The Ferrar Large Igneous Province: field and geochemical constraints on supra-crustal (high-level) emplacement of the magmatic system

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Abstract: The Ferrar Large Igneous Province forms a linear outcrop belt for 3250 km across Antarctica, which then diverges into SE Australia and New Zealand. The province comprises numerous sills, a layered mafic intrusion, remnants of extensive lava fields and minor pyroclastic deposits. High-precision zircon geochronology demonstrates a restricted emplacement duration (<0.4 myr) at *c.* 182.7 Ma, and geochemistry demonstrates marked coherence for most of the Ferrar province. Dyke swarms forming magma feeders have not been recognized, but locally have been inferred geophysically. The emplacement order of the various components of the magmatic system at supra-crustal levels has been inferred to be from the top-down lavas first, followed by progressively deeper emplacement of sills. This order was primarily controlled by magma density, and the emptying of large differentiated magma bodies from depth. An alternative proposal is that the magma transport paths were through sills, with magmas moving upwards to eventually reach the surface to be erupted as extrusive rocks. These two hypotheses are evaluated in terms of field relationships and geochemistry in the five regional areas where both lavas and sills crop out. Either scenario is possible in one or more instances, but neither hypothesis applies on a province-wide basis.

Supplementary material: The locations of samples, and trace element data and major element analyses of samples are available at: https://doi.org/10.6084/m9.figshare.c.3819454

Large Igneous Provinces (LIPs) are characterized by the eruption of large volumes of magma in a relatively short span of time (Coffin & Eldholm 1994; Eldholm & Coffin 2000). Some old provinces are represented mainly by intrusive rocks (e.g. Mackenzie Dyke Swarm and the Muskox Intrusion: LeCheminant & Heaman 1989; Baragar *et al.* 1996), whereas others, young in age, are primarily known only from extrusive lava flows (e.g. Columbia River Basalts: Reidel *et al.* 2013). Provinces associated with the break-up of Gondwana in Mesozoic time (Paraná: Piccirillo *et al.* 1990; Peate 1997; Karoo: Marsh *et al.* 1997; Neumann *et al.* 2011) provide a more complete cross-section of the supra-crustal magmatic architecture, which is represented by a mix of intrusive and extrusive components. These Mesozoic provinces offer the possibility of addressing the mechanisms of emplacement by examination of the various elements of the magmatic system in the context of the spatial, temporal and geochemical relationships. The order of emplacement of the various elements of the system can potentially be assessed by field and geochronological data. Whereas lavas have clear stratigraphic chronology, field relationships seldom provide compelling evidence for the order of sill emplacement, nor for the order between intrusive and extrusive magmatic phases. Geochronological data in complex provinces such as the Karoo (Jourdan *et al.* 2005, 2007, 2008) have yielded a wide range of $^{40}Ar/^{39}Ar$ ages (determined on plagioclase), with uncertainties that make interpretation of the order of emplacement difficult to assess. These uncertainties remain, even though U–Pb age determinations have been conducted on zircons from Karoo dolerites and Lebombo rhyolites (Riley *et al.* 2004; Svensen *et al.* 2012; Sell *et al.* 2014).

The Ferrar LIP, which crops out principally in Antarctica but extends to SE Australia and New Zealand (Fig. 1), is a relatively simple province, with a limited range of geochemical types. The purpose of this paper is to evaluate, through field and geochemical data, two alternative hypotheses for the mechanisms of emplacement of sills and lavas.

The Ferrar Large Igneous Province

The Ferrar Large Igneous Province (FLIP), in outcrop, has a narrow linear distribution for 3250 km

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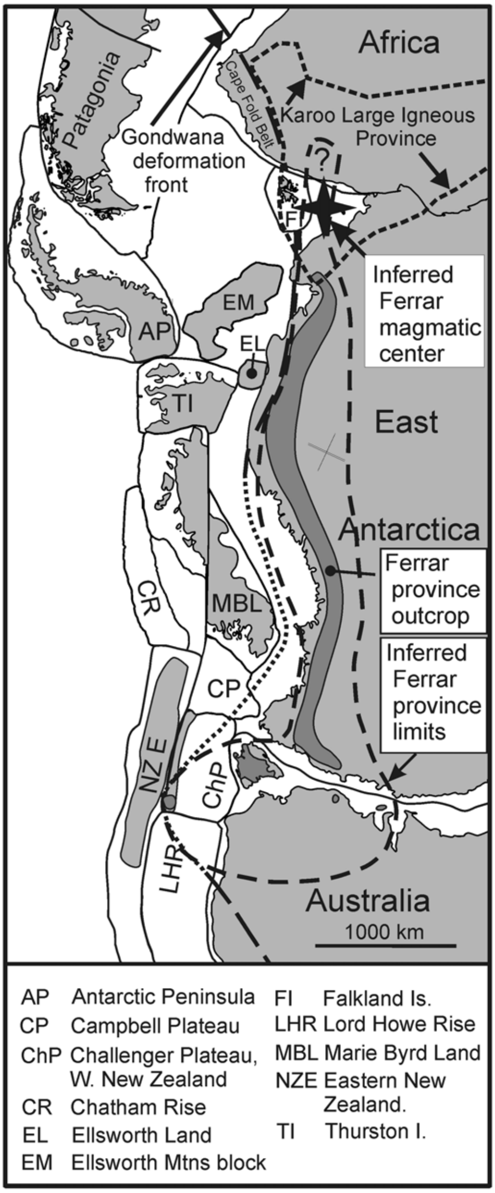


Fig. 1. Distribution of the Ferrar LIP in Gondwana (Gondwana modified from a reconstruction provided by the PLATES Project at the Institute of Geophysics at the University of Texas at Austin). The original extent of the Ferrar province beneath the East Antarctic Ice Sheet is speculative. The present-day South Pole is marked by a cross in East Antarctica.

across Antarctica from the Theron Mountains to north Victoria Land (Fig. 2), but then extends for another 500 km, and diverges to a width of about 1500 km to encompass New Zealand, Tasmania and SE Australia. The outcrop pattern in Antarctica is controlled mainly by Cenozoic uplift of the Transantarctic Mountains (see Elliot 2013). The distribution at the time of emplacement was undoubtedly much greater. Intrusive rocks comprise the Ferrar Dolerite sills and minor dykes (Elliot & Fleming 2004), and the Dufek layered mafic intrusion (Ford & Himmelberg 1991). The sills, with individual thicknesses generally between 100 and 200 m and cumulative thickness of 1500 m or more, occur predominantly in the 2.0–2.5 km-thick Devonian–Triassic Beacon Supergroup (Fig. 3) (Barrett 1991; Collinson *et al.* 1994; Bradshaw 2013). The sills, excluding outliers at and near Horn Bluff (longitude *c.* 150°E, about 700 km NW of the Mesa Range in Fig. 2), occur in a nearly continuous outcrop belt extending for about 2000 km from north Victoria Land to the Ohio Range, and intermittently thereafter for a further 1300 km to the Theron Mountains. Massive dolerite sills are particularly abundant south of the Mackay Glacier in south Victoria Land. Dykes are not common, but intrude both basement rocks and the Beacon sequence. In rare instances, dykes are observed cutting across Ferrar sills. The Dufek intrusion, as a whole, was first estimated to have a volume of approximately 50 000 km^3 and a thickness of 8–9 km (Behrendt *et al.* 1981; Ford & Himmelberg 1991), although later investigations led to the suggestion that it is two separate bodies with lesser thicknesses and a much smaller cumulative volume of approximately 6600 km^3 (Ferris *et al.* 1998). Extrusive rocks in the Ferrar province consist of basaltic pyroclastic rocks overlain by flood lavas of the Kirkpatrick Basalt, which attain a maximum extant thickness of approximately 900 m (Elliot & Fleming 2008). Intrusive rocks form 99% of the Ferrar outcrops and have an estimated volume of approximately 1.7×10^5 km^3, assuming a 150 km-wide original outcrop belt, whereas extrusive rocks, with an estimated extant volume of approximately 7000 km^3, are confined to widely spaced remnants of formerly more extensive lava fields (Fleming *et al.* 1995).

No strata younger than the Kirkpatrick Basalt lavas are present in the Transantarctic Mountains, except for Upper Cenozoic glacial deposits and alkaline volcanic rocks. A significant amount of stratigraphic section (Ferrar lavas and post-Ferrar sedimentary rocks) may be missing as a result of post-Early Jurassic erosion resulting mainly from uplift of the Transantarctic Mountains.

Geochemistry

The unifying characteristic of the FLIP is the distinctive geochemistry. Ferrar rocks are characterized by enriched Sr and Nd initial isotope ratios (Fig. 4), and crust-like trace element patterns (Fig. 5). The FLIP is

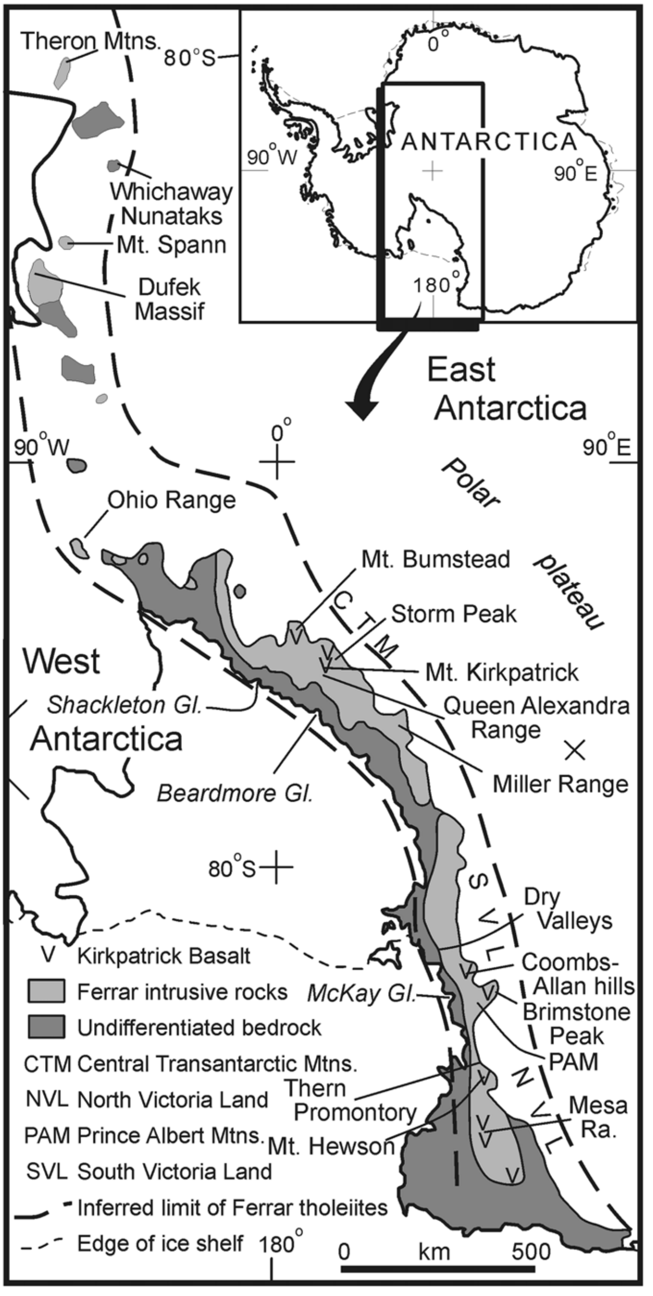
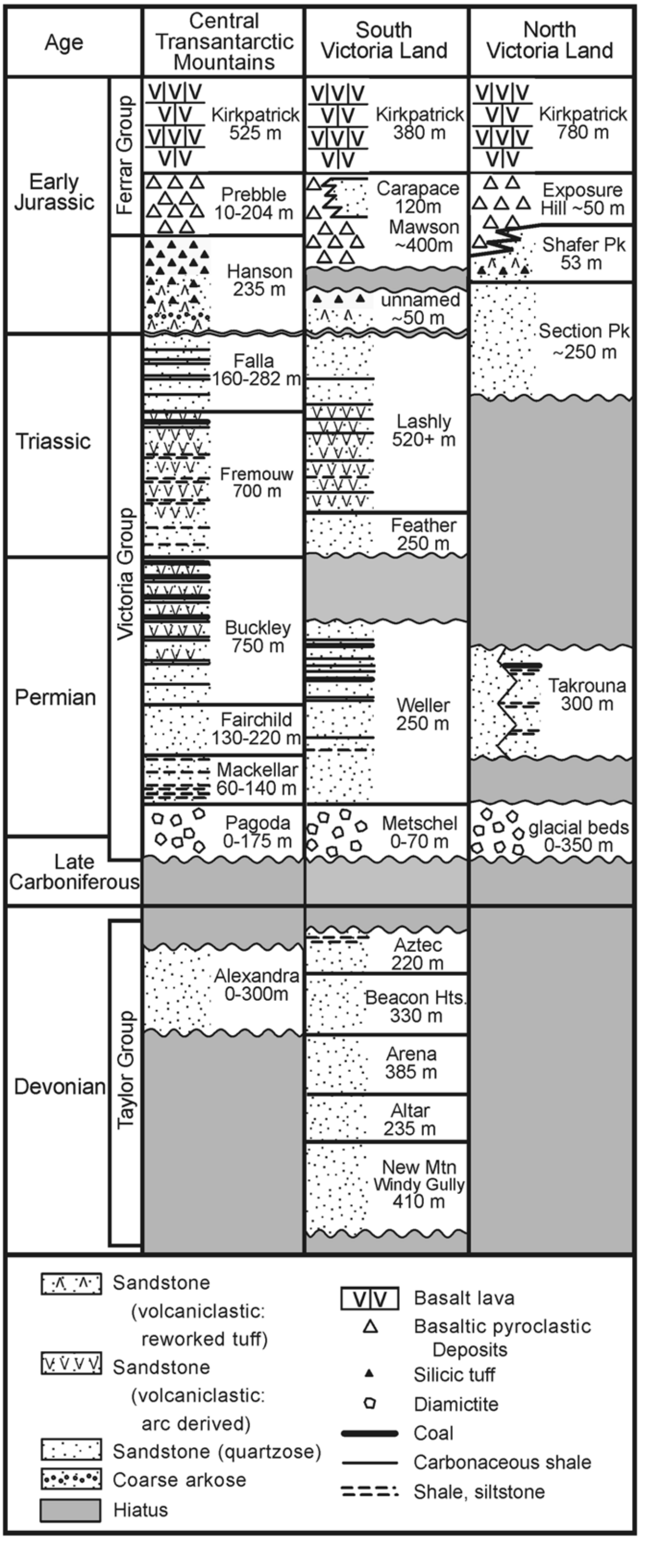


Fig. 2. Location map for the Ferrar LIP in Antarctica.

separated into the Mount Fazio Chemical Type (MFCT) and the Scarab Peak Chemical Type (SPCT) (Fleming *et al.* 1992) (Table 1). The MFCT comprises 99% of the province and includes the majority of all analysed rocks. The SPCT occurs as the stratigraphically youngest lava flow(s) in the central Transantarctic Mountains, and south and north Victoria Land, and also as sills in the Theron Mountains and the Whichaway Nunataks (Fig. 2) (Brewer *et al.* 1992; Leat *et al.* 2006). One sill from north Victoria Land has been reported to have SPCT composition (Hanemann & Viereck-Götte 2004), but



Age
Central Transantarctic Mountains
South Victoria Land
North Victoria Land
Early Jurassic
Ferrar Group
Kirkpatrick 525 m
Kirkpatrick 380 m
Kirkpatrick 780 m
Prebble 10-204 m
Carapace 120m
Mawson ~400m
Exposure Hill ~50 m
Shafer Pk 53 m
Hanson 235 m
unnamed ~50 m
Section Pk ~250 m
Triassic
Falla 160-282 m
Lashly 520+ m
Fremouw 700 m
Feather 250 m
Victoria Group
Permian
Buckley 750 m
Weller 250 m
Takrouna 300 m
Fairchild 130-220 m
Mackellar 60-140 m
Pagoda 0-175 m
Metschel 0-70 m
glacial beds 0-350 m
Late Carboniferous
Devonian
Taylor Group
Alexandra 0-300m
Aztec 220 m
Beacon Hts. 330 m
Arena 385 m
Altar 235 m
New Mtn Windy Gully 410 m
Sandstone (volcaniclastic: reworked tuff)
Sandstone (volcaniclastic: arc derived)
Sandstone (quartzose)
Coarse arkose
Hiatus
Basalt lava
Basaltic pyroclastic Deposits
Silicic tuff
Diamictite
Coal
Carbonaceous shale
Shale, siltstone

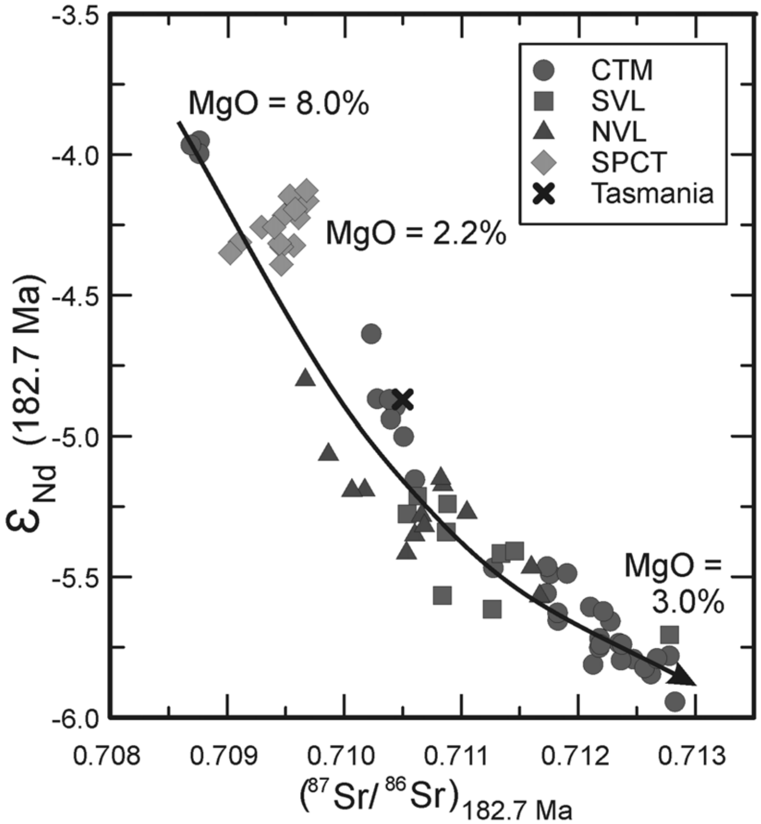


Fig. 4. ε_{Nd} v. $^{87}Sr/^{86}Sr$ at 183 Ma for Ferrar Large Igneous Province sills and lavas. Data sources: Tasmania – Hergt *et al.* (1989*b*); Transantarctic Mountains – Fleming *et al.* (1995); Elliot *et al.* (1999); Elliot & Fleming (2004).

here is regarded as a more highly evolved MFCT composition because it falls outside the restricted SPCT compositional range (having lower TiO_2, Y and Zr abundances, and higher Mg number).

The MFCT exhibits a range of geochemical compositions ($^{87}Sr/^{86}Sr_i$, *c.* 0.709–0.712; MgO, *c.* 9.3–2.6%; Zr, *c.* 60–175 ppm), which can be related by fractional crystallization accompanied by approximately 5% crustal assimilation (Figs 4–6) (Fleming *et al.* 1995). Although only data collected by the authors are illustrated here, analyses of Ferrar Dolerite sills in south Victoria Land (e.g. Hamilton 1965; Gunn 1966; Morrison & Reay 1995; Wilhelm & Wörner 1996; Antonini *et al.* 1999; Demarchi *et al.* 2001; Zieg & Marsh 2012) and north Victoria Land (e.g. Brotzu *et al.* 1988, 1992; Hornig 1993; Antonini *et al.* 1997; Hanemann & Viereck-Götte 2004) show that all belong to the MFCT, and they do not change the range of compositions except for samples from the Thern Promontory (Brotzu *et al.* 1988; Antonini *et al.* 1997), which include some compositions that are slightly more evolved. The SPCT has a distinct, evolved and restricted composition (Sr_i, *c.* 0.7095; MgO, *c.* 2.3%; Zr, *c.* 230 ppm), which lies off the chemical trends of the MFCT (Elliot *et al.* 1999).

Fig. 3. Simplified stratigraphic columns for the Taylor and Victoria groups of the Beacon Supergroup. Sources – Taylor and Victoria Groups in the central Transantarctic Mountains and south Victoria Land: Barrett (1991); Falla Formation: Elliot (1996); Hanson Formation: Elliot *et al.* (2017); Prebble Formation: Hanson & Elliot (1996); unnamed strata, south Victoria Land: Elliot & Grimes (2011); Mawson Formation: Ross *et al.* (2008); Prince Albert Mountains, south Victoria Land: Skinner & Ricker (1968); north Victoria Land glacial beds and the Takrouna Formation: Collinson *et al.* (1986); Section Peak and Shafer Peak formations: Schöner *et al.* (2011, 2007, respectively); Exposure Hill beds: Viereck-Götte *et al.* (2007); Kirkpatrick Basalt: Elliot & Fleming (2008). Note that the Victoria Group in south Victoria Land is half the thickness of that in the central Transantarctic Mountains.

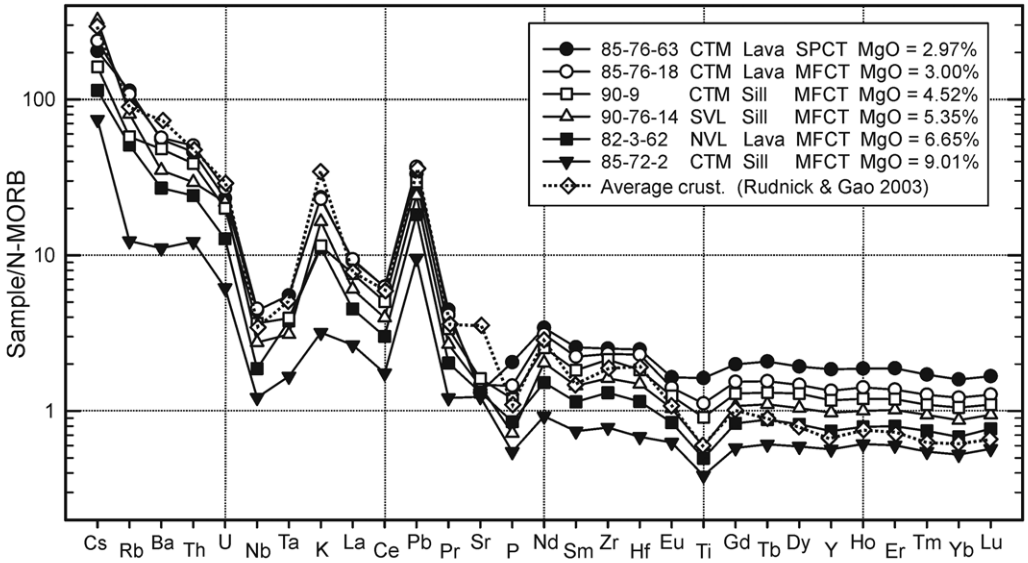


Fig. 5. MORB-normalized trace element diagram for selected samples of the Ferrar Group. The samples cover the entire range of MgO concentrations observed. Normalization factors from Sun & McDonough (1989). Data source: see the Supplementary material. Sample locations: 85-72-2 – Dawson Peak (Fig. 8); 82-3-62 – Haban Spur (Fig. 12); 90-76-14 – Pearse Valley (Fig. 10); 90-9 – Mt Black (Fig. 8); 85-76-18 & 63 – Storm Peak (Fig. 8).

Geochronology

Age determinations on the Ferrar LIP yielded a narrow range of dates by $^{40}Ar/^{39}Ar$ analysis of plagioclase crystals (Heimann *et al.* 1994; Fleming *et al.* 1997; Elliot *et al.* 1999), which established the duration of magmatic activity as relatively short (<2 myr) and close to the precision of the techniques. The accuracy of these dates, however, was compromised by issues related to uncertainty in the absolute age of international Ar reference materials (Renne *et al.* 1998). Subsequent multi-grain analyses of zircons, by the U–Pb thermal ionization mass spectrometry (TIMS) technique, provided a more accurate framework for the age of the Ferrar LIP (Encarnación *et al.* 1996; Minor & Mukasa 1997). More recently, zircons extracted from Ferrar samples have been analysed by the much more precise single-crystal chemical-abrasion isotope-dilution TIMS (CA ID-TIMS) method and have documented an even more restricted duration of emplacement (<0.4 myr), ranging from 182.779 ± 0.033 to 182.59 ± 0.079 Ma (2σ uncertainties) for the MFCT (Burgess *et al.* 2015). There is no clear temporal distinction between sills and lavas, although a limited number of analyses of SPCT rocks suggest that it is, permissibly, slightly younger (as young as 182.43 ± 0.036 Ma).

Source and mantle–lower crustal dispersal paths

Long-distance transport of Ferrar MFCT magmas from magmatic centres in the proto-Weddell Sea region was first proposed by Fleming *et al.* (1997) and Storey & Kyle (1997). Fleming *et al.* (1997) proposed that dykes, emanating from the magmatic centre, formed the feeders for the FLIP. Subsequently, the coherence of the SPCT geochemistry was interpreted to provide compelling support for the long-distance dyke transport proposal (Elliot *et al.* 1999; Elliot & Fleming 2000). Storey & Kyle (1997) suggested that the magmas originated at a mantle plume, migrated into large magma chambers with associated thermal bulges or topographical highs, and then flowed as sills and lavas along the length of the Transantarctic Mountains. Later, Ferris *et al.* (2003) advocated that Ferrar magmas entered the supra-crustal sedimentary sequences at the Dufek intrusion, which then formed the point source for long-distance magma transport through sills. Leat (2008), following Storey & Kyle (1997), also advocated long-distance transport through sills; however, long-distance sill transport is regarded as improbable because it requires magmas to cross a palaeotopographical high (the Ross High of Collinson *et al.* 1994) and then burrow down through the Taylor Group and penetrate the

Table 1. *Major element analyses of representative Ferrar sills and lavas*

Sample	85-72-2	11-5-1	96-73-16	85-51-20	85-51-41	04-01-01	02-09-58	02-11-64	90-75-5
Type	MFCT Sill	MFCT Sill	MFCT Sill	MFCT Lava	SPCT Lava	MFCT Sill	MFCT Sill	MFCT Sill	MFCT Lava
Region	CTM	CTM	CTM	CTM	CTM	SVL	SVL	SVL	SVL
SiO_2	52.05	54.60	56.90	58.33	56.85	55.12	57.32	58.41	57.56
TiO_2	0.49	0.63	1.13	1.59	1.97	0.63	0.94	1.09	0.99
Al_2O_3	16.37	15.06	13.84	12.81	12.07	14.77	14.44	14.51	13.70
Fe_2O_3	1.12	1.21	1.44	1.68	1.98	1.20	1.37	1.46	1.48
FeO	7.48	8.09	9.63	11.18	13.17	7.98	9.15	9.77	9.90
MnO	0.17	0.18	0.18	0.19	0.21	0.17	0.17	0.17	0.19
MgO	9.04	6.90	4.41	2.78	2.20	6.81	4.38	3.97	4.02
CaO	11.53	10.82	9.11	7.42	7.05	11.00	9.03	7.74	8.63
Na_2O	1.50	1.63	2.19	2.34	2.38	1.42	1.93	2.55	2.04
K_2O	0.20	0.78	1.03	1.47	1.83	0.84	1.15	0.17	1.33
P_2O_5	0.06	0.10	0.14	0.21	0.30	0.06	0.12	0.16	0.15
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LOI	1.93	0.74	0.76	0.59	0.33	-0.09	1.08	1.98	0.95
Mg#	68.3	60.3	44.9	30.7	22.9	60.3	46.1	42.0	42.0
Sample	97-62-12	97-68-3	97-57-2	97-51-6	97-51-52	82-9-2	82-10-2	81-2-30	82-2-5
Type	MFCT Sill	MFCT Sill	MFCT Sill	MFCT Lava	SPCT Lava	MFCT Sill	MFCT Sill	MFCT Lava	SPCT Lava
Region	SVL	SVL	SVL	SVL	SVL	NVL	NVL	NVL	NVL
SiO_2	53.34	54.97	56.41	56.07	57.02	56.37	58.25	55.34	57.08
TiO_2	0.51	0.63	0.73	0.82	1.96	0.73	1.04	0.65	1.99
Al_2O_3	14.70	14.59	14.59	14.03	11.91	14.40	13.84	14.71	12.00
Fe_2O_3	1.18	1.20	1.25	1.35	1.98	1.29	1.38	1.22	1.98
FeO	7.89	8.03	8.32	8.98	13.18	8.59	9.19	8.13	13.22
MnO	0.17	0.17	0.18	0.18	0.19	0.16	0.19	0.18	0.22
MgO	9.84	6.88	5.75	5.54	2.26	5.60	3.75	6.49	2.21
CaO	10.36	10.63	9.77	10.04	7.02	9.57	8.47	10.98	7.04
Na_2O	1.46	2.07	2.04	1.89	2.44	2.01	2.13	1.79	2.15
K_2O	0.49	0.74	0.85	0.98	1.78	1.16	1.57	0.40	1.82
P_2O_5	0.07	0.09	0.12	0.12	0.26	0.12	0.18	0.09	0.28
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
LOI	0.63	0.34	0.03	0.17	0.16	1.54	1.35	1.42	0.38
Mg#	69.0	60.4	55.2	52.4	23.4	53.73	42.1	58.7	23.0

Analyses were performed by EDXRF at the Southern Connecticut State University and WDXRF at New Mexico Tech using Li-metaborate fusion methologies modified after Norrish & Hutton (1969). Major element analyses given in wt% and normalized to 100% loss-free with $Fe_2O_3/FeO = 0.15$. CTM: central Transantarctic Mountains; NVL: north Victoria Land; SVL: south Victoria Land; LOI, loss on ignition; Mg#, Mg number. Sample locations are given in the Supplementary material.

basement rocks in the Dry Valleys to form the thick Basement Sill (Marsh 2004). That sill has been studied exhaustively in Wright Valley and is part of a more complex intrusion system, which includes a thick body with well-defined mineral layering at The Dais in Wright Valley (Marsh 2004; Marsh *et al.* 2005; Bédard *et al.* 2007). A thick tongue of orthopyroxene crystals, formed by flow differentiation and entrained in the Basement Sill during its emplacement, thins away from the region of Bull Pass; the feeder itself, an approximately 10 km-diameter funnel, is centred in the mountains immediately to the east of Bull Pass (Marsh *et al.* 2005) and implies vertical transport from reservoirs at depth. Although dykes are very sparse and widely distributed, several transect basement rocks, indicating the transport of magmas from depth at those sites, and not by transport through supra-crustal sills. Nevertheless, it is clear that magmas were dispersed laterally in sills for at least tens of kilometres, epitomized by the Basement Sill which has been identified over an area of about 10 000 km^2 (Marsh 2007).

The Muskox Intrusion, Coppermine River lavas and the Mackenzie Dyke Swarm, the latter known to extend over 2500 km (Baragar *et al.* 1996), are considered to be the best analogues for the FLIP but represent deeper levels of erosion of a possibly similar magmatic system. The Mackenzie Dyke Swarm, as observed today, occurs in rocks that were at mid-crustal depths.

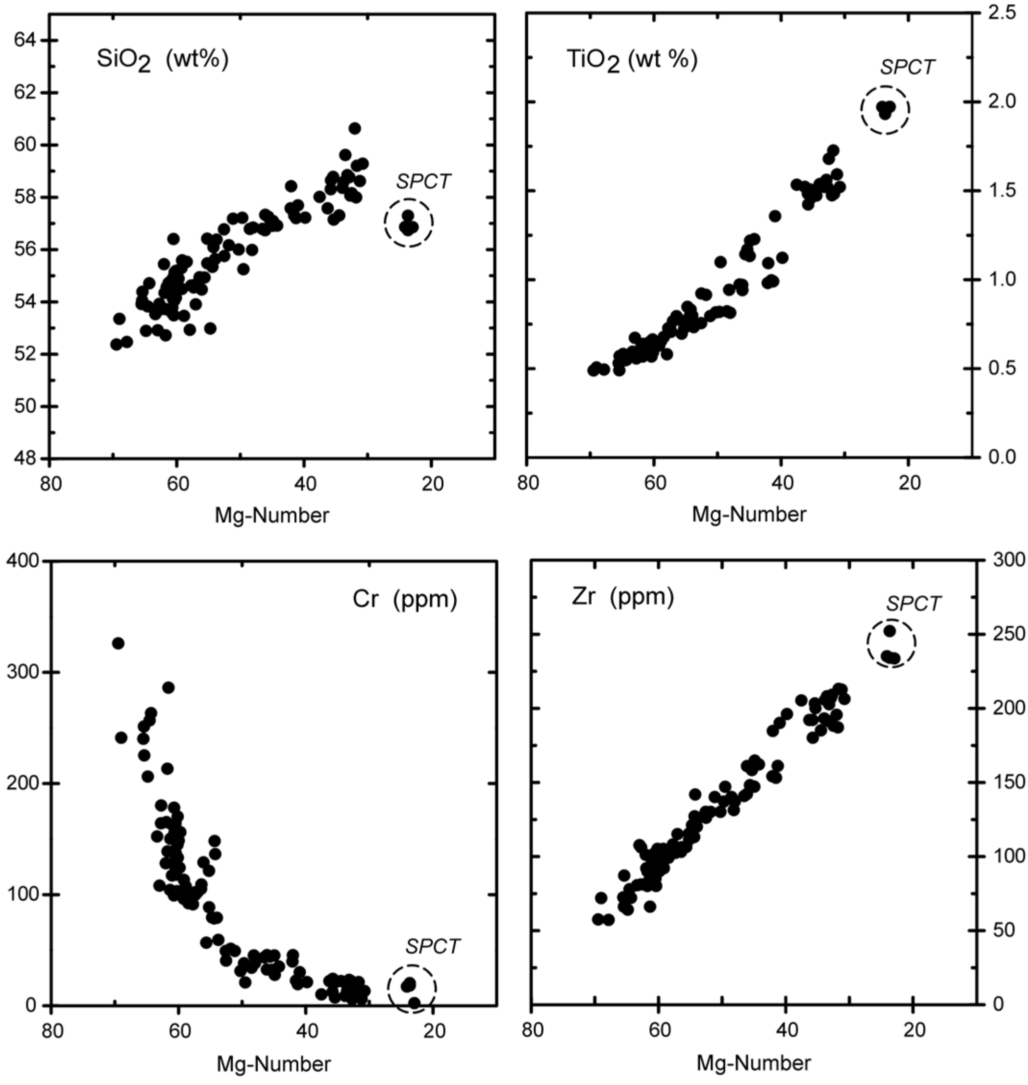


Fig. 6. Variation diagrams for selected major and trace elements for Ferrar Group lavas and sills to illustrate the geochemical coherence of the MFCT and the restricted and different composition of the SPCT. Data from Elliot *et al.* (1995, 1999) and Fleming *et al.* (1995, 1997).

With respect to the possibility of long-distance surface dispersal of lava flows, the Pomona flow of the Columbia River Basalt LIP has been traced for 600 km (Hooper 1997). Further, Self *et al.* (2008) correlated the Rajahmundry Trap lavas on the east coast of the Indian Peninsula with specific Deccan lava formations, and proposed that subaerial lava flow of more than 1000 km is probable given the right combination of magma eruption rates and topography. The SPCT composition occurs as a single lava flow at all outcrops (Elliot *et al.* 1999), except in north Victoria Land where multiple flows, or possibly flow lobes from a single eruptive event, are present (Mensing *et al.* 1991). These lava-flow outcrops, spread out over about 1500 km, are unlikely to represent surface transport from a single source (such as the Dufek intrusion, a further 1100 km distant) given that the flow path would have been along a rift valley system with inferred topographical lows (Elliot & Fleming 2004, 2008). Nevertheless, a regional gradient from a topographical high over a possible plume head in the proto-Weddell Sea region across Antarctica cannot be totally discounted.

Controls on shallow-level (supra-crustal) emplacement

Marsh (2004) examined the sills in the Dry Valleys region of south Victoria Land and proposed that density provided the fundamental control on the emplacement level of Ferrar magmas. The primary control on density was interpreted to be principally the proportion of phenocrysts (mainly orthopyroxene) carried by the magmas. In this hypothesis, the least dense, crystal-free magmas (proxied by MgO content) were initially emplaced as lavas through a system of regional dykes. With time, the magmatic system delivered increasingly dense magmas from depth. A point was reached at which the magmas became too dense for eruption and they were then emplaced as sills; with progressively increasing density (MgO content), the magmas were intruded at progressively greater depths in the Beacon sedimentary sequence. Marsh (2004) cited the lavas at Coombs Hills and Allan Hills, and the sills in the Dry Valleys, as exemplifying this process. Thus, in an ideal situation, the lavas should exhibit increasing MgO upsection and the sills increasing MgO down through the sill complex in the Beacon strata and basement rocks.

Airoldi *et al.* (2012) and Muirhead *et al.* (2012, 2014) examined dykes, inclined sheets and sills in the Coombs Hills, Allan Hills and the Dry Valleys region, and proposed an entirely different emplacement mechanism. They argued, on the basis of structural and magnetic studies, that the Ferrar dykes and inclined sheets were intruded into a neutral stress field, not an extensional stress field, which has long been accepted for dyke emplacement (Anderson 1951). In this hypothesis, the random orientation of dykes observed at Allan Hills reflects the neutral stress field, and dykes together with inclined sheets form the magma pathways from one sill to an overlying sill and eventually to the surface for eruption as lavas. Thus, the neutral stress field and sill inflation play a critical role in magma ascent, leading to a sill-fed dyke network overlain by lavas supplied by the underlying dyke field. This scenario has been referred to as the ‘cracked-lid’ hypothesis for flood basalt eruption (Muirhead *et al.* 2014). Nevertheless, this scenario invokes magma transport in dykes through crustal rocks, prior to invasion of supra-crustal rocks; this necessarily implies a regional stress field affecting the igneous and metamorphic crustal rocks. This scenario also suggests that there should be a link between lava compositions and those of underlying sills.

Stratigraphic and geochemical relationships

To assess the possible relationships between sill and lava compositions, the five areas with extant extrusive and intrusive phases, are examined (Figs 7–12). The stratigraphic distribution of the illustrated sills is based on their occurrence through the Beacon Supergroup and do not represent a simple vertical stack of sills at any one locality. Progressively younger strata of the Beacon Supergroup, which in the Shackleton Glacier region, the Dry Valleys of south Victoria Land and the Prince Albert Mountains (Fig. 2) have a low dip to the west (toward the ice-covered polar plateau), crop out at increasing elevations back from the mountain front. In the Queen Alexandra Range, the Beacon Supergroup describes a broad, shallow syncline, whereas, in north Victoria Land, the Permian strata fill a possible trough or rift with the Triassic Section Peak Formation cropping out on the inboard shoulder (polar plateau flank). Thus, the stratigraphic succession of sills may be spread out geographically over a lateral distance of 100 km or more, as is the case for the Shackleton Glacier region, the Dry Valleys of south Victoria Land and north Victoria Land, whereas, in the Queen Alexandra Range and the Prince Albert Mountains, the lavas and sills are in somewhat closer association. Further, sills may terminate and connect via thin dykes to other sills at higher stratigraphic levels, exchange stratigraphic positions and form climbing sheets connecting to other sills (Hamilton 1965; Elliot & Fleming 2004; Muirhead *et al.* 2012).

It should be noted that the thickest Devonian Taylor Group succession crops out in south Victoria Land, whereas the thickest Permo-Triassic Victoria Group succession is displayed in the central Transantarctic Mountains. The Beacon Supergroup in the Prince Albert Mountains is not well studied and its age is uncertain (Skinner & Ricker 1968); however, the occurrence of carbonaceous debris in the sequence suggests that it is part of the Victoria Group. In north Victoria Land, the Beacon strata are geographically scattered, and the composite stratigraphic column illustrated is less definitive than the columns for south Victoria Land and the central Transantarctic Mountains.

The MgO concentrations of chilled margins of sills are plotted adjacent to the stratigraphic columns. Those of fine-grained samples of lava flows in the same regions are plotted in the same figures but at a different scale (note that the SPCT magma type is indicated where present). In the Shackleton Glacier region (Figs 7a & 8), the MgO concentrations of the sills have a range of MgO = 4.3–7.3%, without any stratigraphic trend. The lavas at Mt Bumstead, above the lowest exposed flow, which

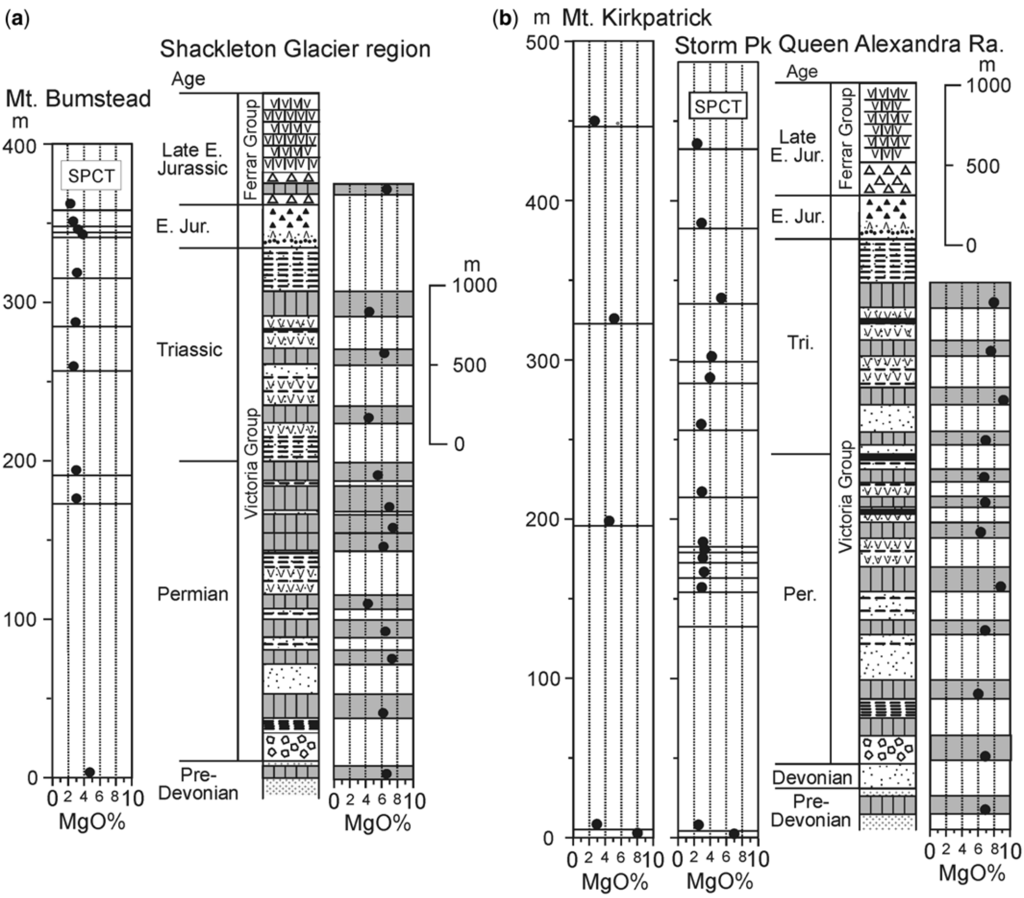


Fig. 7. (**a**) Schematic column to show the distribution of Ferrar Dolerite sills in basement rocks and the Victoria Group of the Beacon Supergroup in the Shackleton Glacier region, and a stratigraphic column for Kirkpatrick Basalt lavas at Mt Bumstead (see Fig. 8 for the locations). (**b**) Schematic column to show the distribution of Ferrar Dolerite sills in the Victoria Group of the Beacon Supergroup in the Queen Alexandra Range, and stratigraphic columns for Kirkpatrick Basalt lavas at Mt Kirkpatrick and Storm Peak (see Fig. 8 for the locations). The plotted points are the MgO concentrations of chilled margins of sills and of fine-grained lavas. In this and other figures, sills are projected onto the stratigraphic column and do not represent a single vertical sequence. Data sources: Hergt *et al.* (1989*a*: Portal Peak sill, third from the base in Fig. 7b); see the Supplementary material for other sills and lavas.

has MgO = 4.5%, are uniformly highly evolved (MgO = 2.7–3.4%). In the Queen Alexandra Range (Figs 7b & 8), the sills are relatively higher in MgO (6.0–9.4%), but again with no trend, and with the most MgO-rich olivine dolerite sills occurring in the middle and upper part of the Buckley Formation. Two lava columns are illustrated, the localities being 38 km apart. Both begin with a very thin flow with MgO > 7.0%. At Storm Peak overlying lavas are much less evolved (MgO = 2.6–5.7%) and without any clear trend. At Mt Kirkpatrick, there are only four very thick flows above the basal lava and they show an initial trend to less MgO-poor compositions. The lava sequence at Mt Falla, only 15 km distant from Mt Kirkpatrick, is similar to Storm Peak, with at least two correlative thick flows (second flow and capping flow: Barrett *et al.* 1986).

In the Dry Valleys of south Victoria Land (Figs 9a & 10), the sills are progressively higher in MgO downsection. The nearest lava flows occur about 100 km to the NNW at Carapace Nunatak (Fig. 10), and those flows, with the exception of the summit flow, show increasing MgO upsection (note that a flow with the SPCT composition is absent, and the sequence is much thinner than at all the major lava outcrop regions). Dolerite plugs and a thin sill invade the Mawson Formation at Coombs Hills and Allan Hills (Ross *et al.* 2008);

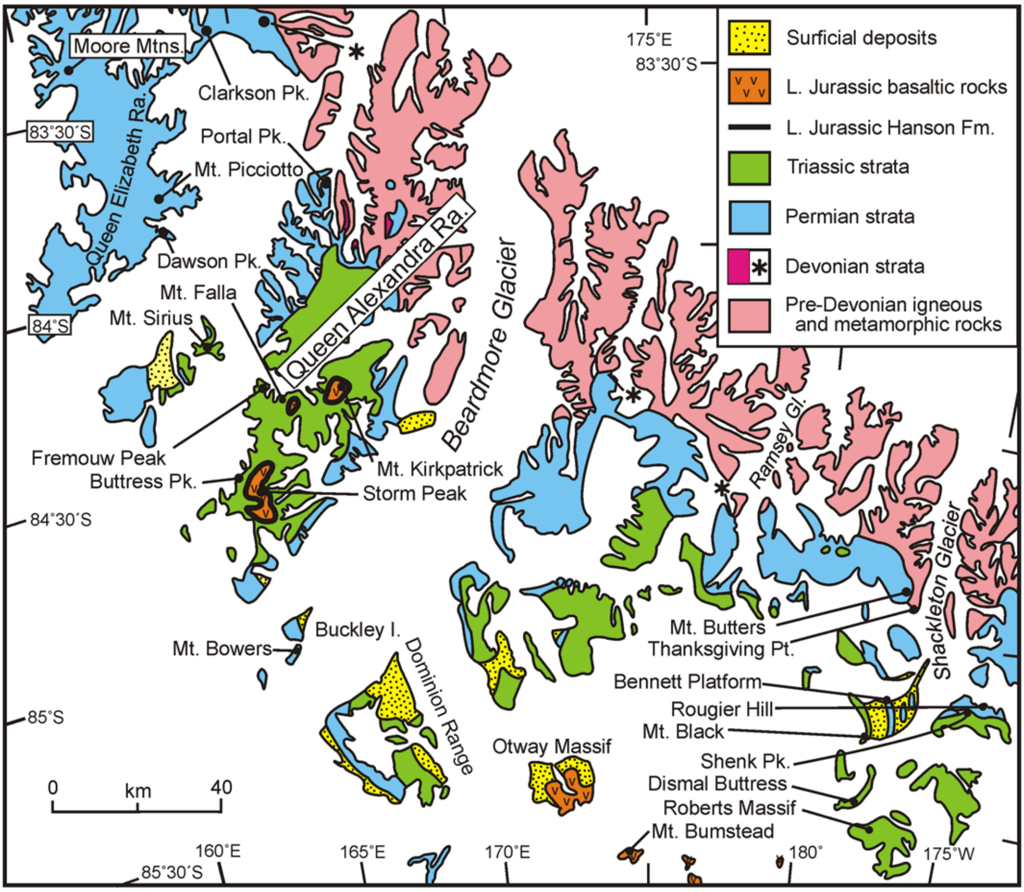


Fig. 8. Simplified geological map of the central Transantarctic Mountains to show the geographical distribution of Kirkpatrick Basalt lava flows, and Beacon Supergroup strata and associated Ferrar Dolerite sills.

all have MgO > 6.3%. In the Prince Albert Mountains (Figs 9b & 10), the sill and lava compositions overlap (3.9–7.3% MgO) and no clear trends are evident.

In north Victoria Land (Figs 11 & 12), the Victoria Group crops out over a wide area (250 km linear distribution) with only Triassic–Jurassic beds in close proximity to the lavas. To the south and west of the Mesa Range, sills are confined to Triassic–Jurassic quartzose strata; to the north, however, sills have been mapped in the Permian Takrouna Formation. North of the Mesa Range, chilled margin compositions (MgO = 7.1–7.2%) are available for only three sills (Hornig 1993; Hanemann & Viereck-Götte 2004: note that the Hanemann & Viereck-Götte 2004 sample from Mt Apolotok is reported to be a sill but is listed in their table as a dyke margin); one sill is documented to be 300 m thick (Hornig 1993) and is possibly at or near the top of the Permian section, and is illustrated as such in Figure 11; the sill at Mt Bower must be close to or at the base of the Section Peak Formation (Schöner *et al.* 2011). Several sills in this quartzose Triassic–Jurassic sequence are exposed in a nunatak (Exposure Hill) adjacent to the lavas in the southern Mesa Range (Elliot *et al.* 1986) and these have MgO = 3.7–5.6%. These sills are probably high in the Section Peak Formation, but a fault must separate Exposure Hill from the adjacent Mesa Range lavas, and neither the top nor the base of the formation is exposed there. The analysed sill samples to the south of the Mesa Range all have MgO < 4.5% (Brotzu *et al.* 1988). The Mesa Range Kirkpatrick lavas are predominantly more MgO-rich (mainly 6–8% MgO, with only two as low as 5% MgO) than sills south of the Mesa Range and at Exposure Hill; the lava sequence does not exhibit any trend upsection.

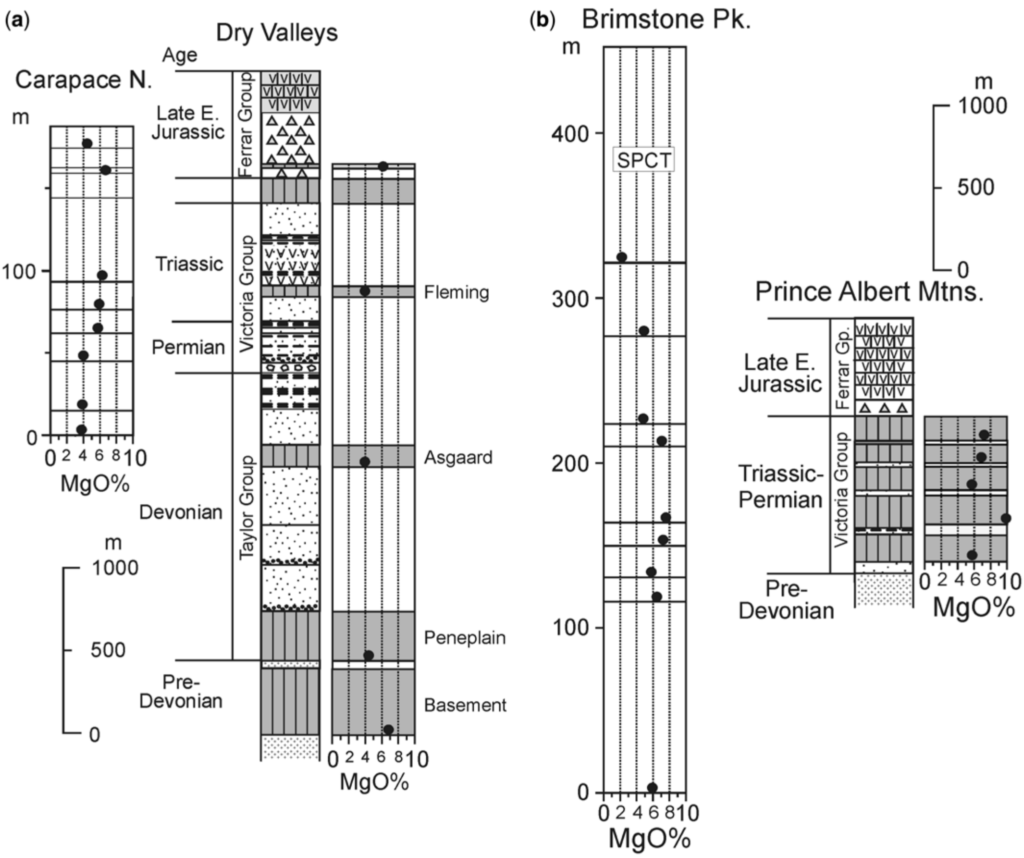


Fig. 9. (**a**) Schematic column to show the distribution of Ferrar Dolerite sills in the basement rocks and the Beacon Supergroup (Taylor and Victoria groups) in the Dry Valleys of south Victoria Land and a stratigraphic column for Kirkpatrick Basalt lavas at Carapace Nunatak (see Fig. 10 for the locations). (**b**) Schematic column to show the distribution of Ferrar Dolerite sills in the Beacon Supergroup (assumed to be the Victoria Group because of the presence of carbonaceous material) in the Prince Albert Mountains and a stratigraphic column for Kirkpatrick Basalt lavas at Brimstone Peak (see Fig. 10 for the locations). The plotted points are the MgO concentrations of chilled margins of sills and of fine-grained lavas. Data sources: Marsh (2007, chilled margin of the Fleming sill); Ross *et al.* (2008, sample 73160, stratigraphically highest sill); see also the Supplementary material.

The Mesa Range lavas overlie Lower Jurassic, silicic pyroclastic rocks, which have a regional thickness of about 50 m (Schöner *et al.* 2007, 2011). These overlie the 250 m-thick quartzose Section Peak Formation, which is intruded by two thick sills at Section Peak and along the escarpment that extends south to the Deep Freeze Range region (Fig. 12) where another section of Kirkpatrick Basalt lavas crops out at and near Mt Hewson (Brotzu *et al.* 1988). The sills at Section Peak are thick and uniform, and, together with the sills at Exposure Hill, show no sign of shallow intrusion such as vesicularity. This implies that the lavas, which generally have higher MgO than the sills, were erupted first in order for sufficient overburden to be present for sills to lack signs of degassing.

Discussion

In the density-driven vertical-emplacement hypothesis (Marsh 2004), eruption of the most evolved magma occurs first and subsequent magmas are increasingly MgO-rich up lava section; a point is reached at which magmas are no longer erupted at the surface, but are intruded sequentially, and with increasing MgO, downsection through the Beacon Supergroup. This relationship is not observed in north Victoria Land. There is no clear pattern in the Prince Albert Mountains that would support the hypothesis, whereas in the Dry Valleys region, the geochemistry, in general, is not inconsistent with it. In the Queen Alexandra Range, apart from the high-MgO basal flow, the lavas at Mt Kirkpatrick partially support the hypothesis,

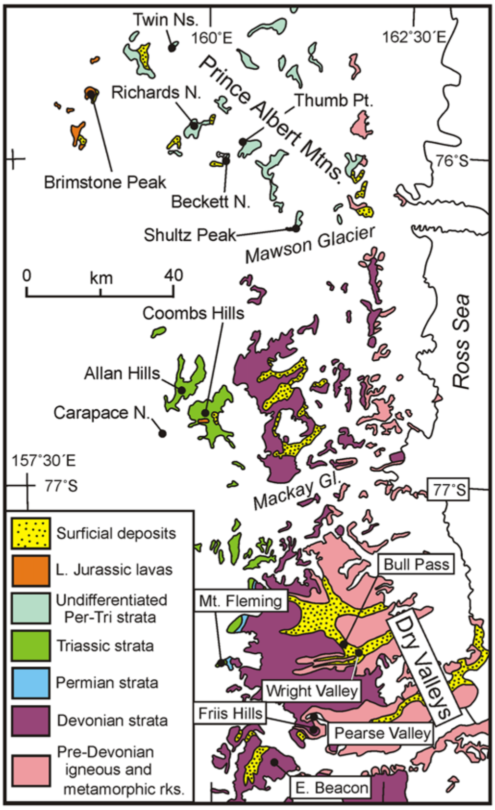


Fig. 10. Simplified geological map of south Victoria Land to show the geographical distribution of Kirkpatrick Basalt lava flows, and Beacon Supergroup strata and associated Ferrar Dolerite sills. Note that basaltic pyroclastic rocks, erupted prior to flood basalt effusion, occur in the western Coombs Hills and southern Allan Hills, and form small outcrops elsewhere but are here included with Triassic beds.

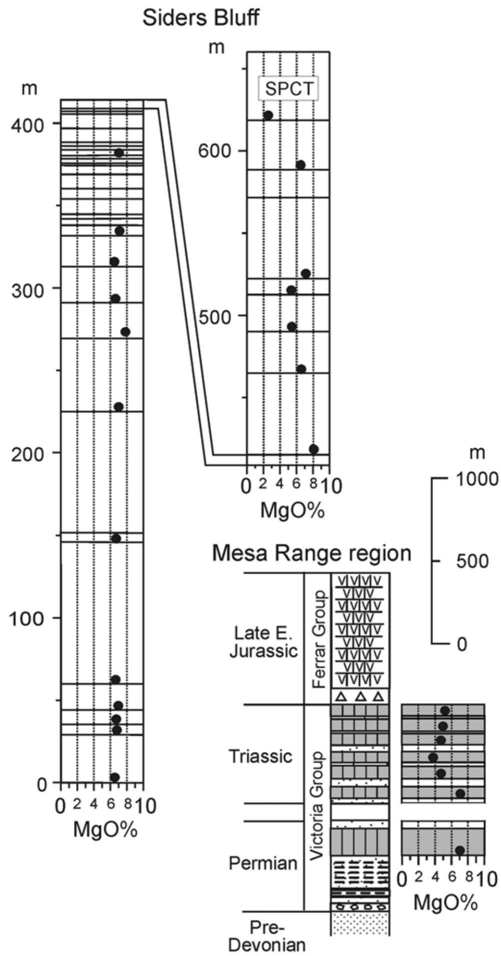


Fig. 11. Schematic column to show the distribution of Ferrar Dolerite sills in the Beacon Supergroup in the Mesa Range region of north Victoria Land and a stratigraphic column for Kirkpatrick Basalt lavas at Siders Bluff, Mesa Range (see Fig. 12 for the locations). The plotted points are the MgO concentrations of chilled margins of sills and of fine-grained lavas. The stratigraphic column is broken because there is no continuity between the Permian and Triassic strata. Data sources: Hornig (1993, sample FD004, Boggs Valley); Hanemann & Viereck-Götte (2004, sample RH54a, Mt Bower); see also the Supplementary material.

whereas the Storm Peak flows marginally support it. The sills, however, show no pattern of increasing MgO with depth. Similarly in the Shackleton Glacier region, apart from the basal very thick flow at Mt Bumstead, the lavas are uniformly strongly evolved. In contrast, the sills are higher in MgO except for three that are relatively evolved (*c.* 4.5%). In summary, the geochemistry is not inconsistent with the density-driven hypothesis in the Dry Valleys, but appears to negate the hypothesis in north Victoria Land and shows inconsistent patterns in the three other regions. It is clear that factors other than density play a significant role in the emplacement of magmas either at depth or at the surface.

In the cracked-lid sill-fed hypothesis (Muirhead *et al.* 2014), in which lavas are fed directly from underlying intrusions, there should be some geochemical correlation between the lava flows and the sills. In addition, this hypothesis implies that sills are intruded first and, with time, magmas migrate upwards forming younger and stratigraphically higher sills, eventually breaking through to the surface; lava flows cannot be erupted without corresponding sill emplacement at depth. Further, this hypothesis suggests dykes somewhere should be observed cutting strata immediately underlying the lavas and penetrating the lava succession, but no feeder dykes for

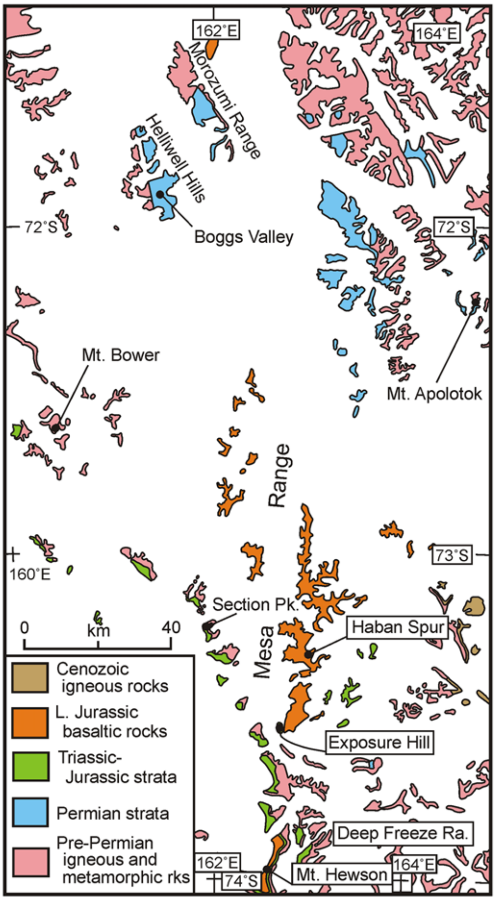


Fig. 12. Simplified geological map of north Victoria Land to show the geographical distribution of Kirkpatrick Basalt lava flows, and Beacon Supergroup strata and associated Ferrar Dolerite sills.

the lavas have been positively identified so far. There are instances of thin dykes connecting sills in the Shackleton Glacier region (Elliot & Fleming 2004), and examples of thicker inclined sheets and massive dolerite plugs with connecting dykes and sills in south Victoria Land (Hamilton 1965; Morrison & Reay 1995; Elliot & Fleming 2004; Muirhead *et al.* 2012). If the locations of lavas reflect sites of eruption associated with palaeotopographical lows in a Jurassic rift system (Elliot & Fleming 2008), there should be evidence for feeders. In the Coombs Hills–Allan Hills region (Ross *et al.* 2008; Muirhead *et al.* 2012) and at the Otway Massif (Elliot & Hanson 2001), massive dolerite bodies are present in association with, and intruded into, cauldron-like phreatomagmatic deposits (White & McClintock 2001) measuring as much as 350 m in thickness, and all overlain by Kirkpatrick Basalt lavas. These were sites of major extrusive activity; yet, the absence of reported vesicularity in the sills implies significant overburden at the time of intrusion (i.e. the lava column already existed at the time of dolerite emplacement).

In evaluating these hypotheses, uncertainties arise because sills and lavas in any one area assessed in this study crop out as much as 100 km apart. In the Shackleton Glacier region, given that some of the sills have higher MgO than the lava flows, it is plausible that the evolved lavas are the products of magma evolution in sill bodies. However, most sills are too thin to show significant *in situ* differentiation and no sill in this region shows any evidence (layering and accumulation of plagioclase and mafic minerals) for the extended fractional crystallization required to produce the evolved lavas, nor are there any sills with the evolved character of the lavas that could be considered constituent parts of the conduit systems. Further, an orthopyroxene mush comparable to that of the Basement Sill in south Victoria Land, a critical factor in the density-driven hypothesis, is not known to be present in any sill elsewhere. In the Queen Alexandra Range, the situation is similar. The very thick (up to nearly 200 m) evolved flows at Mt Kirkpatrick would require large reservoirs of cumulates, which have not been observed in any sill, and no sill has a composition suggesting that it might be part of the conduit system. In south Victoria Land, the range of lava and sill compositions is compatible with direct connections between them, and the same is the case in the Prince Albert Mountains. In north Victoria Land, the geochemistry is marginally consistent with a connection between the lava flows and sills north of the Mesa Range,

Many factors affect the emplacement of magmas, whether as sills or lava flows. These include density, lithostatic pressures, magma overpressures required for lateral emplacement, wall-rock composition and physical properties, and when and where the evolving source was tapped. It is interesting to note that thick (100+ m) flows are present at Mt Kirkpatrick where there are three such flows, one at Storm Peak that is highly evolved and quenched, and one at Mt Bumstead (and others at the adjacent Otway Massif). The margin of the thick flows at Mt Kirkpatrick have MgO = 2.5–4.5%, and at Mt Bumstead MgO = 4.5%; the lowest two flows at Mt Kirkpatrick have particularly evolved compositions. There are no suitable counterparts, such as thick cumulate zones indicating *in situ* fractional crystallization and evolution, in the underlying sills for the evolved flows, if the flows were to have originated via migration of magma into, and evolution within, the sills.

The SPCT magma composition provides an important constraint on the relationship between the intrusive and extrusive elements of the Ferrar magmatic system. Among the lavas, it is represented only by the uppermost flow(s) in the lava sequences. It is not represented by any analysed sill in the Transantarctic Mountains between Mt Spann (Fig. 2) and north Victoria Land (nor in SE Australasia), although it is represented in the Whichaway Nunataks and Theron Mountains (Fig. 2), which are 1250 km from the nearest extant lava in the Shackleton Glacier region. The SPCT lavas share chemical characteristics with the MFCT rocks, such as enriched initial isotope ratios of Sr and Nd, and crust-like trace element patterns. However, they clearly must have had a different evolutionary path because their evolved major and trace element geochemistry (Figs 5 & 6) is accompanied by Sr and Nd initial isotope ratios that lie at the least evolved end of the Ferrar province range (Fig. 4). The SPCT rocks could be compatible with the density-driven hypothesis, but as an entirely separate event. However, they are incompatible with the sill-fed cracked-lid hypothesis (Muirhead *et al.* 2014), and clearly demand a different emplacement path. SPCT lateral transport may have been predominantly at lower-crustal depths with ascent into supra-crustal rocks and to the surface outside the existing Ferrar outcrop belt. The SPCT plumbing system was not rooted in the subjacent extant supra-crustal Beacon sedimentary succession. This also opens the possibility that emplacement of at least some of the MFCT rocks may have included such transport from outside the area of existing outcrop.

Conclusions

The geochemical coherence of the principal geochemical type recognized in the Ferrar Large Igneous Province (99% of the province) suggests that it is a single episode of magmatism, which occurred over a limited time span. The mode and relative timing of emplacement of various elements of the magmatic architecture, however, are not entirely clear. No large dyke swarms or feeders have been recognized, leading to the suggestion, based on geochemical coherence, of a single source in the proto-Weddell Sea region of Gondwana, followed by lower-crustal transport and migration to the surface at a limited number of sites. Two scenarios have been proposed to explain the shallow emplacement history: one driven by magma physical properties (density) (Marsh 2004), and the other based on structural and field evidence (Muirhead *et al.* 2012, 2014). The contrasting hypotheses have been evaluated on field and geochemical data. Evidence from the Dry Valleys and Carapace Nunatak, south Victoria Land, is not inconsistent with the density-driven emplacement mechanism (Marsh 2004). At the remaining localities, field and geochemical data are inconsistent with the hypothesis. Field and geochemical data do not support the sill-fed hypothesis (Muirhead *et al.* 2014) as a geographically widespread scenario. Each process may be of local importance but neither hypothesis, based on field and geochemical data, applies province-wide.

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