Interconnected sills and inclined sheet intrusions control shallow magma transport in the Ferrar large igneous province, Antarctica

James D. Muirhead1,2, Giulia Airoldi2, Julie V. Rowland3, and James D.L. White2
1School of Environment, University of Auckland, Private Bag 92019, Auckland, New Zealand
2Geology Department, University of Otago, Leith Street, P.O. Box 56, Dunedin 9054, New Zealand

ABSTRACT

Field observations and structural data from intrusive complexes at Allan Hills and Terra Cotta Mountain, South Victoria Land, Antarctica, demonstrate that interconnected sills and inclined sheets transported magma through the shallow subsurface. These sills and sheets represent the upper-crustal (top 4 km) plumbing system of the 183 Ma Ferrar large igneous province. The sills are short in length (<1500 m), are moderately inclined (47° and 51° means), and show meter-scale variations in attitude; in places, they intruded bedding planes, resulting in stepped sheet-sill geometries. Sheet geometries and their relationship to the surrounding country rock are consistent with peripheral sheet intrusion under local magmatic stresses arising from roof-lift during sill injection. The sheet intrusions thus reflect the intrusive process itself rather than a far-field tectonic stress regime. The sills and sheets, together with local dolerite masses, formed the intrusive network that supplied magma to the Mawson Formation pyroclastic rocks in various parts of South Victoria Land and, by inference, the Kirkpatrick flood basalt lavas. The predominance of inclined sheets rather than steeply dipping dikes indicates a magmatic environment that is unlike the Jurassic rift arm inferred by previous authors. This could be explained using any of the following three scenarios. (1) The axis of the rift, and hence any rift-hosted dikes, lies beyond the current exposure area. (2) The regionally extensive Ferrar sills may have provided rheologically weak horizons that limited mechanical coupling of the basement rocks and overlying Beacon Supergroup, locally detaching the upper 4 km of the crust from possible syn-magmatic basement extension below. (3) The Ferrar large igneous province was emplaced in a neutral tectonic setting. In this scenario, broad-scale distribution of magma through the province was controlled by preexisting structure in the basement, and local intrusion geometries reflect the physical interaction of intruding magma with bedding anisotropy of the Beacon Supergroup.

INTRODUCTION

Development of subvertical sheets plays an important role in the growth of magmatic systems. In brittle regions of the crust, these structures connect large magmatic bodies at different stratigraphic levels (Watanabe et al., 1999; Ebingher et al., 2010), providing pathways that allow magma to ascend through the lithosphere and eventually erupt at the surface. Dike intrusion is the primary mechanism for vertical magma ascent in the seismogenic crust. These near-vertical, planar sheets form from lithospheric stretching and/or high magmatic pressures, recording in their orientation the directions of the principal compressive stresses of the tectonic regime in which they formed (Anderson, 1951; Lister and Kerr, 1991; Rubin, 1995). Development of subvertical sheets in sills complexes, however, diverges from this classic model of dike emplacement. Recent anisotropy of magnetic susceptibility (Polteau et al., 2008a), geophysical (Trude et al., 2003; Shoulders and Cartwright, 2004; Thomson and Hutton, 2004; Hansen and Cartwright, 2006; Thomson, 2007b), and experimental (Galland et al., 2009) studies have demonstrated that subvertical sheets also form at sill peripheries. The phenomenon has been interpreted to result from deformation associated with doming of the sill overburden (i.e., Pollard and Johnson, 1973). These investigations highlight the need for detailed field observations of sheet intrusions in sill complexes, where inclined sheets extending from sill peripheries can be easily mistaken for steeply dipping dikes (Galerne et al., 2008). If sill-fed sheets are not recognized, misleading paleostress analyses may result.

The present study focuses on intrusion of tholeiitic sheets that are components of the 183 Ma Ferrar large igneous province (Encarnación et al., 1996). Today, remnants are observed in New Zealand and Australia, but most prominently on the Antarctic continent (Fig. 1). Many studies have focused on the geochemistry of the Ferrar large igneous province (Gunn and Warren, 1962; Hall et al., 1982; Fleming et al., 1992, 1995, 1997; Heimann et al., 1994; Elliot et al., 1999; Marsh, 2004; Bédard et al., 2007; Leat, 2008), yet few have addressed the physical controls on magma transport (Grapes et al., 1974; Wilson, 1990, 1993; White et al., 2009; Airoldi et al., 2011). Exposure of the Ferrar large igneous province is confined to a narrow belt, 160 x 3500 km, where post-Jurassic tectonism has created highlands protruding through the Antarctic ice sheet (Elliot and Fleming, 2004) (Fig. 1). Although the geometry of the province during the Jurassic is not fully constrained, the current map-view linearity has been interpreted to represent a narrow, continental failed-rift setting (Elliot and Fleming, 2000). Previous emplacement models favor a far-field extensional regime, with magma traveling laterally for more than 3000 km from a center in the Weddell Sea region (Elliot et al., 1999; Elliot and Fleming, 2004, 2008; Leat, 2008). Direct evidence for this rift system is lacking. Major rift-bounding faults and regional dike swarms, characteristic of rift systems in Iceland and East Africa, are yet to be observed here (Elliot and Fleming, 2004, 2008). Rather, indirect evidence of a failed-rift setting has been inferred from monoclinal folds in basalt lavas and tuff layers, and from granite clasts interpreted to be derived from exposures

GSA Bulletin; January/February 2012; v. 124; no. 1/2; p. 162–180; doi: 10.1130/B30455.1; 14 figures; 1 table.

© 2012 Geological Society of America
of basement along possible rift-related border faults (Elliot, 1992; Elliot and Larsen, 1993).

More recent assessments of the basic structure and distribution of Ferrar dikes and sills have led to a shift in ideas regarding development of the Ferrar magmatic system (White et al., 2005, 2009). Intrusions that were previously used to infer regional tectonic stresses (i.e., Wilson, 1993) are now suspected to have been contained in “flattened linds” of sedimentary strata buoyed up on molten sills. It is even suggested that Ferrar intrusions bear little relationship to the far-field tectonic processes prevailing during the Jurassic (White et al., 2005; Elliot and Fleming, 2008; White et al., 2009). This hypothesis has broad implications for the active geological processes occurring in the upper few kilometers of the crust along the East Antarctic margin during Ferrar large igneous province emplacement, and it requires structural data to test its viability. The work presented here investigates the geometry of Ferrar sheet intrusions in two well-exposed swarms at Allan Hills and Terra Cotta Mountain, South Victoria Land (Fig. 2). The dimensions and structure of these intrusions are examined to assess the environment of emplacement and controls on sheet geometry. By identifying the key structural elements of the Ferrar Dolerite in South Victoria Land, we can reconstruct the geometry of the Ferrar large igneous province plumbing system. Finally, we provide an emplacement model that best fits the structural features described in this paper and the long, narrow exposure of the Ferrar Dolerite.

FERRAR LARGE IGNEOUS PROVINCE IN SOUTH VICTORIA LAND

The Transantarctic Mountains are the world’s highest noncontractional mountain chain. Mesozoic and Cenozoic uplift was accompanied by very little deformation, producing a series of tilted fault blocks with a minor 1°–2° dip to the west (Gleadow and Fitzgerald, 1987). Igneous remnants of the Ferrar magmatic event are exposed along this tract for 3500 km (Elliot and Fleming, 2008). The arid Antarctic climate produces exceptional exposures, which reveal arguably the world’s most complete view of the intrusive and extrusive architecture of a large-scale, flood basalt system.

The total volume of the Ferrar large igneous province is estimated to approach $2.3 \times 10^5$ km$^3$ (Elliot and Fleming, 2004), and the province was active for no more than 1 m.y. (Heimann et al., 1994). Nearly all the province intrudes into or overlies Devonian to Permian sedimentary rocks of the Beacon Supergroup (Elliot and Fleming, 2008; Table 1). The extrusive expression of Ferrar large igneous province magmatism includes early-stage pyroclastic deposits (Prebble, Mawson, and Exposure Hill Formations) and eroded remnants of late-stage flood basalt lavas known as the Kirkpatrick Basalt (Elliot and Fleming, 2008). The intrusive component includes the Dufek layered mafic intrusion (Storey and Kyle, 1997) and the volumetrically dominant dikes and sills of the Ferrar Dolerite (1.7 $\times 10^5$ km$^3$; Fleming et al., 1997).

Superb examples of the Ferrar Dolerite occur in the McMurdo Dry Valleys and adjacent regions in South Victoria Land (Fig. 2). Here, a vertically interconnected stack of four ~300-m-thick sills stretches across the stratigraphy for tens of kilometers, often with little geometrical change (Marsh, 2004; Elliot and Fleming, 2008). Minor sills (tens of meters thick) are present in the upper levels of the Beacon sequence (Marsh, 2004; Elliot and Fleming, 2008). Dikes and inclined sheets (defined in the next section) form only a small component of the Ferrar Dolerite. The spacing between individual dikes is typically on the order of kilometers, with rare sheet swarms present near the Convoy Ranges at Allan and Coombs Hills and by Taylor Glacier at Terra Cotta Mountain. No Ferrar dikes are known to cut basement rock in South Victoria Land; however, a basement feeder has been proposed by Marsh (2004) at Bull Pass, only a few kilometers north of Wright Valley (Fig. 2C).

FIELD DATA

Structural data presented here were collected at Allan Hills and Terra Cotta Mountain during the 2006 and 2007 Antarctic summer field seasons. Eleven dolerite sheets measured on the east slopes of Terra Cotta Mountain by Morrison (1989) are also included. Intrusion attitudes were measured on country rock contacts along the lengths of the sheets, and crosscutting relationships (Fig. 3B) between intrusions were analyzed to reconstruct emplacement successions. To account for the Cenozoic tilting of the Transantarctic Mountains (Gleadow and Fitzgerald, 1987), all the data have been back-rotated 2°E along a 000° axis.

Observations of aerial photographs from two adjacent flight lines across the northeast arm of Allan Hills have been included as a supplement to field measurements (Fig. 3). In these images, the dark-brown, protruding ribs of Ferrar Dolerite are easily distinguished from cream-colored country rock (Figs. 3A and 3B). Where scree coverage is sparse, dip direction can be inferred on shallow-dipping sheets. By comparing the distances between points measured in the field with those measured on the aerial photographs, we can calculate a scale of ~1:10,000. The smallest identifiable features are 0.5 m wide. We have combined the field and remote data sources to reduce effects of sampling biases in the Allan Hills data set.

Distinguishing sheets from dikes can provide insight into the controls on magma emplacement in volcanic settings (Annels, 1967; Klau- sen, 2004; Pasquaré and Tibaldi, 2007; Siler and Karson, 2009). Dikes typically reflect a far-field tectonic environment, whereas shallow-dipping sheets are the product of an overpressured magmatic environment (Geshi, 2005) and deformation of country rock ahead of an advancing sill (Johnson and Pollard, 1973). In this study, intrusions dipping 10°–70° are referred to as sheets. Intrusions that follow bedding planes and/or dip <10° are referred to as sills, whereas discordant intrusions with dips >70° are dikes.

Allan Hills

The Allan Hills area is located 8 km west of the Convoy Range, just beyond the NW corner of the McMurdo Dry Valleys (Fig. 2).
Figure 2. Simplified geologic maps for distinct regions in South Victoria Land: (A) Allan and Coombs Hills, (B) the McMurdo Dry Valleys, and (C) Terra Cotta Mountain. Geological maps are from Morrison (1989), McClintock and White (2006), and Bédard et al. (2007). TAM—Transantarctic Mountains.
Interconnected sills and inclined sheet intrusions control shallow magma transport in the Ferrar large igneous province, Antarctica.

Table 1. Basic geology of South Victoria Land, Antarctica (modified from McClintock, 2001; Airoldi et al., 2011).
The area encompasses ~60 km² of Permian–Triassic Beacon Supergroup rocks cut and overlain by the Ferrar Group (Grapes et al., 1974; Fig. 2A). The presence of both the upper Beacon units and Ferrar extrusive rocks (i.e., Mawson Formation) suggests that intrusions at Allan Hills were injected into a shallow environment (<1000 m depth; Grapes et al., 1974; Korsch, 1984; Reubi et al., 2005; Ross et al., 2008). Data for this study were collected from the northeast arm of Allan Hills, in an ~6 km² area exhibiting the greatest density of sheet intrusions (Fig. 4). A NNW-striking subparallel swarm and a radial swarm have been identified (Airoldi et al., 2011) and are referred to herein as set A and set B, respectively. This section focuses on the structural observations from set A for three reasons: (1) It represents the earliest intrusive phase in the area, based on crosscutting relationships; (2) it provides the greater number of sheets visible in aerial photographs \( n = 39 \) for set A vs. \( n = 11 \) for set B; and, (3) most importantly, set A represents the initiation of subvertical magma pathways in shallow regions of the Ferrar large igneous province plumbing system at Allan Hills, whereas the radial pattern in set B suggests a more localized response to magmatic stress conditions that likely occurred after emplacement of set A (Airoldi et al., 2011).

Measurements of set A taken in the field (Fig. 4B) are distinguished from those inferred from aerial photography (Fig. 4A). Field measurements were obtained along the lengths of sheet intrusions and are shown on stereonets as contour plots of poles to planes. Sheet trajectories (i.e., dip direction; Klausen, 2004) are presented as arrows in both maps. Bedding measurements in the area reveal a dominant 15° bedding dip to the northeast.

Sheet Structure and Segmentation

Ferrar sheets at Allan Hills are composed of numerous short segments averaging 60 m in length, which in many cases link along strike to form interconnected sheets that have exposed lengths <1500 m. Their along-strike dimensions are unusually short compared to those in other swarms worldwide, such as regional dike swarms in Iceland (Gudmundsson, 1995). The geometry of Allan Hills intrusions varies over short distances (>10 m), changing attitude both along their lengths and vertically through the Beacon sequence (Figs. 5A and 5B). Sheet geometries are irregular (defined by Hoek, 1991), with no preferred stepping direction between individual segments along the length of the sheet. Furthermore, intrusions display zigzag geometries at laterally tapering ends (Fig. 5B), and, locally, en echelon segmentation occurs in the interaction zones of encroaching sheets. Exposures on steep slopes and cliff faces reveal a tendency for intrusions to exploit bedding planes in the Beacon strata, producing small-scale sills that form bridges between discordant, inclined sheets (Fig. 5C).

Sheet Attitude and Sampling Bias

Sampling bias was investigated by comparing field measurements of strike and dip in set A (Fig. 4) with those inferred from aerial photography. Despite the variable attitudes observed along individual intrusions, field measurements give a 154° ± 9.3° preferred trend in strike (95% confidence), and this is corroborated by aerial photography data (153° ± 10° to 95% confidence; Fig. 4A). Dip data from both techniques are also in good agreement and exhibit a mean 47° dip to the west (Fig. 4B).

Associated Host-Rock Deformation

Localized damage zones, composed of sheet-parallel deformation bands and tension fractures, are observed within 3 m of intrusion margins (Fig. 6). Damage zone joints can be distinguished from other joints by their proximity to sheet selvages (<3 m), close spacing (2–25 cm), and short lengths (<5 m). The zones
Interconnected sills and inclined sheet intrusions control shallow magma transport in the Ferrar large igneous province, Antarctica.

Figure 4. Aerial (A) and field (B) measurements of set A sheets in the northeastern arm of Allan Hills. Gray arrows on rose diagrams indicate the mean trend. Black arrows indicate the inferred sheet trajectory of individual intrusions. (B) Field measurements from areas A1, A2, A3, and A4 (gray ellipses) given as contour plots of poles to sheet planes and a frequency histogram of all dip measurements. Long black arrows indicate the average sheet trajectory in the highlighted region, and dashed lines represent the margin of error to 95% confidence.
are coincident with steps, offsets, and tips, and their modes of occurrence and geometries are similar to damage zones alongside dikes at Makhtesh Ramon, Israel (Weinberger et al., 1995), and the Swartztruggens kimberlite dike swarm, South Africa (Brown et al., 2007). These damage zones form as localized lobes, as opposed to the broadly distributed, dike-parallel joints described by Delaney et al. (1986). A plot of sheet thicknesses versus related damage zones (Fig. 6D) shows a weak, positive linear trend ($r^2 = 0.34; p < 0.007$). A similar relationship has been noted in oblique damage lobes observed by Weinberger et al. (1995).

**Intrusion Density and Kinematics**

Adopting the approach of Gudmundsson (1995), we estimated crustal extension using a country rock to intrusions ratio determined along four transects in Allan Hills (Fig. 7). Each transect runs normal to mean sheet strike ($063^\circ$–$243^\circ$) and dissects the study area. The total frequency of intrusive sheets was summed along all transects, and total thickness was calculated by assuming a mean sheet thickness of 0.75 m for all sheets (Airoldi et al., 2011). Based on these results, we suggest that, as a first-order approximation, sheet intrusions represent a maximum crustal extension of 0.17% in Allan Hills. The distribution of strain, however, exhibits local

![Figure 5](image-url)
variations. In the Weller Coal Measures in the southern region of Allan Hills, sheet intrusions account for an estimated <0.04% of the rock along any sheet-normal transect (Fig. 7A). Within the northeast arm, subvertical sheet intrusions occasionally occupy >0.65% of the rock (Fig. 7B).

Calcite veins are common along sheet selvages in the northeast arm and often exhibit striations with near-vertical rakes (Fig. 8A). These veins indicate a component of resolved shear along the intrusive plane. Three possible scenarios may explain this observation: (1) Sheets intruded into preexisting fault structures (Wilson, 1993; Valentine and Krogh, 2006; Gaffney et al., 2007); (2) the striations record the direction of magma flow (Varga et al., 1998; Correa-Gomes et al., 2001, and references therein); or (3) sheet propagation occurred under hybrid fracture mechanics (i.e., mixed-mode opening; Pollard, 1987; Ramsey and Chester, 2004).

Airoldi et al. (2011) described the processes leading to alternating sheet-sill geometries at Allan Hills, which were adapted from models of saucer-shaped sill formation (Malthe-Sørenssen et al., 2004; Hansen and Cartwright, 2006; Polteau et al., 2008a; Galland et al., 2009). A fundamental factor to this process is the jacking up of strata above the sill (“roof-lift”), creating extensional shear fractures that are exploited by inclined sheets at the sill peripheries. Magma-fracture propagation at the peripheries of these sills is controlled by both internal magma pressure in the inclined sheets and roof-lift in the sill. Buckled strata immediately above sill segments of sheet intrusions at Allan Hills (Fig. 8B) reveal that intrusions opened in part by lifting the overlying strata. Therefore, sheet-sill geometries at Allan Hills likely reflect two components of sheet-opening: (1) subvertical opening in the sill segments; and (2) opening normal to the sheet plane. We suggest that the following scenario would culminate in hybrid shear kinematics (Pozzobon et al., 2010) and subvertical opening oblique to the sheet plane (Fig. 8D). This style of opening has been observed in cone sheets on Gran Canaria (Schirnicker et al., 1999) and is expected with sheet propagation under hybrid fracture mechanics (i.e., scenario 3).

**Terra Cotta Mountain**

Terra Cotta Mountain is located at the intersection between the Taylor and Ferrar Glaciers, 150 km SSE of Allan Hills. The area consists of basement granitoids and Taylor Group rocks intruded by Ferrar sheets and sills. Ferrar sheets at Terra Cotta Mountain occur below a thick sill (~200 m) that prior to erosion would have been overlain by Victoria Group rocks (~842 m thick; Table 1) and possibly Ferrar sills and Kirkpatrick lavas. Therefore, it is likely that intrusions at Terra Cotta Mountain were situated in a deeper level of the Ferrar large igneous province plumbing system than those at Allan Hills (1000–2000 m depth, compared to <1000 m depth at Allan Hills).

Sheet exposure at Terra Cotta Mountain is predominantly confined to steep slopes and cliff faces on the southeast and east slopes of the mountain. On the southeast slopes, Ferrar sheets transect the stratigraphy and connect with an overlying sill, known as the Summit Mass (Morrison and Reay, 1995). On the east slopes, another series of thick Ferrar intrusions dissects Beacon strata.

Morrison (1989) distinguished at least four intrusive phases on the east slopes. However, crosscutting and intrusion phase relationships on the southeast slopes are equivocal, due in part to a paucity of observable crosscutting localities. Chilled contacts are also absent, and the margins of intrusions at sheet intersections are poorly defined. There are also no distinct differences in coloration or geochemistry defining possible intrusive sets (Morrison, 1989), and age relationships are therefore undetermined on the southeast slopes. Bedding on the southeast slopes displays a shallow 3° dip to the west. Although the terrain limited access to sheet exposures, structural measurements were obtained from ~90% of the observable Ferrar intrusions.
sheets. Field measurements collected in the area are shown with data collected by Morrison (1989) from the east slopes (Fig. 9).

**Sheet Structure and Attitude**

As observed at Allan Hills, intrusions at Terra Cotta Mountain exhibit irregular geometries, show variable attitudes, and are occasionally concordant to bedding (Fig. 10). It is observed that some sheets have split into secondary structures known as apophyses (defined by Hoek, 1991). These smaller sheets occasionally thin and terminate some tens of meters above their parent intrusion, consistent with either: (1) injection from an underlying source; or (2) lateral propagation as a bladed dike (Lister and Kerr, 1991). Sheet strikes are variable (043° ± 24° mean to 95% confidence), but the majority of measurements occupy the northeast and southwest quadrants of rose plots (Fig. 9), with preferred 060°–070° and 020°–030° trends. Sheet dips vary across a broad range (typically 30°–80°) with an average value of 51°, similar to that of Allan Hills. Sheet trajectories point southeast of the field area (Fig. 9).

**Intrusion Density and Kinematics**

Sheet intrusions at Terra Cotta Mountain are more prominent than at Allan Hills. Mean intrusion thickness is 6 m, and the cumulative thickness is 241 m. As at Allan Hills, mineral striations were observed along sheet selvages at Terra Cotta Mountain, and the presence of alternating sheet-sill geometries again indicates a vertical opening component. Crosscutting localities on the east face support these conclusions (Morrison, 1989). Here, sheets dissected by later intrusions are vertically displaced on either side of the younger sheet walls, suggesting relative uplift of strata on the hanging-wall side of the intrusions (Morrison, 1989; White et al., 2009).

**DISCUSSION: CONTROLS ON FERRAR LARGE IGNEOUS PROVINCE MAGMA TRANSPORT**

**Controls on Sheet Emplacement**

The geometries of sheet intrusions at Allan Hills and Terra Cotta Mountain have broad implications for the controls on sheet formation in these swarms and the magmatic-tectonic environment in South Victoria Land at the time of emplacement. In this section, we outline first-principle controls on sheet geometry in magmatic rifts and briefly discuss them in context with the field observations. In general, the geometry of sheet intrusions in volcano-tectonic rifts relates to deeper-seated tectonic and/or shallow-seated magmatic processes that have evolved within the system over time (i.e., Gudmundsson, 1995; Geshi, 2005). Magma injected into these rifts originates from reservoirs located near the crust-mantle boundary (Gudmundsson, 1995; Ebinger et al., 2010). Subvertical magma transport from these depths occurs through numerous, steeply dipping, subparallel dikes that form regional or, in the case of large igneous provinces, giant dike swarms (Gudmundsson, 1995; Ernst et al., 2001).

In addition to these deep sources, some volcano-tectonic rifts contain sill networks and shallow magma chambers at <12 km depth, which are fed by dikes from below (Gudmundsson, 1995; Hansen and Cartwright, 2006). In Iceland, the development of shallow loci of partial melt produces plutons or layered mafic intrusions (Gudmundsson, 1998). In the case of large igneous provinces, injection into sedimentary basins can result in the reorientation of magmatic structures and the subsequent development of sill complexes (e.g., Coronation Sills, Canada; Ernst and Buchan, 1997; Bryan and Ernst, 2008, and references therein).

Three types of subvertical intrusions typically come from shallow magma reservoirs: cone sheets, peripheral sheets, and laterally propagating dikes (Anderson, 1936; Johnson and Pollard, 1973; Brandsdóttir and Einarsson, 1979; Buck et al., 2006; Paquet et al., 2007). The geometry of these shallow systems may be decoupled from their deep-seated counterparts. In such a scenario, shallowly to moderately dipping intrusions, such as cone sheets and peripheral sheet intrusions, dominate over steeply dipping dikes. Cone sheets typically form in isotropic, igneous host rocks during periods of high magma influx into centers of partial melt. The system is overpressurized,

Figure 7. Percentage of sheet intrusions along four transects in Allan Hills. Sheet intrusions recognized in aerial photographs are represented as gray lines. The thickness of these lines does not correspond to their true thickness. Aerial photographs (A and B) illustrate sheet density distribution at Allan Hills.
and local magmatic stress overcomes any far-field tectonic influence (Gudmundsson, 1998; Geshi, 2005). Sheets therefore align to the local stress field, exhibiting shallow to moderate dips with trajectories that point to the local magma source (Anderson, 1936; Schirnick et al., 1999; Klausen, 2004; O’Driscoll et al., 2006; Siler and Karson, 2009). When magma input exceeds the rate of extension, sill emplacement can become the dominant form of sheet intrusion (Parsons and Thompson, 1991), particularly in shallow, strongly layered regions of the crust where magma pressure is more likely to exceed lithospheric overburden (Mudge, 1968). This is often the case for large igneous provinces, where magma input is exceptionally high (Bryan and Ernst, 2008). Development of subvertical sheets in these environments often depends on magma exploiting fractures produced during the forceful injection of sills, resulting in the formation of saucer-shaped sills and peripheral sheet intrusions (Pollard and Johnson, 1973; Thomson and Hutton, 2004; Thomson, 2007b; Galland et al., 2009). As with cone sheets, the inclined sheets in these systems dip shallow to moderately (20°–60°), with trajectories pointing to the sill periphery from which they originated (Johnson and Pollard, 1973; Chevallier and Woodford, 1999; Galland et al., 2009).

Sheet geometries at Allan Hills and Terra Cotta Mountain are consistent with the dominance of peripheral sheet intrusions rather than dikes and cone sheets for the following reasons:

1. The intrusions dip moderately (mean dips 47°–51°), and sheet trajectories point to a common area, indicating formation as cone sheets or peripheral intrusions under shallow magmatic stresses.

2. Large mafic bodies capable of supplying cone sheets (i.e., laccoliths, batholiths, plutons, and layered mafic intrusions) are extremely rare in the Ferrar Province, and none are observed in the McMurdo Dry Valleys region, either geophysically or in outcrop.

3. Sills, which supply peripheral sheets, are the dominant component of the Ferrar Dolerite (Elliot and Fleming, 2008) and are therefore a likely source for any shallowly sourced sheet swarm.

4. Peripheral sheet intrusion is consistent with observations elsewhere in South Victoria Land, including Mount Gran and Pearse Valley (Elliot and Fleming, 2008; Fig. 11).

As such, we propose that intrusions at Allan Hills and Terra Cotta Mountain reflect near-field stresses relating to a shallow magmatic environment as opposed to a deeper-seated, far-field tectonic regime.

Modeling the Ferrar Plumbing System in South Victoria Land

An assessment of the interactions between the major constituents of the Ferrar Dolerite presented in this study and those described throughout the literature provides the framework for a conceptual model of the Ferrar plumbing system (Fig. 12). In the following section, we divide the Ferrar Dolerite into four major components: sills, sheet swarms, thick sheets and dolerite masses, and small-scale peripheral swarms. The distribution of and geometrical relationships between these components are discussed to provide insight onto the broad-scale controls on magma transport at shallow (upper 4 km) crustal levels.

Sills

Ferrar Dolerite sills in South Victoria Land constitute the dominant expression of the frozen magmatic plumbing system at its current level of exposure. The sills have been studied by a number of authors (e.g., Gunn and Warren, 1962; Fleming et al., 1997; Marsh and Zeig, 1997; Marsh, 2004), and they are documented in greatest detail in the McMurdo Dry Valleys, where excellent exposure allows some sills to be traced laterally >50 km. Marsh (2004) distinguished four sills that were ~300 m thick and reached maximum thicknesses of 700 m. The areal extent of these intrusions is remarkable.
compared to other Ferrar components; the Peneplain and Basement Sills cover areas of 19,000 and 6,000 km$^2$, respectively (Gunn and Warren, 1962; Fig. 13). Cumulatively, the four sills account for ~1200 m of vertical extension (inflation, uplift) in the South Victoria Land region.

**Sheet Swarms**

Compared to dike swarms in large igneous provinces and volcano-tectonic rifts observed elsewhere, such as the Independence dike swarm (Glazner et al., 1999), Iceland Tertiary rifts (Gudmundsson, 1995) and the Okavango giant dike swarm (Aubourg et al., 2008), sheet swarms are rare in South Victoria Land and do not exhibit any regional continuity (Elliot and Fleming, 2008). Only a few thick (>10 m), steeply dipping dikes are recorded, and none of these occur in swarms. Sheet intrusions measured at Allan Hills, Coombs Hills, and Terra Cotta Mountain ($n=361$; Guegan, 2006; Airoldi et al., 2011; this paper) exhibit a very weak, NNW preferred strike (346° ± 23.4°, 95% confidence; Fig. 13), and all orientations are well represented. These sheets dip shallowly to moderately and often exploit bedding planes. Oblique damage zones alongside intrusions record intense fracturing of country rock during the intrusion process (Mériaux et al., 1999; Brown et al., 2007; Fig. 6). Mean sheet thickness in these swarms is 2.8 m. Plan-view exposures of sheet arrays at Allan and Coombs Hills reveal inclined sheet intrusions with average lengths of 375 m and 174 m, respectively (Guegan, 2006; Airoldi et al., 2011). Assuming that all sheets at Terra Cotta Mountain extend laterally to the exposed northeast and southwest margins of the swarm, these intrusions would have lengths of ~3000 m. Based on these length and thickness values, exposed sheet swarms in South Victoria Land cover an area of ~0.6 km$^2$. This estimate is a minimum value because ice cover frequently masks the along-strike continuation of Ferrar rocks. However, swarms cannot be traced along strike from any of these locations to other nunataks within South Victoria Land.

**Thick Sheets and Dolerite Masses**

Several thick, inclined sheets and large dolerite masses are present in South Victoria Land. The Windy Gully dike is a 50-m-wide, inclined sheet that is exposed along strike for ~5 km on the western side of Terra Cotta Mountain, and it likely connects the summit mass with a lower sill (Elliot and Fleming, 2004). A similar inclined sheet is reported on the southern end of Knobhead Mountain, where a sill ascends 900 m of the stratigraphy via two sheets connected by a bedding-parallel segment (Hamilton, 1965; Elliot and Fleming, 2004). At Mount Gran, a large dolerite mass, described by Elliot and Fleming (2004) as a “plug-like body,” extends from the periphery of a sill (White et al., 2009), and a similar intrusion is documented south of Mount Gran on the opposite side of the Mackay Glacier (Gunn and Warren, 1962).

**Small-Scale Peripheral Swarms**

The other subvertical intrusions observed in South Victoria Land are the small peripheral sheet swarms at Mount Gran and on the southern slopes of the Asgard Range (Fig. 2B) in Pearse Valley (Fig. 11). These dip toward a sill front and occasionally exploit bedding planes. At Pearse Valley, they traverse the stratigraphy vertically no more than 100 m before they connect with an overlying sill. Similarly, at Mount Gran,
the peripheral sheets ascend the stratigraphy no more than 50 m between sills.

**Geometrical Relations of the Ferrar Components**

Several of the interactions amongst the components of the Ferrar large igneous province shed light onto the development of the plumbing system at shallow crustal levels. (1) At Mount Gran and Pearse Valley, inclined sheets and sills form the same interconnected structures, indicating contemporaneous emplacement; small-scale sheet swarms connect to the periphery of a sill and, at Pearse Valley in particular, connect to an overlying sill (Fig. 11). (2) White et al. (2009) noted the displacement of country rock on either side of these intrusions (Fig. 11). (3) The thicker (>30 m) sheets and plugs at Mount Gran, Terra Cotta Mountain, and Knobhead Mountain all connect to a sill (Elliot and Fleming, 2004, 2008; White et al., 2009). It is still unclear whether these intrusions acted as large-scale magmatic feeders to the sills or were supplied by them.

**A Model for Shallow (Upper 4 Km) Ferrar Sheet Emplacement**

Field relationships in the Ferrar large igneous province plumbing system point to a magmatic environment that is partly detached from the Jurassic rift inferred by previous authors (Storey et al., 1992; Wilson, 1993; Elliot and Fleming, 2000; Martin, 2007). Magma injection into active rift zones typically occurs through voluminous, regionally continuous, parallel dike swarms. Extensional regimes like the East African Rift, Afar, produce 8–10-km-long, 1–2-m-wide dikes injected into 65-km-long rift segments (e.g., Dabbahu rifting episode, 2005 to present; Keir et al., 2009; Ebinger et al., 2010). In extinct large igneous provinces, these intrusions can be significantly larger, reaching thicknesses >40 m and extending for >100 km along strike (Ernst et al., 2001; Bryan and Ernst, 2008). Exposures of extinct Tertiary rift segments in Iceland reveal parallel dike swarms that occupy between 1% and 10% of the observable rock volume over areas >300 km² (Gudmundsson, 1995). Although the nature of the exposure at Terra Cotta Mountain limits such an analysis, at Allan Hills, sheet swarms occupy a maximum of 0.17% of rock along any one transect, and the total contribution of all Ferrar sheets to the entire province is an order of magnitude lower.

Rather, data from both this study and previous literature indicate that the Ferrar Dolerite in South Victoria Land provides a record of the forceful intrusion of sills into a thick (2.5 km) sedimentary pile (Fig. 12). Sill intrusion at shallow paleodepths, where the rock overburden is low, is typically accommodated by uplifting the overlying roof rock (Johnson and Pollard, 1973; Thomson, 2007b; Polteau et al., 2008b; Galland et al., 2009). This process has been ascribed to the Ferrar sills by previous authors (White and Garland, 2007; White et al., 2009) and is expressed in buckled strata above sills at Allan Hills and Shapeless Mountain (Grapes et al., 1974; Korsch, 1984; Fig. 8). Subvertical magma transport in the shallow plumbing system occurred locally in peripheral sheet swarms or larger plug-like bodies and inclined sheets. Most of these structures formed contemporaneously with sills, and the sheets either fed magma into the sills or vice versa. The presence of peripheral sheet swarms at Mount Gran, Pearse Valley, Allan Hills, and Terra Cotta Mountain demonstrates that magma traveled vertically by exploiting fractures created from the stresses transmitted into uplifting country rock during sill propagation (Johnson and Pollard, 1973; White et al., 2005, 2009). These sheets developed under near-field stresses and reflect the intrusive process itself, rather than a regional tectonic influence.

**Contributions to Sill Complexes in General**

Field observations of sheets and sills of the Ferrar Dolerite help address current questions regarding magma transport in sill complexes.
and other volcanic environments, notably: (1) To what extent are sill networks capable of feeding volcanic eruptions? (2) What are the responses of host rock to sill emplacement and the host’s role in formation of peripheral sheets? Ascent of magma through the seismogenic crust is classically depicted as intrusion of dikes (Anderson, 1951; Lister and Kerr, 1991), and dike swarms are considered the primary feeders to flood basalt eruptions (Ernst et al., 1995). The influence of sill intrusions on vertical ascent of magma has been largely overlooked. Advances in seismic-reflection studies, however, have revealed interconnected sill complexes that may extend vertically >10 km through the crust (Møre and Voring Basins, Norway; Cartwright and Hansen, 2006).

Our investigation reveals that interconnected shallow to moderately dipping sheets and sills...
Some authors favor buoyancy-controlled processes observed in sedimentary basins stress rotations resulting from changes in stiff-sills can form in igneous host rock under local onstrated that inclined sheets in saucer-shaped province may be considered in the context of Garland, 2007; Airoldi et al., 2011). This recent study by Hansen et al. (2011) dem-onstrated that inclined sheets in saucer-shaped sills acted as conduits that fed Mawson Formation rocks (Elliot and Fleming, 2008; White et al., 2009; Airoldi et al., 2011). In the absence of any significant dike swarms, it is additionally plausible that Ferrar sheets and sills also fed the Kirkpatrick flood basalts (White and Garland, 2007; Airoldi et al., 2011).

Observations from the Ferrar large igneous province may be considered in the context of models for emplacement of saucer-shaped sills. A recent study by Hansen et al. (2011) dem-onstrated that inclined sheets in saucer-shaped sills can form in igneous host rock under local stress rotations resulting from changes in stiffness with depth, as opposed to the roof-jacking processes observed in sedimentary basins (Polteau et al., 2008b, and references therein). Some authors favor buoyancy-controlled models for both sill transgressions and sau-cerer-shaped sill emplacement (Bradley, 1965; Francis, 1982; Chevallier and Woodford, 1999; Goulty, 2005). Schofield et al. (2010) high-lighted the importance of inelastic deformation, including host-rock fluidization, to form magma fingers in inclined sheets of the Golden Valley Sill, South Africa. Although analog experiments and numerical simulations produce inclined sheet intrusions at sill peripheries in response to roof-lift (Pollard and Johnson, 1973; Malthe-Sørenssen et al., 2004; Galland et al., 2009), field exposures relating these processes are rare. Folds above saucer-shaped sills in seismic-reflection surveys may be the best evidence for roof-lift (Hansen and Cartwright, 2006; Hansen et al., 2008). These could, however, also be interpreted as downslope layering on the flanks of overlying shield volcanoes (Hansen and Cartwright, 2007; Thomson, 2007a), and seismic reflection cannot resolve structures on scales <100 m. In accordance with models of laccolith-type sill formation (Polteau et al., 2008b, and references therein), the Ferrar Province shows evidence for elastic accommodation by uplift of the surrounding country rock and accompanying exploita-
tion of instabilities by peripheral sheet arrays (Grapes et al., 1974; Korsch, 1984; White et al., 2009; Airoldi et al., 2011). These sheets ascend the stratigraphy before exploiting suit-able bedrock horizons as sills (e.g., Terra Cotta Mountain and Pearse Valley; Figs. 10A and 11), and, similar to emplacement models proposed by Thomson and Schofield (2008), the process repeats itself until magma either reaches the surface or stalls and solidifies. These sheet-sill interactions are recorded on a variety of scales throughout the province as either alternating sheet-sill segments constituting thin (<10 m thick) intrusions (Fig. 5C), or thick (50 m) sheets or sheet arrays exposed at the lateral ends of the larger sills (e.g., Mount Gran; Elliot and Fleming, 2004). For more detail on this process with reference to observations at Allan Hills, see Airoldi et al. (2011).

**Gondwana Magmatism in the Jurassic**

The age, geochemistry, and geographic position of igneous rocks in the Antarctic and African continents during the Jurassic link the Ferrar large igneous province to the syn-
chronously emplaced Karoo igneous province (Heimann et al., 1994; Encarnación et al., 1996; Marsh et al., 1997; Elliot and Fleming, 2000; Polteau et al., 2010). This widespread magmatism was centered near the current location of the Weddell Sea, where the head of a mantle plume impinged on vast areas of southern Africa and Queen Maud Land, Antarcti-ca (Storey, 1995; Elliot and Fleming, 2000, 2004). Both subparallel dike arrays (e.g., Okavango giant dike swarm; Aubourg et al., 2008) and saucer-shaped sills in the western Karoo Basin, South Africa (Chevallier and Woodford, 1999), are exposed in these regions. The geometry of the shallow intrusive network in the Karoo province shows greater complexity than the Ferrar large igneous province, which may be attributed to tectonic conditions in that area. Giant dike swarms of the Karoo appear to have formed at a triple junction (Klausen, 2009). The distribution and geomet-ry of dikes in the western Karoo indicate a broadly distributed (200–400 km wide) zone of right-lateral shear; these dikes and accom-
panying sills are thought to have formed in a failed transform boundary setting (Chevallier and Woodford, 1999). Dikes exhibit complex relationships with surrounding saucer-shaped sills; they crosscut sills, feed multiple sills at different stratigraphic levels, and in places multiple dikes supply a single sill (Chevallier and Woodford, 1999). Additionally, adjacent saucer-shaped sills show evidence of contemporaneous injection (Galerne et al., 2008),

---

**Figure 13. Distribution of the basement sill (gray) in South Victoria Land (modified from Marsh, 2004) and rose diagram of strikes of individual sheets recorded from sheet swarms in South Victoria Land (SVL).**
and in some areas magma traveled vertically >1400 m between interconnected sills (Polteau et al., 2008a).

Like the Ferrar Dolerite, the intrusive complex in the western Karoo Basin lacks classic rift-intrusion structures and subparallel dike swarms. Both provinces were emplaced in thick sedimentary basins, and the emplacement of the sills is best explained by laccolith-type models (Johnson and Pollard, 1973; Polteau et al., 2008b; White et al., 2009). Saucer-shaped structures are abundant in the Karoo and at least locally present at certain crustal levels in the Ferrar, but ice cover limits exposure. Certainly, the distribution of shallow-level sill and sheet intrusions in areas of Coombs Hills and the NE arm of Allan Hills could resemble a saucer-shaped geometry (refer to fig. 4 in Airoldi et al., 2011) if there were more plan-view exposures like those available in the Karoo Basin, which cover areas >1 × 10³ km². Apart from aerial analysis by Elliot and Fleming (2008), which suggests that a saucer-shaped intrusion may be present on the northwest flank of Beardmore Glacier, we are unaware of observations of these sill geometries anywhere else throughout the province.

Regional Feeders

Despite the complex relationships observed between dikes and sills in the Karoo Province, the spatial coincidence of a thermal anomaly and Jurassic magmas in southern Africa and Queen Maud Land highlights that magma in these areas primarily originated from depth. From here, magma may have been distributed laterally by giant dike swarms (Aubourg et al., 2008), and it did move vertically at shallow crustal levels in interconnected sill networks (Polteau et al., 2008a). On the other hand, the broad-scale controls on magma transport in the laterally extensive Ferrar Province are poorly understood. Mapped and known Ferrar rocks form a long (3500 km) and narrow (160–320 km) belt in the Transantarctic Mountains that disappears beneath thick ice toward the pole and thinner ice over the West Antarctic rift basin. Geochemical evidence favors long-distance transport from areas in the Weddell Sea and/or Queen Maud Land via dikes or sills (Elliot et al., 1999; Ferris et al., 2003; Elliot and Fleming, 2008; Leat, 2008). However, the physical connection between Ferrar intrusions and those of Queen Maud Land remains enigmatic, and no large-scale feeders are known.

In the absence of such feeders, we assert that development of a 3500 × 320 km sill, such as that proposed by Leat (2008), would be unlikely considering: (1) the mechanical constraints on sill dimensions (Cruden and McCaffrey, 2002; Goulty and Schofield, 2008); and (2) the elongate geometry of the intrusion (11:1 length to width ratio). Furthermore, emplacement of a sill of these dimensions would be unfavorable in a massive basement where sills would be expected to spread radially. It would require the assistance of a preexisting, laterally continuous sedimentary basin like the Beacon Supergroup (Barret, 1982; Leat, 2008), but no regionally continuous sill has been recognized there. Petrologic evidence from South Victoria Land demonstrates that magma rose vertically from a basement source and then traveled outward as sills (Marsh, 2004), rather than flowing along the north-south axis expected in the long-distance sill transport scenario.

Magma transport via giant dike swarms within the basement is a feasible explanation (Fleming et al., 1997; Elliot et al., 1999; Elliot and Fleming, 2008); the elongate distribution is consistent with observations of giant dike swarms elsewhere, and these swarms are known to feed sill complexes over long distances (>1500 km from source; Ernst and Buchan, 1997; Buchan et al., 1998). In this case, a giant dike swarm was emplaced laterally from a source in the Weddell Sea region (Elliot et al., 1999; Leat, 2008). Propagation of such dikes is driven by both magma overpressures and the topographic effects associated with crustal doming above a plume head (Fialko and Rubin, 1999; Elliot and Fleming, 2000, 2004), and we infer that the great length of the province was controlled by the dimensions of the giant dike swarm, which intruded into either a failed Jurassic rift (Elliot et al., 1999) or preexisting structures trending parallel to the continental margin (discussed further in the following). Magma from this swarm rose into the Beacon Supergroup at various centers along the Transantarctic Mountains (i.e., Central Transantarctic Mountains, South Victoria Land, North Victoria Land; Elliot et al., 1999; Elliot and Fleming, 2004) and then, as demonstrated in South Victoria Land, spread outward as sills (Marsh, 2004).

A Jurassic Magmatic-Tectonic Regime

Considering both the length and total exposure of the Ferrar large igneous province, it seems remarkable that no regional or giant dike swarm is observed in the exposed upper 4 km of the plumbing system along the entire province. Even the contemporaneously emplaced Karoo Province exhibits dike swarms (some >1000 km in length) that reflect far-field tectonic conditions at the time of emplacement (Aubourg et al., 2008; Klausen, 2009). Consequently, the process of shallow intrusion in the Ferrar large igneous province appears to have been decoupled from any regional-scale processes that controlled the cross-continental distribution of the plumbing system. This discrepancy requires further investigation and may be explored within the context of the following scenarios.

Scenario 1. As suggested by Elliot and Fleming (2004), magma may have traveled through giant dike swarms in a rift located beyond the exposed area. The swarms may be hidden to the east or west of the Transantarctic Mountains below either: (1) the thick Antarctic ice sheet or (2) the Ross Sea. When magma encountered the Beacon Supergroup, it descended downward as sills into the central axis of the Transantarctic Mountains.

Scenario 2. Emplacement of the regionally extensive Ferrar sills created a tectonically stratified brittle crust, where the upper 4 km were locally detached, albeit over areas up to 1 × 10³ km², from the deeper-seated tectonic processes (Fig. 14). Depending on both the length scale and the thermal regime of the magmatic system in which they are contained, sills are known to maintain deformable interiors for long periods after emplacement (10⁵–10⁶ yr) (Marsh, 2007). Consequently, it is feasible that the regionally extensive Ferrar sills provided rheologically weak horizons, limiting mechanical coupling between the basement and overlying Beacon Supergroup (White et al., 2009). Emplacement of the sills would have detached the Beacon Supergroup from the far-field tectonic regime, creating a neutral tectonic setting in the upper few kilometers of the crust, where preexisting discontinuities, such as bedding, provided the dominant pathways for magma transport. Magma was supplied to the sill network by dike swarms situated at basement depths.

Tensile stresses related to dike propagation and arrest at shallow crustal levels in rift zones are typically accommodated via normal faulting in the overlying lithosphere (Rubin and Pollard, 1988; Buck et al., 2006; Rowland et al., 2007). However, there is little evidence for normal faulting in the central parts of the Ferrar large igneous province. So under this model, strain induced by deeper-seated dike injection must have been accommodated along border faults at the rift flanks (Elliot and Larsen, 1993). Today, these faults possibly lie hidden below the Ross Sea and/or the Antarctic plateau (Elliot and Fleming, 2004).

Scenario 3. Instead of magma emplacement into an extensional regime, magma propagated in a neutral tectonic setting and was primarily directed along preexisting structures trending subparallel to the East Antarctic margin. Analog and field studies reveal that low-viscosity
magma can actively propagate in faults and suture zones, even in compressional tectonic environments (Tibaldi, 2005; Galland et al., 2007). If structural anisotropies trending parallel to the East Antarctica margin were present in the Jurassic, then these structures could have guided a dike swarm within basement rock along the length of the province. The Ferrar Province extends a great length parallel to the paleo–Pacific margin, and, given the numerous Paleozoic and Mesozoic tectonic cycles affecting the margin prior to Ferrar magmatism (Storey et al., 1992; Encarnación and Gunrow, 1996; Goode et al., 2004), it is very probable that significant margin-parallel structures exist in the basement. The reactivation of basement structures in the Mesozoic and Cenozoic is locally supported by field observations and photogeological analysis of Hidden Valley, South Victoria Land (Jones, 1997); however, no Ferrar intrusions have been observed intruding these structures.

Of the models presented here, the latter two are considered more likely. Ferrar intrusions have not been detected geophysically in the McMurdo Sound or below the polar ice sheet (Chiappini et al., 2002). Xenoliths of Ferrar composition in Cenozoic volcanic deposits do not extend past the foothills of the Transantarctic Mountains (Elliot, 1992). Although such xenoliths may yet be found, this likely suggests that Ferrar magmas never extended farther east than the Ross Sea shores. Instead, petrologic evidence from Marsh (2004) indicates that magma rose near the center of the McMurdo Dry Valleys (Bull Pass; Fig. 2) and spread outward, rather than entering the region from its eastern or western flanks.

CONCLUSIONS

Intrusions of the Ferrar large igneous province in South Victoria Land, Antarctica, form an interconnected sheet-sill network for more than 4 km depth. This intrusive network supplied magma to the Mawson Formation volcanics and may have provided a conduit for the Kirkpatrick flood basalt lavas. These observations support the hypothesis that interconnected sills have the capacity to transport magma vertically and erupt at the surface. Field observations of sheet intrusions at Allan Hills and Terra Cotta Mountain indicate that subvertical sheets in the Ferrar large igneous province formed under local magmatic stresses in response to roof-lift during sill injection, rather than far-field tectonic controls. In particular, the lack of observable structures characterizing rift systems (i.e., regionally consistent normal faults and parallel dike swarms) suggests that the upper portions of the plumbing system were not influenced by an extensional tectonic regime.

ACKNOWLEDGMENTS

We acknowledge the University of Auckland Maori and Pacific Graduate Scholarship and the Natasha Divich Memorial Award for postgraduate funding to J.D. Muirhead. Antarctica New Zealand, Helicopters New Zealand, and a University of Auckland research grant (UARF 3607851) provided support for field activities. Assistance in the field was provided by Rob Dunn and Kimberly Wallace. We thank reviewers Olivier Galland and Bruce Marsh for their helpful comments. We are grateful to David Elliot for providing Figure 1 and Alexa Van Eaton for her help reviewing the manuscript.

REFERENCES CITED


Interconnected sills and sheet intrusions control shallow magma transport in the Ferrar large igneous province, Antarctica


White, J.D.L., Thordarson, T., McClintock, M.K., and Ross, P.-S., 2005, Cracking the lid—Dike emplacement above large sills of the Ferrar Province, Antarctica: Eos (Transactions, American Geophysical Union), v. 86, Fall Meeting supplement, abstract V23A–0690.


SCIENCE EDITOR: A. HOPE JAHREN
ASSOCIATE EDITOR: JEAN BÉDARD
MANUSCRIPT RECEIVED 20 NOVEMBER 2010
REVISED MANUSCRIPT RECEIVED 25 MARCH 2011
MANUSCRIPT ACCEPTED 6 APRIL 2011
Printed in the USA