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Anisotropy of magnetic susceptibility studies in Tertiary ridge-parallel dykes (Iceland), Tertiary margin-normal Aishihik dykes (Yukon), and Proterozoic Kenora–Kabetogama composite dykes (Minnesota and Ontario)

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Abstract

Mafic dykes of different ages were collected from three different tectonic settings and analyzed using anisotropy of magnetic susceptibility (AMS) as a proxy for magmatic flow during intrusion. In Iceland, ridge-parallel basaltic dykes were sampled on each side of the active tectonic boundary. The dykes are <10 m wide along a 1–2 km strike, and are the result of a single intrusion from 1–2 km deep magma chambers in oceanic crust. Thirteen samples were collected (7 N. American plate; 6 European) and 153 cores were analyzed by AMS and preserve a vertical K_{max} orientation indicating vertical emplacement. The Eocene Aishihik dyke swarm intrudes the Yukon–Tanana terrane in the Yukon province, Canada over an area ~200 by 60 km. These dykes were intruded normal to the accretionary margin, are porphyritic andesites, and have an intermediate geochemical signature based on major and trace element analyses. Ten dykes were sampled and 111 cores analyzed using AMS, and the dykes preserve a vertical K_{max} orientation, indicating intrusion was vertical through ~30 km of continental crust. The 2.06 Ga Kenora–Kabetogama dykes in northern Minnesota and western Ontario crosscut a variety of Archean terranes (thickness ~50 km) in a radiating pattern. The unmetamorphosed basaltic dykes are 1–120 m wide, 10–110 km in length, are vertical in orientation and can be grouped as either being single intrusion or multiple intrusion (composite) dykes. AMS data preserve a vertical K_{max} orientation for the southerly locations (2 dykes, $n=53$) and horizontal K_{max} for the remainder to the northwest (15 dykes, $n=194$). Maximum magnetic susceptibility axes (4 dykes, $n=92$) for composite dykes are scattered and yield inconsistent flow directions with regard to the dyke margin. Almost all of our results are "normal" in that, the magnetic foliation (the plane containing K_{max} and K_{int}, normal to K_{min}) is parallel to the dyke planes, which gives us confidence that the magnetic lineations (i.e., K_{max} orientations) are parallel to magmatic flow.

Keywords: Mafic dykes; Intrusion mechanisms; AMS; Tectonics

1. Introduction

Intrusion of magmatic fluids into crustal rocks has always been a mechanical paradox contrasting hot weak fluids being forced into cold, stiff host rocks with minimal metamorphic alteration or deformation in the host. Field and petrographic observations in dyke swarms are often complex (forking directions, cryptic layering in composite dykes, xenolith alignment, etc.; Philpotts and Asher, 1994) and indicate multiple intrusive flow directions. Knight and Walker (1988) and Ernst (1990) have pioneered the application of AMS methods to Proterozoic mafic dyke swarms (Ernst and Baragar, 1992; Ernst and Duncan, 1995) as a proxy for primary magmatic flow directions during dyke intrusion. AMS studies on dyke swarms in other tectonic settings have been completed: Hawaii (Knight and Walker, 1988); the Troodos ophiolite (Staudigel et al., 1992); Makhtesh Ramon, Israel (Baer, 1995)

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and the Independence dyke swarm, California (Dinter et al., 1996) and others (see Cañón-Tapia, 2004 for a recent review). A variety of complicating factors are now recognized, including the “inverse” AMS of single-domain magnetite (Rochette et al. 1992; Ferre, 2002; Potter and Stephenson, 1988), the “distribution anisotropy” of clusters of magnetic grains (Stephenson, 1994; Hargraves et al., 1991), non-flow-parallel grain alignment by viscous fluid flow (Cañón-Tapia and Chávez-Álvarez, 2004), and tectonic overprinting of primary flow fabric (Park et al., 1988). Aware of these caveats, our goal in this study was to use the AMS technique to document igneous flow fabrics in the Proterozoic Kenora–Kabetogama swarm in cratonic North America (Archean Superior province; ~50 km thick) and compare this with Eocene dykes in an accreted terrane (Yukon–Tanana terrane; ~30 km thick), and with ridge-parallel dykes in thin, active Iceland (30 km thick, with magma chambers at 1–5 km depth) along the Mid-Atlantic ridge.

2. Methods

2.1. Magnetic instrumentation

Oriented hand samples (Iceland, Aishihik, KK) or cores (KK, some composite dykes) were collected from the various field locations, and oriented cores (or cubes) were prepared for AMS analysis (Table 1; Tauxe et al., 1998). The “Roly-Poly” is a low-field AC magnetic susceptibility bridge with an automated sample handler for determining anisotropy of susceptibility at room temperature, and is housed at the Institute for Rock Magnetism at the University of Minnesota. An alternating current in the external “drive” coils produces an alternating magnetic field in the sample space with a frequency of 680 Hz and an amplitude of up to 1 mT. The induced magnetization of a sample is detected by a pair of “pickup” coils, with a sensitivity of 1.2E−6 SI volume units. For anisotropy determination, a sample is rotated about three orthogonal axes, and susceptibility is measured at 1.8° intervals in each of the three measurement planes. The susceptibility tensor is computed by least squares from the resulting 600 directional measurements. Very high precision results from the large number of measurements; in most cases principal axis orientations are reproducible to within two degrees, and axial ratios to within about 1%.

Table 1
AMS results

Sample	Dykes sampled	$n=$	Anisotropy (%)	Lineation	Foliation
Iceland basaltic dykes	13	153	14.9	11.86	3.16
Aishihik dykes, Yukon	11	111	13.65	7.09	6.43
Kenora–Kabetogama dykes	21				
Single intrusion	17	247	14.21	3.14	2.06
Composite intrusions	4	92	11.9	7.6	6.8

Explanation: anisotropy ($K_{max}-K_{min}/K_{mean}$); lineation ($K_{max}-K_{int}/K_{mean}$); foliation ($K_{int}-K_{min}/K_{mean}$) for the Roly-Poly instrument.

2.2. X-ray fluorescence

Eleven of the Aishihik Lake dyke samples were analyzed for major and trace element composition using X-ray fluorescence as there was no geochemical data on these intrusions. Samples were split with a vise wedge and only pieces lacking weathered or saw-marked edges were selected to be used in XRF analyses. Powders were prepared by further splitting the sample and reducing these pieces to a fine powder in a Spex 8510 Shatterbox. The use of pre-contaminated bowls (iron for trace element and tungsten for major element powders) reduced the chance of cross contamination between the samples.

Pressed powder pellets were prepared for trace element analyses by mixing exactly 10 g of rock powder with 15 drops of 2% polyvinyl alcohol and pressing the mixture into pellets on a stainless steel mold under a pressure of 6 tons. Major elements were prepared by first heating approximately 10 g of each major element powder to 1000 °C to drive off all water. The amount of water lost in heating (loss on ignition) was recorded after samples had cooled and these numbers were taken into account in the reporting of element totals. Exactly 1 g of dried powder was mixed with 5 g lithium metaborate/tetraborate flux and 0.1 g NH_3NO_4. Once mixed, the powder was placed in a platinum crucible and 2 drops of HBr were added. The crucibles were heated on a Spex Fluxy until the material was molten, then poured into a platinum mold creating a homogenous glass disk. The pellets and beads were analyzed by a Phillips PW-2400 XRF.

3. Field relations and results

3.1. Iceland ridge-parallel swarm

Iceland is one of the best-exposed and best-studied geological settings in the world, combining a mid-ocean ridge, a hotspot plume, active glaciation, and little vegetation covering the rocks which range from 16–0 Ma (Gudmundson and Kjartansson, 1996). The interplay of these geologic processes results in some very complex local geodynamics, as recorded by a variety of methods: seismicity and focal mechanism solutions, fault slip data, GPS and borehole strainmeter surveys, tiltmeter-elevation change and gravity surveys, and hydrofracture and overcoring measurements. Most recently, Linde et al. (1993; Mt. Hekla) and Stefansson et al. (1993; South Iceland Lowland project), have made significant advances in monitoring and predicting both volcanic eruptions and destructive seismic events, respectively. Dyke intrusion has been observed seismically (Einarsson and Brandisdottir, 1980) and studied extensively by Sigurdsson (1980), Gudmundsson and Brynjolfsson (1993) and Paquet et al. (2007).

Thirteen single-intrusion basaltic dykes were sampled around Iceland and all but one (sample 4) strikes parallel to the ridge axis (Fig. 1; site data). The dykes are generally <1 m wide and can be traced a few tens of meters along strike. In ten