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Research paper

Rock magnetic stratigraphy of a mafic layered sill: A key to the Karoo volcanics plumbing system

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Abstract

The Insizwa sill is an ~1 km-thick subhorizontal layered mafic intrusion and part of the Karoo Large Igneous Province in South Africa. This well-exposed intrusion consists of several superimposed petrologically and geochemically distinct units. Magnetic methods were used to study the intrusion in order to constrain the physical processes active in these types of bodies during crystallization. Rock magnetism studies indicate that within different petrologic units bulk susceptibility is controlled by primary magnetite (with minor pyrrhotite) and/or paramagnetic minerals (olivine, pyroxene). New magnetic data based on 659 specimens obtained from 3 vertical borehole cores, each spaced 5 km apart, confirm the prominent vertical zonation in low field magnetic susceptibility (K_{lf}), degree of anisotropy (P_{j}) and orientation of the anisotropy of magnetic susceptibility (AMS) axes. The magnetic susceptibility correlates very well with petrographic units and the lateral continuity of magnetic units between boreholes is very consistent. Petrologic units with high, but variable, K_{lf}, also show moderate anisotropy and dominantly vertical foliations. We interpret these patterns to result from inverse fabrics from single domain magnetite. The degree of anisotropy is low in petrologic units with low K_{lf}, which also show shallowly dipping magnetic foliations. We interpret that the magnetic properties of these units are dominated by the paramagnetic minerals. These low K_{lf} petrologic units also show no systematic increase in K_{lf}, suggesting that only minor differentiation is occurring in these units. The dataset derived from 2 surface sampling traverses are consistent with borehole core AMS data, showing a pattern of dominantly steep magnetic foliation and variably plunging magnetic lineation with a NW–SE trend.

Keywords: AMS; magnetic susceptibility; Karoo; Insizwa; gabbro

1. Introduction

Studies of Large Igneous Provinces (LIPs) have commonly focused on the extrusive volcanic rocks, and placing these in a plate tectonic context (Coffin and Eldhom, 1992; Mahoney and Coffin and references therein, 1997; Ernst and Buchan, 2003). Given that a mantle source is required for the generation of basaltic volcanism, much of the work has focused on detailed geochemical studies and particularly on the depth of the magma source region (White and McKenzie, 1995; White, 1997; Marques et al., 1999; Riley et al., 2003). Significantly less work has focused on the chambers from which these magmas were extracted. Deep-seated magma chambers are generally unavailable for direct study. In contrast, the conduits and staging chambers are locally exposed as networks of dikes and large sills, respectively, which are ubiquitous components of LIPs.

The dikes and large sills provide critical information about the magma frozen in conduits and staging chambers (e.g., Raposo, 1997; Archanjo et al., 2000; Correa-Gomes et al., 2001; Callot et al., 2001; Aspler, 2002; Archanjo et al., 2002; Callot and Geoffroy, 2004; Middleton et al., 2004; Féménias et al., 2004). Geochemical studies of the crystallized bodies are instructive for a variety of reasons. First, they determine the magma source, specifically indicating a mantle source for

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many LIPs. Second, geochemical techniques allow correlation between extrusive flows and intrusive bodies. Third, different magma pulses within a single intrusive body can be distinguished (Cawthorn et al., 1988, 1991; Marsh et al., 2003, Cawthorn and Kruger, 2004). These studies have differentiated between open-systems, which are supplied by multiple batches of magma, and closed systems, in which crystallization occurs after a single magma pulse.

In contrast, the physical processes occurring in these magma chambers are relatively poorly known. These physical processes (flow segregation, crystal settling, magma chamber recharge, magma mixing during initial infilling; Naslund and McBirney (1996)) have direct effects on the chemistry and physical evolution of these magma chambers. Since the extrusive component of LIPs is supplied by these magma staging chambers, interpretations of the geochemical properties of the extrusive rocks require an understanding of the physical processes occurring within these staging chambers — sills (Marsh, 2004a,b).

Studies of physical properties and rock fabrics can be used in these layered mafic sills to corroborate and expand upon geochemical analysis. We utilize rock magnetic properties to investigate these bodies. Specifically, variation in magnetic properties can be used to identify: 1) distinct pulses of magma; 2) the physical processes of layer formation; and 3) determine lateral continuity of recognizable petrologic layers. Magnetic analysis also provides information about rock fabric. This fabric data provides additional information about magma flow direction and formation of layering.

We applied this approach to the Insizwa sill, which is part of the Karoo Igneous Province in South Africa (Cox, 1970; Eales et al., 1984; White, 1997). The magnetic properties corresponded to petrologically and geochemically determined layers, allowing us to determine the lateral extent of these units between field outcrops and three drill cores. Further, individual petrologic units can be broken into sub-units using variations in magnetic properties. Variation in magnetic properties allows us to document that the sill formed by multiple pulses of magma, corroborating earlier geochemical work (Cawthorn et al., 1988, 1991; Maier et al., 2002; Marsh et al., 2003; Cawthorn and Kruger, 2004). Last, variations in magnetic properties can be used in specific cases to interpret whether differentiation occurs within a particular petrologic horizon.

2. Geology of the Insizwa sill

2.1. Karoo Igneous Province

The Karoo Igneous Province of southern Africa is one of the largest, oldest and best exposed of the Gondwana tholeiitic continental flood basalts (e.g., White and McKenzie, 1995). Prior to initial fragmentation of Gondwana along Proterozoic and older crustal discontinuities, continental sedimentation resulted in deposition of the 9 km-thick Permian to early Jurassic Karoo sequence. The main sedimentary groups from base to top are: Dwyka, Ecca, Beaufort, Molteno, Elliot and Clarens. Igneous bodies are preferentially emplaced at contacts between the Dwyka and Ecca and Upper Ecca and Lower Beaufort groups of the Karoo sedimentary sequence (Chevallier and Woodford, 1999).

A temporal and spatial relationship exists between the Karoo province of Southern Africa and the Ferrar province of Antarctica and Australia. U–Pb zircon ages from mafic dikes within the southern Karoo (183.7±0.6 Ma) and the Dufek intrusion of the Ferrar province (182.7±0.5) (Encarnacion et al., 1996), suggest a single magmatic event throughout Gondwana. In addition, Ar–Ar ages of mafic dikes within the Karoo basin (183±1 Ma, Duncan et al., 1997), and the Dufek intrusion (182.5±2.4 Ma, Brewer et al., 1996), also place the formation of these provinces as broadly contemporaneous. Radiometric ages are in agreement with paleomagnetic data (Lanza and Zanella, 1993; Hattingh and de Wet, 1996; Hargraves et al., 1997).

Although much of the basalt has been eroded, it has been estimated that the basaltic cover across southern Africa may have reached a surface area larger than 10^6 km^2 (Cox, 1970). Presently, Karoo basalt outcrop covers about 140,000 km^2. When considered together the Karoo and Ferrar provinces represent a minimum volume of ~3.0×10^6 km^3 of magmas formed synchronously with Gondwana breakup (Encarnacion et al., 1996). Underplating and intrusion at the base of the crust are common features of flood basalt provinces; therefore an estimate of the total magmatic volume of the Karoo Igneous Province likely exceeds 10×10^6 km^3 (White and McKenzie, 1995).

An estimated 80% of the Karoo magmas was emplaced during a 3–4 My period, suggestive of a plume source (White, 1997). Further evidence of a plume source include: 1) indistinguishable paleomagnetic pole positions within principal formations (Hargraves et al., 1997), indicating that the duration of magmatism was relatively short lived, 2) the presence of high temperature picrites (lherzolite), which require a constant magma supply to produce the present thicknesses observed, and 3) the presence of basalt outcrop over the stable Kaapvaal Craton in the interior of South Africa. Remnants of the continental basalts are found throughout southern Africa where a dense network of dikes and sills cuts through the Karoo Basin (e.g., Marsh et al., 1997), some of which are considered to be feeders to the continental tholeiitic basalts (Marsh and Mndaweni, 1998) although the exact relationships are not well established.

2.2. Insizwa sill

The Insizwa sill is one of five units that comprise the Mount Ayliff Complex, part of the central Karoo Igneous Province (Fig. 1). The Mount Ayliff Complex, located southeast of the Lesotho mountains in southeastern South Africa, near the town of Kokstadt, is associated with low-Ti tholeiitic basalts (e.g., Cawthorn et al., 1988; Maier et al., 2002). Individual units of the intrusion – Insizwa, Ingeli, Horseshoe,Tonti, and Tabankulu – may represent erosional remnants of a sheet of magma intruded at various levels into the Karoo sedimentary sequence.

With a surface area of 500 km^2, the Insizwa sill is one of the largest sills that intruded the undeformed Beaufort Group sandstones of the Karoo Basin. The thickness of the Insizwa sill