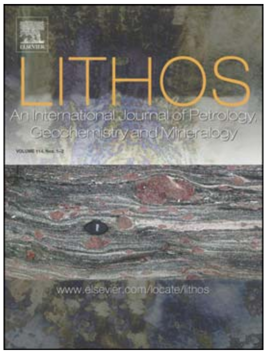

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Evolution of the Antarctic Peninsula lithosphere: evidence from Mesozoic mafic rocks

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Abstract

New geochronology from a thick (>800m) basaltic succession along the eastern margin of the Antarctic Peninsula confirm a Middle Jurassic age (178 ± 1 Ma). This marginally postdates the adjacent Ferrar large igneous province of the Transantarctic Mountains and predates the extensive silicic volcanism of the Mapple Formation (~170 Ma) of the Antarctic Peninsula. The geochemistry of other rare, but broadly contemporaneous, basaltic successions of the Antarctic Peninsula, along with Cretaceous-age mafic dykes, are used to interpret the influences of lithospheric and asthenospheric mantle sources during the Mesozoic. Two significant high magmatic addition rate events occurred along the Antarctic Peninsula continental margin at 170 and 110 Ma and can be correlated to events along the South American Cordillera. These 'flare-up' events are characterised by extensive silicic (mostly ignimbrite) volcanism of the Chon Aike Province (V2 event: 170 Ma) and significant granitoid batholith emplacement of the Lassiter Coast intrusive suite (110 Ma). The 170 Ma event is exposed across large parts of the northern Antarctic Peninsula, whilst the 110 Ma event is more widespread across the southern Antarctic Peninsula. The basaltic volcanism described here precedes the 'flare-up' event at 170 Ma and has geochemical characteristics that indicate a thickened lithosphere prevailed. A major dyke swarm that followed the 170 Ma event indicates that extensive lithospheric thinning had occurred, which allowed the ascent of depleted mafic melts. The thinning was the direct result of widespread lower crustal/upper lithospheric melting associated with the silicic volcanism. In the southern Antarctic Peninsula, the lithosphere remained over thickened until the emplacement of the major batholiths of the Lassiter Coast intrusive suite at 110 Ma and was then immediately followed by the emplacement of more asthenosphere-like melts indicating extensive lithospheric thinning.

Keywords: basalt, continental margin, Chon Aike Province, Gondwana

1. Introduction

Basaltic successions along the Antarctic Peninsula continental margin are rare during the Jurassic. Widespread silicic volcanism, granitoid plutonism and the development of extensive marine and terrestrial sedimentary successions of that age are dominant, and are associated with the emplacement of extensive dolerite dykes.

Four separate areas have been identified along the eastern margin of the Antarctic Peninsula where significant basaltic lava successions crop out. The Sweeney Formation of southeast Palmer Land (Hunter et al., 2006), the basalts of Standring Inlet (Jason Peninsula; Riley et al., 2003a), the basalts of Kamenev Nunatak (Wever and Storey, 1992; this study) and the amygdaloidal basalt succession at Eland Mountains (this study;Fig. 1). All of the basaltic successions are related geographically and temporally to the extensive silicic volcanic rocks of the wider Chon Aike Province (Pankhurst et al., 2000); the Jason Peninsula basalts at Standring Inlet associated with the Mapple Formation rhyolitic tuffs (Riley and Leat, 1999), the Sweeney Formation basalts are associated with the Mount Poster Formation rhyodacites (Riley et al., 2001), and the basalts of Kamenev Nunataks and the Eland Mountains are associated with the rhyolitic lavas and tuffs of the Brennecke Formation (Wever and Storey, 1992). No direct geochronology exists for the basaltic successions from the southern Antarctic Peninsula, although accurate dates exist for the basaltic units at Jason Peninsula (Riley et al., 2003a).

New geochronology and geochemistry are presented here from the basaltic succession at the Eland Mountains and they are compared to the other eastern Antarctic Peninsula basaltic units, as well as the extensive Mesozoic mafic dykes of the Antarctic Peninsula (Leat et al., 2002). The timing and geochemistry of the basaltic successions are used to monitor the lithospheric conditions of the Antarctic Peninsula during the Mesozoic and how two significant silicic magmatic events caused a major change in lithospheric thickness. The basaltic successions overlap with the later stages of volcanism associated with the Karoo large igneous province (~184 – 178 Ma; Jourdan et al., 2005), but postdate the short-lived magmatism of the Ferrar large igneous province (Burgess et al., 2015).

2. Geological Setting

The Antarctic Peninsula was initially interpreted as an autochthonous continental arc of the Gondwanan margin, which developed during Mesozoic subduction (Suarez, 1976). However, following the identification of a major shear zone in the southern Antarctic Peninsula (the eastern Palmer Land shear zone) the composite geology of the Peninsula was reinterpreted as representing a series of para-autochthonous and allochthonous terranes which accreted onto the Gondwana margin (Vaughan and Storey, 2000). The accreted terrane hypothesis has recently been challenged by Burton-Johnson and Riley (2015) who favour a model involving in situ continental arc evolution.

The Middle Jurassic silicic volcanic rocks of the east coast of the Antarctic Peninsula (Mapple Formation; Riley and Leat, 1999) are closely associated with granitoid (tonalite-quartz diorite-granodiorite) plutonic rocks also of Middle Jurrasic age (Pankhurst et al., 2000) and thick (at least 800 m) sequences of Middle Jurassic terrestrial sedimentary rocks (e.g. Hunter et al, 2005). The Mesozoic formations of the east coast all have a characteristic continental affinity (Riley and Leat, 1999) and in the northern Antarctic Peninsula unconformably overlie Carboniferous – Triassic metasedimentary rocks of the Trinity Peninsula Group (Barbeau et al., 2010; Bradshaw et al., 2010). The Trinity Peninsdula Group is estimated to have a thickness of at least 5 km and facies analysis suggest that they were deposited as submarine fans along a continental margin (Hathway, 2000). The Trinity Peninsula Group overlaps with and is likely to overlie ` Ordovician – Permian age crystalline basement (e.g. Hervé et al., 1996; Bradshaw et al., 2012).

The Mesozoic sequences of Graham Land have undergone low-medium grade metamorphism and deformation, possibly during the Palmer Land deformation event (107 103 Ma; Vaughan and Storey, 2000) or during an earlier Peninsula deformation event (Storey et al., 1987). Farther south (Palmer Land) along the eastern margin of the Antarctic Peninsula, the sequences are closely related to those in the north (Graham Land) although basement ages in Graham Land are mostly Permian – Triassic in age (Flowerdew, 2008; Riley et al., 2012). The Early – Middle Jurassic silicic volcanic rocks of Palmer Land include the Brennecke and Mount Poster formations (Riley et al., 2001; Hunter et al., 2006), which are associated with the basaltic successions and the extensive shallow marine sedimentary rocks of the Latady Group (Hunter and Cantrill, 2006). The sedimentary sequences of the Black Coast region (Fig. 1) are known locally as the Mount Hill Formation and are interpreted to be a correlative of the Latady Formation. The granitoid plutons of Palmer Land are typically mid-Cretaceous in age (~105 Ma; Flowerdew et al., 2005) and are part of the more extensive Lassiter Coast intrusive suite (LCIS), which intrudes the Jurassic sequences.

3. Basaltic sequences

3.1 Sweeney Formation basalts, southeast Palmer Land

The most distinctive facies are the amygdaloidal basalts with a melanocratic fine grained matrix and cream or white amygdales, which have a pronounced lineation (Hunter et al., 2006). The amygdales vary in quantity and size between flows from less than 1 cm up to 6 cm in diameter. Other basaltic flows can be aphyric or weakly phyric with minor amounts of plagioclase, clinoyroxene, apatite and magnetite. Rarely, basaltic flows are vesicular and occasionally basaltic pillow lavas crop out at Mount Ballard and neighbouring outcrops (Fig. 1). Interbedded, ash-rich ignimbrite units or finely bedded ash-fall horizons occur at irregular intervals throughout the succession. Hunter et al. (2006) interpreted the Sweeney Formation basaltic lavas to be broadly contemporaneous with the silicic Mount Poster Formation at ~183 Ma based on detrital zircons from interbedded sedimentary sequences. This interpretation is consistent with the field observations.

3.2 Standring Inlet basalts, Jason Peninsula

Basic volcanic rocks have been identified from two areas on Jason Peninsula (Riley et al., 2003a). One area on the eastern side of Standring Inlet (Fig. 1) has three prominent exposures, the northernmost of which is characterised by basic volcanic rocks and volcaniclastic sedimentary rocks. The other prominent outcrops are silicic crystal tuffs. At Standring Inlet, the basalts are fine grained and individual lava flows are up to 50m in thickness associated with breccia components. The basic rocks have a characteristic spheroidal weathering texture. The basalts are generally fresh, plagioclase-phyric lavas with sparse accessory phases, including apatite, titanomagnetite and orthopyroxene. No olivine was identified in the groundmass or as a phenocryst phase. The basaltic rocks from the lowermost flow at Standring Inlet are typically aphyric, fine grained lavas, whereas those from the upper flow are plagioclase porphyritic. The basaltic rocks from Stratton Inlet (Fig. 1) are also fine-grained and typically aphyric.

3.3. Hjort Formation basaltic lavas, Black Coast

Basic greenstones crop out at several localities along the Black Coast of Palmer Land (Fig. 1). The greenstones consist of aphanitic metabasaltic rocks, which have, in part, been hornfelsed (Storey et al., 1987). Amygdales, often filled with quartz and epidote are common, particularly at Kamenev Nunataks (Fig. 1). The type locality occurs at Hjort Massif (Fig. 1) where a 150m thick succession of amphibolitic greenstones conformably overlie a westward dipping sequence of deformed metasedimentary rocks (probable Mount Hill Formation). The mineralogy of the mafic rocks is dominated by green hornblende and plagioclase, with minor epidote, titanite and chlorite.

At Mount Whiting (Fig. 1) the dominant lithology is a very fine grained mafic greenstone widely recrystallised to greenschist facies. The unit is extensively intruded by multiple amphibole-plagioclase megacrystic dykes and associated pegmatites, such that in places, the intrusive rocks can constitute >50% of the total outcrop.

Amygdaloidal, fine grained-aphyric basalts occur widely in the Black Coast region and are often associated with metasedimentary rocks of the Mount Hill Formation, which either overlie or are interbedded with the Hjort Formation.

A continuation of this sequence is also seen farther south into the Lassiter Coast (Fig. 1) where thin basaltic lava and breccias units are interbedded with clastic sedimentary rocks of the Latady Formation (Rowley et al., 1983).

3.4. Eland Mountains, northeast Palmer Land

The geology of the Eland Mountains to Eielson Peninsula area (Fig. 1) is dominated by highly deformed, low grade metabasic and metasedimentary rocks forming a greenstone succession, which is intruded by largely undeformed diorite- granodiorite-tonalite- granite plutons assumed to be part of the Mid Cretaceous age Lassiter Coast intrusive suite (Flowerdew et al., 2005). The most extensive and consistent stratigraphical unit within the area is a thick (≥ 800m) succession of generally aphyric, predominantly amygdaloidal metabasalts that form the entirety of the Eland Mountains massif and crop out at several localities across the area. Individual units comprising the succession are difficult to identify on the ground due to the nature of the exposure and subsequent lower greenschist facies metamorphism and deformation, however, where identified they were measured at up to 6m thick. Pipe amygdales were identified at the base of several units with more equant amygdales (quartz and epidote) forming horizons at the top of the unit. The amygdales are generally quite large, commonly up to 2-3 cm in diameter, being both widely distributed throughout the exposures, as well as forming concentrated horizons that are structurally parallel to the other units.

Throughout the study area the metabasic succession is punctuated by several aphyric (one example was feldspar phyric), cream-grey coloured, felsic units (these are the units dated here) displaying widespread epidote mineralisation and evidence of devitrification. These felsic units are up to 5m thick (mean 1.7m) and are parallel to the stratification of the metabasalt succession, with two localities displaying downward intruding dykes. In general, where tectonic strain is low, the lower contact of the felsic units show convolute/cusp and lobe relationship with the underlying metabasalt (Fig. 2). Highly globular inclusions of basalt are commonly found within the felsic units, the margins of which can be intricately cuspate and displaying chilled margins. These contact relationships (mutually intrusive at a small scale) together with the presence of chilled margins within basaltic enclaves that have become entrained within the felsic unit suggest that both basaltic and felsic units were comagmatic at the time of emplacement.

The stratified nature of the overwhelmingly basalt succession within the Eland Mountains – Eielson Peninsula area has two possible origins: 1) a succession of nested sills, or 2) a succession of laterally extensive lava flows. Due to low grade metamorphism and epidote mineralisation it is often difficult to observe discrete contacts, but where they are observed there is no evidence of chilled margins along the upper contact of any individual unit and no evidence for screens of country rock that might be expected to have survived, at least as small rafts of isolated wall rocks. In contrast, evidence for an extrusive origin is provided by the contact relationships between the rare felsic units that consistently display highly convolute/cuspate lower contacts with the underlying basalt, suggestive of comagmatic relationship, whereas the upper contact is exclusively planar (Fig. 2). This asymmetry in contact geometry is repeated in the distribution of mutual intrusive features (i.e. minor dykes and digitations of magma) with small scale dykes of felsic material cutting down into the underlying basalt, never up, and basalt mingling upward into a felsic unit, never down. These minor dykes all exhibit cuspate margins. Together, these relationships suggest that the felsic magmas were erupted contemporaneously upon the basaltic flows that were still partially molten, and cooled against an upper free surface prior to the next basaltic flow. For these reasons, the >800m thick, predominantly basaltic succession is interpreted as a lava succession and the felsic units are considered to punctuate the basaltic units, hence their age will represent that of the basaltic pile. The stratigraphical relationships to other lithologies are uncertain due to deformation and poor exposure of the contact. In the Leineiger Peak area (Fig. 1), the metabasalt succession overlies a thick, massive, medium grained quartz-feldspar porphyry unit and is overlain by metasedimentary rocks (pelite and quartzite units), whereas in the mountains to the south of Mount Strong (Fig. 1), a highly variable succession of metasedimentary and igneous rocks appear to underlie the thick metabasalt succession.

The mafic lithologies are dark green to black and contain leucocratic amygdaloidal structures of irregular to ovoid form, which are confined to particular horizons. The mafic rocks contain a large amount of fibrous amphibole, usually actinolite, although hornblende also occurs as anhedral phases. Plagioclase, epidote, chlorite, titanite and minor quartz are present in most lithologies. The amygdales are predominantly composed of quartz and epidote. Most rocks have some degree of foliation and have been metamorphosed to amphibolite grade.

Age information and geochemistry for the Eland Mountains succession are the subject of this paper in comparison to other mafic units from the eastern Antarctic Peninsula.

3.5 Cretaceous mafic dykes

Also relevant to this study are a suite of primitive mafic dykes of mid-Cretaceous age, which crop out irregularly along the entire length of the Antarctic Peninsula. They are typically east-west striking (perpendicular to the continental margin) and are interpreted to have been intruded during arc compression, which may coincide with the Palmer Land deformation event (Vaughan and Storey, 2000; Vaughan et al., 2002). They have been dated using ^{40}Ar-^{39}Ar geochronology (Leat et al., 2002) and yield ages in the interval 126 – 106 Ma (mid-Cretaceous), preceding the main episode of LCIS emplacement (Flowerdew et al., 2005).

4. Geochronology

4.1 Analytical procedures

U-Pb geochronology was carried out using the Cameca IMS 1280 ion microprobe, housed at the NORDSIM isotope facility, Swedish Museum of Natural History. Zircons, separated by standard heavy liquid procedures were mounted in epoxy and polished to expose their interiors. They were imaged by optical microscopy and cathodo-luminesence (CL) prior to analysis. The CL images were used as guides for analysis targets because they reveal the internal structure of the grains. The analytical method closely followed that detailed by Whitehouse and Kamber (2005). U/Pb ratio calibration was based on analysis of the Geostandard reference zircon 91500, which has a ^{206}Pb/^{238}U age of 1065.4 ± 0.6 Ma and U and Pb concentrations of 81 and 15 ppm respectively (Wiedenbeck et al., 1995).

Common lead corrections were applied using a modern day average terrestrial common lead composition (^{207}Pb/^{206}Pb = 0.83; Stacey and Kramers, 1975) where significant ^{204}Pb counts were recorded. Age calculations were made using Isoplot v.3.1 (Ludwig, 2003) and the calculation of concordia ages followed the procedure of Ludwig (1998). The results are summarised in Table 1.

4.2 Previous geochronology

Reliable age data (whole rock and plagioclase ^{40}Ar/^{39}Ar and zircon U-Pb) from the basaltic sequences of the eastern Antarctic Peninsula exist for Jason Peninsula (Standring Inlet) and indirectly for the Sweeney Formation, but there is no reliable age information for the extensive Hjort Formation of the Black Coast.

Jason Peninsula: Six samples from Standring Inlet (Jason Peninsula; Fig. 1) were sampled from two stratigraphically close sequences that would be anticipated to yield an overlapping set of ages; four of the six ages do overlap with a mean age of 174.4 ± 1.6 Ma (Riley et al., 2003a). The two other samples yield younger ages of ~168 Ma, but do not yield plateaux, therefore the best estimate for the age of the Jason Peninsula sequence is probably 174.4 ± 1.6 Ma, which predates the main pulse of silicic volcanism of the adjacent Mapple Formation (171 – 168 Ma; Pankhurst et al., 2000).

Sweeney Formation: The Sweeney Formation basaltic rocks have been dated indirectly by the age of detrital zircons from the interbedded sedimentary units. The detrital material yielded a concordia age of 183 ± 4 Ma (Hunter et al., 2006), which is the maximum age of deposition of the sedimentary units and is also taken as the best age estimate for the basaltic succession. This is contemporaneous with the silicic Mount Poster Formation (183.4 ± 1.4 Ma; Hunter et al., 2006), which is the likely source of the detrital material.

Hjort Formation: The Hjort Formation basaltic sequences of the Black Coast, initially described by Wever and Storey (1992) have not been accurately dated, although Pankhurst et al. (2000) interpreted the Hjort Formation to be essentially contemporaneous with the 184 ± 2 Ma Brennecke Formation, implying a similar relationship to that of the Sweeney and Mount Poster formations.

4.3 This study

Two felsic samples from the dominantly basaltic succession at Eland Mountains are dated here using U-Pb zircon geochronology, which provide the first reliable ages for the significant basalt successions of the Black Coast region of Palmer Land. The samples are from the silicic units that punctuate the basaltic succession in the Eland Mountains. The felsic units have a mean thickness of ~2m and are parallel to the stratification of the metabasalt succession. The contact relationships are shown in Fig. 2 and indicate that the felsic units are interbedded and therefore their age accurately reflects that of the major metabasaltic unit. Sample N10.2.1 comes from an interbedded silicic unit near the base of the basaltic pile, whereas sample N10.7.1 comes from an interbedded silicic unit close to the centre of the basaltic pile.

Zircons from sample N10.2.1 are bright, clear, well facted prismatic grains (Fig. 3a). Cathodoluminescence (CL) images of zircons display growth zoning that is typical of zircon which crystallised from a magma (e.g. Corfu et al. 2003), as is the relatively rare core and rim relationships. The few zircons which display distinct cores were avoided as the cores of the grains were interpreted to be inherited and would not date the silicic volcanism. Nineteen analyses were carried out on 19 separate grains. Fifteen analyses yield a concordia age of 180.2 ± 0.7 Ma (Fig. 4a) and a weighted mean of the common Pb corrected $^{207}Pb/^{206}Pb$ ages (Ludwig, 2003) of 179.9 ± 1.0 Ma, which is taken to date crystallisation of the silicic unit. One analysis (spot 16; Fig. 3a) inadvertently sampled an inherited core with a $^{206}Pb/^{238}U$ age of 511 ±7 Ma. Three analyses (spots 2, 15 and 18; Fig. 3a) with $^{207}Pb/^{206}Pb_c$ ages younger than c. 174 Ma are assumed to have suffered minor degrees of recent Pb loss and so were also excluded from the age calculation.

A second interbedded felsic unit, N10.7.1, yielded zircons which are also bright, well-faceted, clear, prismatic grains (Fig. 3b). Under CL they strongly resemble the character of those from sample N10.2.1 with oscillatory zoning and few cores. Twenty analyses were carried out on 19 separate grains. Fourteen of these analyses yield a concordia age of 177.6 ± 1.0 Ma, and a weighted mean of the common Pb corrected $^{207}Pb/^{206}Pb$ ages (Ludwig, 2003) of 178.1 ± 1.4 Ma (Fig. 4b), which is taken to date crystallisation of the silicic unit. This age is within error of sample N10.2.1. Therefore an age for the 800m basaltic succession of ~178 Ma is preferred, postdating the main episode of silicic volcanism of the Brennecke and Mount Poster formations.

The data for both of the dated samples are shown in Table 1.

5. Geochemistry

Major elements and selected (Cr, Ni, etc) trace element abundances were determined by X-ray fluorescence (XRF) at the University of Leicester, essentially using the methods described fully by Floyd (1985). Higher precision trace element abundances were determined by inductively couple plasma mass spectrometry (ICP-MS) at the University of Durham. The analytical methods, precision and detection limits are comparable to those of Ottley et al. (2003).

5.1 Results

Data from both the mafic and the two dated silicic rocks from the Black Coast region (Eland Mountains, Kamenev Nunataks and Mount Whiting; Fig. 1) are presented in Table 2.

5.2 Alteration

The mafic volcanic rocks of the Black Coast region have been variably deformed and undergone some degree of hydrothermal alteration and amphibolite grade metamorphism. The chemical effects of amphibolite grade metamorphism are anticipated to include the significant mobilisation of the alkali elements (Na, K, Rb, Cs) and the alkali earth elements such as Ca, Sr and Ba (e.g. Vaughan et al., 2012). The high field strength elements, such as Nb, Ta, Ti, Zr, Hf as well as the rare earth elements (REE) are anticipated to be immobile and are hence suitable for petrogenetic interpretation.

5.3 Comparison of basaltic groups

The Nb/Yb vs. Th/Yb plot (Fig. 5) uses trace elements that are likely to have been immobile during alteration and metamorphism. Figure 5 shows the field of basaltic rocks from Jason Peninsula (Riley et al., 2003a), Sweeney Mountains (Hunter et al., 2006) and several distinct groups from the Black Coast region (Wever and Storey, 1992; this study). The basaltic rocks are plotted relative to the MORB-OIB array (Pearce and Peate, 1995) as well as specific chemical groups from the broadly contemporaneous Karoo and Ferrar large igneous provinces (Riley et al., 2005 and references therein, 2006; Luttinen and Furnes, 2000) as well as the Cretaceous mafic dykes of the Antarctic Peninsula (Leat et al., 2002; Vaughan et al., 2012).

The basaltic andesites and basalts of Jason Peninsula plot within the field of calc-alkaline rocks and have the most enriched compositions of the Mesozoic mafic rocks of the Antarctic Peninsula with high Th/Yb and Nb/Yb with respect to MORB and OIB. Such compositions are characteristic of rocks from mature continental margin arcs derived from a lithospheric mantle source that was enriched in Th as a result of modification by subduction-derived fluids.

The basaltic rocks of the Sweeney Formation (Hunter et al., 2006) lie close to the MORB-OIB array and are characteristic of island arc tholeiites derived from a mantle source depleted in Nb/Yb, but transitional to calc-alkaline rocks.

Two separate suites of Cretaceous primitive mafic dykes from the east coast of the Antarctic Peninsula have been described by Leat et al. (2002). One of the suites in the north of the Antarctic Peninsula (Oscar II Coast, eastern Graham Land) was intruded at approximately 120 Ma. The dykes are depleted in Nb relative to Yb with respect to MORB, and have high Th/Nb relative to MORB and OIB. They were interpreted by Leat et al. (2002) to be partial melts of asthenospheric mantle underlying the Antarctic Peninsula magmatic arc. Cretaceous (106 – 126 Ma) mafic dykes of the Black Coast region (Palmer Land) have high LREE/HREE ratios, are not depleted in Nb relative to Yb with respect to MORB, and have high Th/Nb relative to the MORB-OIB array. These basalts were interpreted to be partial melts of lithospheric mantle underlying the continental arc, which was modified at some time by fluids and sediments from a subduction zone.

The lava sequences from the Black Coast are interpreted to all be Middle Jurassic in age and show a broad distribution on Fig. 5. The amygdaloidal basaltic lavas of the Eland Mountains (this study) and Kamenev Nunatak (Group III of Wever and Storey, 1992; this study) plot close to the field of global subducting sediment (GLOSS; Plank and Langmuir, 1998) indicating a significant contribution from continental crust or partial melts of subduction-modified lithosphere. They plot within the field of calc-alkaline rocks, but are not as enriched in Th as the broadly contemporaneous basaltic rocks from Jason Peninsula. The basaltic rocks from the Eland Mountains and Kamenev Nunataks also overlap in composition with the geographically overlapping, but Cretaceous-age, Black Coast mafic dykes and also overlap with the field of Early Jurassic-age Ferrar large igneous province dolerite dykes and sills of the Transantarctic Mountains (Molzahn et al., 1996; Riley et al., 2003b; 2006). Two mafic dykes from the Mount Whiting area (Fig. 1) are associated with a nearby gabbroic pluton, which is likely to be mid-Cretaceous in age (Flowerdew et al., 2005). The Mount Whiting dykes are therefore one of the final phases of magmatism in the Black Coast region.

Amygdaloidal basalts, mafic greenstones and mafic dykes from the Hjort Massif, Mount Hill, Eland Mountains, Mount Strong and Mount Whiting (Fig. 1) are all tholeiitic or transitional to calc-alkaline. They plot close to the MORB-OIB array and range from relatively depleted compositions (Mount Whiting) to compositions that are characteristic of island arc tholeiites and overlap with the amygdaloidal basalts of the marginally older Sweeney Formation of southeast Palmer Land (Hunter et al., 2006).

The $(Gd/Yb)_{PM}$ vs $(Nb/La)_{PM}$ diagram (Fig. 6a) identifies several distinct groups corresponding to the different settings of the basaltic rocks. These ratios (normalised to primitive mantle; McDonough and Sun, 1995) are controlled by the depth of melting within the mantle $(Gd/Yb)_{PM}$ and by the contribution from the arc lithosphere $(Nb/La)_{PM}$ (Jowitt and Ernst, 2013). Those groups with the strongest arc signature are the basalts from Jason Peninsula and the dykes from the Black Coast (Fig. 6a), whilst the thick amygdaloidal basaltic successions at Eland Mountains (this study) and those of the Sweeney Formation (Hunter et al., 2006) have $(Nb/La)_{PM}$ values >0.6 indicating a far less significant contribution from the arc lithosphere. The distinct groupings are also evident in Fig. 6b, $(Gd/Yb)_{PM}$ vs $(La/Sm)_{PM}$, with $(La/Sm)_{PM}$ representing the degree of crustal contributions or the level of source enrichment (Wallace et al., 2015). The basalts from Jason Peninsula and the Black Coast Cretaceous dykes are the most enriched, whilst the Oscar II Coast dykes and the greenstones from Mount Whiting are the most depleted (Fig. 6b). The basalts from the Sweeney Formation and the Eland Mountains are intermediate, with only modest levels of enrichment.

5.4 Major elements

The total alkali vs. SiO_2 plot for the basaltic groups and mafic dykes of the eastern Antarctic Peninsula are shown in Fig. 7. The basalts from the Sweeney Formation of southeast Palmer Land are all transitional between alkaline basalts and sub-alkaline basalts, with several of the basalts considered primitive with FeO*/MgO <1 and Ni contents close to 300 ppm. The mafic rocks from Standring Inlet on Jason Peninsula (Fig. 1) are mostly basaltic andesite in composition and are calc-alkaline. None of the Jason Peninsula basaltic andesite rocks are primitive in composition with FeO*/MgO ratios >1 and Ni contents <50 ppm suggesting they have experienced significant fractional crystallisation from mantle-derived melts. The three basaltic groups defined from the Hjort Formation by Wever and Storey (1992) show a broad variation, with groups 2 and 3 predominantly alkaline, whereas the group 1 basalts are sub-alkaline and tholeiitic in composition (Fig. 7). The group 1 basalts are relatively primitive with FeO*/MgO ~ 1 and Ni contents >100 ppm. The group 2 basaltic greenstones are not as primitive as group 1, with MgO contents in the range, 5 – 9 wt% and Ni contents in the range 46 – 184 ppm, whereas the group 3 mafic rocks have MgO contents of 5 – 7 wt% and low Ni contents, <60 ppm. The lavas from Kamenev Nunatak (Fig. 1) are intermediate in composition and plot at calc-alkaline compositions with close similarity to the basaltic andesites of Jason Peninsula.

The mafic rocks from the Eland Mountains (Fig. 1) show considerable variation, with two calc-alkaline andesites and the remaining samples are alkaline basalts akin to the group 3 Hjort Formation and the Cretaceous dykes from the Black Coast (Leat et al., 2002). The Oscar II Coast Cretacoeus age dykes are all high MgO basalts (8 – 12 wt%) with Ni contents typically >200 ppm. The low SiO_2 (<42 wt%) mafic dykes from Mount Whiting are transitional between alkaline and sub-alkaline, with moderately high MgO contents (6 – 12 wt%). A mafic greenstone from Mount Whiting has higher SiO_2 and is transitional between tholeiitic and calc-alkaline.

5.5 Rare earth elements

Chondrite normalised rare earth element (REE) plots for the range of mafic rocks from the eastern region of the Antarctic Peninsula are shown in Fig. 8. The most striking compositions are those of the depleted tholeiitic, Cretaceous-age Oscar II Coast dykes (Leat et al., 2002), which all have light REE-depleted signatures. The two primitive Cretaceous mafic dykes from Mount Whiting (Fig. 1) also have LREE depleted signatures, as do one of the Sweeney Formation basalts (Hunter et al., 2006) and a single Cretaceous dyke from the Black Coast (Leat et al., 2002). The majority of the basaltic groups are calc-alkaline and are consistently LREE-enriched with $(La/Yb)_N$ ratios up to 14. The most enriched compositions are from the Cretaceous Black Coast mafic dykes described by Leat et al. (2002).

6. Discussion

Long-lived continental margin arcs are characterised by periods of high magmatic addition rates (MARs) or 'flare ups'. High MAR episodes typically last 5 – 20 Myr, which alternate with longer periods of 30 – 70 Myr of low-MAR episodes (De Celles et al., 2009). Continental margin 'flare-ups' are interpreted to be related to the upper plate tectonic regime; although the processes can be varied, they are typically associated with mafic underplating and lithospheric thickening.

There is evidence for a magmatic 'flare-up' on the eastern margin of the Antarctic Peninsula at ~170 Ma, which in eastern Graham Land (Oscar II Coast; Fig. 1) is marked by voluminous silicic volcanism and granitoid emplacement at 171 – 168 Ma (Pankhurst et al., 2000; Riley et al., 2001). The silicic magmatism is contemporaneous with part of the Chon Aike Province in Patagonia (Pankhurst et al., 1998).

A magmatic 'flare-up' in the southern Andean Cordillera (Paterson and Ducca, 2015) also occurred at ~170 Ma and at ~112 Ma, which overlap with other 'flare-up' events along the North and South American margins.

Approximately 50% of the contribution to the high MAR is derived from the lithospheric underplate and crustal melting (De Celles et al., 2009). Therefore, the generation and emplacement of extensive silicic volcanism and crustally-derived granitoids/ignimbrites at ~170 Ma will have subsequently led to extensive thinning of the lithosphere and crust in those areas where silicic volcanism was widespread. The high MAR along the Antarctic Peninsula at ~170 Ma was the result of prolonged subcrustal thermal input, coupled with ongoing subduction and the onset of Gondwana breakup (Riley et al., 2001). The lithospheric extension associated with Gondwana breakup would have led to an influx of asthenospheric melts to higher levels following the silicic volcanism/granitoid 'flare-up'

This process is demonstrated in the geological and geochemical record in eastern Graham Land (Oscar II Coast) with the intrusion of a suite of asthenosphere-derived mafic dykes in the Mid-Cretaceous (Leat et al., 2002) suggesting that the lithosphere had been extensively thinned following the silicic magmatism at ~170 Ma, which permitted an influx of melt from the asthenosphere. The MORB-like, asthenosphere-derived melts typified by the Cretaceous dykes of the Oscar II Coast are probably related to slab-derived melts associated with ongoing subduction. Further support for this petrogenetic model is provided by the basaltic-intermediate volcanism exposed at Standring Inlet

(Jason Peninsula; Fig. 1). This basaltic-andesitic volcanism was relatively minor in volume, but crucially it predated (174 Ma; Riley et al., 2003a) the silicic magmatism 'flare-up' at ~170 Ma (Pankhurst et al., 2000). The source for the basaltic magmatism at Jason Peninsula had a strong lithospheric and crustal signature indicating the prevailing conditions prior to the silicic magmatic 'flare-up' were dominated by a thickened lithosphere.

The lithospheric conditions during the Mid Cretaceous in the eastern Palmer Land (Black Coast) region closely resemble the lithospheric conditions in eastern Graham Land (Oscar II Coast) at the time of the silicic 'flare-up' at 170 Ma. Leat et al. (2002) and Riley et al. (2003a) suggested that the absence of extensive Early – Middle Jurassic silicic magmatism in eastern Palmer Land (Black Coast) meant that the lithosphere was not thinned and depleted to the same extent as the lithosphere in eastern Graham Land (Oscar II Coast). The identification of a single geochemically depleted Cretaceous mafic dyke from the Black Coast region was interpreted by Leat et al. (2002) to indicate that lithospheric and asthenospheric magma sources were present but remained distinct and there was no mixing involved. However, the range of basaltic groups from eastern Palmer Land (e.g. Fig. 5) implies a more complex petrogenesis than suggested by Leat et al. (2002). Many of the basaltic rocks from eastern Palmer Land are intermediate between the asthenosphere and lithosphere end members defined by Leat et al. (2002), indicating that there is a diverse compositional range (Fig. 5, Fig. 6). A petrogenetic model that invokes two distinct sources can be dismissed, given the variability within individual outcrops; for example, two samples (N10.6.1, N10.178.1; Table 1) from the Eland Mountains (Fig. 1) plot at contrasting positions on Fig. 5, despite being sampled from stratigraphically close lava units.

It is clear from the differences in basalt geochemistry between Graham Land and Palmer Land that there was significantly less lithospheric thinning/delamination in the southern part of the Antarctic Peninsula during the Middle Jurassic. The basalts from the Black Coast (Palmer Land) are typified by a broad range of compositions, indicating a range of sources, subduction and crustal inputs and differing depths of melting.

Crucially, the two mafic dykes from Mount Whiting (Fig. 1) which are associated with Cretaceous-age gabbros (Flowerdew et al., 2005) have depleted REE signatures (Fig. 8) and immobile trace element characteristics (Fig. 5) akin to those of the depleted basaltic dykes of the Oscar II Coast. The gabbroic magmatism in the region postdates the main felsic magmatism of the Lassiter Coast intrusive suite, therefore the mafic dykes associated with the Mount Whiting gabbro suggest the establishment of a thinned lithospheric upper mantle, enabling the melting of a more depleted source. The mafic dykes of the Black Coast predate (~110 – 120 Ma; Leat et al., 2002) the Lassiter

Coast intrusive suite, and have retained lithosphere-derived signatures and were probably related to ongoing subduction and slab-derived melts.

Although there was no silicic volcanism 'flare-up' in Palmer Land, on the scale of the ~170 Ma event in eastern Graham land, the episode of felsic magmatism at ~110 – 105 Ma (Flowerdew et al., 2005) associated with the emplacement of the Lassiter Coast intrusive suite (Rowley et al., 1983) is on a similar scale. The Lassiter Coast intrusive suite forms a network of mostly tonalite-quartz diorite-granodiorite plutons and batholiths that have an areal extent of >13,000 km^2 and although silicic volcanism is not preserved, the intrusive record indicates a significant episode of melting that will have led to lithospheric thinning. This particular high MAR 'flare-up' postdates the Middle Jurassic event (170 Ma) by approximately 60 Myr, an interval that is consistent with the model proposed by De Celles et al. (2009) for the Andean margin. A 'flare-up' event at ~110 Ma is also consistent with the 112 Ma event in the southern Andean Cordillera (Paterson and Ducca, 2015).

7. Summary

A metabasaltic succession of 800m thickness from the Black Coast region of the Antarctic Peninsula has been dated at 178 ± 1 Ma and provides the first accurate date for the basaltic units of the southern Antarctic Peninsula. The sequences of mafic and felsic magmatism along the east coast of the Antarctic Peninsula are a valuable indicator of lithospheric conditions during the Mesozoic along this continental margin. Two distinct high magma addition rate events at ~170 Ma and ~110 Ma are recognised along the Antarctic Peninsula; (1)the extensive Chon Aike Province silicic volcanic event (specifically the V2 episode at 170 Ma) and (2) the Lassiter Coast intrusive suite batholith at 110 Ma. Both of these events led to significant thinning of the thickened lithospheric mantle such that after each 'flare-up' event the mafic volcanism has a clear asthenospheric signature, in contrast to the mafic magmatism that directly precedes the 170 and 110 Ma 'flare-up' events (Fig. 9).

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Durham performed the ICP-MS analyses. Kerstin Lindén and Lev Ilyinsky are thanked for their assistance at the NORDSIM facility. This is NORDSIM contribution number XXX.

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List of Figures

Figure 1. Location map of the Antarctic Peninsula highlighting the location of relevant place names and sample locations. The major basaltic units and silicic magmatism of the Chon Aike Province and Lassiter Coast intrusive suite are also marked The star indicates the location of the crystalline basement of Graham Land.

Figure 2. The lower contact of the felsic unit (N10.2.1) displaying intimate relationship with the underlying metabasalt resulting in the formation of globular basaltic enclaves exhibiting highly cuspate, chilled margins: (a) field photograph; (b) schematic interpretation of the relationship.

Figure 3. Concordia diagrams for the two felsic units interbedded with the basaltic succession at Eland Mountains, eastern Palmer Land: (a) Sample N10.2.1; (b) Sample N10.7.1.

Figure 4. Zircon cathodoluminesence images and spot analysis positions (scale bar 200µm) of the two felsic samples: (a) Sample N10.2.1; (b) Sample N10.7.1.

Figure 5. Variations in Th/Yb vs. Nb/Yb showing the composition of mafic rocks from the east coast of the Antarctic Peninsula relative to the MORB-OIB array (Pearce and Peate, 1995). Average Ferrar is from Molzahn et al. (1996) and GLOSS is average global subducting sediment from Plank and Langmuir (1998).

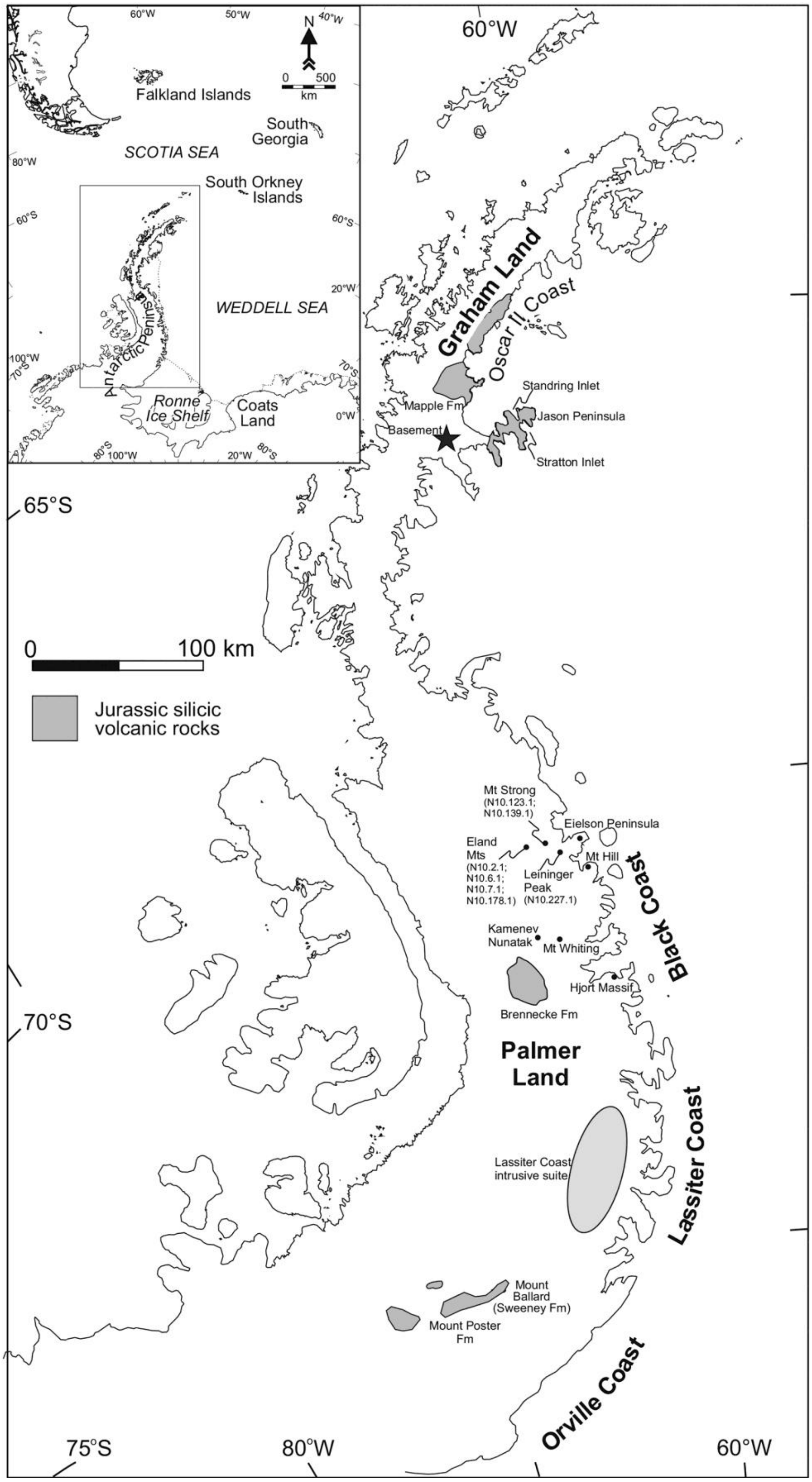
Figure 6. (a) $(Gd/Yb)_{PM}$ vs $(Nb/La)_{PM}$ with ratios normalized to primitive mantle (PM) values of McDonough and Sun (1995). Increasing $(Gd/Yb)_{PM}$ ratios indicate increasing depth of mantle melting and $(Nb/La)_{PM}$ ratios indicate the contribution of arc-related components. (b) $(Gd/Yb)_{PM}$ vs. $(La/Sm)_{PM}$ with $(La/Sm)_{PM}$ used as a proxy for crustal contamination or source enrichment.

Figure 7. Total alkalis vs. SiO_2 diagram (wt%) for the basaltic successions from the east coast of the Antarctic Peninsula. The samples are basalt or basaltic andesite. The dashed line is the division between alkaline and sub-alkaline rock types.

Figure 8. Chondrite (Nakamura, 1974) normalized REE diagrams for the basaltic successions from the east coast of the Antarctic Peninsula. (A) Mount Whiting; (B) Sweeney Formation; (C) Oscar II Coast dykes; (D) Kamenev Nunatak; (E) Eland Mountains; (F) Jason Peninsula; (G) Black Coast dykes.

Figure 9. Summary of the major geological events in eastern Graham Land and eastern Palmer Land and the likely lithospheric conditions.

Fiugre 1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50°W
40°W
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km
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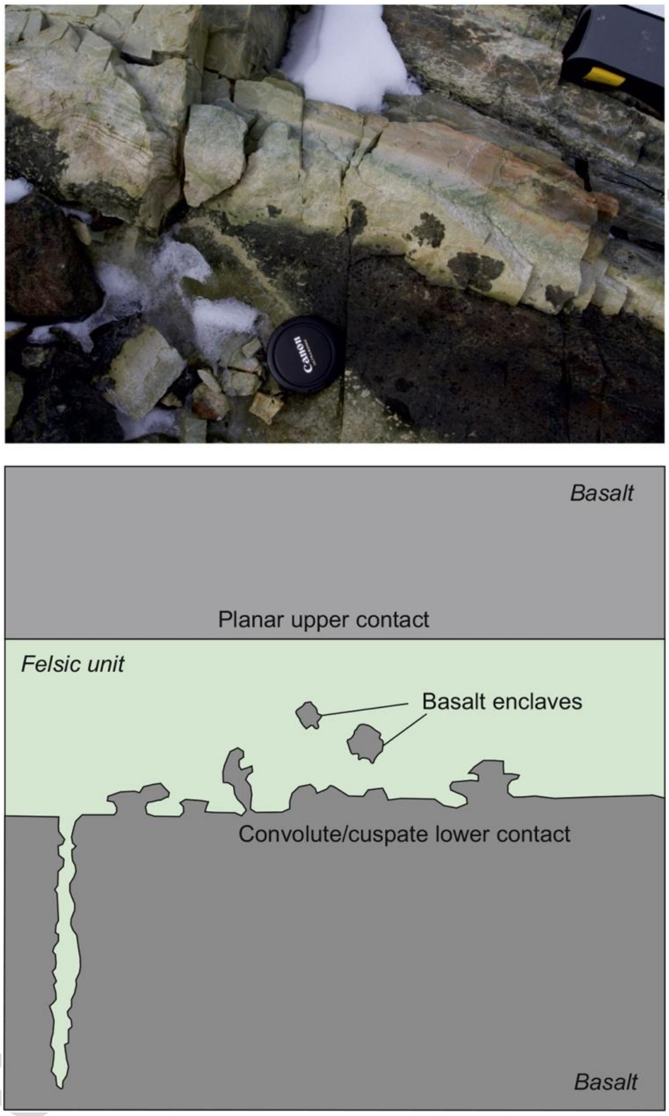
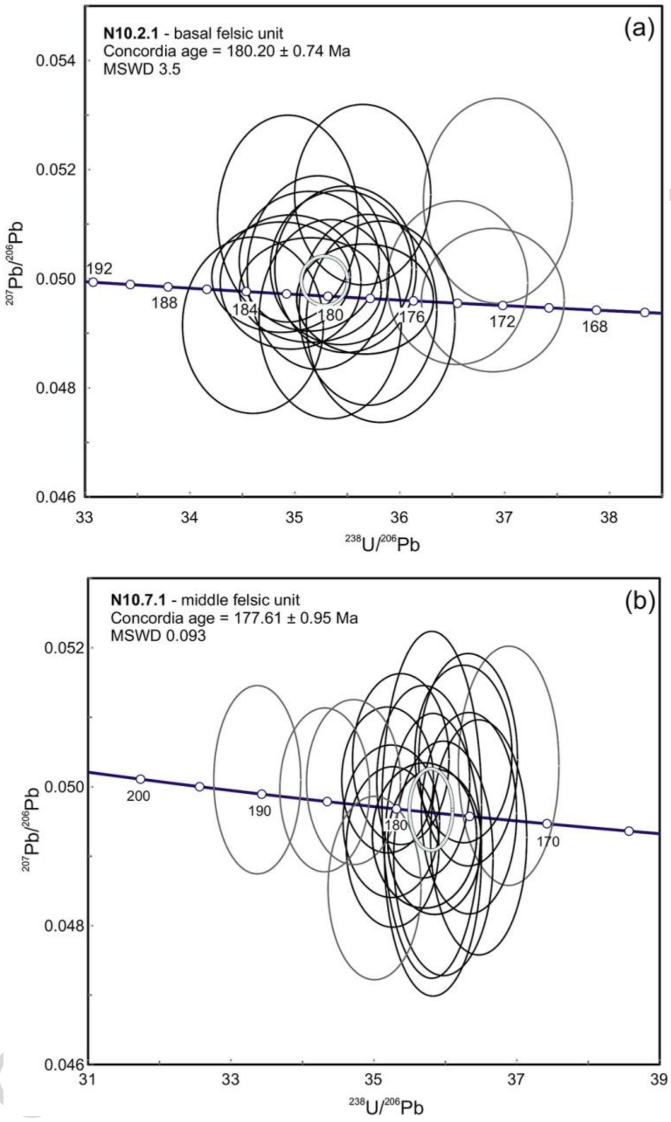
South Georgia
SCOTIA SEA
80°W
South Orkney Islands
60°S
60°S
20°W
WEDDELL SEA
Antarctic Peninsula
100°W
70°S
70°S
Ronne Ice Shelf
Coats Land
0°W
80°S
100°W
20°W
80°S
60°W
Graham Land
Oscar II Coast
Standring Inlet
Mapple Fm
Jason Peninsula
Basement
Stratton Inlet
65°S
0
100 km
Jurassic silicic volcanic rocks
Mt Strong (N10.123.1; N10.139.1)
Eielson Peninsula
Eland Mts (N10.2.1; N10.6.1; N10.7.1; N10.178.1)
Mt Hill
Leininger Peak (N10.227.1)
Black Coast
Kamenev Nunatak
Mt Whiting
Hjort Massif
Brennecke Fm
70°S
Palmer Land
Lassiter Coast intrusive suite
Lassiter Coast
Mount Ballard (Sweeney Fm)
Mount Poster Fm
Orville Coast
75°S
80°W
60°W

Fiugre 2


Canon
Basalt
Planar upper contact
Felsic unit
Basalt enclaves
Convolute/cuspate lower contact
Basalt

Fiugre 3


N10.2.1 - basal felsic unit
Concordia age = 180.20 ± 0.74 Ma
MSWD 3.5
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0.052
0.050
0.048
0.046
207Pb/206Pb
192
188
184
180
176
172
168
33
34
35
36
37
38
238U/206Pb
N10.7.1 - middle felsic unit
Concordia age = 177.61 ± 0.95 Ma
MSWD 0.093
(b)
0.052
0.050
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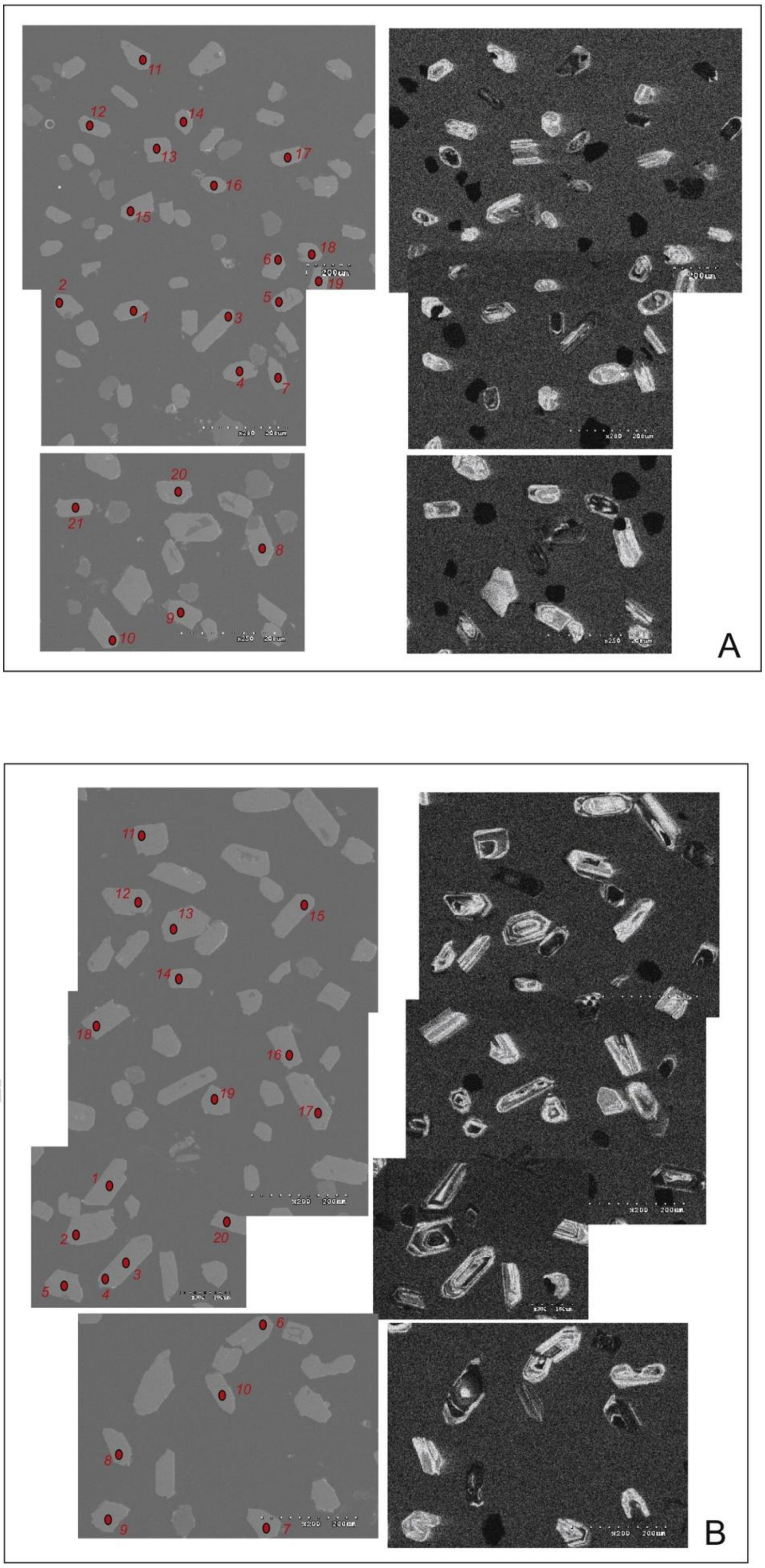
238U/206Pb

Fiugre 4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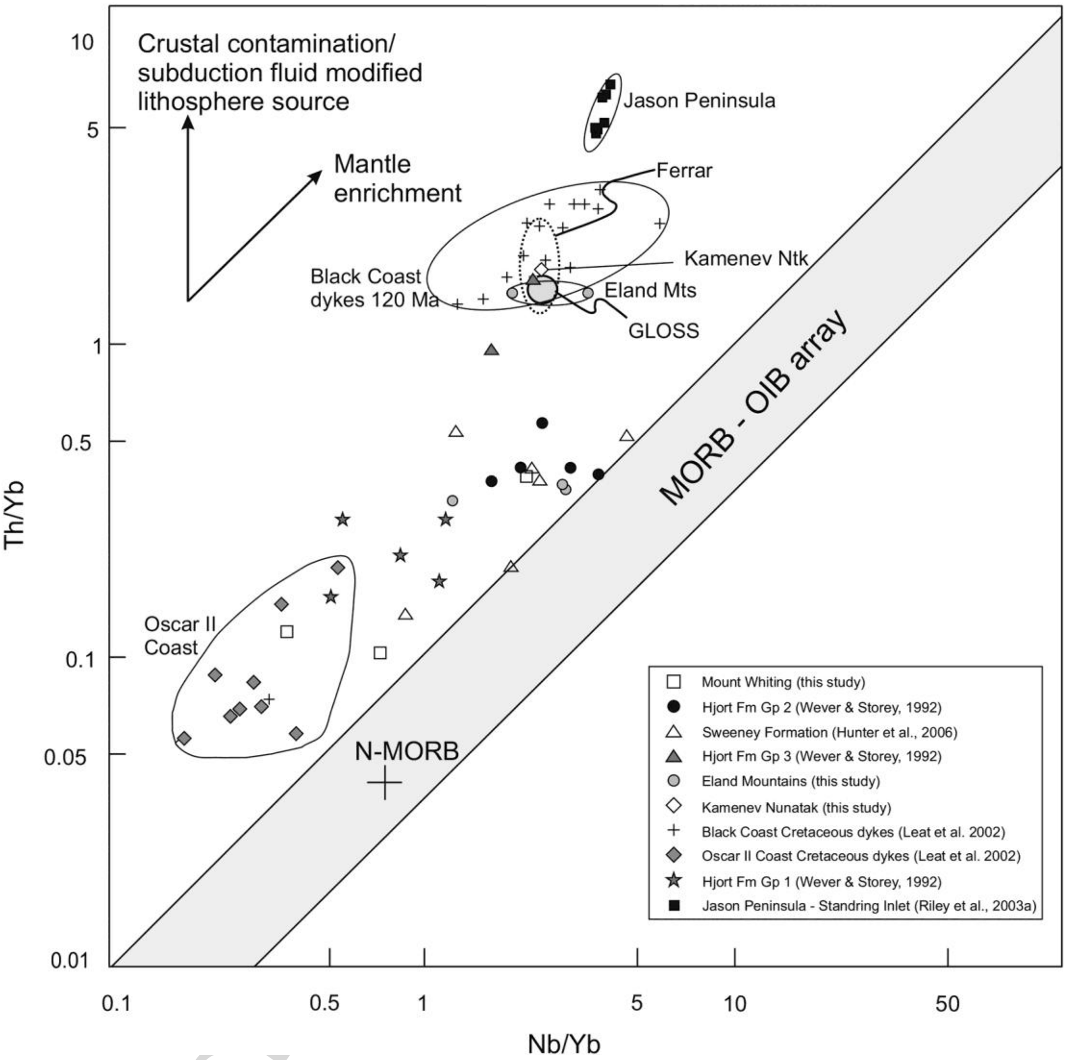
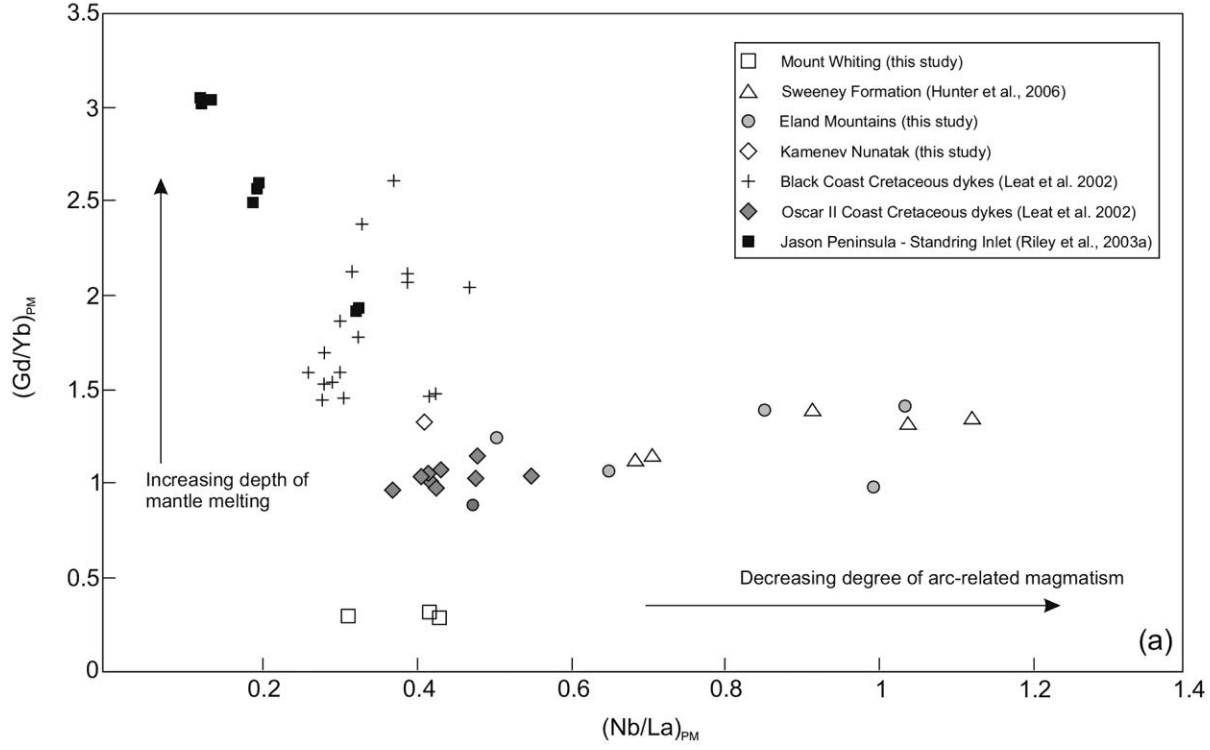
Fiugre 5


Crustal contamination/
subduction fluid modified
lithosphere source
Mantle
enrichment
Jason Peninsula
Ferrar
Kamenev Ntk
Black Coast
dykes 120 Ma
Eland Mts
GLOSS
MORB - OIB array
Oscar II
Coast
N-MORB
Th/Yb
Nb/Yb
10
5
1
0.5
0.1
0.05
0.01
0.1
0.5
1
5
10
50
□ Mount Whiting (this study)
● Hjort Fm Gp 2 (Wever & Storey, 1992)
△ Sweeney Formation (Hunter et al., 2006)
▲ Hjort Fm Gp 3 (Wever & Storey, 1992)
● Eland Mountains (this study)
◇ Kamenev Nunatak (this study)
+ Black Coast Cretaceous dykes (Leat et al. 2002)
◆ Oscar II Coast Cretaceous dykes (Leat et al. 2002)
★ Hjort Fm Gp 1 (Wever & Storey, 1992)
■ Jason Peninsula - Standring Inlet (Riley et al., 2003a)

Fiugre 6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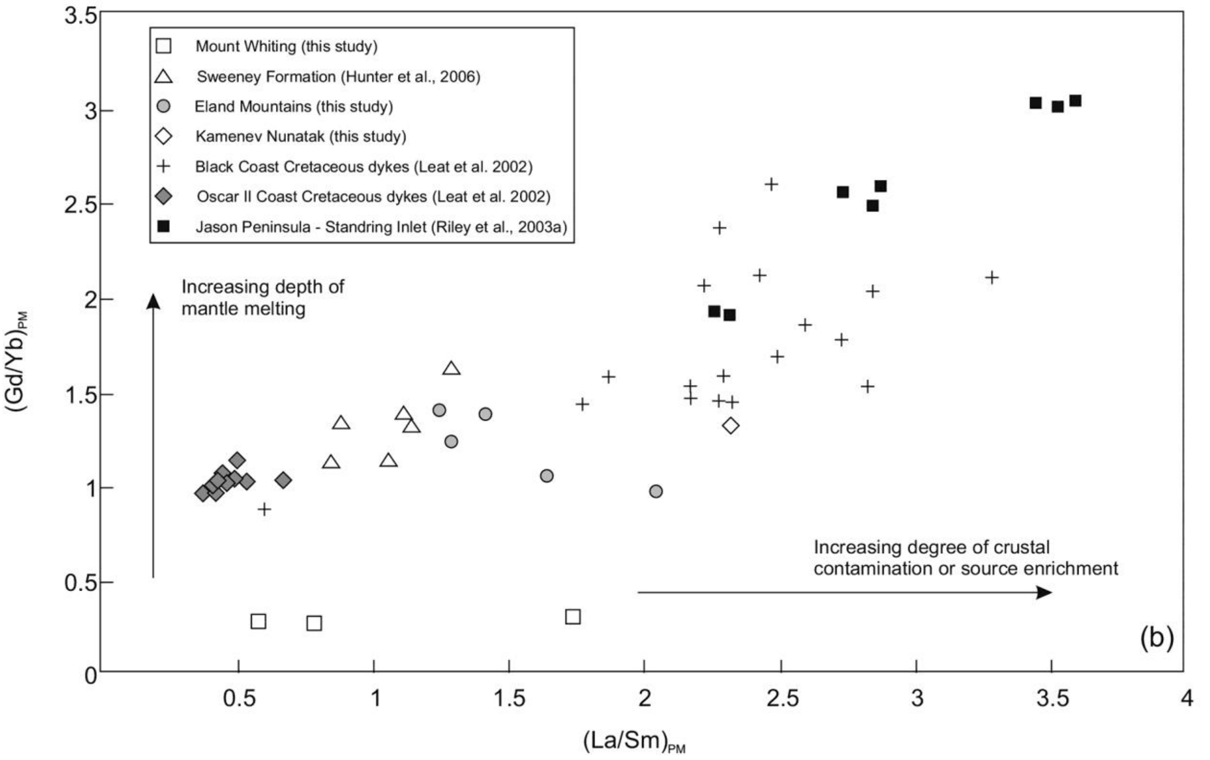
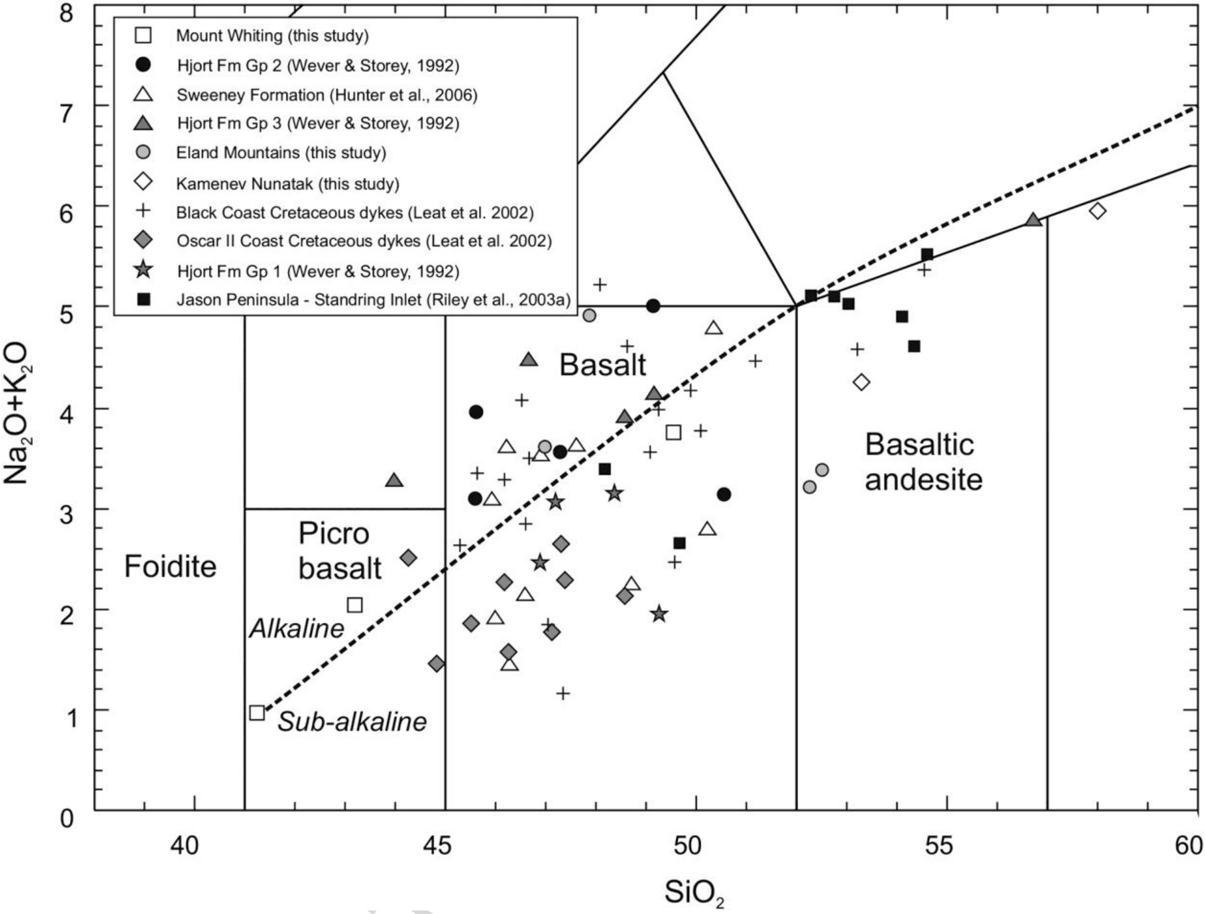
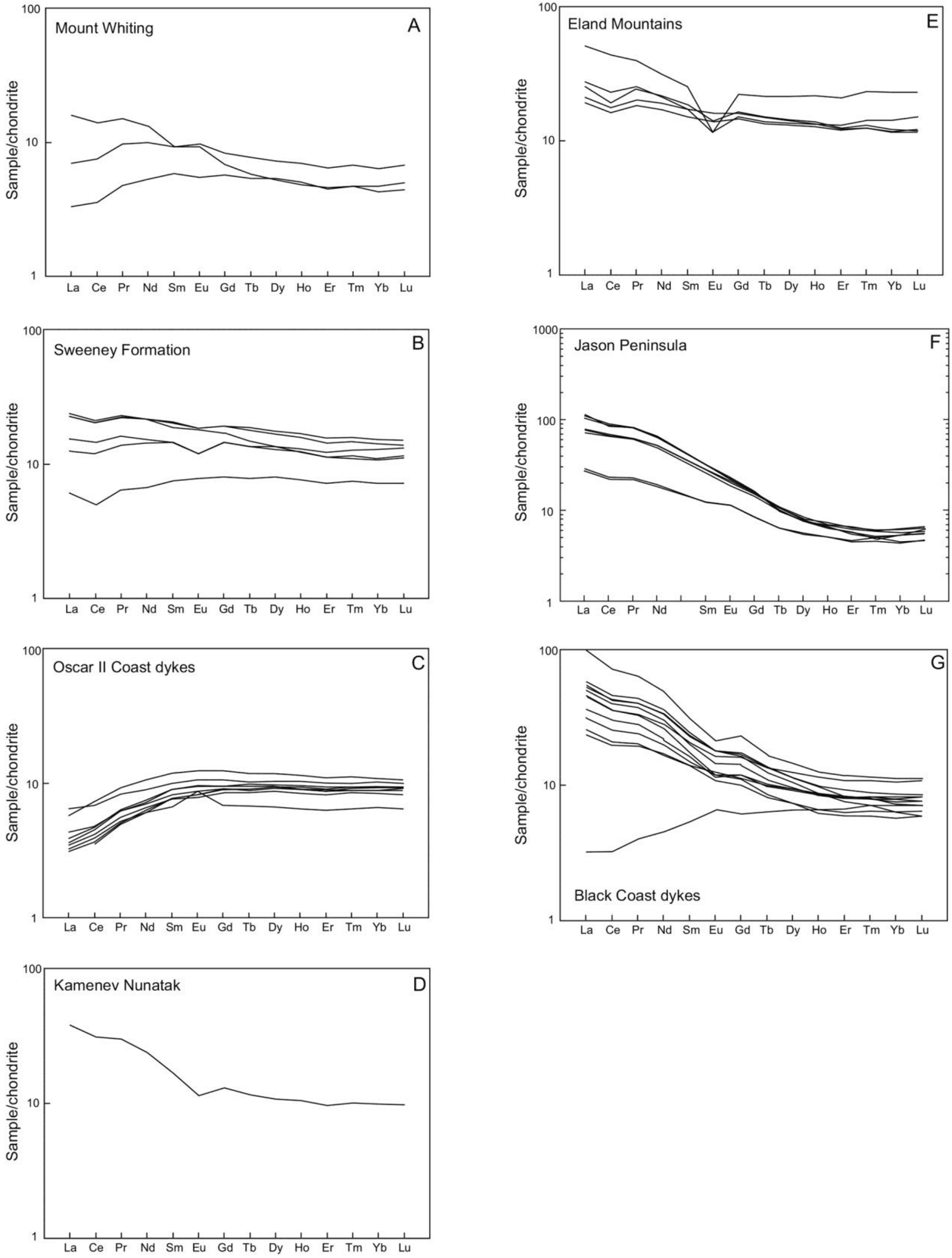
2
1.5
1
0.5
0
(Gd/Yb)PM
0.2
0.4
0.6
0.8
1
1.2
1.4
(Nb/La)PM
□ Mount Whiting (this study)
△ Sweeney Formation (Hunter et al., 2006)
● Eland Mountains (this study)
◇ Kamenev Nunatak (this study)
+ Black Coast Cretaceous dykes (Leat et al. 2002)
◆ Oscar II Coast Cretaceous dykes (Leat et al. 2002)
■ Jason Peninsula - Standring Inlet (Riley et al., 2003a)
Increasing depth of mantle melting
Decreasing degree of arc-related magmatism
(a)


3.5
3
2.5
2
1.5
1
0.5
0
(Gd/Yb)PM
0.5
1
1.5
2
2.5
3
3.5
4
(La/Sm)PM
□ Mount Whiting (this study)
△ Sweeney Formation (Hunter et al., 2006)
● Eland Mountains (this study)
◇ Kamenev Nunatak (this study)
+ Black Coast Cretaceous dykes (Leat et al. 2002)
◆ Oscar II Coast Cretaceous dykes (Leat et al. 2002)
■ Jason Peninsula - Standring Inlet (Riley et al., 2003a)
Increasing depth of mantle melting
Increasing degree of crustal contamination or source enrichment
(b)

Fiugre 7


Mount Whiting (this study)
Hjort Fm Gp 2 (Wever & Storey, 1992)
Sweeney Formation (Hunter et al., 2006)
Hjort Fm Gp 3 (Wever & Storey, 1992)
Eland Mountains (this study)
Kamenev Nunatak (this study)
Black Coast Cretaceous dykes (Leat et al. 2002)
Oscar II Coast Cretaceous dykes (Leat et al. 2002)
Hjort Fm Gp 1 (Wever & Storey, 1992)
Jason Peninsula - Standring Inlet (Riley et al., 2003a)
Foidite
Picro basalt
Basalt
Basaltic andesite
Alkaline
Sub-alkaline
Na2O+K2O
SiO2
0
1
2
3
4
5
6
7
8
40
45
50
55
60

Fiugre 8


Mount Whiting
A
Eland Mountains
E
Sweeney Formation
B
Jason Peninsula
F
Oscar II Coast dykes
C
Black Coast dykes
G
Kamenev Nunatak
D
Sample/chondrite
1000
100
10
1
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu

Fiugre 9

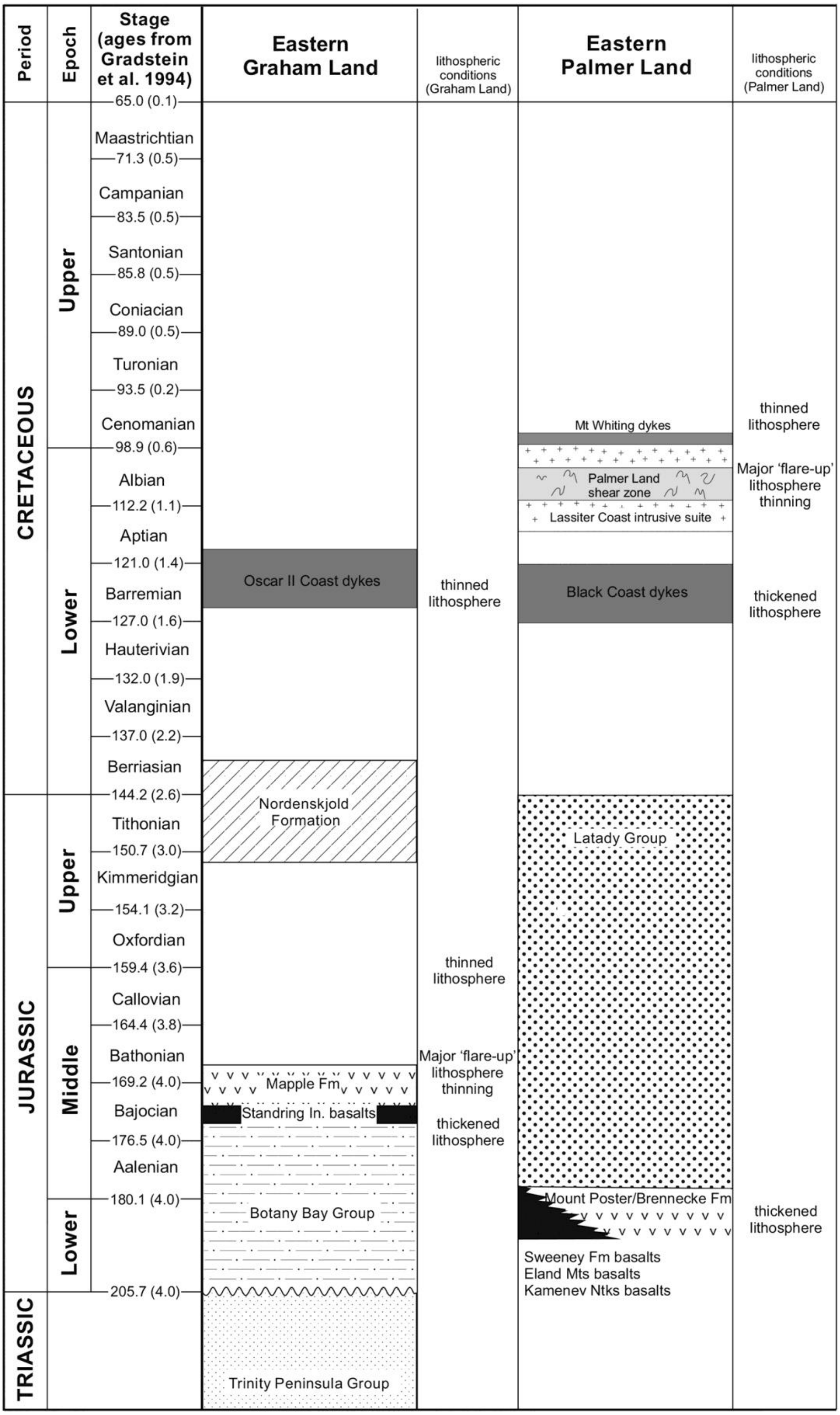

Period
Epoch
Stage (ages from Gradstein et al. 1994)
Eastern Graham Land
lithospheric conditions (Graham Land)
Eastern Palmer Land
lithospheric conditions (Palmer Land)
65.0 (0.1)
Maastrichtian
71.3 (0.5)
Campanian
83.5 (0.5)
Santonian
85.8 (0.5)
Coniacian
89.0 (0.5)
Turonian
93.5 (0.2)
Cenomanian
98.9 (0.6)
Albian
112.2 (1.1)
Aptian
121.0 (1.4)
Barremian
127.0 (1.6)
Hauterivian
132.0 (1.9)
Valanginian
137.0 (2.2)
Berriasian
144.2 (2.6)
Tithonian
150.7 (3.0)
Kimmeridgian
154.1 (3.2)
Oxfordian
159.4 (3.6)
Callovian
164.4 (3.8)
Bathonian
169.2 (4.0)
Bajocian
176.5 (4.0)
Aalenian
180.1 (4.0)
205.7 (4.0)
CRETACEOUS
JURASSIC
TRIASSIC
Upper
Lower
Upper
Middle
Lower
Oscar II Coast dykes
Nordenskjold Formation
Mapple Fm
Standring In. basalts
Botany Bay Group
Trinity Peninsula Group
thinned lithosphere
thinned lithosphere
Major ‘flare-up’ lithosphere thinning
thickened lithosphere
Mt Whiting dykes
Palmer Land shear zone
Lassiter Coast intrusive suite
Black Coast dykes
Latady Group
Mount Poster/Brennecke Fm
Sweeney Fm basalts
Eland Mts basalts
Kamenev Ntks basalts
thinned lithosphere
Major ‘flare-up’ lithosphere thinning
thickened lithosphere
thickened lithosphere

Table 1: Zircon U-Pb ion-microprobe geochronology

Spot[1]	U (ppm)	Th (ppm)	Pb (ppm)	Th/U	f^{206} (%)[2]	$^{238}U/^{206}Pb$	±s (%)	$^{207}Pb/^{206}Pb$	±s (%)	$^{207}Pb/^{206}Pb$ age (Ma)	±s	$^{206}Pb/^{238}U$ age (Ma)	±s	$^{207}Pb/^{206}Pb$[3] age (Ma)	±s
N10.2.1. Silicic unit at base of Eland Mountains basaltic pile															
2x	369.5	303.8	12.0	0.82	0.56	36.9350	0.78	0.051429	1.49	260.1	34.7	172.2	1.3	171.8	1.3
15x	702.2	222.4	21.7	0.32	0.12	36.8867	0.75	0.049608	1.08	176.7	25.4	172.4	1.3	172.4	1.3
18x	519.1	352.7	17.8	0.68	0.66	36.5483	0.75	0.049926	1.23	191.6	28.8	174.0	1.3	173.9	1.3
20	316.8	98.8	9.5	0.31	[2.09]	35.8175	0.81	0.049211	1.53	157.9	36.2	177.5	1.4	177.6	1.4
14	294.3	147.2	10.0	0.50	0.04	35.6970	0.75	0.049429	1.45	168.2	34.1	178.1	1.3	178.2	1.3
19	867.4	657.2	31.2	0.76	0.08	35.6693	0.75	0.049628	0.83	177.6	19.5	178.2	1.3	178.2	1.3
11	338.2	155.6	11.4	0.46	0.12	35.6468	0.74	0.051541	1.31	265.1	30.4	178.4	1.3	177.9	1.3
4	525.0	344.9	18.6	0.66	0.06	35.4830	0.78	0.050173	1.24	203.0	29.1	179.2	1.4	179.0	1.4
1	706.4	390.7	24.2	0.55	0.17	35.4403	0.78	0.050204	1.15	204.5	26.9	179.4	1.4	179.3	1.4
7	358.8	121.6	11.7	0.34	0.17	35.3374	0.79	0.049259	1.51	160.2	35.8	179.9	1.4	180.0	1.4
8	374.3	266.8	13.5	0.71	0.11	35.2219	0.78	0.050113	1.45	200.2	33.9	180.5	1.4	180.4	1.4
10	1434.3	717.3	49.3	0.50	0.04	35.1478	0.79	0.049793	0.79	185.3	18.4	180.8	1.4	180.8	1.4
6	762.9	277.0	25.2	0.36	0.08	35.1374	0.78	0.050320	1.04	209.8	24.3	180.9	1.4	180.8	1.4
13	669.3	541.6	24.7	0.81	0.26	34.9595	0.78	0.049939	1.01	192.2	23.6	181.8	1.4	181.8	1.4
12	1009.6	217.1	32.0	0.22	0.43	34.9332	0.78	0.051102	1.52	245.4	35.3	181.9	1.4	181.6	1.4
5	1213.3	1128.3	46.7	0.93	0.04	34.8697	0.77	0.050029	0.83	196.3	19.3	182.3	1.4	182.2	1.4
9i	432.3	157.9	14.5	0.37	0.10	34.6000	0.79	0.049147	1.34	154.9	31.8	183.7	1.4	183.8	1.5
3i	1410.3	981.3	64.7	0.70	0.05	27.6532	0.77	0.050603	0.70	222.8	16.3	229.0	1.7	229.0	1.8
16i	447.6	162.9	43.1	0.36	0.21	12.1304	0.74	0.058016	0.69	530.4	15.2	510.7	3.6	510.3	3.7
N10.7.1. Silicic unit in middle of Eland Mountains basaltic pile															
3x	828.5	381.0	26.9	0.46	[0.40]	36.8862	0.78	0.050301	1.40	208.9	32.7	172.4	1.3	172.3	1.3
12	331.1	79.1	10.2	0.24	0.02	36.4664	0.75	0.049271	1.40	160.7	33.2	174.4	1.3	174.5	1.3
15	464.7	158.4	14.8	0.34	0.15	36.3314	0.75	0.049619	1.19	177.2	28.1	175.0	1.3	175.0	1.3
7	587.1	240.1	19.1	0.41	0.05	36.3192	0.78	0.050388	1.24	212.9	29.0	175.1	1.3	174.9	1.4
13	768.2	407.7	25.7	0.53	0.10	36.2538	0.77	0.050471	1.03	216.8	24.1	175.4	1.3	175.2	1.3
6	511.0	214.3	16.8	0.42	0.01	35.9730	0.79	0.048968	1.41	146.3	33.4	176.8	1.4	176.9	1.4
17	794.7	292.9	25.8	0.37	0.03	35.8502	0.75	0.049207	0.87	157.7	20.5	177.4	1.3	177.4	1.3
18	216.4	105.4	7.3	0.49	0.14	35.8268	0.77	0.049020	1.70	148.8	40.2	177.5	1.4	177.6	1.4
9	211.6	127.4	7.2	0.60	0.28	35.8099	0.79	0.049739	2.05	182.8	48.5	177.5	1.4	177.5	1.4
5	1028.3	484.5	34.5	0.47	0.04	35.7090	0.84	0.049297	0.87	162.0	20.4	178.0	1.5	178.1	1.5
20	496.3	258.2	17.0	0.52	0.08	35.6915	0.74	0.050071	1.13	198.3	26.5	178.1	1.3	178.0	1.3
4	780.0	446.7	26.7	0.57	0.18	35.3770	0.78	0.050397	1.00	213.3	23.3	179.7	1.4	179.5	1.4
21	627.1	505.6	23.3	0.81	0.08	35.2620	0.75	0.049133	0.96	154.2	22.7	180.3	1.3	180.4	1.3
2	1015.0	551.4	35.1	0.54	0.04	35.2439	0.78	0.049503	0.91	171.7	21.3	180.4	1.4	180.4	1.4
11	826.0	503.0	29.2	0.61	0.05	35.1921	0.75	0.050097	0.86	199.5	20.0	180.6	1.3	180.5	1.3
19i	608.7	603.0	23.6	0.99	0.12	35.0093	0.76	0.048542	1.11	125.7	26.4	181.6	1.4	181.8	1.4
1i	852.7	489.1	30.2	0.57	0.05	34.7152	0.77	0.050066	0.97	198.1	22.7	183.1	1.4	183.0	1.4
14i	745.6	319.6	25.8	0.43	0.16	34.3113	0.75	0.049954	0.96	192.8	22.6	185.2	1.4	185.2	1.4
16i	545.8	411.1	21.0	0.75	0.14	33.3681	0.75	0.050100	1.11	199.7	25.9	190.4	1.4	190.3	1.4
10i	553.3	610.9	68.6	1.10	0.02	11.2066	0.77	0.058414	0.67	545.3	14.8	551.0	4.1	551.1	4.2

[1] Analysis identification. Identifiers followed by x are indicate analyses excluded from age calculations. i indicates inherited grain.

[2] Percentage of common ^{206}Pb estimated from the measured ^{204}Pb. Data is not corrected for common Pb, except for values given in parentheses.

[3] Ages calculated by projecting from an assumed common Pb composition [present day value from Stacey and Kramers (1975)] onto Concordia (Ludwig 2003)

Highlights

1. First direct age of basaltic successions from the southern Antarctic Peninsula
2. Used in conjunction with other rare basaltic units and Cretaceous dyke swarms, the evolution of the Antarctic Peninsula lithosphere is charted.
3. Its evolution is directly related to two silicic 'flare-up' events on the Antarctic Peninsula at 170 and 110 Ma, which are in turn related to wider events along the proto-Pacific margin of Gondwana.