On the Long Distance Transport of Ferrar Magmas

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Abstract:
The distribution and geochemical relationships of the Early Jurassic Ferrar large igneous province (LIP) are examined and it is concluded that they support the lateral flow model for the emplacement of the province, with a source along the strongly magmatic Early Jurassic Antarctica-Africa rifted margin. Published data and new analyses from the Pensacola Range are used to show that the dominant magma type in the Ferrar, the Mount Fazio chemical type (MFCT) occurs in the Theron Mountains, Shackleton Range, Whichaway Nunataks, Pensacola Mountains (all Antarctica), and South Africa, as well as well-known outcrops in Victoria Land, Antarctica, southeast Australia and New Zealand. Chemical compositions are shown to be somewhat varied, but similar enough for them to be considered as representing closely related magmas. Examination of geochemical trends with distance from the interpreted magma source indicates that Mg# and MgO abundances decline with distance travelled, and it is argued that this is consistent with the lateral flow model. The Scarab Peak chemical type (SPCT) occurs as sills in the Theron Mountains and Whichaway Nunataks, and as lavas in Victoria Land, is geochemically very homogeneous. Despite this, Mg#, MgO, Ti/Y and Ti/Zr all fall with distance from the interpreted source, consistent with fractional crystallisation occurring during the lateral flow of the magmas. Flow took place in dykes or (more likely) sills. No feeder dyke swarm has been identified. The distances flowed, at least 4 100 km for MFCT and 3 700 km for SPCT are the longest interpreted lateral magma flows on Earth.

End of abstract

Keywords: Ferrar province, magma transport, LIP, geochemistry, dyke, sill

The Ferrar Magmatic province is a dominantly basaltic large igneous province (LIP) emplaced during the early stages of Gondwana break-up. It has long been an enigma among basaltic LIPs. It was emplaced at about 183 Ma (Early Jurassic), during the emplacement of the adjacent Karoo LIP (Heimann *et al*. 1994; Encarnación *et a*l. 1996; Duncan *et al*. 1997; Fleming *et al*. 1997; Minor & Mukasa 1997; Riley & Knight 2001). It forms an elongate outcrop that is over 3 500 km long by only some 160 km wide (Fig. 1) (Elliot & Fleming 2004), which is unusual among LIPs – however, the extent to which the elongate outcrop is a function of ice cover limiting its outcrop is uncertain. Its main outcrops are in Antarctica (Kyle 1980; Kyle *et al*. 1981; Elliot & Fleming 2004), but it also occurs in southeast Australia, (Hergt *et al*. 1989, 1992) New Zealand (Mortimer *et al*. 1995), and probably South Africa also (Riley *et al*. 2005). Its volume can be estimated to be around 200 000 km^3, allowing 60 000 km^3 for the Dufek-Forrestal intrusions, 125 000 km^3 for sills lavas and dykes in Antarctica, and 15 000 km^3 for sills in Tasmania (Hergt *et al*. 1989a; Elliot & Fleming 2000). This is a considerable reduction from early estimates of 500 000 km^3 (e.g. Kyle *et al*. 1981), the difference being a reduction in the interpreted size of the Dufek and Forrestal intrusions (Ferris *et al*. 1998).

The Ferrar LIP is volumetrically overwhelmingly dominated by monotonous low-Ti tholeiitic basalt with noticeably arc-like trace elements characteristics, with no trace of normal asthenospheric or mantle plume-derived compositions, except for a few lamprophyres that appear to have been derived from HIMU plume mantle (Leat *et al*. 2000; Riley *et al*. 2003), and an almost exclusively lithospheric mantle source of the basalts has been strongly favoured (Kyle, 1980; Hergt *et al*. 1991; Molzahn *et al*. 1996; Hergt & Brauns 2001). Suggestions for why the Ferrar LIP erupted in its linear form have tended to emphasize either the extensional nature of the rift-like structure along which the magmas intruded (Storey *et al*. 1992; Elliot 1992; Wilson 1993) or a linear melting (possible heat) anomaly perhaps related to the proximity to a long-lived subduction zone on the Gondwana margin (Cox 1988, 1992; Storey 1995).

It is not the purpose of this paper to review all the geochemical evidence for the origin of the Ferrar province. However, two features of the Ferrar basalts are important to debate of their emplacement mechanisms. The first is that they are very homogeneous in composition (once the effects of essentially closed-system fractional crystallization are take into account). This homogeneity is evident whether comparisons are made between lavas or sills in one location, or compositions are compared across the province as a whole. This feature of the province was noted by Kyle (1980), Kyle *et al.* (1983), Hergt *et al.* (1989b, 1991), Fleming *et al.* (1992, 1995) and Hergt & Brauns (2001). The one significant exception to this is the chemical division of the Ferrar LIP into two chemical groups, as discussed below. The second feature is that they have compositions that indicate that they were derived from a modified source in the lithospheric mantle. Given the homogeneous nature of the magmas, this would imply that the lithospheric sources were homogeneous over a distance of at least 3 700 km, if the magmas are envisaged to have risen more-or-less vertically from their mantle sources. Because of the inherently heterogeneous composition of lithospheric mantle (Hawkesworth *et al.* 1984; Gibson *et al.* 1995; Pearson & Nowell 2002), this is unlikely. The Ferrar crosses a significant lithospheric boundary between the Theron Mountains – Shackleton Range parts of its distribution (Late Proterozoic crust) and the Transantartic Mountains – southeast Australia parts (Early Palaeozoic terranes). This lithospheric boundary is reflected in the compositions of other lithosphere-derived mafic igneous rocks (Leat *et al.* 2005), but does not correspond to any significant change in Ferrar compositions, showing that regional lithosphere compositions did not affect Ferrar magma compositions.

Because of the unsatisfactory nature of models involving vertical rise of Ferrar magmas, several authors have, in recent years, suggested that they were emplaced by a lateral flow mechanism of magma though continental crust (Storey & Kyle, 1997; Elliot *et al.* 1999; Elliot & Fleming 2000, 2004; Ferris *et al.* 2003; Riley *et al.* 2005; Leat *et al.* 2006). Lateral flow models can maintain the lithosphere-derived geochemical models, but explain the homogeneity of the LIP by origin of all the magmas from one point source.

If correct, this is the greatest distance in any volcanic event on Earth that magmas are thought to have flowed laterally as intrusions through the crust. The evidence for lateral flow of the Ferrar magmas is itself largely geochemical. This paper reviews the state of this geochemical evidence, and finds the evidence to be robust.

Chemical types of Ferrar magmas

The Ferrar LIP is chemically distinct from the contemporaneous Karoo LIP. Ferrar compositions are closest to the low-Ti magmas of the Karoo, particularly those found in the Central Area (Marsh *et al.* 1997). The main distinguishing features are Sr and Nd isotopes: Ferrar basalts have initial $^{87}Sr/^{86}Sr$ ratios of >0.708 (εSr_{183}=53), and εNd_{183} values of >-7.0 (Faure & Elliot 1971; Kyle 1980; Kyle *et al.* 1983; Hergt *et al.* 1989a) – no Karoo rocks fall in this range.

The 'type locality' for the Ferrar LIP is Victoria Land, Antarctica. The basaltic lava sequences in the area, the Kirkpatrick Basalts, comprise two distinct chemical types. The volumetrically dominant type that forms the lower part of the sequence has relatively low Si, Ti, Fe and K and is called Mount Fazio Chemical Type (MFCT). The upper lavas belong to a different, high Si, Ti, Fe and Ti group called the Scarab Peak Chemical Type (SPCT) (Fleming *et al.* 1995, 1999; Elliot *et al.* 1999). The SPCT is isotopically similar to the low-$^{87}Sr/^{86}Sr$ members of the

MFCT, to which they are thought to be related by fractional crystallisation (Fleming *et al*. 1995, 1999; Elliot *et al*. 1999).

Representative analyses of MFCT and SPCT from parts of the Ferrar LIP are presented in Tables 1 & 2. The analyses are taken from the literature, with the exception of the new analyses from Pensacola Mountains. Inevitably, there are differences in quality resulting from different analytical techniques and interlab errors. Nd and Sr isotope data are recalculated to initial values at 183 Ma.

Distribution of Ferrar magmas

The distribution of MFCT and SPCT are critical to the evidence for lateral flow models of the Ferrar. Their distribution in Antarctica is shown in Fig. 2. Ferrar sills and lavas are spatially closely associated with the Beacon Supergroup and its correlatives (Table 1; Fig. 1). The Beacon Supergroup is a generally flat-lying basin-filling sequence of Devonian to Early Jurassic siliciclastic sedimentary rocks that crops out in the Transantarctic Mountains and Victoria Land, Antarctica, where it unconformably overlies Ordovician and older rocks (Barrett 1991). It has widespread correlatives in Antarctica, and in Tasmania and New Zealand. It is also correlated with Karoo Supergroup of Southern Africa. The entire basin fill is thickest in the southern Africa area (locally over 10 km; Johnson *et al*. 1996), thinning across Antarctica, where the Beacon Supergroup is 2.5 km thick (Barrett 1991), toward Australia (1 km thick in Tasmania; Hergt *et al*. 1989a) (Table 1).

Southern Africa

The Karoo province of southern Africa is overwhelmingly chemically distinct from the Ferrar, but a few Ferrar-like low-Ti compositions have been identified: (1) The low-Ti lavas of the Central Area (in and around Lesotho) are the Karoo lavas most similar to Ferrar compositions (Marsh *et al*. 1997). Elliot & Fleming (2000) suggested that the Golden Gate lavas, within the Central Area, might represent magmas derived form the same source as the Ferrar magmas. The Central Area basalt lavas are dated by Ar-Ar and U-Pb as being about the same age as the Ferrar province (Encarnación *et al*. 1996; Duncan *et al*. 1997). The Golden Gate lavas have εSr_{183} values of 52.9 to 65.0 (Marsh *et al*. 1997), at the low end of the Ferrar range, and εNd_{183} values similar to Ferrar basalts (Elliot & Fleming 2000). However, elementally they are not identical to Ferrar, for example they have higher TiO_2 abundances (1.00 – 1.07 wt.%; Marsh *et al*. 1997). (2) Riley *et al*. (2006) suggested that some basaltic dykes, within a group of mainly northwest-southeast trending dykes around Underberg, KwaZulu-Natal, emplaced between the Central Area lavas and the rifted margin, are Ferrar correlatives. The most Ferrar-like dyke (sample SA.3.1) gave an Ar-Ar plateau age of 176.36±1.23 Ma on plagioclase (Riley *et al*. 2006), close to dates for the Ferrar in Antarctica. Anisotropy of magnetic susceptibility (AMS) data for the dykes indicate that magma flow in most was lateral, with flow from southeast to northwest dominating (Riley *et al*. 2006). Sample SA.3.1 is similar to the Antarctic MFCT group (Table 1), and has a εSr_{183} value of 66.3 and a εSr_{183} value of –3.8 (Riley *et al*. 2006).

Theron Mountains

The Theron Mountains (Fig. 3) is a 110 km long escarpment, up to 760 m high, which exposes horizontal terrestrial sedimentary deposits intruded, mostly conformably, by basalt sills and rare dykes (Brook 1972; Leat *et al*. 2006). The sedimentary rocks contain coal horizons, and a *Glossopteris* flora indicates a Permian age (Brook 1972). The sills belong to several chemical types, similar to both the Ferrar and basalts of the Karoo province, and the Theron Mountains have therefore been described as marking the overlap between the Ferrar and Karoo provinces (Brewer 1990; Brewer *et al*. 1992). The sills are all Jurassic in age, based on Ar-Ar dating and cross-cutting relationships (Brewer *et al*. 1996). Leat *et al*. (2006) showed that the sills form four chemical types. Two types, probably represented by only one sill each, are similar to

Karoo lavas of the Lebombo Monocline, South Africa and some dykes in Dronning Maud Land. The other two types are Ferrar-like. The most common type is MFCT-like (Table 1). There are at least six sills of this type, ranging in thickness from 0.3 to 32 m. The forth type forms a single sill, some 200 m thick, and is SPCT in composition (Table 2). The MFCT-like sills have εNd_{183} values of –3.7 to –5.0, and εSr_{183} values in the range 55-75. The SPCT sill has εNd_{183} values of –3.8 to –3.9 and εSr_{183} values of 63 to 80 (Leat *et al*. 2006).

Shackleton Range

The Shackleton Range is a large (200 x 70 km), apparently uplifted block of Proterozoic to Early Palaeozoic rocks (Clarkson *et al*. 1995; Lisker *et al*. 1999). The rocks were deformed during the Early Palaeozoic Ross orogeny, and the Range may mark a suture of the closed Mozambique Ocean between East and West Gondwana (Tessensohn *et al*. 1999 - see also other papers from the EUOSHACK Project in the same volume of *Terra Antartica*). The youngest sedimentary rocks in the Range are the Ordovician Blaiklock Glacier Group (Buggish & Henjes-Kunst 1999). There are no exposed sedimentary rocks in the Range equivalent to the Beacon Supergroup.

Despite the extensive outcrop of the Shackleton Range, which exposes many dykes that are mainly of Proterozoic and Palaeozoic age (Hofmann *et al*. 1980; Clarkson 1981; Hotten 1993, 1995; Spaeth *et al*. 1995; Techmer *et al*. 1995; Leat *et al*. 2005), only four Jurassic dykes have been identified. Using the dyke numbering system of Spaeth *et al*. (1995), these are dykes 16a and 16b from Mount Beney, Lagrange Nunataks (may be continuations of the same dyke: these are also equivalents of samples Z.726.1 and Z.726.4 of Clarkson 1981), dyke 25 from Mount Skidmore, Legrange Nunataks (may be equivalent to dyke 8 of Hofmann *et al*. 1980), and dyke 17 from Mount Provender Haskard Highlands. All these are from the northern part of the Shackleton Range.

Dykes 16a, 16b and 25 have been dated by whole-rock, plagioclase and pyroxene K-Ar with all ages falling in the range 176.6±4.7 to 182.9±11.3 Ma and are clearly Jurassic (Hotten 1993). Dyke 17 is assigned to the same group on compositional grounds (Spaeth *et al*. 1995: Techmer *et al*. 1995). The dykes were assigned to the Ferrar magma type by previous authors (e.g. Spaeth *et al*. 1995; Techmer *et al*. 1995). I further identify the Jurassic dykes as MFCT magmas (Table 1).

Whichaway Nunataks

The Whichaway Nunataks expose a flat-lying, sandstone-dominated sedimentary sequence (Whichaway Formation) conformably intruded by basalt sills (Omega dolerites) (Stephenson 1966; Brewer 1989). The sedimentary sequence contains a *Glossopteris* flora, and correlates with the Beacon Supergroup. The contacts of the sills are poorly exposed or non-exposed. However, at least two sills are present and are > 50 m thick. A basaltic dyke cuts one of the sills. Hofmann *et al*. (1980) reported two whole-rock K-Ar ages of 163±13 and 171±14 Ma, which are interpreted as confirming a Jurassic age. The data presented by Stephenson (1966) and Brewer (1989) suggest that there is a low-Ti sill that crops out at about 840 m altitude in the main nunatak group, and a high-Ti sill that outcrops at 1115-1310 m altitude in the main nunatak group and at Omega Nunatak, some 50 km to the south. The high-Ti sill has εNd_{183} values of –1.9 to –3.3 and εSr_{183} values of 83.9 to 85.4, and the low-Ti sill a εNd_{183} value of –3.4 and a εSr_{183} value of 106.4 (Brewer *et al*. 1992).

Based on the geochemical data provided by Brewer (1989), I interpret the high-Ti sill to belong to the SPCT Ferrar group, and the low-Ti sill to belong to the MFCT Ferrar group (Table 1, 2).

Pensacola Mountains

The Pensacola Mountains consist of probable Early Cambrian to Permian sedimentary sequences and interbedded igneous rocks deformed during several orogenic episodes, most importantly the Ross event (Storey *et al*. 1996; Rowell *et al*. 2001; Curtis & Storey 2003). The north of the mountain range is dominated by the Dufek and Forrestal gabbro intrusions, which according to the geophysical interpretation of Ferris *et al*. (1998) together cover some 6 600 km^2 and are thought on grounds of composition and age to be part of the Ferrar intrusive episode (Ford & Kistler 1980; Minor & Mukasa 1997).

Jurassic minor intrusions are known to crop out at two places in the Pensacola Mountains: Pecora Escarpment and Cordiner Peaks. At Pecora Escarpment, several sill leaves intrude gently dipping Permian sediments of the Pecora Formation. The sills were dated at 195±5 Ma using K-Ar determinations on pyroxenes and plagioclases (Ford & Kistler 1980). At least one dyke is reported from Rosser Ridge, Cordiner Peaks, intruding the Devonian Dover Sandstone and interpreted as Jurassic in age (Ford *et al*. 1978; Ford & Kistler 1980). Both Pecora Escarpment sills and Cordiner Peaks dyke were interpreted by Ford & Kistler (1980) to belong to the Ferrar Group on age and compositional grounds. Furthermore, the Cordiner Peaks is interpreted to be part of a swarm of dykes associated with the Dufek and Forrestal intrusions that have been imaged aeromagnetically (Ferris *et al*. 2003). Sr isotope data for a Pecora Escarpment sill and the Rosser Ridge dyke give εSr_{183} values of 85 and 116 respectively (Ford & Kistler 1980).

Our new analyses of the Rosser Ridge dyke and a Pecora Escarpment sill show that they both belong to the MFCT group of Ferrar magmas (Table 1).

Victoria Land

The very extensive basaltic sills of Victoria Land are a prominent feature of this part of Antarctica. The sills are spectacularly exposed for 2 000 km in the Transantarctic Mountains (Kyle 1980; Kyle *et al*. 1981; Elliot & Fleming 2004). The sills intrude basement (Ordovician and older) and, more commonly, the near-flat-lying, Devonian to Jurassic Beacon Supergroup (Barrett 1991). The sills are thought to locally thicken to 2 km (Behrendt *et al*. 1995), and it is clear that the magma volume represented by the sills of Victoria Land is considerable – they could underlie an area of $2x10^5$ km^2 and may represent a volume of $0.6\text{-}1.0x10^5$ km^3, a sizable proportion of the total volume of Ferrar sills in Antarctica (Elliott & Fleming 2000). Dykes are volumetrically insignificant compared to the sills. The sills have been dated as Jurassic (183.6 ± 1.0 by U-Pb on zircon and baddeleyite; Encarnación *et al*. 1996), confirming Ar-Ar results (Fleming *et al*. 1997). Lavas forming the Kirkpatrick Basalts are the eruptive equivalent of the Ferrar sills, with which they are contemporaneous, as dated by Ar-Ar (Heimann *et al*. 1994). The Kirkpatrick Basalts are locally over 700 m thick and associated with phreatomagmatic deposits that indicate local eruptions (Hanson & Elliot 1996). The sills and lavas are compositionally very close. εSr_{183} values for both are in the range 61-109, and εNd_{183} values range from –3.2 to –5.8 (Hergt *et al*. 1989b; Fleming *et al*. 1995: Molzahn *et al*. 1996; Elliot *et al*. 1999). As outlined above, the sills belong to the MFCT group, whereas both SPCT overlies MFCT chemical groups occur in the lavas – with SPCT always overlying MFCT in the lava succession (Fleming *et al*. 1992, 1995; Elliot *et al*. 1999; Elliot & Fleming 2004).

Southeast Australia

Jurassic dolerite sills outcrop over some 30 000 km^2 in Tasmania, with a total volume of about 15 000 km^3, and intrude the flat-lying sedimentary Late Carboniferous to Triassic Parmeener Supergroup – a Beacon Supergroup equivalent (Hergt *et al*. 1989a). The sills are K-Ar dated at 175±8 (recalculated from Schmidt & McDougall 1977). The sills have εNd_{183} values in the range –5.2 to –6.6 and εSr_{183} values ranging from 80 to 120 (Hergt *et al*. 1989a). Compositionally similar Jurassic basalts crop out in western Victoria (εNd_{183} –5.2 to –5.6;

εSr_{183} 81.0 to 83.2) and on Kangaroo Island, South Australia (εNd_{183} –5.7 to –8.1; εSr_{183} 83.6 to 98.7) (Hergt *et al*. 1991). The Tasmanian dolerites have long been correlated with the Ferrar of Victoria Land (Hergt *et al*. 1989a; Brauns *et al*. 2000; Hergt & Brauns 2001). Hergt *et al*. (1991) made the same correlation for the western Victoria and Kangaroo Island basalts. All these Australian basalts clearly belong to the MFCT group (Table 1).

New Zealand

The Kiwans dolerite, a 1 km^2 outcrop in South Island is the only Ferrar magma type identified in New Zealand (Mortimer *et al*. 1995). It intruded the Triassic Topfer Formation, thought to be the only correlative of the Beacon Supergroup in New Zealand (Mortimer & Smale 1996). The intrusion yielded Jurassic whole-rock K-Ar ages of up to 172.1±2.2 Ma (Mortimer *et al*. 1995). Four εNd_{183} values for the dolerite range –5.3 to –5.4, with εSr_{183} values ranging from 84.2 to 91.4 (recalculated from Mortimer *et al*. 1995).

The Kiwans dolerite belongs to the MFCT Ferrar group, based on its age, isotope composition, major and trace element abundances (Table 1), and association with a sedimentary sequence correlated with the Beacon Supergroup (Mortimer *et al*. 1995; Mortimer & Smale 1996).

Discussion

Evidence for lateral flow

The distribution of MFCT and SPCT within Antarctica is shown in Fig. 2. Note that the Ferrar is more widespread in Victoria Land than shown by the two stars. MFCT occurs in all known outcrops of the Ferrar LIP, from the Theron Mountains to Northern Victoria Land in Antarctica, and in Australia, probably South Africa, and New Zealand (not shown). The known lateral spread within Antarctica is 3 300 km. The Australian outcrops, adjacent to Northern Victoria Land in reconstructed Gondwana, add at least another 400 km. The homogeneity of this magma group is strong evidence for long-distance lateral magma flow from a single source. The likely source is at the Antarctica-Africa rifted margin (Elliot *et al*. 1999; Elliot and Fleming 2000, 2004, and see below), some 400 km along the strike of the LIP from the Theron Mountains, so the total distance the MFCT magmas flowed from source is at least 4 100 km (Fig. 3). Flow of MFCT magmas into southern Africa was only some 150 km.

SPCT magmas are known only as lavas in Northern and Southern Victoria Land and sills in the Theron Mountains and Whichaway Nunataks. The spread of the magma type nevertheless is almost as great as that of the MFCT (Fig. 3). The SPCT extends over 3 300 km from the Theron Mountains to Northern Victoria Land, and must have travelled 3 700 km from the putative source in the rifted continental margin. The exceptional distance of at least 4 100 km that it is proposed that the Ferrar magmas travelled laterally can be related to the exceptional size of the Gondwana continent, probably assisted by travel along an active rift zone, parallel to the subducting Pacific margin.

Source of the Ferrar magmas

Storey & Kyle (1997) suggested that the Ferrar magmas flowed laterally away from magma chambers, like that represented by the Dufek intrusion, emplaced in crust up-domed by an underlying ‘megaplume’ in the mantle of the South Atlantic region. Elliot *et al*. (1999) and Elliot & Fleming (2000, 2004) put the source in a similar position, within the Antarctic-Africa rifted margin, close to the Explora anomaly, and within the region of the Weddell triple junction. The rifted margin between Antarctica and Africa was strongly magmatic during Early Jurassic times. Along the Lebombo Monocline, a seaward-dipping lava sequence, the Karoo lavas are some 2.5 km thick (Sweeney *et al*. 1994). On the Antarctic margin, a prominent magnetic anomaly, the Explora anomaly follows the continental edge (Fig. 4) and is interpreted as a seaward-dipping volcanic sequence, based on potential field and seismic interpretation (Kristoffersen & Hinz 1991; Hunter *et al*. 1996; Jokat *et al*. 1996; Leitchenkov *et al*. 1996; Ferris *et al*. 2000). The Explora anomaly (also known as the Explora Wedge because of its seaward dipping reflectors) is interpreted as Jurassic by most authors (consistent with it being the conjugate margin to the Lebombo Monocline, and with the widespread Jurassic magmatism in the area, while Cretaceous magmatism is minor), but Jokat *et al*. (2003) suggested a Cretaceous age. The Filchner anomaly follows the projection of the Explora anomaly and is also interpreted as basaltic intrusions or volcanics (Ferris *et al*. 2000). The Berkner Island anomaly follows this trend toward the Jurassic Dufek and Forrestal intrusions, and is likely to be caused by basalt lavas and intrusions also. The Orion anomaly, a smaller Lozenge-shaped anomaly to the south, and the northwest margin (reconstructed orientation) of the Falkland Islands block (Figs. 4,5) are also interpreted as Jurassic rifted margin volcanic or intrusive sequences (Barker 1999; Ferris *et al*. 2000).

The region where the Antarctic, Africa, Falkland Islands and Filchner microplate blocks rifted apart during early Gondwana break-up was a zone of strongly magmatic rifted margin formation (Fig. 5). The rifted margins focus on the Weddell Sea triple junction, and most of the magmatism is likely to Early Jurassic, approximately contemporaneous with the emplacement of the Karoo and Ferrar LIPs. In Figs. 4 and 5, the strike of the Ferrar LIP, passing through the Theron Mountains, projects into the Explora anomaly, which is a plausible candidate for the source area for the Ferrar LIP.

Transport mechanisms and geochemical relationships

The nature of the transport conduits for the flow of Ferrar magmas is a matter of conjecture, as no sills or dykes have been identified as feeders for long distance flow. The abundance of sills and paucity of dykes within the LIP makes a *prima face* case that the magmas were transported in sills, perhaps mainly emplaced into the Beacon Supergroup sediments, as proposed by Storey & Kyle (1997). Elliot *et* al. (1999) suggested that transport in dykes is more likely, as sill size is controlled by size of the host sedimentary basin. This mechanism is supported by the lateral emplacement of magma in giant dyke swarms such as the 2 000 km long Mackenzie dyke swarm, Canada (Baragar *et al*. 1996), and others on Earth, Venus and Mars that range up to 3 000 km long (Ernst *et al*. 2001). However, there is little evidence for the dyke swarm required to emplace the Ferrar LIP in this way. There is aeromagnetic evidence for limited Ferrar dykes in the Pensacola Mountains associated with the Dufek-Forrestal intrusions (Ferris *et al*. 2003), and even less outcrop evidence in the same area, where only one Ferrar dyke has been confirmed (see *Pensacola Mountains*). The evidence is no better in the Shackleton Range, an uplifted area some 60x170 km, which exposes (pre-Beacon Supergroup) basement. Only three different Ferrar dykes have been positively identified (see *Shackleton Range*). There is no evidence for a Ferrar dyke swarm on the regional ADMAP aeromagnetic compilation (Golynsky *et al*. 2001). Regional aerogeophysical data sets in Victoria Land likewise fail to show Ferrar dykes, although sills appear to be locally widespread (Ferraccioli & Bozzo 1999, 2003). However, this may be because survey lines are too closely spaced to identify dykes of the order of 10 m wide. The impression given is that any Ferrar feeder dyke swarm has, if it exists, proved very elusive; but detailed aeromagnetic surveys may yet find it. The close association of Ferrar sills with the Beacon Supergroup and its correlatives is fascinating. The Ferrar sills closely follow the basin of the Beacon Supergroup, but are not found in parts of the basin such as the Ellsworth Mountains and Falkland Islands that were affected by the Late Palaeozoic-Early Mesozoic Gondwanian orogeny (Fig. 1). As the Beacon Supergroup is thought to have formed a more-or-less continuous basin fill (Barrett, 1991) that was, in the areas unaffected by Gondwanian deformation, flat-lying at the time of emplacement of the Ferrar LIP, and as the Ferrar is commonly observed in sills but rarely in dykes, the most likely mode of emplacement is within sills that propagated through the sedimentary basin. In this model, the sills would have initially intruded close to the thickest part of the sedimentary basin fill, and propagated to the thinner edge of the basin (Table 1; Fig. 1).

Theoretical studies of emplacements of dykes indicate that magma flow distances of about 5 000 km can be achieved without freezing of magma, assuming normal dyke widths of >10 m and moderate magma overpressure and a topographically high source magma chamber (such as within up-domed crust above a rising mantle plume) (Macdonald *et al*. 1988; Fialko & Rubin 1999). The 200 000 km^3 volume of magma represented by the Ferrar LIP was certainly to large to have been held in one magma chamber at one time, and batches of magma must have repeatedly been expelled from one or more compositionally similar magma chambers. Numerous emplacement events are necessary to explain crosscutting relationships between MFCT sills in the Theron Mountains (author's unpublished observations) and Victoria Land (Elliot & Fleming 2004).

During flow of the magma away from the source, the magma is expected to become more evolved (by removal of phenocrysts), and more contaminated (as a result of assimilation of wall rocks). Examination of Tables 1 and 2 indicates that overall geochemical trends with distance from the putative source are consistent with such a model. In the case of the MFCT group, all the analyses are similar, but show some variation, as would be expected if they represent numerous batches of magma. The South Africa dyke has slightly higher Ti/Y and lower Zr/Y and La_N/Yb_N ratios than the other analyses, and the Kangaroo Island lava has relatively high Ti/Zr and La_N/Yb_N ratios. However, both samples are sufficiently similar to the others to be consistent with all the magmas being closely related. Mg# and MgO abundances are highest in the samples from the east of the province (left hand side of the table), being highest in the South Africa, Theron Mountains and Shackleton Range samples, and lowest in the Victoria Land and Tasmania samples from the west of the province. (Whichaway Nunatak is an exception to this trend, and a fractionated part of a large sill appears to have been sampled). These trends are consistent with fractional crystallisation having occurred during flow of magmas from a source near the Theron Mountains.

In the SPCT group, all the analyses are remarkably similar, suggesting they are derived from a small number of very closely related magma batches, perhaps even just one intrusion/eruption event. Mg# and MgO abundances decline from east (Theron Mountains) to west (Victoria Land), as is the case with MFCT. Ti/Y and Ti/Zr ratios also fall from east to east, consistent with removal of small about of Ti-bearing oxide phenocrysts during flow. Zr/Y and La_N/Yb_N ratios are constant, within analytical errors, consistent with the incompatibility of these elements.

Conclusions

The geochemical evidence from the Ferrar LIP is consistent with the lateral flow model, with a source for the magmas in the rift that had developed between the African and Antarctic plates during Early Jurassic times, during the break-up of Gondwana. The Ferrar LIP consists of two distinct geochemical types. The volumetrically dominant Mount Fazio chemical type (MFCT) has long been well known from Victoria Land and southeast Australia. It also occurs in the Theron Mountains, Shackleton Range, Whichaway Nunataks, Pensacola Mountains (all Antarctica), New Zealand and South Africa. The MFCT magmas flowed laterally through the crust for distances of at least 4 100 km, the longest magma flow known on Earth. The Scarab Peak chemical type (SPCT) occurs as sills in the Theron Mountains and Whichaway Nunataks, and as lavas in Victoria Land, and flowed 3 700 km from its source. Geochemical data show that the Mg# and MgO abundances of both MFCT and SPCT fall along the direction of magma flow from the Theron Mountains to Victoria Land (and Australia in the case of MFCT). Ti/Y and Ti/Zr ratios fall along the same trend in SPCT samples. These relationships are consistent with fractional crystallisation occurring during the lateral flow of the magmas.

The source of the magmas was in an area around the Weddell triple junction which potential field and seismic data show was characterised by very abundant magmatism as Africa, Antarctica and several smaller plates rifted apart. The Ferrar province projects into the magnetically defined Explora anomaly on the Antarctic continental margin, which is interpreted on the basis of seismic reflection, magnetic and gravity data as a magmatic rifted margin. Sills are very widely distributed over the province, mostly intruding flat-lying Beacon Supergroup sediments, but dykes are rare. A geophysically defined dyke swarm has not been identified, but it is possible that future high-resolution aeromagnetic surveys may yet identify one. Lateral flow was probably mainly in sills that propagated though the Beacon Supergroup sedimentary basin, but flow in dykes may also have been considerable.

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Figure captions

Fig. 1. Reconstruction of Gondwana prior to break-up showing the distribution of Beacon Supergroup and correlatives in relation to that of Ferrar magmatism (thick solid line) and the Gondwanian Fold Belt (after Barrett 1991; Tingey 1991). DML, Dronning Maud Land; TM, Theron Mountains; WN, Whichaway Nunataks; PM, Pensacola Mountains; TF, Topfer Formation. Crustal blocks of West Antarctica: EWM, Ellsworth-Whitmore Mountains; FM, Filchner Microplate; AP, Antarctic Peninsula, TI, Thurston Island, MBL, Marie Byrd Land.

Fig. 2. Map of Antarctica, showing the distribution of MFCT and SPCT magma groups of the Ferrar LIP.

Fig. 3. Photograph of Marø Cliffs, part of the northwest-facing escarpment of the Theron Mountains, Antarctica, showing sills intruding the flat-lying sediments that are correlatives of the Beacon Supergroup. The height of the cliff is approximately 700 m. The thickest sill at the top belongs to the SPCT magma group, The thinner sills toward the base are mostly MFCT magma type.

Fig. 4. Magnetic map of the Weddell Embayment – Coats Land area of Antarctica, showing extensive magnetic anomalies interpreted to be caused by voluminous basaltic lavas and intrusions emplaced during the initial stages of Gondwana break-up. A. ADMAP magnetic anomaly map (Golynsky *et al*. 2001). B. Interpretation of magnetic anomalies based on A and more recent data offshore Dronning Maud Land (Jokat *et al*. 2003). Anomalies shown in red are interpreted as mafic igneous rocks: L1, Lozenge 1 (Ferris *et al*. 2000); FA, Filchner anomalies; BIA, Berkner Island anomaly. The magnetically flat area GC, marked in green, is the Archaean Grunehogna craton. Other labels: TM, Theron Mountains; SR, Shackleton Range; FIS, Filchner Ice Shelf; RIS, Ronne Ice shelf; PM, Pensacola Mountains; HN, Haag Nunataks; EM, Ellsworth Mountains.

Fig. 5. Reconstruction of the rifted margins of southern Africa and Antarctica in Gondwana, showing the relationship of the eastern 'proximal' end on the Ferrar Magmatic province in relation to the Karoo magmatic province, inferred major triple junctions (stars) and magmatic rifted margins. The Magmatic rifted margins along the Antarctic plate and Filchner microplates are as for Fig. 4B. Note that the Filchner microplate is likely to have been smaller in area before distributed extension at the time of break-up (King 2000). The magmatic rifted margin of the Falkland Islands block is after Barker (1999). KZND = KwaZulu-Natal dykes.

Table 1. *Correlatives of the Beacon Supergroup in Gondwana associated with Ferrar sills*

	South Africa*	Theron Mountains	Whichaway Nunataks	Pensacola Mountains	Victoria Land	Tasmania	New Zealand
Name	Karoo Supergroup	Theron Formation	Whichaway Formation	Pecora Formation	Beacon Supergroup	Parmeener Supergroup	Topfer Formation
Age	Late Carboniferous-Early Jurassic	Probably Permian	Permo-Carboniferous	Permian	Devonian-Jurassic	Late Carboniferous-Triassic	Triassic
Thickness	> 10 000 m	> 760 m	>244	>110 m	2 500 m	~ 1 000 m	na
Atitude	Gently dipping	Flat-lying	Horizontal	Gently dipping	Flat-lying	Flat-lying	Deformed
Lithology	Variable, siliciclastic	Sandstone to mudstone, coal	Mainly sandstone	Sandstone, siltstone, coal	Sandstone, mudstone, conglomerate, tillite, coal	Sandstone, siltstone, tillite, coal	Volcanicalstic sandstone, mudstone, conglomerate, coal
References	Johnson *et al*. (1996)	Stephenson (1966), Brook (1972), Leat *et al*. (2006)	Plumstead (1962), Stephenson (1966)	Williams (1969), Ford & Kistler (1980)	Barrett (1991)	Hergt *et al*. (1989a)	Mortimer & Smale (1996)

*Included for completeness. No Ferrar sills have been recorded intruding the Karoo Supergroup, but it is intruded by Ferrar-like dykes and numerous sills of Karoo-type basaltic magmas.
na; information not available.

Table 2. *Comparison of MFCT basalts in South Africa, Antarctica, Australia and New Zealand*

	S. Africa	Theron Mts.	Shackleton Range	Whichaway Nunataks	Pensacola Mts. Rosser Ridge	Pensacola Mts. Pecora Escarpment	Victoria Land	Victoria Land	Kangaroo Island	Tasmania
	dyke	sill	dyke	sill	dyke	sill	sills	lavas	lava	sill
Sample	SA.3.1	Z.1605.3	XX.2	TAE.302/5	Z.1631.1	Z.1626.1	CM av	MFCT av	87-135	84 138
SiO_2	52.35	52.20	51.63	57.16	53.70	54.64	53.88	55.16	54.68	54.37
TiO_2	0.89	0.87	0.75	0.83	0.68	0.68	0.78	0.73	0.64	0.64
Al_2O_3	15.16	15.29	16.04	13.50	14.44	13.73	14.37	14.56	14.61	14.79
Fe_2O_3(T)	9.93	10.00	9.77	11.30	10.38	10.32	10.50	10.45	9.21	9.74
MnO	0.16	0.16	0.15	0.17	0.17	0.17	0.15	0.17	0.17	0.17
MgO	8.04	8.64	8.81	4.78	7.19	7.07	6.44	5.82	7.24	6.63
CaO	10.71	9.93	10.19	8.77	10.32	10.46	10.96	10.20	10.81	10.86
Na_2O	2.11	1.84	1.74	2.19	2.13	1.89	2.05	1.92	1.84	1.86
K_2O	0.56	0.86	0.75	1.17	0.86	0.94	0.76	0.88	0.69	0.86
P_2O_5	0.10	0.20	0.16	0.12	0.12	0.10	0.11	0.11	0.09	0.09
Mg#	61.8	63.4	64.3	45.8	58.1	57.8	55.1	52.7	61.1	57.7
Cr	397	674	659	45	160	113	105	101		115
Ni	90	54	68	39	96	87	88	62		80
Rb	14.73	24.91	25	42	21.95	37.05	19.5	35	26.0	31.7
Sr	138.6	166	140	147	218.4	147.6	151	124	155.4	123.9
Y	24.6	29.5	20	31	22.5	24.4	22	28	18	20.6
Zr	81	116.1	121	147	90.7	100.3	103	121	70	95
Nb	2.88	5.59	<8	9	6.29	5.24	5	7	5.0	4.0
Ba	190	228	150	313	256	226	210	221	195	190
La	8.1	12.93	10.1		10.95	11.96	11.4	14.1	12.6	11.0
Ce	17.6	27.63	19.6		22.95	25.34	26.5	31.8	28.6	23.9
Sm	2.92	3.79	3.2		2.94	3.17	3.35	3.58	2.85	3.09
Eu	0.89	1.14	0.98		0.89	0.87	0.96	0.96	0.74	0.822

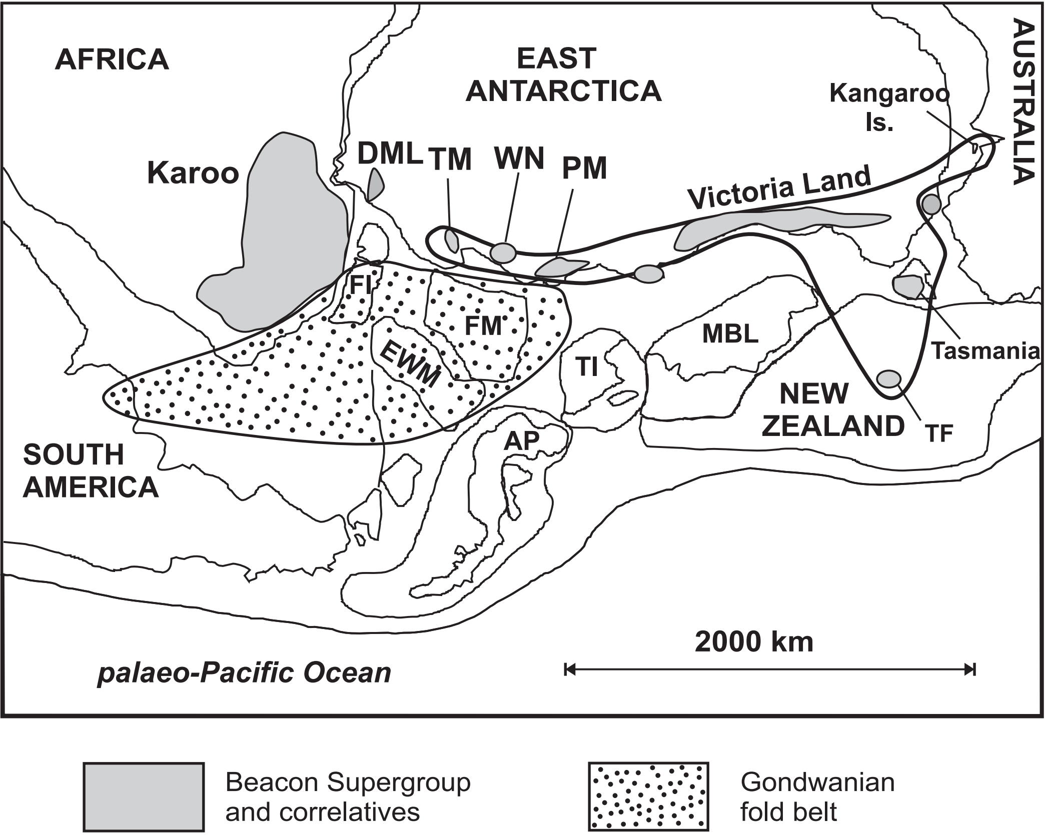
Gd	3.67	4.34			3.34	3.72	3.7		2.74	3.0
Tb	0.65	0.74	0.59		0.57	0.63	0.62	0.69	0.49	0.57
Yb	2.30	2.93	2.4		2.37	2.47	2.60	2.77	2.17	2.37
Lu	0.38	0.50	0.41		0.40	0.41	0.42	0.50		0.366
Hf	2.17	2.90	2.6		2.33	2.69	2.1	3.4	2.46	1.9
Ta	0.234	0.36	0.31		0.38	0.36		0.6		
Th	1.81	2.03	1.68	9	2.49	3.51	3.4	4.3	3.11	3.4
Ti/Y	217	178	224	160	180	167	213	157	215	185
Ti/Zr	65.8	45.1	37.0	33.8	44.7	40.5	45.4	36.3	55.2	40.2
Zr/Y	3.29	3.94	6.05	4.74	4.03	4.12	4.68	4.32	3.89	4.61
Th/Ta	7.7	5.6	5.4		6.6	9.8		7.2		
La_N/Yb_N	2.4	3.0	2.8		3.1	3.2	2.9	3.4	3.9	3.1

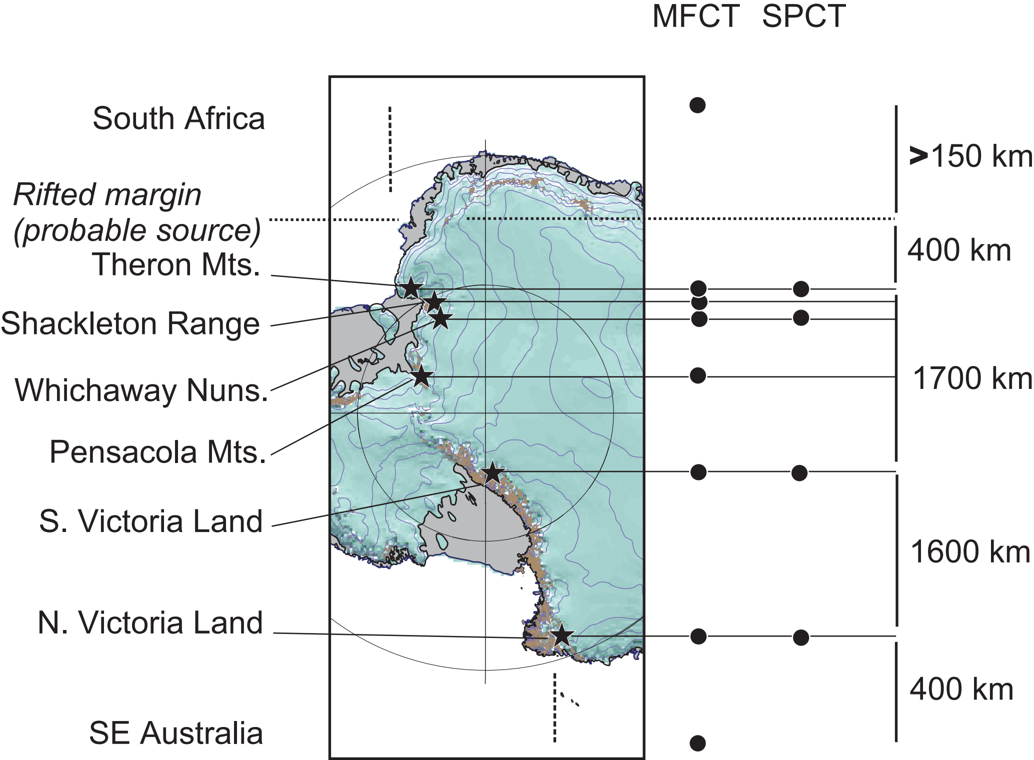
Major elements recalculated to volatile-free total of 100. Mg# is 100.Mg/(Mg+Fe*), where Fe* is total Fe. Data sources and analytical details: SA.3.1 from Riley et al. (2006), XRF (majors) and ICP-MS (traces); Z.1605.3 from Leat et al. (in press), XRF (majors) and ICP-MS (traces); XX.2 from Techmer et al. (1995), AES (Na, K, Rb) XRF (other majors), Ba, Sr, Y, Zr, Nb (ICP-AES) INAA (other traces); TAE.305/5, from Brewer (1989), XRF (majors and traces); Z.1626.1, Z.1631.1, new data, XRF (majors) and ICP-MS (traces), methods as in Leat et al. (in press); CM av (chilled margin average, Hergt et al. 1989b), XRF (majors and traces) and INAA (traces); MFCT av, from Fleming et al. (1995), XRF (majors and traces), INAA (Hf, Ta, Th, REE); 87-135, from Hergt et al. (1991), XRF (majors), SSMS (traces); 84 138 from Hergt et al. (1989a), XRF (majors and traces), INAA Hf, Th, REE).

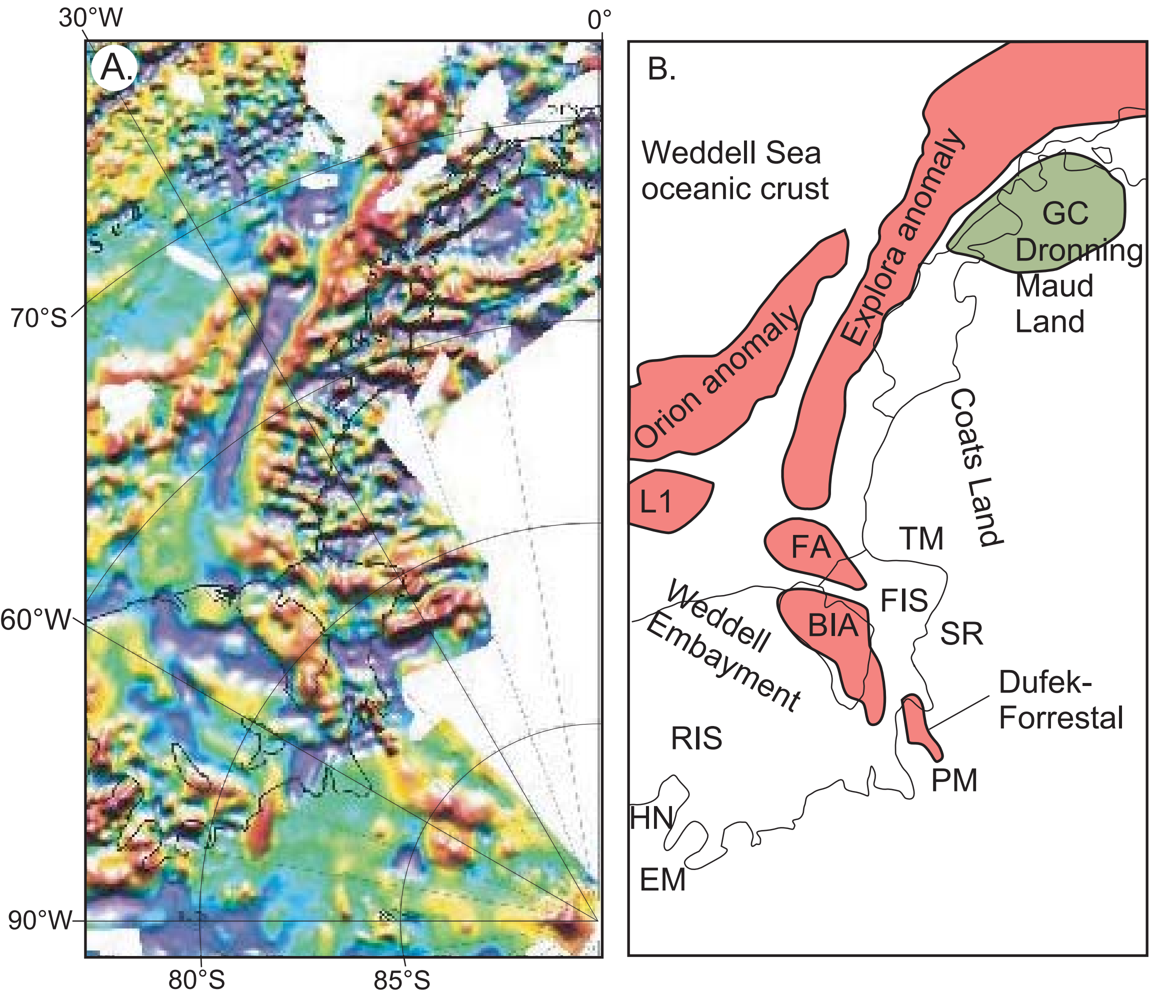
Table 3. *Comparison of SPCT basalts in Antarctica*

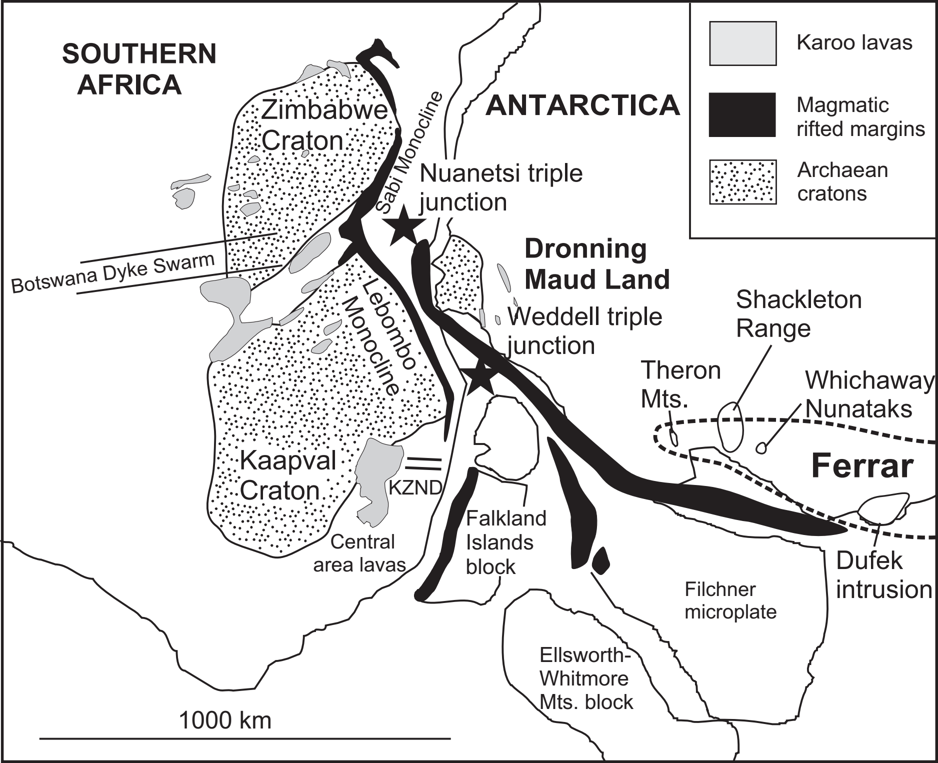
	Theron Mountains	Whichaway Nunataks	S Victoria Land	N Victoria Land
	sill	sill	lava	lava
Sample	Z.1605.15	TAE.304/6	81-2-56	55-45
SiO_2	56.00	56.24	56.08	56.23
TiO_2	2.03	1.89	1.92	1.93
Al_2O_3	12.23	11.95	11.97	11.84
Fe_2O_3(T)	15.76	15.87	16.35	16.31
MnO	0.19	0.19	0.20	0.17
MgO	2.69	2.47	2.25	2.25
CaO	6.87	6.96	6.79	6.74
Na_2O	2.28	2.52	2.12	2.43
K_2O	1.70	1.64	2.07	1.83
P_2O_5	0.26	0.27	0.26	0.26
Mg#	25.5	23.6	21.8	21.9
Cr	8	27	21	12
Ni	15	21	19	18
Rb	72.70	69	70	69
Sr	160	142	129	127
Y	56.4	55	56	56
Zr	236.6	222	243	234
Nb	12.31	11	9	9
Ba	435.9	424	423	391
La	28.16		25.24	25.31
Ce	59.74		57.0	55.0
Sm	8.01		7.16	7.15
Eu	1.90		1.72	1.70
Gd	8.78			
Tb	1.51		1.24	1.31
Yb	5.52		5.02	5.27
Lu	0.90		0.76	0.77
Hf	6.31		6.40	6.28
Ta	0.82		0.78	0.70
Th	7.80	6	6.97	6.99
Ti/Y	215	206	206	207
Ti/Zr	51.3	51.1	47.4	49.4
Zr/Y	4.20	4.04	4.34	4.18
La_N/Yb_N	3.4		3.4	3.2

Major elements recalculated to volatile-free total of 100. Mg# is 100.Mg/(Mg+Fe*), where Fe* is total Fe. Data sources and analytical details: Z.1605.15 from Leat *et al*. (2006), XRF (majors) and ICP-MS (traces); TAE.304/6, from Brewer (1989), XRF (majors and traces); 81-2-56 and 55-45, from Elliot *et al*. (1999), XRF and INAA.


AFRICA
EAST
ANTARCTICA
AUSTRALIA
Kangaroo
Is.
Karoo
DML
TM
WN
PM
Victoria Land
FI
FM
EWM
TI
MBL
Tasmania
NEW
ZEALAND
TF
AP
SOUTH
AMERICA
2000 km
palaeo-Pacific Ocean
Beacon Supergroup
and correlatives
Gondwanian
fold belt


MFCT
SPCT
South Africa
Rifted margin
(probable source)
Theron Mts.
Shackleton Range
Whichaway Nuns.
Pensacola Mts.
S. Victoria Land
N. Victoria Land
SE Australia
>150 km
400 km
1700 km
1600 km
400 km


30°W
0°
A.
70°S
60°W
90°W
80°S
85°S
B.
Weddell Sea
oceanic crust
Explora anomaly
Orion anomaly
GC
Dronning
Maud
Land
Coats Land
L1
FA
TM
FIS
BIA
SR
Weddell
Embayment
Dufek-
Forrestal
RIS
PM
HN
EM



SOUTHERN AFRICA
ANTARCTICA
Karoo lavas
Magmatic rifted margins
Archaean cratons
Zimbabwe Craton
Sabi Monocline
Nuanetsi triple junction
Botswana Dyke Swarm
Dronning Maud Land
Lebombo Monocline
Weddell triple junction
Shackleton Range
Theron Mts.
Whichaway Nunataks
Ferrar
Kaapval Craton
KZND
Falkland Islands block
Central area lavas
Dufek intrusion
Filchner microplate
Ellsworth-Whitmore Mts. block
1000 km