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The Sonju Lake layered intrusion, northeast Minnesota: Internal structure and emplacement history inferred from magnetic fabrics

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Abstract

The Sonju Lake intrusion (SLI), in northeastern Minnesota, is a layered mafic complex of Keweenawan age (1096.1 ± 0.8 Ma) related to the Midcontinent rift. The cumulate paragenesis of the intrusion is recognized as broadly similar to the Skaergaard intrusion, a classic example of closed-system differentiation of a tholeiitic mafic magma. The SLI represents nearly closed-system differentiation through bottom-up fractional crystallization. Geochemical studies have identified the presence of a stratabound, 50–100 m thick zone anomalously enriched in Au + PGE. Similar to the PGE reefs of the Skaergaard intrusion, this PGE-enriched zone is hosted within oxide gabbro cumulates, about two-third of the way up from the base of the intrusion.

We present a petrofabric study using the anisotropy of magnetic susceptibility (AMS) to investigate the emplacement and flow patterns within the Sonju Lake intrusion. Petrographic and electron microprobe studies, combined with AMS and hysteresis measurements indicate the primary source of the magnetic signal is pseudo-single domain (PSD) magnetite or titanomagnetite. Low field AMS was measured at 32 sites within the Sonju Lake intrusion, which provided information about primary igneous fabrics.

The magnetic fabrics in the layered series of the Sonju Lake intrusion are consistent with sub-horizontal to inclined emplacement of the intrusion and show evidence that the cumulate layers were deposited in a dynamic environment. Well-aligned magnetic lineations, consistently plunging shallowly toward the southwest, indicate the source of the magma is a vertical sill-like feeder, presumably located beneath the Finland granite. The Finland granite acted as a density trap for the Sonju Lake magmas, forcing lateral flow of magma to the northeast. The strongly oblate magnetic shape fabrics indicate the shallowly dipping planar fabrics were enhanced by compaction of the crystal mush.

Keywords: AMS; Magnetic susceptibility; Layered mafic intrusion; Sonju Lake; Duluth Complex

1. Introduction

During the development of the 1.1 Ga Keweenawan Midcontinent Rift System (MRS) in northeast Minnesota, a number of subvolcanic intrusions were emplaced into comagmatic volcanics of the North Shore Volcanic Group. The intrusive rocks of the MRS in northeastern Minnesota can be subdivided into two main intrusive complexes (Miller et al., 2002). The Duluth Complex was emplaced close to the unconformity between early basalt flows and pre-rift basement. Postdating the Duluth Complex and emplaced at medial levels within the North Shore Volcanic Group is the

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Beaver Bay Complex (BBC), which occurs as a cluster of small to medium sized, sheet and dike-like intrusions. The Sonju Lake intrusion (SLI) is a 1200 m thick tholeiitic layered intrusion within the BBC, exposed north of Finland, Minnesota. It is also the most strongly differentiated intrusion within the Keweenawan magmatic system (Stevenson, 1974; Miller and Ripley, 1996).

The Sonju Lake intrusion has been studied extensively using petrographic, geochemical, and field data (Stevenson, 1974; Miller et al., 1993; Miller and Ripley, 1996; Miller and Chandler, 1997). These numerous studies have led to a comprehensive knowledge of the cumulate series and igneous stratigraphy, as well as the differentiation trend. More recently, outcrop sampling of the intrusion revealed a stratiform PGE-enriched interval (Miller, 1999), and geochemical studies have since provided information regarding the mineralization within the precious metal zone (Joslin and Miller, 2003; Joslin, 2004). However, very little is currently known about the emplacement dynamics of the intrusion.

Almost all rocks, particularly layered intrusions, exhibit a petrofabric, which provide clues to the emplacement dynamics operating within an intrusion (e.g., Nicholas, 1992). Recognition of mappable mineral fabrics (lineation and foliation) provides invaluable information about structure, magma dynamics, and the importance of accumulation and compaction in the development of layering. Unfortunately, with seemingly isotropic rocks it can be very difficult to collect quantitative petrofabric data in the field. For that reason we rely on the anisotropy of magnetic susceptibility (AMS), which has been successfully used to quantify mineral fabrics, even in visually isotropic rocks (Bouchez, 1997).

We have used magnetic fabric data as a proxy for petrofabric data in the Sonju Lake intrusion. AMS techniques allow us to quantitatively examine a large number of samples in a short time period. Magnetic fabrics can be compared with observable petrofabrics, including igneous laminations and textural layering, to test for correspondence. In this paper we present a detailed magnetic fabric study of the Sonju Lake intrusion. In particular, we use magnetic fabric data to assess the mechanisms that led to fabric development in the layered series as well as to provide constraints on the location of the feeder, magmatic flow patterns, and emplacement history of the intrusion. An understanding of the emplacement mechanisms may also shed light on the formation of PGE-enriched layers in the Sonju Lake intrusion as well as in other layered mafic intrusions.

2. Geologic setting

2.1. The Midcontinent Rift System

The Midcontinent Rift System (MRS), spanning more than 2000 km across the North American Craton, was a major zone of magmatic activity at 1.1 Ga. An abundance of mafic rocks within this arcuate zone generates strong positive gravity and reversed polarity magnetic anomalies, which can be traced in two arms—one from Kansas into western Lake Superior and the other from eastern Lake Superior into the Lower Peninsula of Michigan beneath the Michigan Basin (Fig. 1; Hinze et al., 1966, 1975; Van Schmus and Hinze, 1985). Plume-generated magmatic activity, which spanned 23 million years (1109–1086 Ma; Paces and Miller, 1993), produced an accumulation of up to 20 km of predominantly mafic lavas and imbedded intrusions within the rift, as well as considerable crustal underplating (Cannon et al., 1989; Hutchinson et al., 1990). Post-magmatic subsidence of the MRS resulted in up to 10 km of clastic sedimentary rocks capping the upper third of the rift fill (Hinze et al., 1997). Late compression, related to the Grenville Orogeny at ∼1.1 Ga, caused a structural inversion of the MRS (Cannon, 1992).

The Mesoproterozoic Keweenawan geology of northeastern Minnesota can be divided into two main lithologic suites—volcanic and minor sedimentary rocks of the North Shore Volcanic Group (NSVG), and multiply emplaced subvolcanic intrusions comprising the deeper-seated Duluth Complex, the more hypabyssal BBC, and other miscellaneous intrusive suites (Fig. 1). The NSVG is predominantly composed of a 7–10 km thickness of tholeiitic, subaerial plateau lavas ranging in composition from picrite to rhyolite (Green, 2002). The flows are locally interbedded with volcanogenic clastic redbed sediments that are interpreted as fluvio-lacustrine deposits derived from rift volcanics (Merk and Jirsa, 1982). In general, the volcanic and sedimentary rocks of the NSVG are gently tilted (10–20°) in a broad arcing pattern toward the rift axis. The main exception to this structural picture is the disruption caused by intrusions of the BBC along the central part of the shoreline (Fig. 1).

The Duluth and Beaver Bay Complexes are generally distinguished by different stratigraphic heights of emplacement within the volcanic edifice of the NSVG. The Duluth Complex, one of the largest mafic layered intrusions in the world, intruded close to the unconformity between early basalt flows and pre-rift basement (Miller et al., 2002). This emplacement along an uncon-