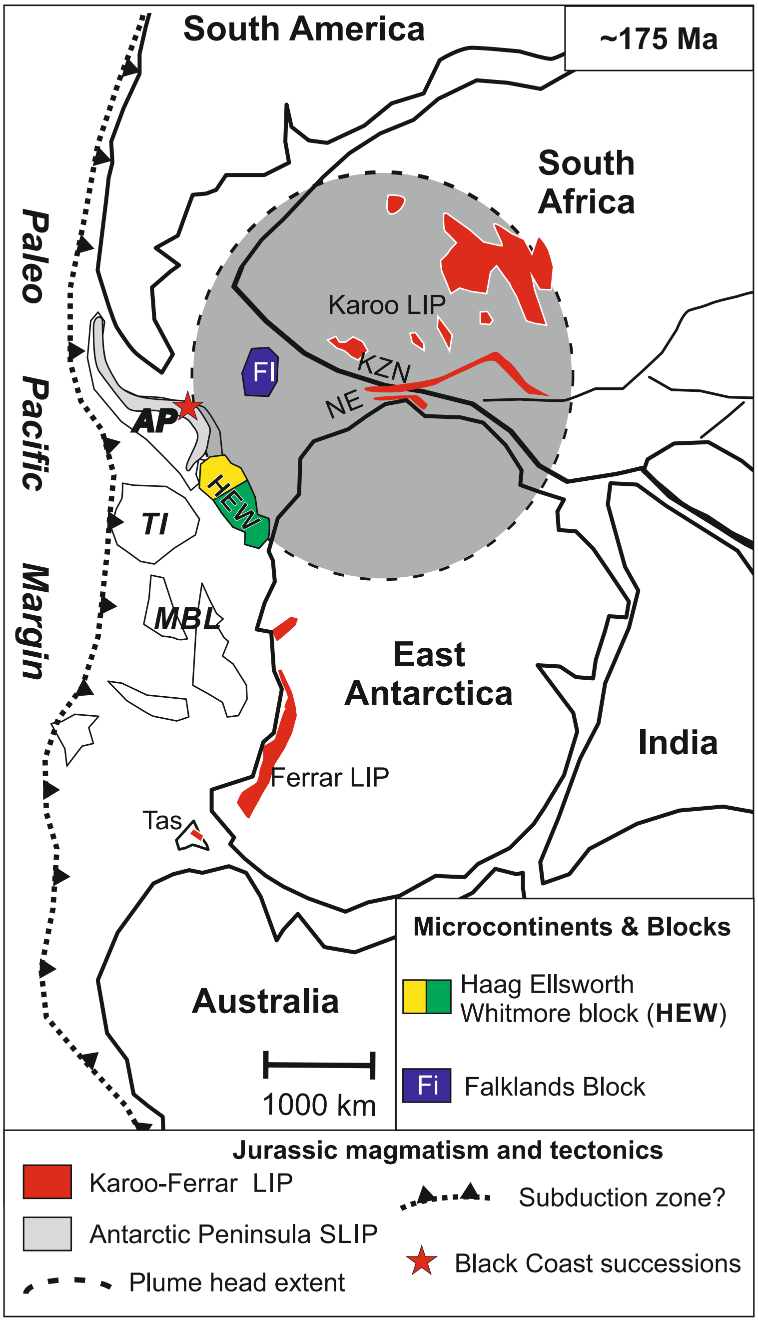
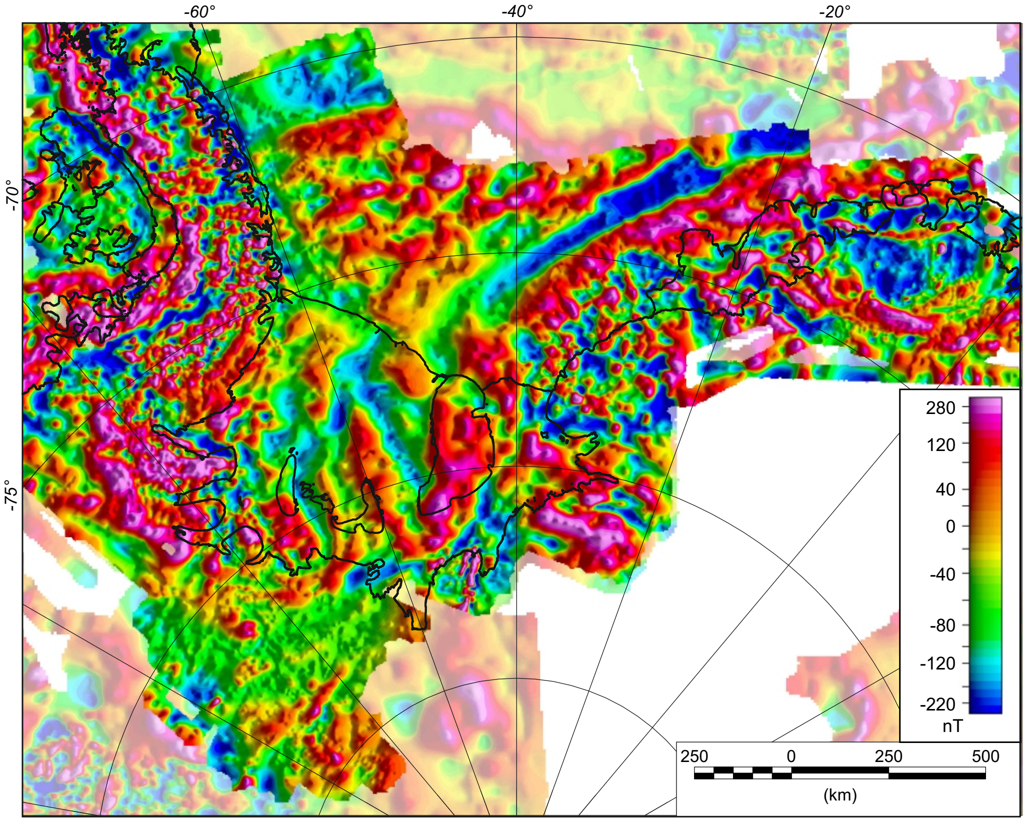

South America
~175 Ma
South Africa
Paleo Pacific Margin
Karoo LIP
FI
KZN
NE
AP
HEW
TI
MBL
East Antarctica
India
Ferrar LIP
Tas
Microcontinents & Blocks
Haag Ellsworth Whitmore block (HEW)
Fi Falklands Block
Australia
1000 km
Jurassic magmatism and tectonics
Karoo-Ferrar LIP
Subduction zone?
Antarctic Peninsula SLIP
Black Coast successions
Plume head extent

Figure 2


-60°
-40°
-20°
-70°
-75°
280
120
40
0
-40
-80
-120
-220
nT
250
0
250
500
(km)

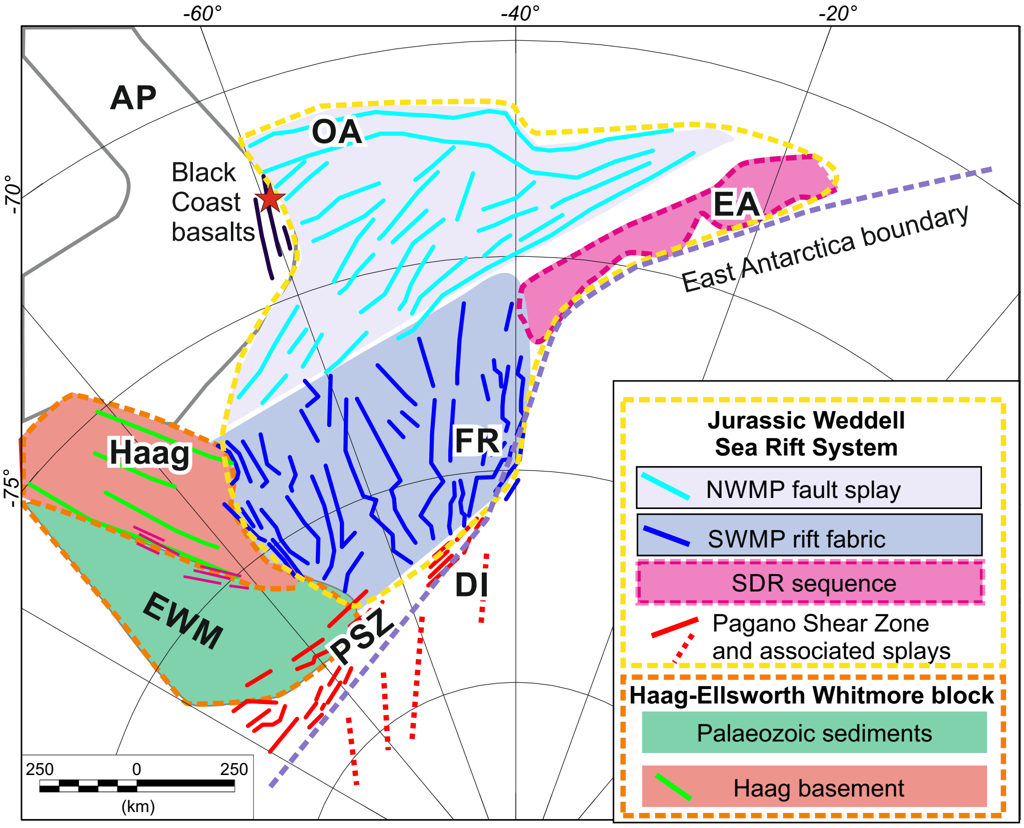

-60°
-40°
-20°
-70°
-75°
AP
OA
Black
Coast
basalts
EA
East Antarctica boundary
Haag
FR
EWM
PSZ
DI
250
0
250
(km)
Jurassic Weddell
Sea Rift System
NWMP fault splay
SWMP rift fabric
SDR sequence
Pagano Shear Zone
and associated splays
Haag-Ellsworth Whitmore block
Palaeozoic sediments
Haag basement

Figure 3

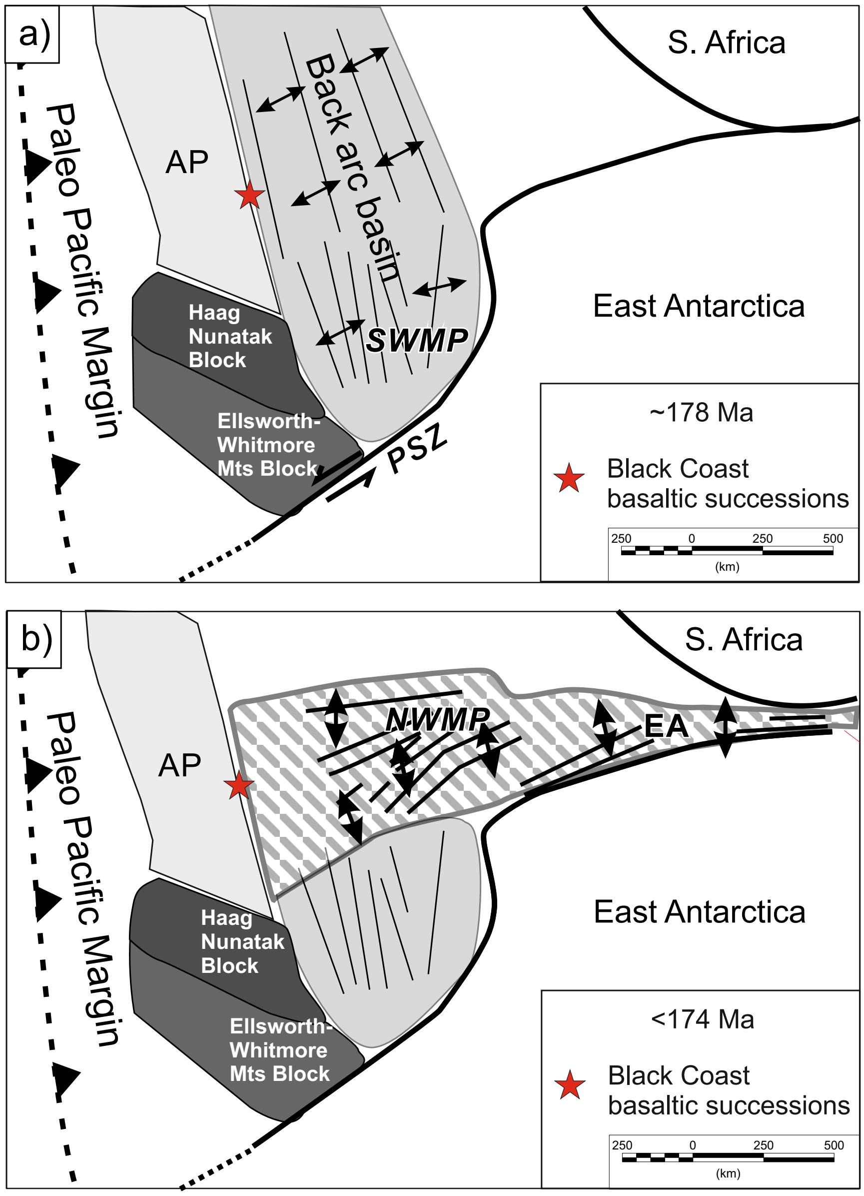

a)
S. Africa
Paleo Pacific Margin
AP
Back arc basin
Haag
Nunatak
Block
SWMP
Ellsworth-
Whitmore
Mts Block
PSZ
East Antarctica
~178 Ma
Black Coast
basaltic successions
250 0 250 500
(km)
b)
S. Africa
Paleo Pacific Margin
AP
NWMP
EA
Haag
Nunatak
Block
Ellsworth-
Whitmore
Mts Block
East Antarctica
<174 Ma
Black Coast
basaltic successions
250 0 250 500
(km)

Figure 4

Figure 5

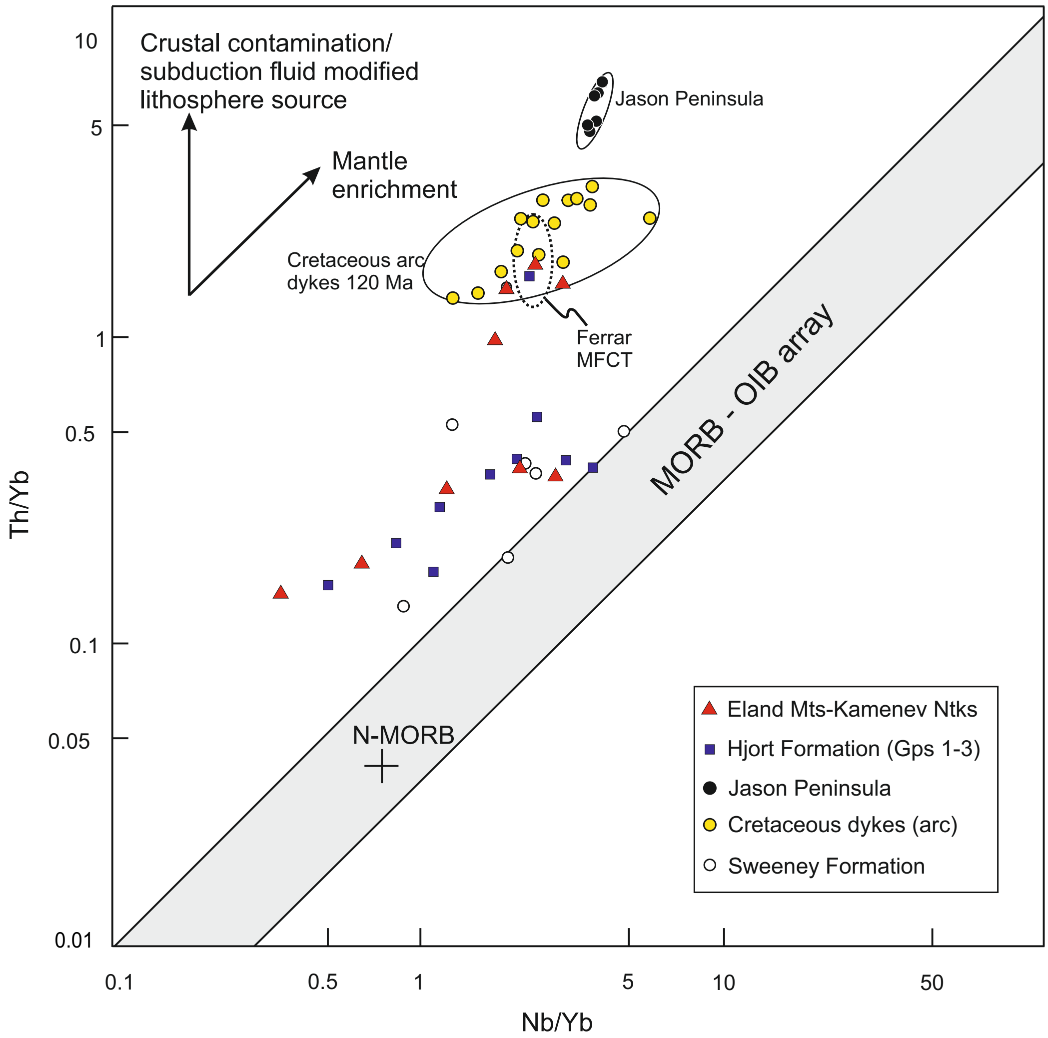

Crustal contamination/
subduction fluid modified
lithosphere source
Mantle
enrichment
Jason Peninsula
Cretaceous arc
dykes 120 Ma
Ferrar
MFCT
MORB - OIB array
N-MORB
Eland Mts-Kamenev Ntks
Hjort Formation (Gps 1-3)
Jason Peninsula
Cretaceous dykes (arc)
Sweeney Formation
Th/Yb
Nb/Yb
10
5
1
0.5
0.1
0.05
0.01
0.1
0.5
1
5
10
50

Figure 6

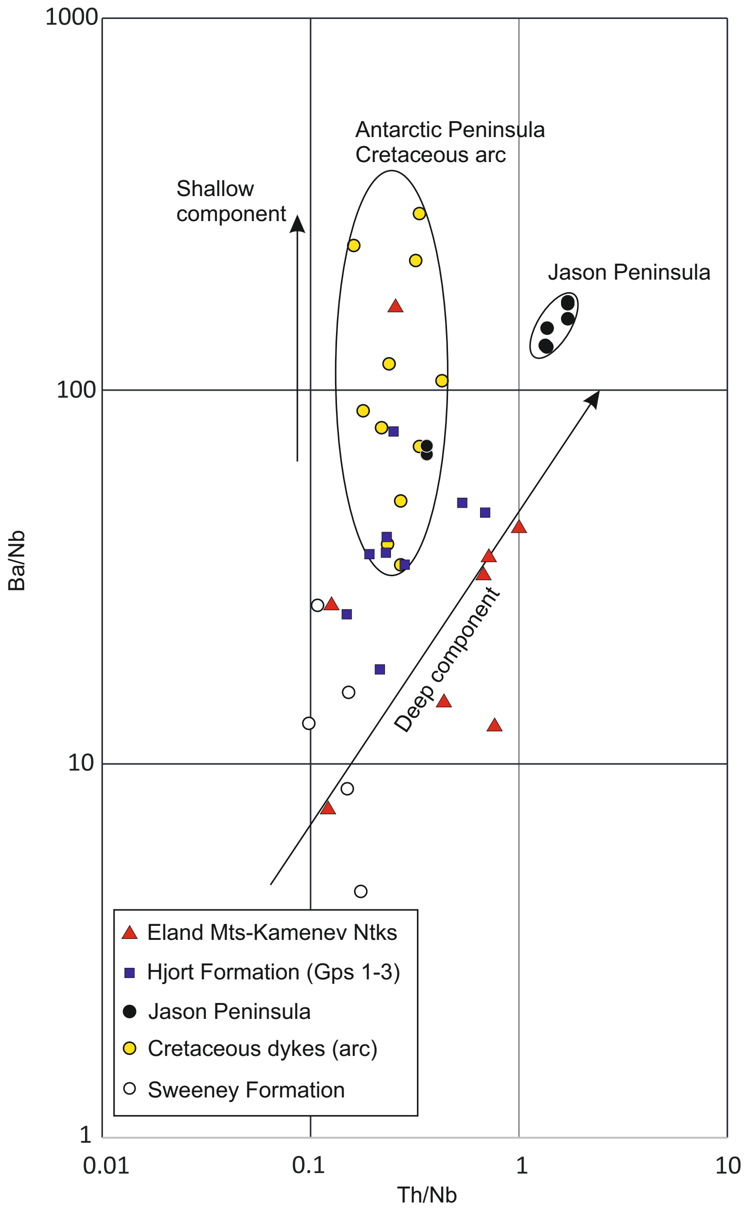

1000
100
10
1
Ba/Nb
0.01
0.1
1
10
Th/Nb
Antarctic Peninsula
Cretaceous arc
Shallow
component
Jason Peninsula
Deep component
Eland Mts-Kamenev Ntks
Hjort Formation (Gps 1-3)
Jason Peninsula
Cretaceous dykes (arc)
Sweeney Formation

Figure 7

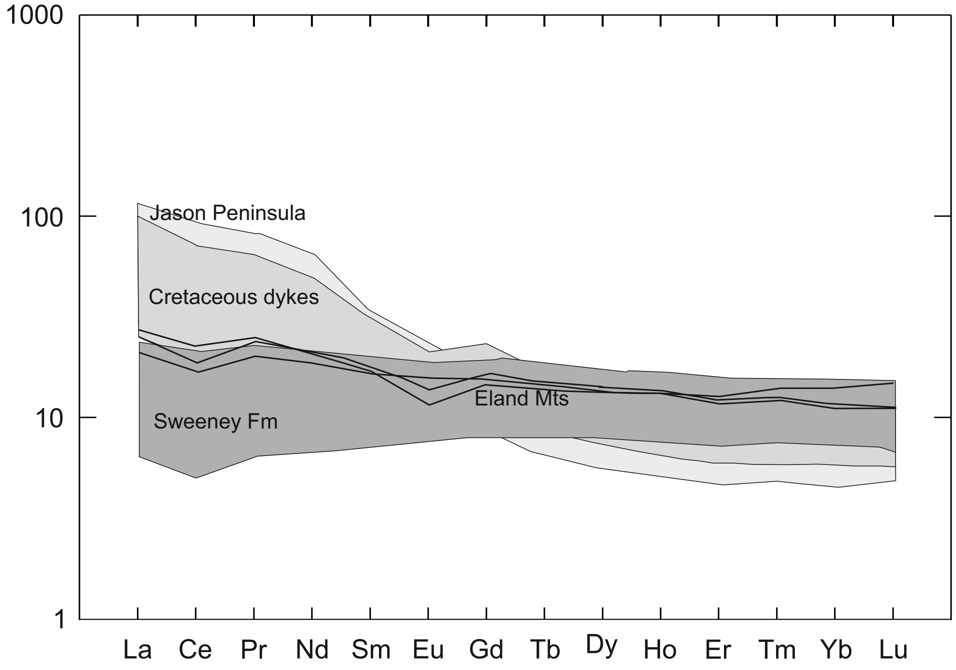
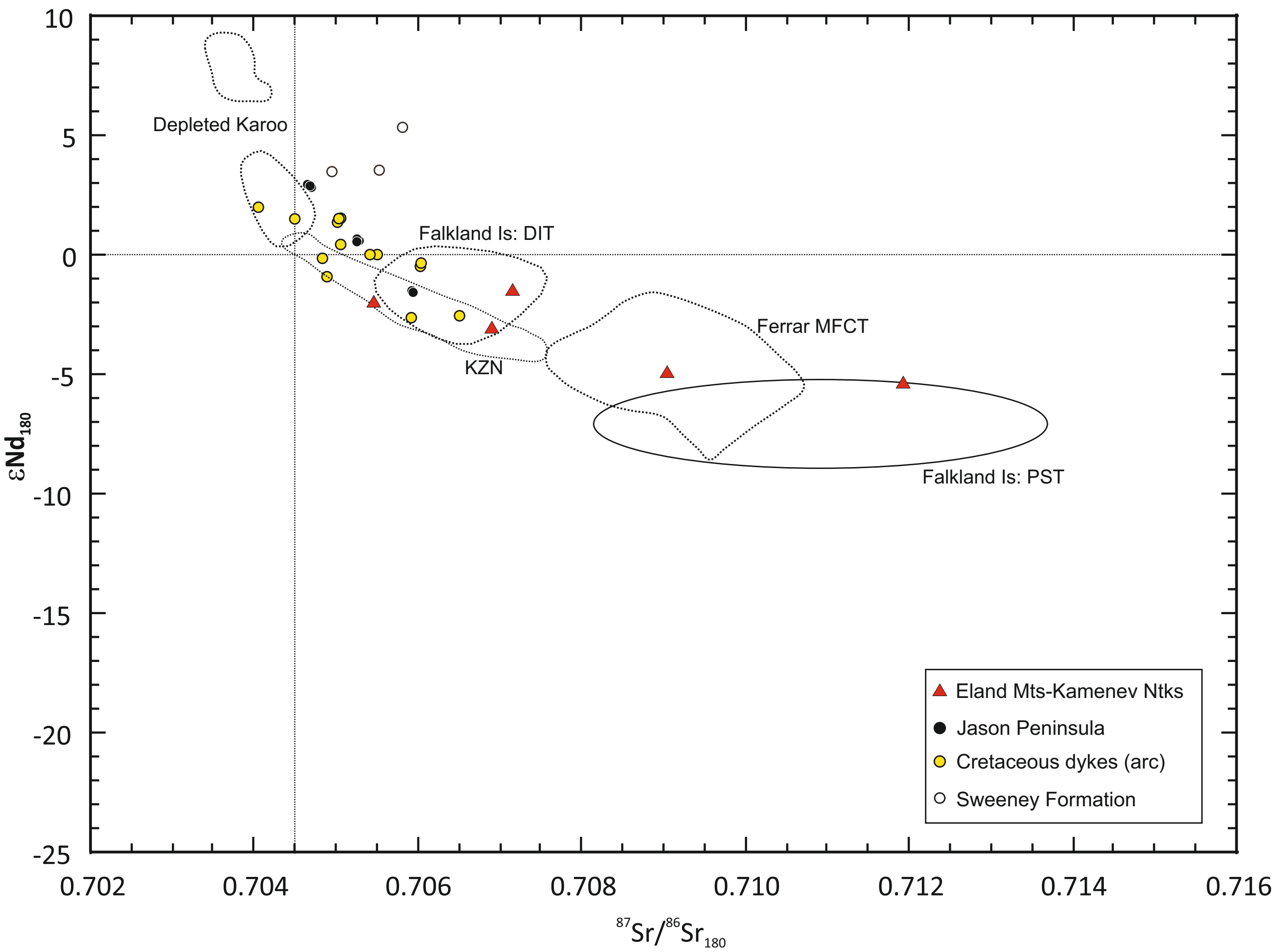

1000
100
10
1
Jason Peninsula
Cretaceous dykes
Eland Mts
Sweeney Fm
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu

Figure 8



10
5
0
-5
-10
-15
-20
-25
εNd180
0.702
0.704
0.706
0.708
0.710
0.712
0.714
0.716
87Sr/86Sr180
Depleted Karoo
Falkland Is: DIT
KZN
Ferrar MFCT
Falkland Is: PST
Eland Mts-Kamenev Ntks
Jason Peninsula
Cretaceous dykes (arc)
Sweeney Formation

Figure 9