The Great Eucrite intrusion of Ardnamurchan, Scotland: Reevaluating the ring-dike concept

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ABSTRACT

Ring-dikes are cylindrical sheet intrusions that develop at a subvolcanic level due to ascent of magma along steep outward-dipping ring fractures. Magma ascent is triggered by central block subsidence, and fully formed ring-dikes are composed of a flat-lying sill-like roof as well as steeply outward-dipping walls on all sides. The Great Eucrite of the Ardnamurchan Paleocene igneous complex, NW Scotland, is a spectacular gabbro intrusion that has been cited as one of the classic examples of a ring-dike for the past 70 yr. We combine field observations, detailed structural measurements of primary magmatic features, and anisotropy of magnetic susceptibility data in a reinvestigation of this intrusive body. Magmatic layering and macroscopic planar crystal arrangements dip inward, and magnetic lineations plunge consistently toward the center of the intrusion, in contrast to what would be expected for a ring-dike. We propose that the Great Eucrite ring-dike is in fact a lopolithic intrusion with an overall funnel-shape geometry. This conclusion brings into question the presence of three individual foci of activity in Ardnamurchan, purported to have shifted throughout the development of the complex. It also has significant implications for the status and structural evolution of other igneous complexes of the British Paleocene igneous province, which contain layered mafic intrusions currently regarded as ring-dikes.

Keywords: Great Eucrite, Ardnamurchan, lopolith, ring-dike.

INTRODUCTION

Caldera ring-fault development and associated subsidence of a central block are the dominant structural processes that allow the intrusion of ring-dikes (Roche et al., 2000). Ring faults are widely envisaged as steeply outward-dipping (reverse) structures, because models for ring-dike development require that subsidence of the central block is accommodated during collapse (Roche et al., 2000; Walter and Troll, 2001). Ring-dikes are therefore traditionally envisaged as having a bell-jar–like geometry, forming broadly cylindrical intrusions at shallow, subvolcanic levels (Fig. 1).

The igneous complexes of the British Paleocene igneous province represent the deeply dissected roots of major volcanoes in a region that was the site of intense igneous activity between ca. 60.5 and 58.7 Ma (Chambers et al., 2005). The British Paleocene igneous province is also where many of the original models for ring-dike emplacement were first developed (Richey and Thomas, 1930; Anderson, 1936). The Ardnamurchan igneous complex hosts the Great Eucrite, frequently referred to as the classic example of a wholly complete mafic ring-dike (Wager and Brown, 1968; Woodcock and Strachan, 2000; Bell and Williamson, 2002). This interpretation has never been seriously questioned since it was first proposed by Richey and Thomas (1930). Our study of magnetic fabrics of the Great Eucrite, combined with structural measurements on macroscopic, primary magmatic features, suggests that magma emplacement was not parallel to outward-dipping ring-fractures (Fig. 1), a key criterion in the identification of ring-dikes (Anderson, 1936; Roche et al., 2000).

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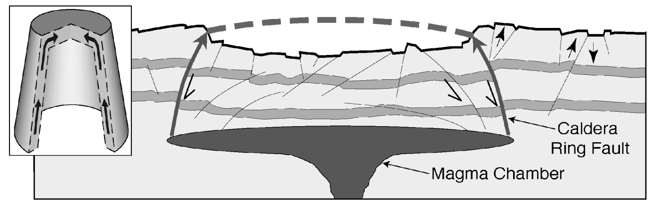

Figure 1. Schematic diagram showing subvolcanic level and ring-fault system along which ring-dikes are emplaced (after Walter and Troll, 2001). Inset: Bell-jar geometry of typical ring-dike intrusion and expected magma flow directions during emplacement.

Three distinct foci of activity have been recognized in the Ardnamurchan complex (centers 1, 2, and 3; Fig. 2). Each of these is dominated by intrusive mafic rocks that were emplaced either as concentric, inward-dipping sets of cone sheets related to doming and extension, or as larger annular intrusions historically interpreted as outward-dipping ring-dikes associated with central subsidence (Richey and Thomas, 1930). The areal extent of center 3 is dominated by the Great Eucrite (~70%), corresponding to the area (~10 km^2) occupied by gabbros 1–4 of this study (Fig. 2). The Great Eucrite wholly encompasses a suite of smaller, arcuate gabbro bodies, which have been interpreted as partial ring-dikes, and a central tonalite body, which is considered to be a late-stage intrusion into these arcuate gabbros (Richey and Thomas, 1930).

LITHOLOGICAL RELATIONSHIPS AND PRIMARY MAGMATIC FEATURES

The term eucrite is given to gabbroic rocks containing plagioclase that is bytownitic to anorthitic in composition (An_{70}–An_{100}). Detailed

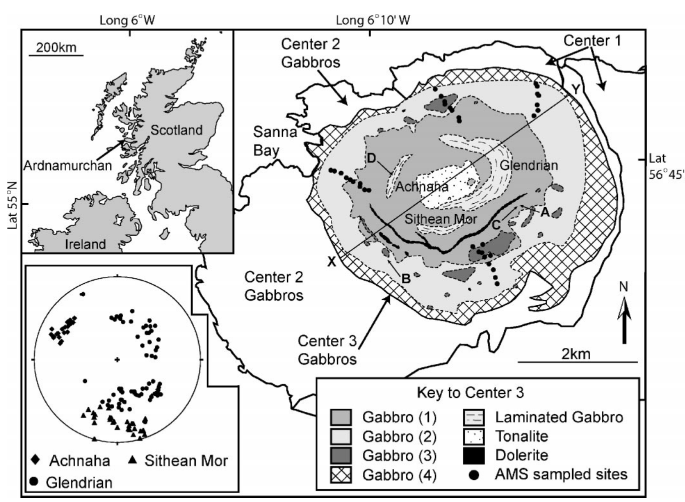

Figure 2. Location map for centers 1, 2 (unornamented), and 3 of Ardnamurchan intrusive complex, together with position of anisotropy of magnetic susceptibility (AMS) sampling traverses. A–D are localities of photographs in Figure 3. Inset bottom left: Equal-area projections illustrating poles to lamination planes for Achnaha, Glendrian, and Sithean Mor areas.

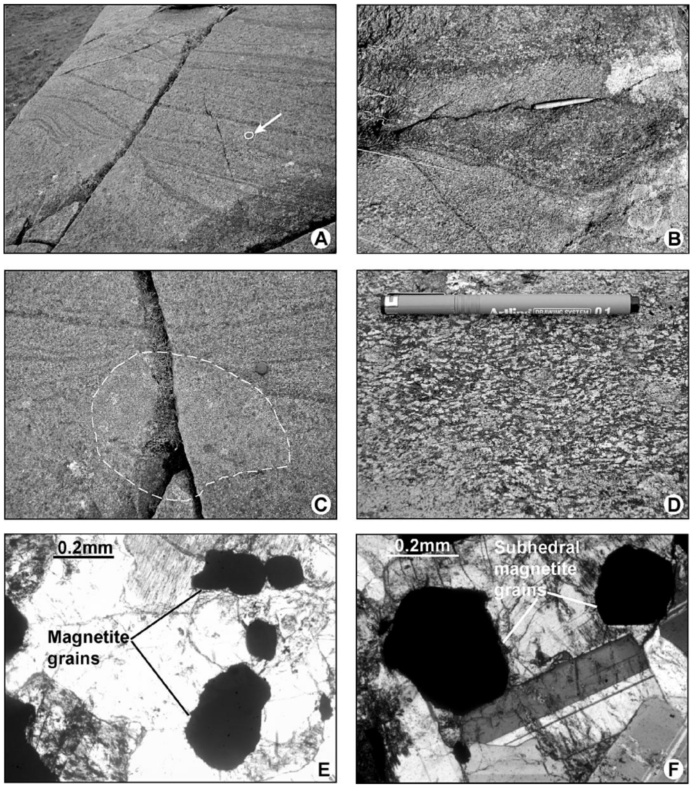

Figure 3. A: Well-developed magmatic layering in gabbro 1 (lens cap for scale is highlighted). B: Slump structure in layered gabbro 2. C: Magmatic layers draping block (highlighted) in gabbro 1 (lens cap for scale above highlighted block). D: Strong lamination of tabular plagioclase feldspars in Achnaha laminated gabbro. E and F: Large subhedral magnetite grains in Great Eucrite gabbro.

remapping of the Great Eucrite of Ardnamurchan suggests it includes four further, distinct petrological facies of gabbro, distinguished on textural and mineralogical grounds, and traceable around the full circumference of the intrusion (Fig. 2). The two most common lithologies are a dark-gray, partially layered olivine gabbro (1) that is surrounded by an extremely heterogeneous, brownish light-gray, partially layered olivine gabbro (2). Both of these rocks contain variably sized xenoliths and rafts (from <1 m up to 1 km in length) of an olivine-glomerocrystic, unlayered gabbro (3). A highly altered, unlayered, olivine-deficient gabbro (4) is found around the outer margin of the intrusion.

Magmatic layering is common in gabbros 1 and 2, composed of thin sequences of plagioclase-rich layers alternating with olivine-rich layers, and less commonly pyroxene-rich layers (Fig. 3A). Individual layer thicknesses rarely exceed 25 cm, and the maximum thicknesses of sequences of layers is typically ~10 m. Layer planes consistently strike parallel to the outer margins of the Great Eucrite, can be traced for up to 20 m laterally, and generally dip inward toward the center of the intrusion at 40–60°. Magmatic sedimentary structures are present and are associated with the layering. These include slump structures, fallen-blocks that affect layering (Figs. 3B and 3C), and graded bedding.

Three arcuate areas of a fifth olivine-deficient, plagioclase-rich gabbro are observed at the center of the pluton, at Achnaha, Sithean Mor, and around Glendrian (Fig. 2). This gabbro is characterized by a very common, sometimes intensely developed, igneous lamination defined by the planar arrangement of tabular plagioclase crystals (Fig. 3D). Earlier work (Richey and Thomas, 1930) referred to these rocks as fluxion gabbros, in particular the Sithean Mor and Glendrian laminated zones, and interpreted them as distinct fluxion gabbro ring-dikes.

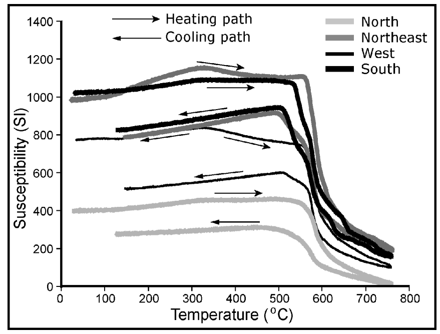

Figure 4. Susceptibility vs. temperature plots showing heating and cooling paths for selected Great Eucrite samples (one from each traverse).

However, no chilled margins or intrusive contacts have been observed between these bodies and gabbro 1, and their lamination always strikes parallel to their outer margins and consistently dips toward the center of the pluton (Fig. 2).

Poor exposure makes contact data from around the outer margin of the Great Eucrite extremely rare, but one boundary with Jurassic sediments in the north of the peninsula is traced laterally for ~15 m and is observed to dip inward at ~50°. Two late bodies intrude the center 3 gabbros (Fig. 2). The first of these is a thin, fine-grained, sheet-like dolerite intrusion extensively net-veined with a younger microgranite. Contact measurements for this intrusion show that it also dips inward at 50–70° around its circumference. The second is the central tonalite that displays a steeply outward-dipping intrusive contact and a chilled margin toward the laminated gabbro.

MAGNETIC FABRIC ANALYSIS

The anisotropy of magnetic susceptibility (AMS) of a rock sample is described by a second rank tensor (K) and can be visualized as a susceptibility ellipsoid (Tarling and Hrouda, 1993; Dunlop and Özdemir, 1997). K is specified by six parameters that define the magnitude and orientation of the three principal susceptibilities ($K_1 \geq K_2 \geq K_3$) of the ellipsoid. These principal susceptibilities are used to derive alternative combinations of magnitude parameters, such as the bulk susceptibility [$K_{mean} = (K_1 + K_2 + K_3)/3$], the magnetic lineation [$L = (K_1–K_3)/K_{mean}$], and magnetic foliation [$F = (K_2–K_3)/K_{mean}$]. The total anisotropy ($H = L + F$) is a measure of the strength of the magnetic fabric (Owens, 1974). The relative strength of L to F is used to classify the shape of the ellipsoid as prolate, triaxial, or oblate.

AMS measurements were carried out on drilled cores from a set of 42 field-orientated gabbro block specimens using an AGICO KLY3 Kappabridge, which measures specimen susceptibility axes to within ±2° (95% confidence limits). Block sampling was carried out at 80–100 m intervals along four radial traverses (8–10 sampled stations each), which were approximately perpendicular to the outer margin of the Great Eucrite (Fig. 2). Ten to fourteen subsamples were then drill-cored from each block, and site mean tensor data were calculated from the measurements (Owens, 2000).

The data revealed bulk susceptibilities of 7.9×10^{-3} to 3.3×10^{-2} SI in the Great Eucrite. These values suggest that the susceptibility (and therefore the AMS) in these samples is overwhelmingly due to magnetite, in volume concentrations of up to ~1% (Balsley and Buddington, 1958). This has been corroborated by measurement of the temperature dependence of susceptibility using an AGICO CS-3 furnace, which also shows the dominance of magnetite with Curie temperatures of 575–580 °C (Fig. 4). Reflected and transmitted light microscopy indicates that magnetite occurs as large (generally >150 μm) subhedral grains throughout the rock (Figs. 3E and 3F).

In magnetite-bearing rocks, susceptibility anisotropy normally arises from the shape-preferred orientation of inequant grains (with the maximum susceptibility in the direction of maximum long-axis concentration). The anisotropic distribution of grains may also influence

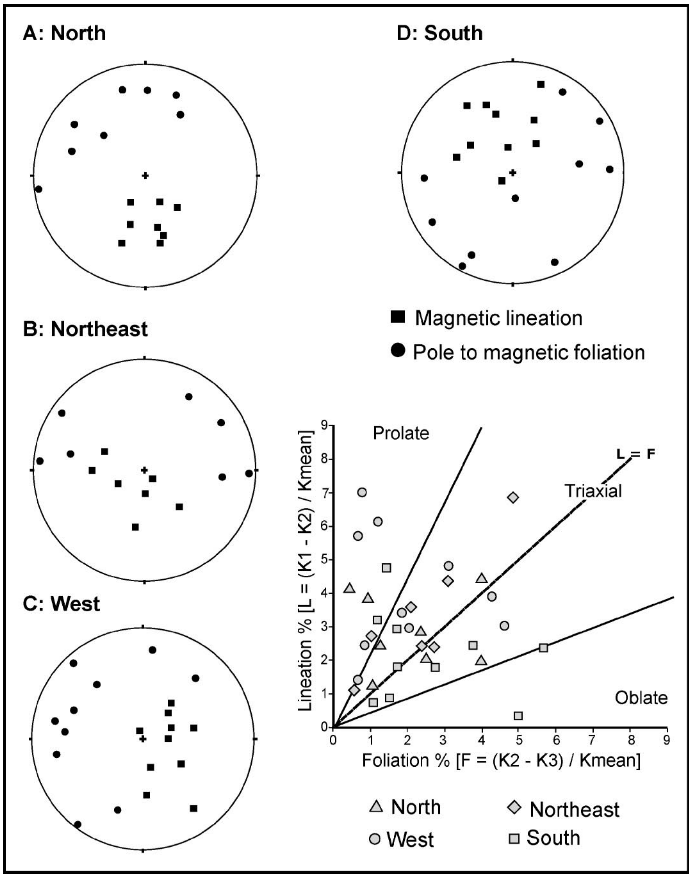

Figure 5. A–D: Equal-area projections illustrating magnetic fabric data for each of four traverses. E: Subdivision of anisotropy of magnetic susceptibility (AMS) data from Great Eucrite into prolate, triaxial, and oblate fabrics on basis of an *L-F* plot.

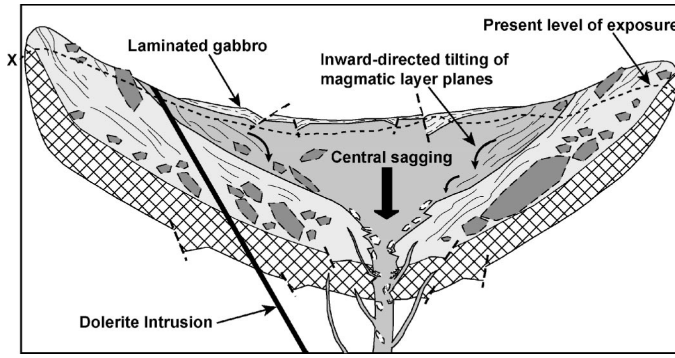

Figure 6. Schematic diagram along the line *X-Y* (see Fig. 2) showing proposed (pre-tonalite) form of center 3 gabbro intrusion and its magma flow planes as suggested by structural data and magnetic fabric results.

the AMS if the magnetite concentration is sufficiently high and the distribution of magnetite sufficiently nonuniform (Hargraves et al., 1991; Bouchez, 1997; Launeau and Cruden, 1998). However, the volume concentration of magnetite in rocks of the Great Eucrite, for which *H* is typically 5% (range 2%–9%), is sufficiently low for it to be unlikely that distribution anisotropy is a significant contributor to the fabric.

The AMS results are summarized in Figure 5. For all but one of the blocks sampled, the susceptibility ellipsoids are triaxial to prolate in shape (Fig. 5E), indicating that the magnetic lineation (K_1) is the most clearly defined component of the magnetic fabric overall. The directions of this axis are remarkably consistent, generally plunging toward the center of the intrusion at 40–70° (Fig. 5A–D). The K_1 axis also exhibits a weak steepening-inward trend on both the southern and northern traverses (see the GSA Data Repository[1]). The magnetic foliation also dips inward without exception, though the strikes are not as consistent, trending either parallel or slightly obliquely to the outer margins of the intrusion at different stations (Fig. 5A–D).

DISCUSSION

The presence of an inward-dipping intrusive contact along the northern margin of the Great Eucrite strongly suggests that the intrusion does not have the classic bell-jar geometry of a ring-dike. The well-developed magmatic layering in gabbros 1 and 2 exhibits sedimentary structures that suggest that layering developed from magmatic flow and associated fluid-dynamic processes. Such localized, gravity-controlled layering is generally considered to form due to the action of crystal-laden density currents on horizontal to gently sloping magma-mush interfaces that are often parallel or subparallel to the outer walls of the intrusion (Wager and Brown, 1968). The fact that layering typically dips comparatively steeply toward a central focal point in the intrusion suggests a significant degree of syn- to postdepositional tilting of basal surfaces toward the center of the pluton.

Magnetic fabrics in the Great Eucrite are dominantly triaxial to prolate, with a clearly defined K_1 axis in the direction of flow described above. These fabrics are unusual as flow fabrics in that they are not oblate (Rochette et al., 1999) and the magnetic foliation is not always coincident with layering. This inconsistency may result from abnormal or complex fabrics, in the sense of Rochette et al. (1999), because of the strongly prolate nature of some of the susceptibility ellipsoids. However, the consistent inward plunge of the magnetic lineation at 40–70° (approximately downdip on layering) in the Great Eucrite suggests that it may be validly used as a structural element. We suggest, therefore, that the magnetic lineation may also have developed due to the sedimentation processes described here, and tilted inward simultaneously with layering.

Evidence from contact relations, magmatic layering, and magnetic fabrics suggests that the center 3 gabbros comprise a lopolithic, composite pluton, of which the Great Eucrite forms a component part (Fig. 6). This is in agreement with one of the principal findings of Wager and Brown (1968) that layered mafic and ultramafic intrusions are predominantly funnel-shaped lopoliths. Rotation of originally subhorizontal, magnetic lineations has been described by Cowan (1999) in the Sudbury igneous complex, where it may have been related to a cantilever-type, syn- to postemplacement, inward-tilting of the intrusion floor (Cruden, 1998). Indeed, such centrally directed sagging and inward-dipping magmatic layering is well documented for layered mafic-ultramafic lopoliths worldwide, e.g., the Bushveld complex (Carr et al., 1994), the Rum Layered Suite (Emeleus et al., 1996), and the Skaergaard intrusion (McBirney and Nicolas, 1997). In addition, the weakly developed steepening-inward trends observed in the northern and southern traverses bear similarities to documented examples of inward-steepening structures attributed to central sagging in a number of mafic-felsic complexes (Wiebe and Collins, 1998).

An important line of evidence used by Richey and Thomas (1930) for their ring-dike model was the reported outward-dipping nature of the late dolerite sheet. The contact data measured for the dolerite sheet in this study indicate that it has the form of a large inward-dipping cone sheet, removing another argument in favor of the ring-dike model for center 3 gabbros. We consider the three arcuate zones of laminated

[1]GSA Data Repository item 2006036, plot of K1 axes vs. distance towards the center of the Great Eucrite, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA

(fluxion) gabbro to be an upper facies of gabbro in the lopolith, in which an originally horizontal to subhorizontal igneous lamination was rotated progressively inward together with the magmatic layering and the magnetic lineations (Fig. 6). A chilled margin and intrusive contact toward the gabbros suggest the central tonalite body represents a late intrusion into center 3.

The interpretation of the center 3 gabbros as an intrusion fed from a central source has significant implications for the presence of the three temporally and spatially distinct foci of activity purported to have shifted throughout the evolution of the Ardnamurchan complex (Richey and Thomas, 1930). K-Ar age studies carried out on the gabbro intrusions of centers 2 and 3 showed that very little time ($\leq$0.2 m.y.) passed between emplacement of both sets of intrusions, and suggest that the center 2 gabbros may actually be the younger intrusions (Mitchell and Reen, 1973). If the layered gabbros of center 2 are also lopolithic in geometry, then the concept of migrating centers of activity may be seriously flawed. In that case, the geometry of the Ardnamurchan intrusions would be best envisaged as a vertical stack of offset funnel-shaped bodies, with the gabbros of center 2 comprising a younger body underlying those of center 3.

The historical importance of the British Paleocene igneous complexes in laying the foundation for understanding the emplacement mechanisms of shallow crustal-level intrusions elsewhere is well documented (see Woodcock and Strachan, 2000, and Bell and Williamson, 2002, for reviews). In particular, the concept of ring-dike intrusion and central subsidence of caldera volcanoes has been applied to subvolcanic geological problems worldwide for decades (Anderson, 1936; Wager and Brown, 1968; Roche et al., 2000), as it provides critical information regarding the way magma system emplacement and evolution occurs, in particular the physical and chemical interaction between the subsiding central block and the underlying magma chamber. However, even though ring-dikes are emplaced at shallow (2–3 km) crustal levels (Saunders, 2004), good examples are rarely well exposed, because they tend to be obscured by sedimentary volcanic caldera infill and other intrusive bodies with different emplacement mechanisms and three-dimensional geometries, e.g., cone sheets, laccoliths, and lopoliths.

We have carried out the first magnetic fabric and structural study of one of the classic British Paleocene igneous province ring-dikes, and propose instead that it has the geometry of a lopolith or funnel-shape intrusion. This raises the prospect that the layered, mafic-ultramafic ‘‘ring-dikes’’ of the other Paleocene igneous complexes, such as Carlingford (NE Ireland) and the Isles of Mull and Skye (Scotland), are lopoliths as well. The implication for British Paleocene igneous complexes is that a reappraisal of the mechanisms of emplacement and structural architecture of their intrusive elements, employing modern methods of igneous fabric analysis together with other advanced geophysical techniques e.g., three-dimensional seismic modeling (cf. Malthe-Sorenssen et al., 2004), is now required. To be identified as ring-dikes, in the British Paleocene igneous province and elsewhere, intrusions must be shown to have intruded along a vertical to outward-dipping concentric ring-fracture and to have been accompanied by block subsidence related to caldera collapse.

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REFERENCES CITED

Anderson, E.M., 1936, The dynamics of the formation of cone-sheets, ring-dikes, and cauldron-subsidence: Proceedings of the Royal Society of Edinburgh, v. 56, p. 128–156.

Balsley, J.R., and Buddington, A.F., 1958, Iron-titanium oxide minerals, rocks and aeromagnetic anomalies of the Adirondack area, New York: Economic Geology and the Society of Economic Geologists Bulletin, v. 53, p. 777–805.

Bell, B.R., and Williamson, I.T., 2002, Tertiary igneous activity, *in* Trewin, N.H., ed., The geology of Scotland (4th edition): London, Geological Society of London, p. 371–408.

Bouchez, J.L., 1997, Granite is never isotropic: An introduction to AMS studies of granitic rocks, *in* Bouchez, J.L., Hutton, D.H.W., and Stephens, W.E., eds., Granite: From segregation of melt to emplacement fabrics: Dordrecht, Kluwer Academic Publishers, p. 95–112.

Carr, H.W., Groves, D.I., and Cawthorn, R.G., 1994, The importance of synmagmatic deformation in the formation of Merensky Reef potholes in the Bushveld complex: Economic Geology and the Society of Economic Geologists Bulletin, v. 89, p. 1398–1410.

Chambers, L.M., Pringle, M.S., and Parrish, R.R., 2005, Rapid formation of the Small Isles Tertiary centre constrained by precise ^{40}Ar/^{39} Ar and U-Pb ages: Lithos, v. 79, p. 367–384.

Cowan, E.J., 1999, Magnetic fabric constraints on the initial geometry of the Sudbury igneous complex: A folded sheet or basin shaped igneous body?: Tectonophysics, v. 307, p. 135–162.

Cruden, A.R., 1998, On the emplacement of tabular granites: Geological Society of London Journal, v. 155, p. 853–862.

Dunlop, D.J., and Özdemir, O., 1997, Rock magnetism, fundamentals and frontiers: Cambridge, Cambridge University Press, 573 p.

Emeleus, C.H., Cheadle, M.J., Hunter, R.H., Upton, B.G.J., and Wadsworth, W.J., 1996, The Rum Layered Suite, *in* Cawthorn, R.G., ed., Layered igneous rocks: Amsterdam, Elsevier, p. 403–440.

Hargraves, R.B., Johnson, D., and Chan, C.Y., 1991, Distribution anisotropy: The cause of AMS in igneous rocks?: Geophysical Research Letters, v. 18, p. 2193–2196.

Launeau, P., and Cruden, A.R., 1998, Magmatic fabric acquisition mechanisms in a syenite: Results of a combined anisotropy of magnetic susceptibility and image analysis study: Journal of Geophysical Research, v. 103, p. 5067–5089.

Malthe-Sorenssen, A., Planke, S., Svensen, H., and Jamtveit, B., 2004, Formation of saucer-shaped sills, *in* Breitkreuz, C., and Petford, N., eds., Physical geology of high-level magmatic systems: Geological Society [London] Special Publication 234, p. 215–227.

McBirney, A.R., and Nicolas, A., 1997, The Skaergaard layered series: Part III. Dynamic layering: Journal of Petrology, v. 38, p. 569–580.

Mitchell, J.G., and Reen, K.P., 1973, Potassium-argon ages from the Tertiary ring complexes of the Ardnamurchan Peninsula, western Scotland: Geological Magazine, v. 110, no. 4, p. 331–340.

Owens, W.H., 1974, Mathematical model studies on factors affecting magnetic anisotropy of deformed rocks: Tectonophysics, v. 24, p. 115–131.

Owens, W.H., 2000, Statistical applications to second-rank tensors in magnetic fabric analysis: Geophysical Journal International, v. 142, p. 115–131.

Richey, J.E., and Thomas, H.H., 1930, The geology of Ardnamurchan, northwest Mull and Coll: Memoir of the Geological Survey [Scotland], HMSO, 393 p.

Roche, O., Druitt, T.H., and Merle, O., 2000, Experimental study of caldera formation: Journal of Geophysical Research, v. 105, p. 395–416.

Rochette, P., Aubourg, C., and Perrin, M., 1999, Is this magnetic fabric normal? A review and case studies in volcanic formations: Tectonophysics, v. 307, p. 219–234.

Saunders, S.J., 2004, The possible contribution of circumferential fault intrusion to caldera resurgence: Bulletin of Volcanology, v. 67, p. 57–71.

Tarling, D.H., and Hrouda, F., 1993, The magnetic anisotropy of rocks: London, Chapman and Hall, 217 p.

Wager, L.R., and Brown, G.M., 1968, Layered igneous rocks: Edinburgh, Oliver and Boyd, 588 p.

Walter, T.R., and Troll, V.R., 2001, Formation of caldera periphery faults: An experimental study: Bulletin of Volcanology, v. 63, p. 191–203.

Wiebe, R.A., and Collins, W.J., 1998, Depositional features and stratigraphic sections in granite plutons: Implications for the emplacement and crystallization of granite magma: Journal of Structural Geology, v. 20, p. 1273–1289.

Woodcock, N., and Strachan, R., 2000, Geological history of Britain and Ireland: Cambridge, Blackwell Science, 423 p.

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