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Cracking the lid: Sill-fed dikes are the likely feeders of flood basalt eruptions

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ABSTRACT

Although subparallel swarms of dikes are thought to be the primary feeders to voluminous volcanic eruptions, increasing recognition of volumetrically significant sill complexes suggests that they too play an important role in magma ascent through the shallow crust. However, the extent to which sills and interconnected, sill-fed dikes actually transport magma to the earth's surface in many large igneous provinces (LIP) is presently unclear. By analyzing field relationships and dimensions of intrusions of the Ferrar LIP in South Victoria Land, Antarctica, we show that sill-fed dikes were the likely feeders for voluminous flood basalt eruptions. These intrusions are small but numerous, with cumulative dimensions equivalent to a feeder network 308,000 km long and 1.8 m wide. Due to the tremendous aerial extent of this intrusive network, each individual dike-feeder segment would only be required to actively feed magma for 2 to 3 days on average to erupt the 70,000 km^3 of flood lavas represented by the Kirkpatrick basalts. The Ferrar intrusions form a broadly-distributed array of small, moderately dipping dikes (<2 km long, 1.8 m wide, 56° mean dip) exhibiting almost any orientation. This sill-fed dike network contrasts with dike swarms conventionally depicted to feed flood basalt provinces, and has the appearance of a variably "cracked lid" atop a sill complex. The cracked lid model may apply to a range of shallow feeder systems (<4 km depth) intruding sedimentary basins, where the effects of far-field tectonic stresses are negligible and sill intrusions exert the dominant control on dike orientations. We conclude that sill inflation, and resulting deformation of surrounding host rock, plays a critical role in the ascent of magma in shallow volcanic systems that span the full spectrum of eruptive volumes.

1. Introduction

Dike intrusion is conventionally considered the dominant process by which magma ascends through cold lithosphere to feed eruptions at the surface (Anderson, 1951; Lister and Kerr, 1991; Rubin, 1995). In particular, giant dike swarms (20–40 m wide, 100s–1000s of km long) are often invoked as the primary feeders to flood basalt eruptions (Ernst et al., 1995; Self et al., 1997; Coffin et al., 2006; Ray et al., 2007; Bryan and Ernst, 2008; Hooper et al., 2010). This key role of regionally extensive, collinear swarms of dikes has been further supported by thermo-mechanical modeling of large-scale intrusions (Fialko and Rubin, 1999) and geochemical links between dike swarms and overlying flood basalt lavas (Hanghøj et al., 2003).

Recent field observations, however, point to limitations in this model. Although most observations of giant dikes occur in Precambrian shields, where they are inferred to have intruded at paleodepths of 6–15 km (e.g. Proterozoic dikes of the Canadian shield: Ernst et al., 1995), sills are volumetrically dominant at shallower paleodepths (<4 km) in many flood basalt provinces. Examples include the 250 Ma Siberian Traps (Hawkesworth et al., 1995), 1.1 Ga Mid-Continental Rift, Canada (Hollings et al., 2010), and 183 Ma western Karoo igneous province, South Africa (Marsh et al., 1997; Chevallier and Woodford, 1999; Hastie et al., 2014). Seismic reflection studies by Cartwright and Hansen (2006) have also revealed interconnected sills over vertical distances of 8–12 km in the Møre and Vøring Basins, offshore Norway. These results imply that sill complexes may play a more important role in shallow magma ascent than generally considered.

However, the extent to which sills and sill-fed dikes are able to feed voluminous lava eruptions at the Earth's surface remains

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unclear (Larsen and Marcussen, 1992; Hald and Tegner, 2000; Cartwright and Hansen, 2006). For many LIPs, the sub-vertical conduits (dikes) connecting flood lavas to underlying sills have not been recognized (e.g., the 1270 Ma Mackenzie and 723 Ma Franklin LIPs: Ernst and Baragar, 1992; Bedard et al., 2012). This owes in part to a lack of preservation at relevant stratigraphic levels. Consequently, the processes controlling the upward transport of magma and the geometric relationships between sills, dikes and lavas are poorly constrained for many sill-dominated LIPs. For example, the 250 Ma Siberian LIP comprises a shallow (<5 km paleodepth) intrusive system dominated by sills (Czamanske et al., 1995; Arndt et al., 1998; Li et al., 2009). Although the intrusive and extrusive components of the system are geochemically linked (Fedorenko and Czamanske, 1997), little has been published about their physical connections. Geochemical studies demonstrate that sills formed the lateral component of the conduit system for the Siberian trap lavas (Naldrett et al., 1995). However, questions remain regarding: (1) the geometrical relationships between sills, dikes and lavas, (2) the processes driving the formation of dikes, and (3) the eruption feeding capacity of the sill-fed dike network that possibly fed the Siberian lavas.

Additional challenges in studies of sill-fed dike networks arise from the limitations of seismic reflection methods, which are key tools for visualizing the 3-D geometry of sill complexes in LIPs (e.g., Malthe-Sørensson et al., 2004; Thomson and Hutton, 2004; Hansen and Cartwright, 2006; Schofield et al., 2012a; Magee et al., 2013). For example, seismic reflection cannot discern thin (<10 m), sub-vertical structures such as dikes, which may be instrumental for transporting magma between sills and the Earth's surface in these systems. Despite these limitations, seismic reflection surveys have successfully detected volcanic constructs a few hundred meters above the lateral terminations of sills in the Ceduna basin, offshore Australia (Magee et al., 2013), and the Faeroe-Shetland basin, offshore UK (Davies et al., 2002). Geophysical studies such as these support the role of sills and sill-fed dikes in feeding eruptions, with the Ceduna examples having relatively small eruptive volumes (typically <10 km^3: Magee et al., 2013).

Here we take a novel approach to investigate the eruption-feeding capacity of sill complexes using observations from shallow (<4 km paleodepth), sill-fed intrusions of the 183 Ma Ferrar LIP, Antarctica (Encarnación et al., 1996). Previous models did not consider the role these intrusions played in feeding the overlying flood lavas (Elliot and Fleming, 2004). It is instead inferred that >100 m-thick megadikes or subparallel dike swarms transported magma upward through the shallow crust to eruption. However, to date, neither have been discovered (Elliot and Fleming, 2004, 2008). To re-examine the necessity of such regionally-extensive, subparallel dike swarms, we ask the following question – might the observed network of sill-fed dikes be responsible for bringing magma to the surface from shallow depths?

2. Review of intrusion dynamics of the Ferrar LIP

The Ferrar LIP is exposed for 3500 km along the Transantarctic Mountains (Elliot and Fleming, 2004). Post-Ferrar uplift has produced a series of tilted fault blocks, and exhumation of the Ferrar intrusions with relatively little deformation (Gleadow and Fitzgerald, 1987; Marsh, 2004). Volume estimates of the Ferrar LIP yield ~300,000 km^3 of magma (Ross et al., 2005), with dikes comprising <1% (Fig. 1). The greatest proportion of magma was emplaced as sills (170,000 km^3), while the Dufek layered mafic intrusion and Kirkpatrick flood basalts represent approximately 60,000 km^3 and 70,000 km^3 of magma, respectively (Ross et al., 2005, and references therein).

South Victoria Land, Antarctica, provides superb exposures of the shallow (<4 km paleodepth) plumbing system of the Ferrar LIP

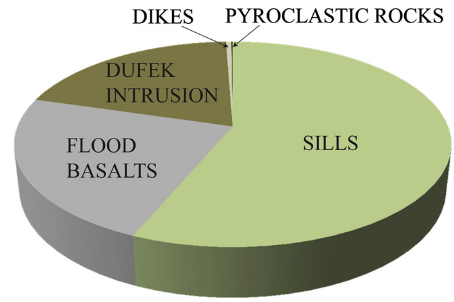


Fig. 1. Pie chart illustrating the relative volumes of the various components of the Ferrar LIP. Volume estimates from Ross et al. (2005). The inferred volume of dikes is calculated from this study.

(see Muirhead et al., 2012, for a detailed review) (Figs. 2 and 3). Up to 2000 m-high vertical exposures of interconnected dikes and sills are present over a ~10,000 km^2 area, and some sills can be traced laterally >50 km along their lengths (Marsh and Zeig, 1997; Marsh, 2004). Key areas along the Transantarctic Mountains (i.e., North Victoria Land and Central Transantarctic Mountains) exhibit similar intrusive networks, suggesting that the Ferrar LIP forms an interconnected sill network within the Beacon Supergroup along its entire length (Elliot and Fleming, 2004; Leat, 2008; Muirhead et al., 2012). In South Victoria Land, Ferrar dike intrusions are hosted by a ~2.5 km-thick sequence of sedimentary rocks (Beacon Supergroup) and volcaniclastics (Mawson Formation), and are rarely observed dissecting the underlying basement granitoids (Table 1). The Beacon Supergroup dips shallowly, 1–2° to the west (Gleadow and Fitzgerald, 1987), although significant local variations exist where strata have been buckled and tilted from the forceful intrusion of Ferrar sills (Grapes et al., 1974; Korsch, 1984; Pyne, 1984; Airoldi et al., 2011). While no regionally distributed, sub-parallel dike swarms are known (Elliot and Fleming, 2004, 2008), swarms of moderately dipping, sill-fed dikes extend from sills at a number of locations, including Coombs Hills, Mt Gran, Terra Cotta Mountain, Allan Hills, and Pearse Valley (Elliot and Fleming, 2004, 2008; White et al., 2009; Muirhead et al., 2012: Figs. 3 and 4).

Early work on intrusion mechanics of the Ferrar LIP highlighted the governing role of sills (Grapes et al., 1974; Korsch, 1984; Pyne, 1984). A later study by Wilson (1993), however, suggested that dike orientations in South Victoria Land were controlled by a far-field transtensional environment. Recent work has tested both models by combining structural analyses (White et al., 2009; Airoldi et al., 2011; Muirhead et al., 2012) and anisotropy of magnetic susceptibility (AMS) analysis of magma flow directions (Guegan, 2006; Airoldi et al., 2012). These studies point to a sill-driven model for Ferrar dike emplacement, and suggest that evidence for a far-field extensional, or trans-tensional, tectonic regime during Ferrar emplacement is lacking.

The current line of thinking is that dike intrusions in the upper 4 km of the plumbing system represent the response of the country rock to forceful intrusion of sills (Muirhead et al., 2012). Ferrar dikes are typically sandwiched between larger sills, producing stepped, dike–sill geometries (Fig. 4A). Field observations show that country rock at the lateral ends of sill segments was buckled upward (Grapes et al., 1974; Korsch, 1984; Airoldi et al., 2011: Fig. 4F), generating local extensional stresses (Johnson and Pollard, 1973; Goulty and Schofield, 2008). These stresses led to the formation of fractures that could be exploited by magma that ascended the stratigraphy before deflecting back into sills at higher stratigraphic levels (Thompson and Schofield, 2008; Airoldi et al., 2011; Muirhead et al., 2012: Fig. 4A and E). AMS studies support these assertions, demonstrating that magma was "passively" drawn into localized zones of high stress generated from underlying sills,

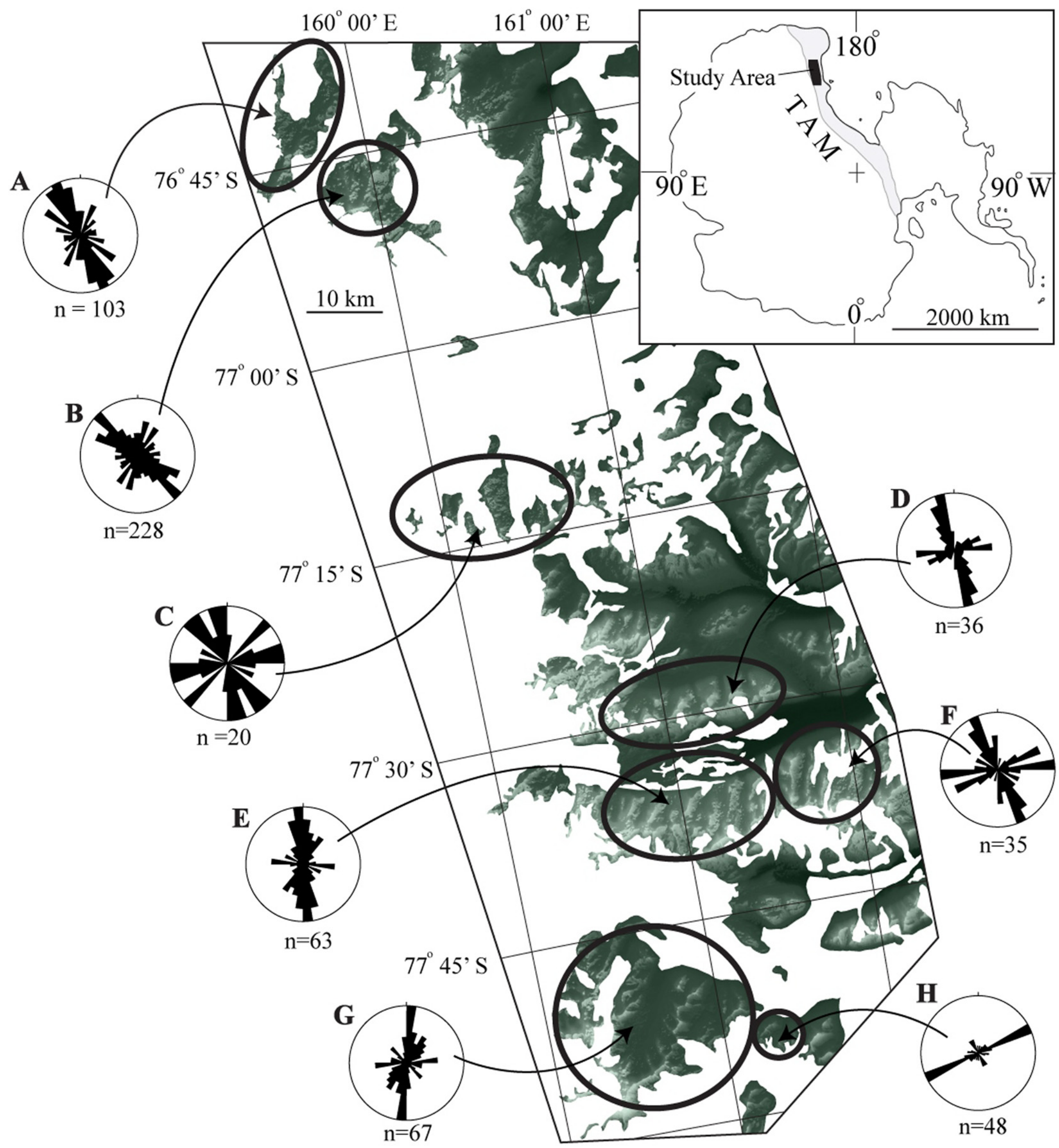


Fig. 2. DEM image of areas of South Victoria Land examined in this study. Areas of persistent ice cover are annotated white. Dikes were only examined at locations where Beacon Supergroup and/or Mawson Formation rocks are present. Rose diagrams are of dike strikes. Only areas where >20 dikes were measured are presented here, and include Allan Hills (A), Coombs Hills (B), Head Mountains (C), Olympus range (D), Asgard Range (E), Fenrir Valley (F), Beacon Heights (G), and Terra Cotta Mountain-Mt Kuipers (H). Inset (top right) shows the location of the study area in Antarctica. TAM = Transantarctic Mountains.

rather than actively forming fractures ahead of the dike tip (Airoldi et al., 2012). In these instances, advancement of the crack in front of the dike did not depend solely on magma pressures in the inflating dike tip, and subsequent widening of dike segments was enhanced by jacking-up of the crust above underlying sills (Fig. 4A and D). The proposed process of intrusion is consistent with dike and sheet formation in sill complexes elsewhere, based on field observations (Johnson and Pollard, 1973; Polteau et al., 2008), numerical simulations (Malthe-Sørenssen et al., 2004), laboratory experiments (Galland et al., 2009), and seismic reflection studies (Thomson and Hutton, 2004; Hansen and Cartwright, 2006; Thompson and Schofield, 2008; Magee et al., 2014).

In line with analogue modelling of sill-fed dike intrusions (Galland et al., 2009), Ferrar dikes exhibit a component of reverse shear along the dike plane (Muirhead et al., 2012). For example, exposures of dikes at Terra Cotta Mountain and Pearse Valley show that dikes dissected by later intrusions were uplifted on the hangingwall side (Morrison, 1989: Fig. 4E). Striated surfaces along dike margins further support a component of shear during the intrusion process (Fig. 4G), although the timing of these shearing events relative to dike emplacement is difficult to constrain (Muirhead et al., 2012). Similar kinematic models have been invoked for cone sheet intrusions on the Canary Islands (Schirnick et al., 1999), and laterally-emplaced regional dikes deflected into inclined sheets at Ardnamurchan, Scotland (Magee et al., 2012). In all, these recent insights add to a growing body of evidence that the shallowly intruded dikes of the Ferrar LIP formed under a dominantly sill-driven process.

3. Methods

To establish a regional picture of the orientations and dimensions of intrusions in South Victoria Land, we analyzed 644 sill-fed dikes, comprising a number of irregular or *en echelon* stepping segments (Appendix A). Dike lengths, widths and strikes were collected from a combination of published maps and datasets

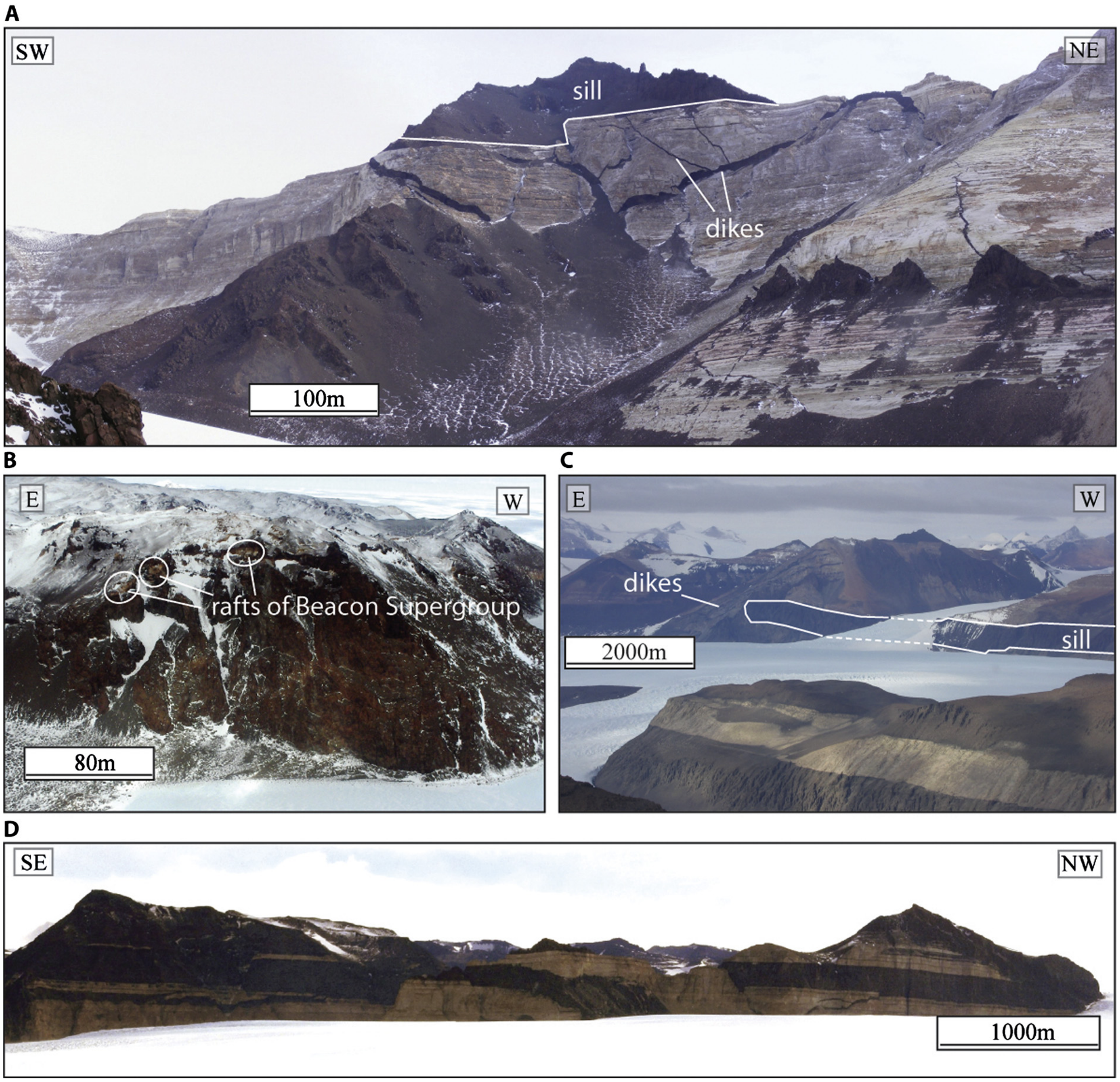


Fig. 3. Photos illustrating the shallow (<4 km paleodepth) plumbing system of the Ferrar LIP in South Victoria Land. A: Dikes at Terra Cotta Mountain ascend the stratigraphy and connect to an overlying sill. B: Exposure of a thick sill at Coombs Hills with country rock rafts near the upper contact. C: Exposures of extensive sills and dike swarms near Taylor Glacier. D: Sills intruding Beacon Supergroup rocks in the Beacon Heights region.

(Korsch, 1984; Pyne, 1984; Guegan, 2006; Airoldi et al., 2011; Muirhead et al., 2012; Cox et al., 2012) and DigitalGlobe satellite imagery (1 to 2 m-horizontal resolution) courtesy of Google Earth (Fig. 5).

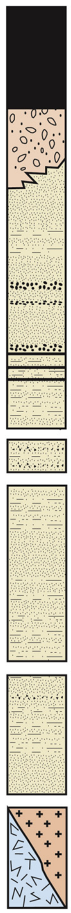
As a result of the data-mining method and the nature of the exposures, certain limitations exist in our dataset. Scree and ice cover limited traceability of ∼75% of dikes, so the reported lengths are minimum values. However, since no dikes can be traced across glaciers into neighboring nunataks, we do not expect that many intrusions exceed lengths of a few km. Dike segment widths were acquired from four previous field studies (Appendix A), and in many instances are not matched with our length data, so we were unable to calculate dike aspect ratios for most intrusions. The segment width data presented here ($n = 401$) is not as complete as the length and strike data, as true dike widths must be collected in the field. Nonetheless, the calculated 1.8 m mean width from 401 dike segments is in agreement with assertions of previous authors, estimating Ferrar dikes to be between 1 and 2 m wide (Pyne, 1984; Wilson, 1993; Ross et al., 2008).

4. Results

Dikes mapped in this study are exposed in the Beacon Supergroup and Mawson Formation over an area of 458 km^2. The dikes are broadly distributed, with mean lengths and widths of 550 m and 1.8 m, respectively (Fig. 6). Field analyses at Allan Hills and Terra Cotta Mountain (Airoldi et al., 2011; Muirhead et al., 2012) show that dikes are moderately dipping (56° mean; Fig. 6C). Where dikes form local, subparallel arrays (e.g., Allan Hills and Terra Cotta Mountain), they also exhibit common dip directions (Figs. 4B and 5F), consistent with intrusion under local, magma-induced stresses (Klausen, 2004; Muirhead et al., 2012). The complete catalogue of dike strikes shows that all orientations are well represented and, similarly, length-weighted histograms of dike strikes show a wide range of orientations (Fig. 7). A weak NNW–SSE alignment is, however, observed in the length-weighted strike data, the implications of which are discussed further in Section 5.3.

We calculate the aerial extent and volume of Ferrar dikes by first considering the ratio of dikes to country rock in the study

Table 1
Simplified stratigraphy of South Victoria Land, Antarctica. Table modified from McClintock (2001) and Airoldi et al. (2011).



Period	Supergroup	Group	Stratigraphic Unit	Description	Max. Thickness
Jurassic		Ferrar Group	Kirkpatrick Basalt	Basalt lava flows and pillow-palagonite breccias, with intercalated Mawson Formation and Beacon Supergroup deposits	380
Jurassic		Ferrar Group	Ferrar Dolerite	Tholeitic sills, dikes and localized sheet swarms	
Jurassic		Ferrar Group	Mawson Formation	Heterolithic, poorly - to unbedded basaltic tuff-breccia and lapilli-tuff, minor bedded lapilli-tuff and tuff. Widespread peperite, hyaloclastite and swirly dikes	400+
Triassic	BEACON SUPERGROUP	Victoria Group	Lashly Formation	Arkosic and volcaniclastic sandstone, greenish grey and grey siltstone. Roots and stems are common in the lower part	520+
Permian	BEACON SUPERGROUP	Victoria Group	Feather Conglomerate	Quartz pebble conglomerate, quartzose and arkose sandstone, siltstone and grit	220
Permian	BEACON SUPERGROUP	Victoria Group	Weller Coal Measures	Quartzose and minor arkosic sandstone and minor carbonaceous siltstone. Pebbles and boulders appear scattered and in lenses. Coal, logs and stems in the upper part	250
Permian	BEACON SUPERGROUP	Victoria Group	Meschel Tillite	Tillite, conglomerate, sandstone and siltstone. Locally slump-folded	70
Devonian	BEACON SUPERGROUP	Taylor Group	Aztec Siltstone	Siltstone and sandstone. Fish fossils, plant roots, mudcracks and ripplemarks are common	220
Devonian	BEACON SUPERGROUP	Taylor Group	Beacon Heights Orthoquartzite	Indurated quartz and arenites with occasional quartz grit lenses. Rare lycopod stems	340
Devonian	BEACON SUPERGROUP	Taylor Group	Arena Sandstone	Quartz arenites and siltstone, ferruginous layers, burrows and trails	360
Devonian	BEACON SUPERGROUP	Taylor Group	Altar Mountain Formation	Sandstone, siltstone and subarkose. Burrows and trails	240
Devonian	BEACON SUPERGROUP	Taylor Group	New Mountain Sandstone	Quartzose sandstone with minor siltstone, breccia, conglomerate and fossils	270
Devonian	BEACON SUPERGROUP	Taylor Group	Terra Cotta Siltstone	Siltstone with interbedded sandstone layers	60
Devonian	BEACON SUPERGROUP	Taylor Group	Windy Gully Sandstone	Pebbly quartzose sandstone	50
Cambrian-Ordivician		Basement	Granite Harbour Intrusives	Undifferentiated granitoids	
Cambrian-Ordivician		Basement	Skelton Group	Upper amphibolite facies metasediments	

area. The 595 dikes mapped in plan view represent a combined aerial extent of 0.56 km^2. This gives an average dike to country rock ratio of 1:815. Applying the same ratio over the full extent of the Ferrar province (3000 × 150 km: Ross et al., 2005), we infer that Ferrar dikes covered a total area of 550 km^2, corresponding to a volume of 1380 km^3 within the 2.5 km-thick Beacon Supergroup and Mawson Formation host rocks. For comparison, a single fissure of equivalent size would be 3000 km long × 184 m wide, or, using the mean width of 1.8 m, a cumulative dike network totaling 308,000 km in length.

5. Discussion

5.1. Did the inferred Ferrar dike-fissure network feed the flood basalts?

Two basic conditions must be met to conclude that sill-fed dikes of the Ferrar large igneous province fed flood basalt lavas: (1) the intrusions must have extended all the way to the surface; and (2) the size of the network must be sufficient to erupt the 70,000 km^3 of flood lavas on a reasonable timescale.

Tracing subsurface dikes vertically to the surface is challenging in the Ferrar, due to rare exposure of the basal contact of the Kirkpatrick lavas. However, a close kinship is observed between Ferrar dikes and volcanic rocks of the Mawson Formation (McClintock and White, 2006). Shallowly intruded sills and sill-fed dikes at Coombs Hills and Shapeless Mountain transition at their lateral ends into intrusive tuff breccias (Korsch, 1984; Elliot and Grimes, 2011), indicating that these sill-fed dikes did indeed feed surface eruptions (Gunn and Warren, 1962; McClintock and White, 2006; Airoldi et al., 2011; Elliot and Grimes, 2011). Furthermore, our study reveals that the dike to country rock ratio remained constant as intrusions ascended toward the surface. This is shown in the Coombs-Allan Hills region (∼800–0 m paleodepth: Ross et al., 2008), where the dike to country rock ratio of 1:880 is comparable with the mean value of 1:815. Consequently, we suggest it would be unreasonable to assume that the sill-fed dike network terminated abruptly only a few tens of meters below the paleosurface. Lastly, in areas exhibiting evidence for extensive volcanism, such as nested diatremes, mafic pyroclastic density currents, fall deposits, and basalt lavas (e.g. Coombs Hills and Allan Hills: White and McClintock, 2001; Ross and White, 2005; McClintock and White, 2006; Ross et al., 2008), the shallow plumbing system is dominated by sill-fed dikes; no other potential feeders are recognized. We suggest that, until competing shallow dike-feeders are discovered throughout the Ferrar LIP, it is fair to assume that the sill-fed dike network locally extended all the way to the surface.

A relatively simple approach may be taken to address criterion (2), the feeding capacity of the sill-fed dike network. We apply a reasonable lava effusion rate to the cumulative dike network (308,000 km long), to establish the time required to produce the 70,000 km^3 Kirkpatrick flood basalts. This method has been similarly applied to dike-feeder systems of the Deccan province (Ray et al., 2007). Lava effusion rates are taken from the 1873–74 eruption of Laki, Iceland, which produced 14.7 ± 1.0 km^3 of lava, representing the most voluminous basaltic lava eruption of historic time.

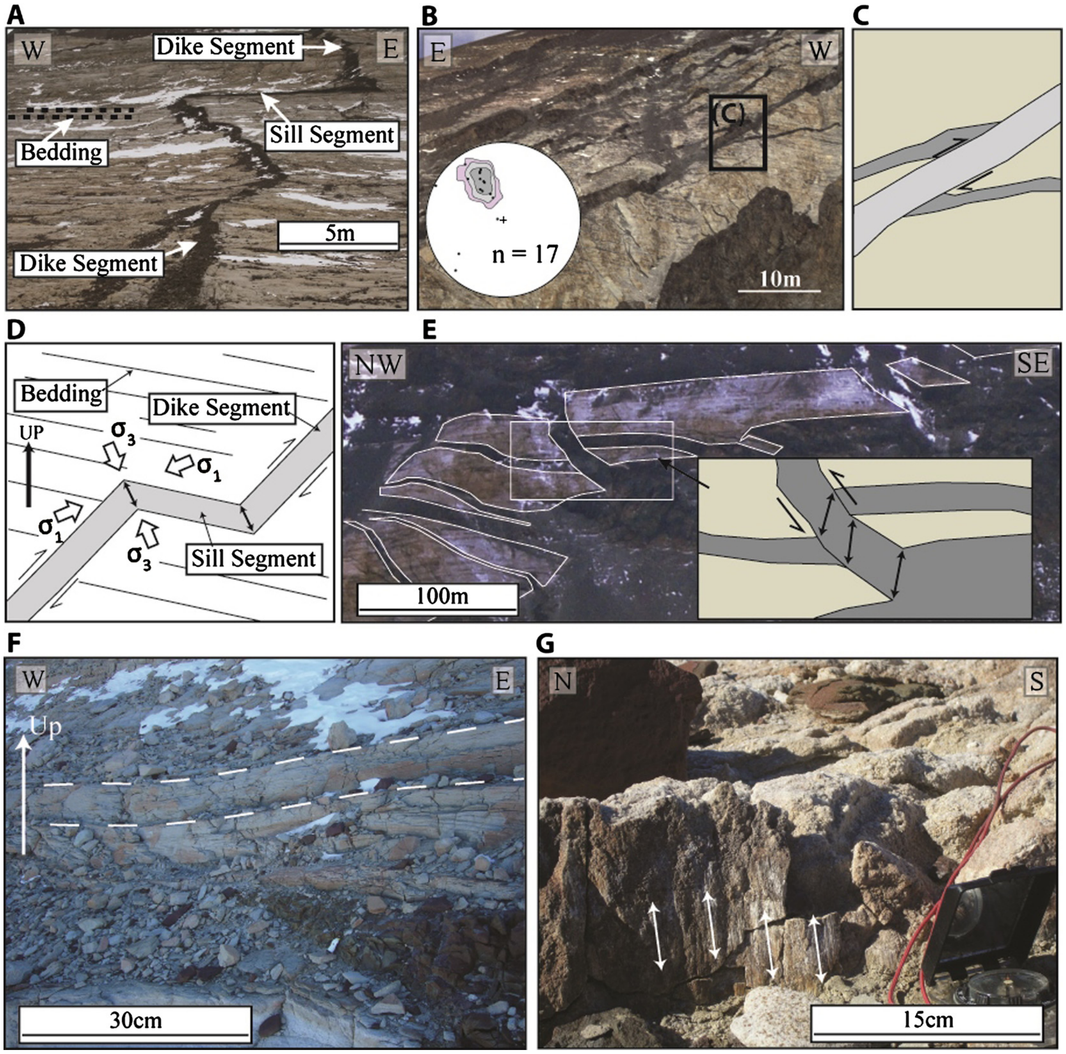


Fig. 4. A: Stepped dike–sill geometry at Allan Hills. B: Moderately inclined dikes on the northern slopes of Terra Cotta Mountain (photo courtesy of Tony Reay). Contour plot of poles to dike planes from Muirhead et al. (2012). C: Schematic of cross-cutting dikes highlighted in B. Half arrows indicate the inferred sense of shear given the offset accrued on the early intruded dike (dark grey). D: Simplified kinematic model after Muirhead et al. (2012) for stepped dike–sill intrusions. Opening normal to both the sill and dike results in a dilation vector (double sided arrow) oblique to both the dike and sill plane, and a component of reverse shear along the dike plane (half arrows). Bold white arrows show the inferred local orientations the least (σ_3) and greatest (σ_1) compressive stresses. E: Photo of intrusions seen from Pearse Valley. Moderately inclined dikes extend from a sill periphery into an overlying sill. Inset illustrates dike kinematics inferred from cross-cutting relationships between dikes. F: Folded strata at the lateral termination of a sill segment. G: Mineral striations on a dike selvage at Allan Hills. Double sided arrows indicate the orientation of the striations.

During this eruption, which lasted 8 months, lava erupted during discrete events on individual dike-fissure segments that were active for weeks to months at a time (Thordarson et al., 1996), with maximum effusion rates of $\sim 2\ m^3\,s^{-1}$ per meter length of fissure (Self et al., 1997). After a few days to weeks of activity, lava effusion on each individual segment reduced and focused on a few point sources (central magma conduits) along the fissures. In some respects, flood basalt eruptions represent scaled-up versions of these basaltic fissure eruptions (Bryan and Ferrari, 2013). Individual flood basalt lavas erupt for years to decades at a time (Self et al., 1997), providing constraints on the timescales over which lavas may be fed from individual feeder dikes. Activity across the entire fissure network occurs over 10^5–10^6 years (Ray et al., 2007; Bryan and Ferrari, 2013), with decades-long eruptions alternating with tens to hundreds of millenia of inactivity. Assigning a conservative lava effusion rate of $1\ m^3\,s^{-1}$ per meter of dike-feeder length in the Ferrar LIP (i.e., mean effusion rates for Kilauea: Self et al., 1997), each individual segment (10^2–10^3 m long) of the 308,000 km-long, dike-feeder system requires an average of only 2 to 3 days of activity to cumulatively produce the volume of the Kirkpatrick basalts over the timescale of Ferrar LIP emplacement ($\sim 10^6$ years: Heimann et al., 1994). Given that individual fissure segments in large-scale basaltic eruptions are observed and theoretically demonstrated to have eruptive durations of 2–3 weeks (Thordarson et al., 1996; Thordarson and Self, 1998), we conclude that it is very likely the Ferrar dike network transported magma upward to eruption throughout the area of its shallow plumbing system to feed the Kirkpatrick flood lavas.

5.2. Additional ascent through conduits and roof collapse

In addition to the dike network, volcanic plugs observed at Coombs Hills, Allan Hills, and Shapeless Mountain have been highlighted as potential feeders to the flood basalts (Korsch, 1984; Reubi et al., 2005; Ross et al., 2008). We concur that these plugs represent complex conduit structures that could have contributed to upward magma transport at shallow depths. They are probably sites where magma flow in dikes localized into point sources (e.g. Delaney and Pollard, 1982), which were enhanced at dike intersections (cf. Appendix 1 of Korsch, 1984). Furthermore, large tilted blocks (up to 500 m in diameter), interpreted by White et al. (2009) as fragmented sill roofs, have been observed “floating”

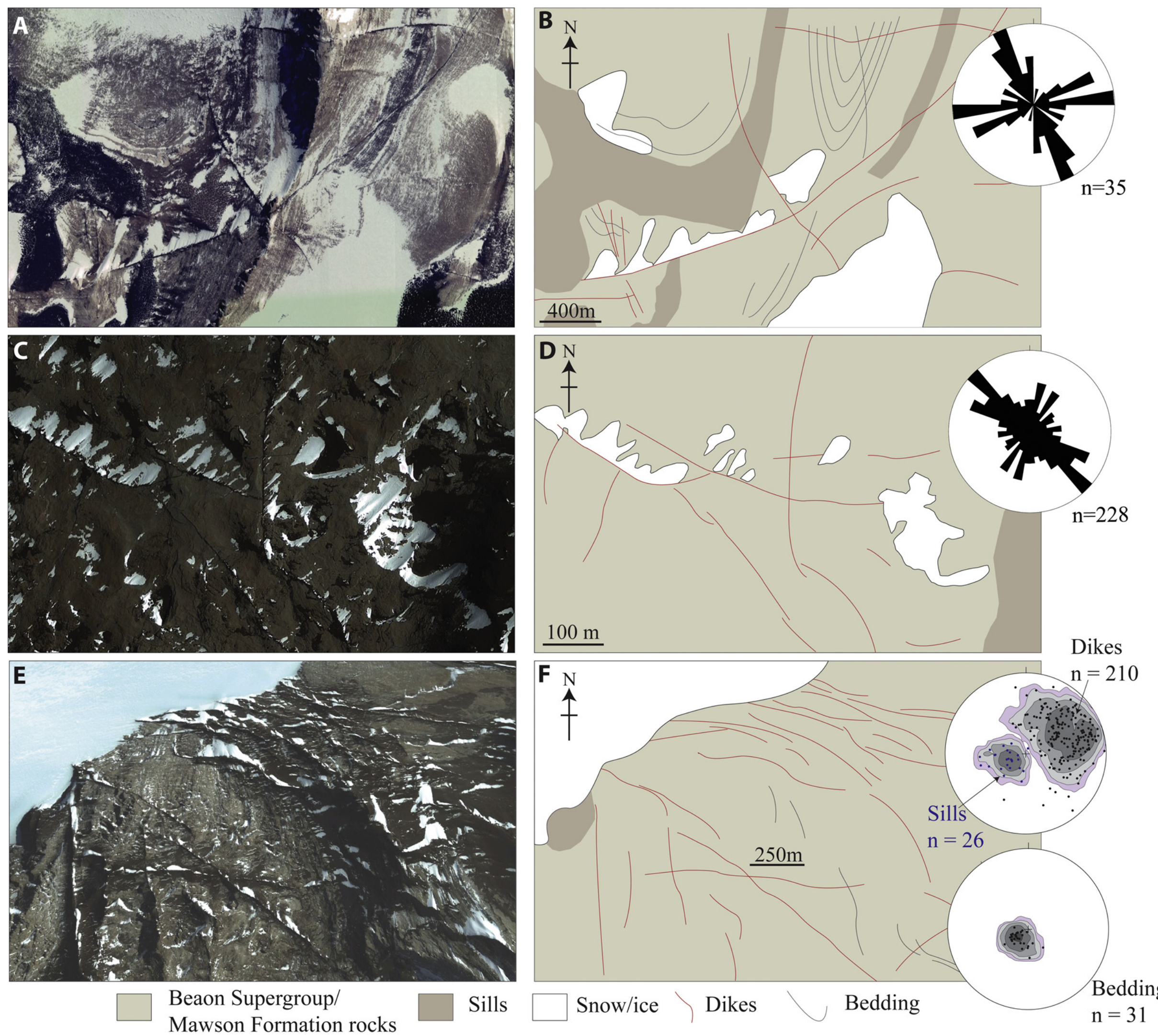


Fig. 5. Google Earth images of Ferrar dikes intruding Beacon Supergroup and Mawson Formation rocks in South Victoria Land. A: Plan-view image of dikes in Fenrir Valley. B: Simplified schematic of A. Rose diagram is of measured dike strikes in Fenrir Valley from this study. C: Plan-view image of dikes at Coombs Hills. D: Simplified schematic of C. Rose diagram is of measured dike strikes at Coombs Hills from this study. E: Oblique aerial view of a sub-parallel swarm of moderately dipping dikes at Allan Hills. F: Simplified schematic of E. Contour plots are of poles to dike, sill, and bedding planes collected in the field by Muirhead et al. (2012). Note the moderate dip of the dikes as well as the common dip direction.

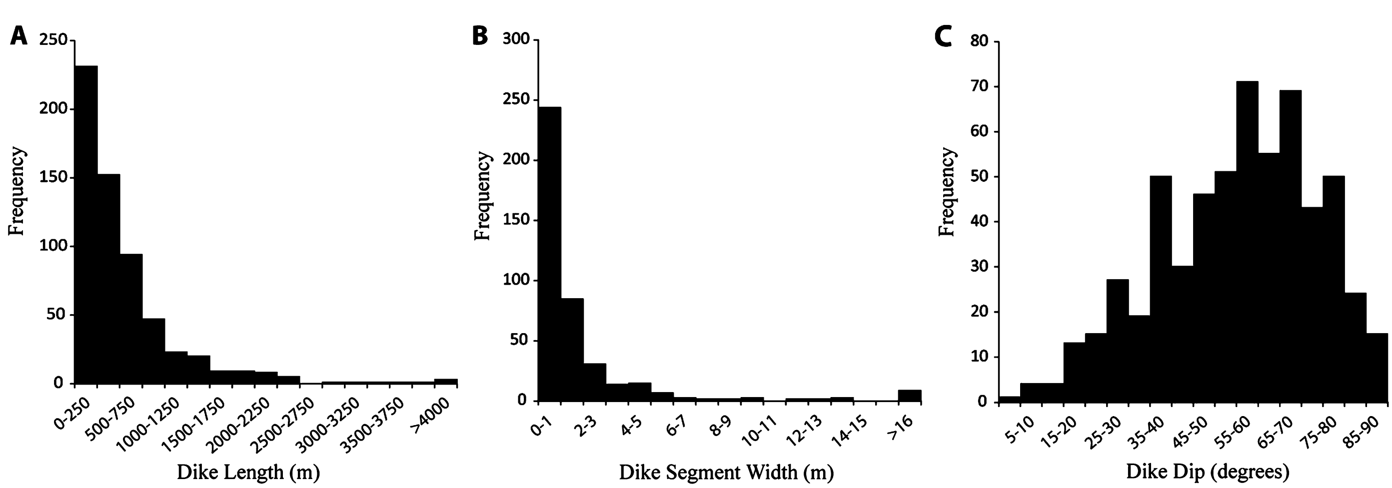


Fig. 6. A: Frequency histogram of dike lengths measured in this study. B: Frequency histogram of measured dike segments. C: Frequency histogram of dike dips.

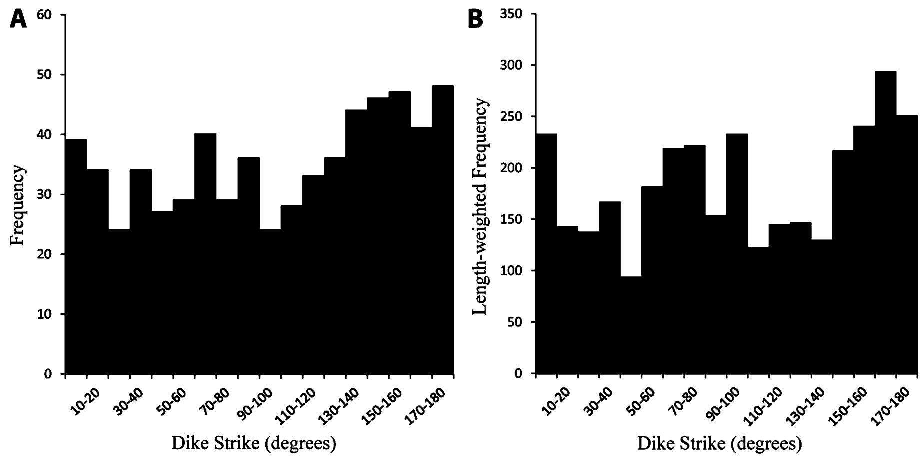


Fig. 7. A: Frequency histogram of dike strikes measured in this study. B: Length-weighted frequency histogram (100 m corresponds to a value of 1) of dike strikes.

in shallow sills that intruded a few hundred meters from the paleosurface (Fig. 3B). Based on these observations, White et al. (2009) suggest that wholesale breakup of country rock occurred at some localities above shallowly intruded sills. The model presented here (Fig. 8) is complementary to this hypothesis, as a variably oriented, crosscutting network of dikes extending vertically from a shallow sill to the surface, or an overlying partially molten sill, is expected to isolate domains of country rock, which can then be engulfed in magma. The domains of country rock described by White et al. (2009) may, however, represent "bridges" that became isolated as adjacent sill segments coalesced (Hutton, 2009; Scholfied et al., 2012a). The isolated blocks observed in Ferrar sills, up to 500 m in diameter, are an order of magnitude larger than broken bridges observed in shallow sills elsewhere (e.g. Theron Mountains, Antarctica: Hutton, 2009).

5.3. *The cracked lid: an end-member feeder style for flood basalt volcanism*

The observed dike network of the Ferrar is at odds with the traditional model of shallow magma ascent invoked for many LIPs, which involve subparallel swarms of large, steep dikes (>100 km long, 20–40 m wide, >75° dip) (Ernst et al., 1995; Ray et al., 2007; Bryan and Ernst, 2008). In contrast, the Ferrar's sill-fed dikes form a broadly-distributed array of smaller, moderately dipping intrusions (<2 km long, 1.8 m wide, 56° mean dip) of any orientation. Although a very weak NNW–SSE trend is present in the length-weighted strike data (Fig. 7), it is significantly weaker than those produced by dikes forming in extensional tectonic regimes in magmatic rifts (e.g., Tertiary rifts of Iceland: Gudmundsson, 1995, 2002) or giant dike systems (e.g., Okavango and Lembobo dike swarms; Aubourg et al., 2008; Klausen, 2009). Rather, Ferrar dike orientations have similarities to dike networks that intruded into isotropic stress regimes, such as the Nasik-Pune swarm of the 66 Ma Deccan Province, India (Hooper, 1990; Vanderkluysen et al., 2011), and dikes of the Navajo volcanic field, USA (Laughlin et al., 1986). These observations imply that a regional extensional stress regime did not influence the orientations of Ferrar dikes at shallow paleodepths (<4 km).

This conclusion is in line with recent studies addressing the controls on Ferrar dike formation (White et al., 2009; Airoldi et al., 2011, 2012; Muirhead et al., 2012). These studies have dismissed shallow dike emplacement as part of a far-field extensional stress regime based on (1) the predominance of Ferrar sills and sill-fed dikes, (2) the moderate dips (∼50° mean) exhibited by dikes, and (3) the lack of steeply dipping, subparallel dike swarms. Instead,

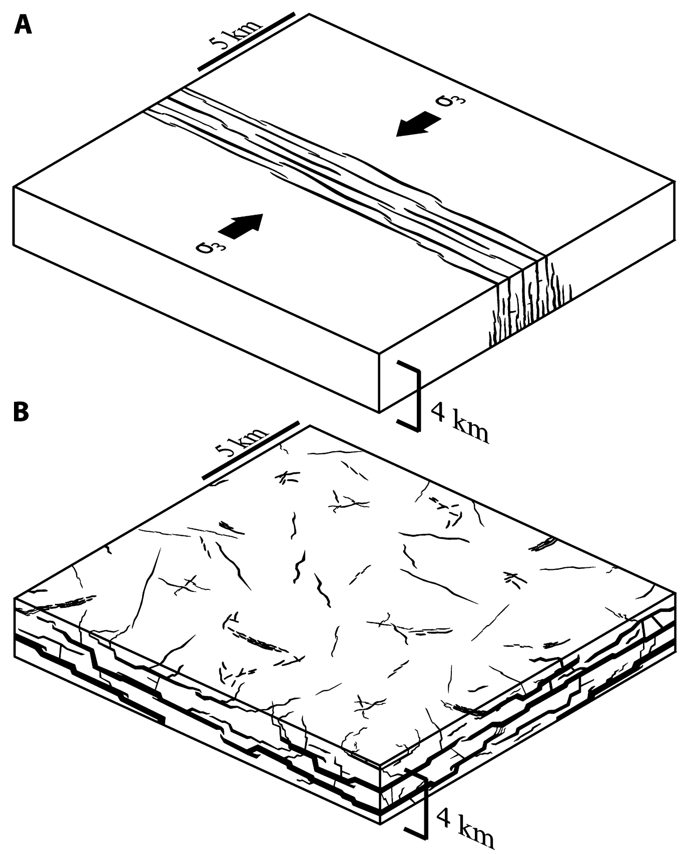


Fig. 8. Schematic illustration of end-member, shallow (<4 km depth) feeder systems for flood basalt provinces. A: Long, subparallel aligned dikes oriented perpendicular to a far-field least compressive stress direction. Note that on the scale of a craton (i.e. 1000 s of km), swarms like these can also form a radial pattern (Ernst et al., 1995). B: The cracked lid model. Short dikes of almost any orientation overlie a network of sills.

dikes at Allan Hills, Coombs Hills and Terra Cotta Mountain appear to have been emplaced into a local magmatic stress regime, with dikes forming at the propagation fronts of sills. We therefore suspect that the weak NNW–SSE trend in Ferrar dike orientations represents a common process related to sill formation, such as a preferred propagation direction (White et al., 2005).

This sill-driven, dike feeder system creates a remarkable scene in plan view, resembling a variably "cracked lid" overlying a sill network (Fig. 8). We propose that this cracked lid model represents an end-member example of a flood basalt feeder system, where the effects of far-field tectonic stresses are negligible and sill intrusions exert the dominant control on dike orientations.

5.4. When does the cracked lid arise?

The cracked lid may be the archetypal model for shallow feeder systems of LIPs that intruded sedimentary basins where the influence of any far-field extensional tectonics is negligible. Seismically observed, sill-dominated LIPs intrude sedimentary basins in offshore Australia (Magee et al., 2013; Rohrman, 2013), Norway (Thomson and Hutton, 2004; Cartwright and Hansen, 2006; Thomson and Schofield, 2008) and Senegal (Hansen et al., 2008). The processes governing dike formation in these provinces are strikingly similar to those inferred for the Ferrar sill-fed dikes. For example, shallowly dipping, concentric dikes of any orientation extend from the peripheries of sills and form in response to sill-roof uplift (Thomson and Hutton, 2004). Observations of sill-fed dikes in seismically observed LIPs are, however, restricted to thicker (>10 m), shallowly dipping (<40°) intrusions. Thus, the distribution and geometry of thinner dikes (<10 m) comprising the vertical component of these feeder systems cannot be easily resolved. Nonetheless, the similarity in dike formation processes combined with the abundance of sills in seismically observed LIPs suggests that a cracked lid feeder system may be present in many of these provinces.

Despite the geometric similarities between the Ferrar plumbing system and sill complexes generally, many seismic reflection studies reveal the presence of "intrusive LIPs" that are not demonstrated to have fed voluminous outpourings of flood lavas (Rohrman, 2013). Further, it is common for seismically imaged sill complexes to be coupled with extrusive components that have small eruptive volumes, such as the Ceduna Sub-basin, offshore Australia, where edifice volumes are typically <10 km^3 (Magee et al., 2013).

Given that many sill complexes do not erupt significant lava volumes, why did sills and sill-fed dikes of the Ferrar LIP lead to eruption of a flood basalt province? Rohrman (2013) demonstrates that, as magma ascends sedimentary basins, decreasing sediment densities produce a corresponding decrease in magma overpressure gradients. Consequently, if a sedimentary sequence is sufficiently thick magma ascent will terminate. Compared to intrusive LIPs observed in seismic reflection surveys (e.g., Rockall Basin, offshore United Kingdom: Thomson and Hutton, 2004), which are known to have been emplaced in basinal sedimentary successions as thick as 12 km (Cartwright and Hansen, 2006), intrusions of the Ferrar LIP traversed only a relatively thin sequence of sedimentary rocks (∼2.5 km) and, as a consequence, breached the surface to feed flood basalt eruptions. This basic observation supports the assertion of Rohrman (2013) that sedimentary basin thickness has a first-order control on the eruptive capacity of a sill complex. In addition to basin thickness, the vertical ascent of magma within sill complexes will also be affected by magma buoyancy, source pressure and solidification, and by the physical properties of the host rock, such as density, rigidity contrasts, pre-existing structures, fluid pressure, and rheology (Kavanagh et al., 2006; Thomson, 2007; Schofield et al., 2012b; Le Corvec et al., 2013; Chanceaux and Menand, 2014; Kavanagh and Pavier, 2014; Krumbholz et al., 2014).

An ideal field location to compare and contrast the controls on magma ascent in the Ferrar LIP is the contemporaneously emplaced dikes and sills of the western Karoo basin (Encarnación et al., 1996; Marsh et al., 1997; Chevallier and Woodford, 1999; Schofield et al., 2010). The intrusive pattern in the western Karoo is similar to that observed in the Ferrar LIP, exhibiting widespread sills and an arrangement of dikes that to some degree mimic the cracked lid pattern described in this study (Marsh et al., 1997; Chevallier and Woodford, 1999; Fig. 8). However, compared to the Ferrar LIP, the Karoo Province records a protracted magmatic/tectonic history (∼183–174 Ma) and the geometry of the shallow plumbing exhibits greater structural complexity (Hastie et al., 2014). Although dikes are observed extending from sill peripheries in the western Karoo basin, imposed on this dike–sill network are broadly distributed (200 to >400 km wide) NW-SE striking dikes, indicating a zone of right-lateral shear (Chevallier and Woodford, 1999). Additionally, long, collinear dike swarms extend along the northern and eastern boundary of the Kaapvaal Craton and appear to form a triple junction (Aubourg et al., 2008; Klausen, 2009; Hastie et al., 2014). Consequently, linking specific dike-feeder systems with Karoo flood basalts is challenging. Geochemical analyses by Galerne et al. (2008) demonstrate a close kinship between the saucer-shaped, Golden Valley Sill and the earliest erupted Lesotho lavas. However, it is yet to be determined whether or not flood lavas of the Karoo LIP were primarily fed by a sill-fed dike system exhibiting a cracked lid pattern, rather than regionally extensive, collinear dike swarms.

5.5. Applications to active volcanic systems

Although larger in scale than any of today's active mafic volcanic systems, intrusions of the Ferrar LIP highlight the influence of sills on upward magma transport, with potential implications for hazard forecasting. Models of shallow, sill-assisted dike intrusion (Johnson and Pollard, 1973; Polteau et al., 2008) diverge from classic depictions of ascending magma (Anderson, 1951), where upward (or lateral) propagation of a dike requires that magma pressure in the dike exceeds the regional least compressive stress. In a shallow, interconnected sill–dike network, sill inflation may promote the ascent of magma in dikes, by creating localized zones of extension at the sill periphery and assisting opening of the dike walls as the sill inflates (Johnson and Pollard, 1973; Goulty and Schofield, 2008; Galland et al., 2009). In these systems, the timing and location of volcanic eruptions may be related to sill inflation/deflation events. Field observations from the Ferrar LIP reveal a shallow magma system composed of complex, interconnected dike–sill geometries, one in which dikes often emanate from the lateral ends of sills (Muirhead et al., 2012; Fig. 4). Given these basic geometric relations we assert that, during Ferrar magmatism, ground deformation related to sill inflation may have been laterally offset from eruption sites. These interpretations are in line with InSAR deformation studies of recent eruptions (e.g., 2004 Asama eruption (Japan), 2005 Fernandina eruption (Galapagos): Chadwick et al., 2011; Aoki et al., 2013), experimental modelling of magmatic intrusions (Galland et al., 2009; Galland, 2012), seismic reflection observations of sills in the Ceduna basin, offshore Australia (Magee et al., 2013), and field observations in monogenetic basaltic fields (Bakony-Balaton Highland Volcanic Field, Hungary: Nemeth and Martin, 2007), where eruption sites occur above the lateral terminations of sills rather than above the sill center.

6. Conclusions

This study is the first to catalogue the dimensions and distribution of regionally exposed sill-fed dike intrusions of the Ferrar LIP in South Victoria Land, Antarctica. Dikes of the Ferrar LIP formed an aerially extensive dike network, with a cumulative length of 308,000 km. Applying reasonable effusion rates to this shallow dike system, we demonstrate that each individual segment of this feeder array could have been active for as little as 2 to 3 days to produce the volume of the Kirkpatrick flood lavas. The observed sill-fed dike network of the Ferrar LIP is at odds with the traditional model of magma ascent invoked for many LIPs, and resembles a variably "cracked lid" atop a sill network. The cracked lid may be the archetypal model for shallow feeder systems of LIPs that intruded sedimentary basins where the influence of far-field extensional tectonics is negligible. This study reveals that shallow magma systems composed dominantly of sills are capable of feeding voluminous outpourings of lava, and highlights the important role sills likely play in feeding active volcanic system.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.08.036.

References

Airoldi, G., Muirhead, J.D., White, J.D.L., Rowland, J., 2011. Emplacement of magma at shallow depth: insights from field relationships at Allan Hills, south Victoria Land, East Antarctica. Antarct. Sci. 23, 281–296.

Airoldi, G., Muirhead, J.D., Zanella, E., White, J.D.L., 2012. Emplacement process of Ferrar Dolerite sheets at Allan Hills (South Victoria Land, Antarctica) inferred from magnetic fabric. Geophys. J. Int. 188, 1046–1060.

Anderson, E.M., 1951. The Dynamics of Faulting and Dyke Formation with Applications to Britain. Oliver and Boyd, Edinburgh.

Aoki, Y., Takeo, M., Ohminato, T., Nagaoka, Y., Nishida, K., 2013. Magma pathway and its structural controls of Asama Volcano, Japan. Geol. Soc. (Lond.) Spec. Publ. 380, 67–84.

Arndt, N., Chauvel, C., Czamanske, G., Fedorenko, V., 1998. Two mantle sources, two plumbing systems: tholeiitic and alkaline magmatism of the Maymecha River basin, Siberian flood volcanic province. Contrib. Mineral. Petrol. 133, 297–313.

Aubourg, C., Tshoso, G., Le Gall, B., Bertrand, H., Tiercelin, J.J., Kampunzu, A.B., Dyment, J., Modisi, M., 2008. Magma flow revealed by magnetic fabric in the Okavango giant dyke swarm, Karoo igneous province, northern Botswana. J. Volcanol. Geotherm. Res. 170, 247–261.

Bedard, J.H., Naslund, H.R., Nabelek, P., Winpenny, A., Hryciuk, M., Macdonald, W., Hayes, B., Steigerwaldt, K., Hadlari, T., Rainbird, R., Dewing, K., Girard, E., 2012. Fault-mediated melt ascent in a Neoproterozoic continental flood basalt province, the Franklin sills, Victoria Island, Canada. Bull. Geol. Soc. Am. 124, 723–736.

Bryan, S.E., Ernst, R.E., 2008. Revised definition of large igneous provinces (LIPs). Earth-Sci. Rev. 86, 175–202.

Bryan, S.E., Ferrari, L., 2013. Large igneous provinces and silicic large igneous provinces: progress in our understanding over the last 25 years. Bull. Geol. Soc. Am. 125, 1053–1078.

Cartwright, J., Hansen, D.M., 2006. Magma transport through the crust via interconnected sill complexes. Geology 34, 929–932.

Chadwick, W.W., Jonsson, S., Geist, D.J., Poland, M., Johnson, D.J., Batt, S., Harpp, K.S., Ruiz, A., 2011. The May 2005 eruption of Fernandina volcano, Galapagos: the first circumferential dike intrusion observed by GPS and InSAR. Bull. Volcanol. 73, 679–697.

Chanceaux, L., Menand, T., 2014. Solidification effects on sill formation: an experimental approach. Earth Planet. Sci. Lett. 403, 79–88.

Chevallier, L., Woodford, A., 1999. Morpho-tectonics and mechanisms of emplacement of the dolerite rings and sills of the western Karoo, South Africa. S. Afr. J. Geol. 102, 43–54.

Coffin, M.F., Duncan, R.A., Eldholm, O., Fitton, J.G., Frey, F.A., Larson, H.C., Mahoney, J.J., Saunders, A.D., Schlich, R., Wallace, P.J., 2006. Large igneous provinces and scientific ocean drilling. Oceanography 19, 150–160.

Cox, S.C., Turnbull, I.M., Isaac, M.J., Townsend, D.B., Smith Lyttle B., 2012. Geology of southern Victoria Land, Antarctica. Institute of Geological & Nuclear Sciences geological map 22, scale 1:250 000, 1 sheet.

Czamanske, G.K., Zen'ko, T.E., Fedorenko, V.A., Calk, L.C., Budahn, J.R., Bullock Jr., J.H., Fries, T.L., King, B.S., Siems, D.F., 1995. Petrography and geochemical characterization of ore-bearing intrusions of the Noril'sk type, Siberia; with discussion of their origin. Res. Geol. (Spec. Issue) 18, 1–48.

Davies, R., Bell, B.R., Cartwright, J.A., Shoulders, S., 2002. Three-dimensional seismic imaging of Paleogene dike-fed submarine volcanoes from the northeast Atlantic margin. Geology 30, 223–226.

Delaney, P.T., Pollard, D.D., 1982. Solidification of basaltic magma during flow in a dike. Am. J. Sci. 282, 856–885.

Elliot, D.H., Fleming, T.H., 2004. Occurrence and dispersal of magmas in the Jurassic Ferrar Large Igneous Province, Antarctica. Gondwana Res. 7, 223–237.

Elliot, D.H., Fleming, T.H., 2008. Physical volcanology and geological relationships of the Jurassic Ferrar Large Igneous Province, Antarctica. J. Volcanol. Geotherm. Res. 172, 20–37.

Elliot, D.H., Grimes, C.G., 2011. Triassic and Jurassic strata at Coombs Hills, south Victoria Land: stratigraphy, petrology and cross-cutting breccia pipes. Antarct. Sci. 23, 268–280.

Encarnación, J., Fleming, T.H., Elliot, D.H., Eales, H.V., 1996. Synchronous emplacement of Ferrar and Karoo dolerites and the early break-up of Gondwana. Geology 24, 535–538.

Ernst, R.E., Baragar, W.R.A., 1992. Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Nature 356, 511–513.

Ernst, R.E., Head, J.W., Parfitt, E., Grosfils, E., Wilson, L., 1995. Giant radiating dyke swarms on Earth and Venus. Earth-Sci. Rev. 39, 1–58.

Fedorenko, V.A., Czamanske, G.K., 1997. Results of new field and geochemical studies of the volcanic and intrusive rocks of the Maymecha-Kotuy area, Siberian flood-basalt province, Russia. Int. Geol. Rev. 39, 479–531.

Fialko, Y.A., Rubin, A.M., 1999. Thermal and mechanical aspects of magma emplacement in giant dyke swarms. J. Geophys. Res. 104, 23033–23049.

Galerne, C.Y., Neumann, E.R., Planke, S., 2008. Emplacement mechanisms of sill complexes: information from the geochemical architecture of the Golden Valley sill complex, South Africa. J. Volcanol. Geotherm. Res. 177, 425–440.

Galland, O., 2012. Experimental modelling of ground deformation associated with shallow magma intrusions. Earth Planet. Sci. Lett. 317, 145–156.

Galland, O., Planke, S., Neumann, E.R., Malthe-Sorenssen, A., 2009. Experimental modelling of shallow magma emplacement: application to saucer-shaped intrusions. Earth Planet. Sci. Lett. 277, 373–383.

Gleadow, A.J.W., Fitzgerald, P.G., 1987. Uplift history and structure of the Transantarctic Mountains – new evidence from fission-track dating of basement apatites in the Dry Valleys area, southern Victoria Land. Earth Planet. Sci. Lett. 82, 1–14.

Goulty, N.R., Schofield, N., 2008. Implications of simple flexure theory for the formation of saucer-shaped sills. J. Struct. Geol. 30, 812–817.

Grapes, R.H., Reid, D.L., McPherson, J.G., 1974. Shallow dolerite intrusion and phreatic eruptions in the Allan Hills region, Antarctica. N.Z. J. Geol. Geophys. 17, 563–577.

Gudmundsson, A., 1995. Infrastructure and mechanics of volcanic systems in Iceland. J. Volcanol. Geotherm. Res. 64, 1–22.

Gudmundsson, A., 2002. Emplacement and arrest of sheets and dykes in central volcanoes. J. Volcanol. Geotherm. Res. 116, 279–298.

Guegan, E.B.M., 2006. Shallow Intrusion Conditions in a Flood-Basalt Province; the Story from Dykes and a Sill Offshoot Along the Contact Between a Vent Complex and Country Rock. University of Otago, Dunedin, p. 187.

Gunn, B.M., Warren, G., 1962. Geology of Victoria Land between the Mawson and Mulock Glaciers, Antarctica. N. Z. Geol. Surv. Bull. 71, 1–157.

Hald, N., Tegner, C., 2000. Composition and age of tertiary sills and dykes, Jameson Land Basin, East Greenland: relation to regional flood volcanism. Lithos 54, 207–233.

Hanghøj, K., Storey, M., Stecher, O., 2003. An isotope and trace element study of the East Greenland dyke swarm. J. Petrol. 44, 2081–2112.

Hansen, D.M., Cartwright, J., 2006. The three-dimensional geometry and growth of forced folds above saucer-shaped igneous sills. J. Struct. Geol. 28, 1520–1535.

Hansen, D.M., Redfern, J., Federici, F., Di Biase, D., Bertozzi, G., 2008. Miocene igneous activity in the Northern Subbasin, offshore Senegal, NW Africa. Mar. Pet. Geol. 25, 1–15.

Hastie, W.W., Watkeys, M.K., Aurbourg, C., 2014. Magma flow in dyke swarms of the Karoo LIP: implications for the mantle plume hypothesis. Gondwana Res. 25, 736–755.

Hawkesworth, C.J., Lightfoot, P.C., Fedorenko, V.A., Blake, S., Naldrett, A.J., Doherty, W., Gorbachev, N.S., 1995. Magma differentiation and mineralisation in the Siberian continental flood basalts. Lithos 34, 61–88.

Heimann, A., Fleming, T.H., Elliot, D.H., Foland, K.A., 1994. A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by $^{40}Ar/^{39}Ar$ geochronology. Earth Planet. Sci. Lett. 121, 19–41.

Hollings, P., Smyk, M., Heaman, L.M., Halls, H., 2010. The geochemistry, geochronology and paleomagnetism of dikes and sills associated with the Mesoproterozoic Midcontinent Rift near Thunder Bay, Ontario, Canada. Precambrian Res. 183, 553–571.

Hooper, P.R., 1990. The timing of crustal extension and the eruption of continental flood basalts. Nature 345, 246–249.

Hooper, P., Widdowson, M., Kelley, S., 2010. Tectonic setting and timing of the final Deccan flood basalt eruptions. Geology 38, 839–842.

Hutton, D.H.W., 2009. Insights into magmatism in volcanic margins: bridge structures and a new mechanism of basic sill emplacement – Theron Mountains, Antarctica. Pet. Geosci. 15, 269–278.

Johnson, A.M., Pollard, D.D., 1973. Mechanics of growth of some laccolith intrusions in Henry Mountains, Utah 1: Field observations, Gilbert's model, physical properties and flow of magma. Tectonophysics 18, 261–309.

Kavanagh, J.L., Pavier, M.J., 2014. Rock interface strength influences fluid-filled fracture propagation pathways in the crust. J. Struct. Geol. 63, 68–75.

Kavanagh, J.L., Menand, T., Sparks, R.S.J., 2006. An experimental investigation of sill formation and propagation in layered elastic media. Earth Planet. Sci. Lett. 245, 799–813.

Klausen, M.B., 2004. Geometry and mode of emplacement of the Thverartindur cone sheet swarm, SE Iceland. J. Volcanol. Geotherm. Res. 138, 185–204.

Klausen, M.B., 2009. The Lebombo monocline and associated feeder dyke swarm: diagnostic of a successful and highly volcanic rifted margin? Tectonophysics 468, 42–62.

Korsch, R.J., 1984. The structure of Shapeless Mountain, Antarctica, and its relation to Jurassic igneous activity. N.Z. J. Geol. Geophys. 27, 487.

Krumbholz, M., Hieronymus, C.F., Burchardt, S., Troll, V.R., Tanner, D.C., Friese, N., 2014. Weibull-distributed dyke thickness reflects probabilistic character of host-rock strength. Nat. Commun. 5.

Larsen, H.C., Marcussen, C., 1992. Sill intrusion, flood basalt emplacement and deep crustal structure of the Scoresby Sund region, East Greenland. In: Storey, B.C., Alabaster, T., Pankhurst, R.J. (Eds.), Magmatism and the causes of continental break-up. Geol. Soc. (Lond.) Spec. Publ. 68, 365–386.

Laughlin, A.W., Aldrich, M.J., Shafiqullah, M., Husler, J., 1986. Tectonic implications of the age, composition, and orientation of lamprophyre dikes, Navajo volcanic field, Arizona. Earth Planet. Sci. Lett. 76, 361–374.

Le Corvec, N., Menand, T., Lindsay, J., 2013. Interaction of ascending magma with pre-existing crustal fractures in monogenetic basaltic volcanism: an experimental approach. J. Geophys. Res., Solid Earth 118, 968–984.

Leat, P.T., 2008. On the long-distance transport of Ferrar magmas. In: Thomson, K., Petford, N. (Eds.), Structure and Emplacement of High-Level Magmatic Systems. Geol. Soc. (Lond.) Spec. Publ. 302, 45–61.

Li, C.S., Ripley, E.M., Naldrett, A.J., 2009. A new generic model of the giant Ni-Cu-PGE sulfide deposits associated with the Siberian Flood Basalts. Econ. Geol. 104, 291–301.

Lister, J.R., Kerr, R.C., 1991. Fluid-mechanical models of crack propagation and their application to magma transport in dykes. J. Geophys. Res. 96, 10049–10077.

Magee, C., Stevenson, C., O'Driscoll, B., Schofield, N., McDermott, K., 2012. An alternative emplacement model for the classic Ardnamurchan cone sheet swarm, NW Scotland, involving lateral magma supply via regional dykes. J. Struct. Geol. 43, 73–91.

Magee, C., Hunt-Stewart, E., Jackson, C.A.L., 2013. Volcano growth mechanisms and the role of sub-volcanic intrusions: insights from 2D seismic reflection data. Earth Planet. Sci. Lett. 373, 41–53.

Magee, C., Jackson, C.A.-L., Schofield, N., 2014. Diachronous sub-volcanic intrusion along deep-water margins: insights from the Irish Rockall Basin. Basin Res. 26, 85–105.

Malthe-Sørensson, A., Planke, S., Svensen, H., Jamtveit, B., 2004. Formation of saucer-shaped sills. In: Breitkreuz, C., Petford, N. (Eds.), Physical Geology of High-Level Magmatic Systems. Geol. Soc. (Lond.) Spec. Publ., 215–227.

Marsh, B.D., 2004. A magmatic mush column Rosetta Stone: the McMurdo Dry Valleys of Antarctica. Eos Trans. AGU 86, 497–502.

Marsh, B.D., Zeig, M.J., 1997. The Dias layered intrusion: a new discovery in the Basement Sill of the McMurdo Dry Valleys. Antarc. J. U.S. 16, 54–55.

Marsh, J.S., Hooper, P.R., Rehacek, J., Duncan, R.A.R.D., 1997. Stratigraphy and age of Karoo basalts of Lesotho and implications for correlations within the Karoo Igneous Province. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. In: Geophys. Monogr., vol. 100. American Geophysical Union, Washington D.C., pp. 247–272.

McClintock, M.K., 2001. Phreatomagmatism at Coombs Hills, Antarctica: Magma-Water Super-Volcanism in a Wet, Failed Rift. University of Otago, Dunedin, p. 174.

McClintock, M., White, J.D.L., 2006. Large phreatomagmatic vent complex at Coombs Hills, Antarctica: wet, explosive initiation of flood basalt volcanism in the Ferrar-Karoo LIP. Bull. Volcanol. 68, 215–239.

Morrison, A.D., 1989. Ferrar Dolerite intrusions at Terra Cotta Mountain, southern Victoria Land, Antarctica. Department of Geology. University of Otago, Dunedin, p. 165.

Muirhead, J.D., Airoldi, G., Rowland, J.V., White, J.D.L., 2012. Interconnected sills and inclined sheet intrusions control shallow magma transport in the Ferrar large igneous province, Antarctica. Bull. Geol. Soc. Am. 124, 162–180.

Naldrett, A.J., Fedorenko, V.A., Lightfoot, P.C., Kunilov, V.I., Gorbachev, N.S., Doherty, W., Johan, Z., 1995. Ni–Cu–PGE deposits of the Noril'sk region, Siberia – their formation in conduits for flood-basalt volcanism. Trans. - Inst. Min. Metall., B, Appl. Earth Sci. 104, B18–B36.

Nemeth, K., Martin, U., 2007. Shallow sill and dyke complex in western Hungary as a possible feeding system of phreatomagmatic volcanoes in "soft-rock" environment. J. Volcanol. Geotherm. Res. 159, 138–152.

Polteau, S., Ferre, E.C., Planke, S., Neumann, E.R., Chevallier, L., 2008. How are saucer-shaped sills emplaced? Constraints from the Golden Valley Sill, South Africa. J. Geophys. Res., Solid Earth 113.

Pyne, A.R., 1984. Geology of the Mt Fleming area, South Victoria Land, Antarctica. N.Z. J. Geol. Geophys. 27, 505–512.

Ray, R., Sheth, H.C., Mallik, J., 2007. Structure and emplacement of the Nandurbar-Dhule mafic dyke swarm, Deccan Traps, and the tectonomagmatic evolution of flood basalts. Bull. Volcanol. 69, 537–551.

Reubi, O., Ross, P.S., White, J.D.L., 2005. Debris avalanche deposits associated with large igneous province volcanism: an example from the Mawson Formation, central Allan Hills, Antarctica. Bull. Geol. Soc. Am. 117, 1615–1628.

Rohrman, M., 2013. Intrusive large igneous provinces below sedimentary basins: an example from the Exmouth Plateau (NW Australia). J. Geophys. Res., Solid Earth 118, 4477–4487.

Ross, P.S., White, J.D.L., 2005. Mafic, large-volume, pyroclastic density current deposits from phreatomagmatic eruptions in the Ferrar large igneous province, Antarctica. J. Geol. 113, 627–649.

Ross, P.S., Peate, I.U., McClintock, M.K., Xu, Y.G., Skilling, I.P., White, J.D.L., Houghton, B.F., 2005. Mafic volcaniclastic deposits in flood basalt provinces: a review. J. Volcanol. Geotherm. Res. 145, 281–314.

Ross, P.S., White, J.D.L., McClintock, M., 2008. Geological evolution of the Coombs-Allan Hills area, Ferrar large igneous province, Antarctica: Debris avalanches, mafic pyroclastic density currents, phreatocauldrons. J. Volcanol. Geotherm. Res. 172, 38–60.

Rubin, A.M., 1995. Propagation of magma-filled cracks. Annu. Rev. Earth Planet. Sci. 23, 287–336.

Schirnick, C., van den Bogaard, P., Schmincke, H.U., 1999. Cone sheet formation and intrusive growth of an oceanic island – the Miocene Tejeda complex on Gran Canaria (Canary Islands). Geology 27, 207–210.

Schofield, N., Stevenson, C., Reston, T., 2010. Magma fingers and host rock fluidization in the emplacement of sills. Geology 38, 63–66.

Schofield, N.J., Brown, D.J., Magee, C., Stevenson, C.T., 2012b. Sill morphology and comparison of brittle and non-brittle emplacement mechanisms. J. Geol. Soc. 169, 127–141.

Schofield, N., Heaton, L., Holford, S.P., Archer, S.G., Jackson, C.A.L., Jolley, D.W., 2012a. Seismic imaging of 'broken bridges': linking seismic to outcrop-scale investigations of intrusive magma lobes. J. Geol. Soc. 169, 421–426.

Self, S., Thordarson, T., Keszthelyi, L., 1997. Emplacement of continental flood basalt lava flows. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. In: Geophys. Monogr., vol. 100. American Geophysical Union, pp. 381–410.

Thomson, K., 2007. Determining magma flow in sills, dykes and laccoliths and their implications for sill emplacement. Bull. Volcanol. 70, 183–201.

Thomson, K., Hutton, D., 2004. Geometry and growth of sill complexes: insights using 3D seismic from the North Rockall Trough. Bull. Volcanol. 66, 364–375.

Thomson, K., Schofield, N., 2008. Lithological and structural controls on the emplacement and morphology of sills in sedimentary basins. In: Thomson, K., Petford, N. (Eds.), Structure and Emplacement of High-Level Magmatic Systems. Geol. Soc. (Lond.) Spec. Publ. 302, 31–44.

Thordarson, T., Self, S., 1998. The Roza Member, Columbia River Basalt Group: a gigantic pahoehoe lava flow field formed by endogenous processes? J. Geophys. Res., Solid Earth 103, 27411–27445.

Thordarson, T., Self, S., Oskarsson, N., Hulsebosch, T., 1996. Sulfur, chlorine, and fluorine degassing and atmospheric loading by the 1783–1784 AD Laki (Skaftar fires) eruption in Iceland. Bull. Volcanol. 58, 205–225.

Vanderkluysen, L., Mahoney, J.J., Hooper, P.R., Sheth, H.C., Ray, R., 2011. The feeder system of the deccan traps (India): insights from dike geochemistry. J. Petrol. 52, 315–343.

White, J.D.L., McClintock, M.K., 2001. Immense vent complex marks flood-basalt eruption in a wet failed rift: Coombs Hills, Antarctica. Geology 29, 935–938.

White, J.D.L., Thordarson, T., McClintock, M.K., Ross, P.-S., 2005. Cracking the Lid – dike emplacement above large sills of the Ferrar Province, Antarctica. Eos Trans. AGU 86. Fall Meeting Suppl., Abstract V23A-0690.

White, J.D.L., Bryan, S.E., Ross, P.-S., Self, S., Thordarson, T., 2009. Physical volcanology of continental large igneous provinces: update and review. In: Thordarson, T., Self, S., Larsen, G., Rowland, S.K., Hoskuldsson, A. (Eds.), Studies in Volcanology: The Legacy of George Walker. Special Publications of IAVCEI, London, pp. 291–321.

Wilson, T.J., 1993. Jurassic faulting and magmatism in the Transantarctic Mountains: Implications for Gondwana breakup. In: Findlay, R.H.U.R.B.M.R.V.J.J. (Ed.), Gondwana 8 – Assembly, Evolution and Dispersal. AA Balkema, Rotterdam, pp. 563–572.