Tectonophysics 478 (2009) 119–134

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

# Remanent and induced magnetic anomalies over a layered intrusion: Effects from crystal fractionation and magma recharge

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ARTICLE INFO

*Article history:*
Received 17 June 2008
Received in revised form 5 September 2008
Accepted 25 November 2008
Available online 6 December 2008

*Keywords:*
Magnetic anomalies
Hemo-ilmenite
Ilmenite
Magnetite
Layered intrusions

ABSTRACT

The Bjerkreim-Sokndal (BKS) norite – quartz mangerite layered intrusion is part of the early Neoproterozoic Rogaland Anorthosite Province intruded into the Fennoscandian shield in south Norway at ~930 Ma. The BKS is exposed over an area of 230 km$^2$ with a thickness of ~7000 m and is of economic interest for ilmenite, magnetite and apatite deposits. From the point of view of magnetic minerals, in the course of fractional crystallization and magma evolution, the ilmenite becomes less $Fe^{3+}$-rich reflected by a change from ilmenite with hematite exsolution to nearly pure ilmenite. Magnetite starts to crystallize relatively late in the intrusive history, but its crystallization is interrupted by influxes of more primitive magma. The variations in aeromagnetic and ground-magnetic anomalies measured over the BKS can be explained in terms of the measured magnetic properties of NRM, susceptibility, and hysteresis presented here, and in terms of mineralogy. Early layers in the intrusion contain hemo-ilmenite. As the magma evolved and magnetite started to crystallize, this caused a distinct change over the layering from remanence-controlled negative anomalies to induced positive anomalies. When new, more primitive magma was injected into the system, hemo-ilmenite returned as the major oxide and the resulting magnetic anomalies are again negative. The most dramatic change in the magnetic signature is in the upper part of the intrusion in MCU IVe, where magnetite became a well established cumulate phase as indicated by susceptibility, but its induced magnetization is overcome by large NRMs associated either with hemo-ilmenite, or with hemo-ilmenite and magnetite exsolved from pyroxenes. The average natural remanent magnetizations change from ~3 A/m in MCU IVd, to 15 A/m in MCU IVe, and back to 2 A/m in the overlying MCU IVf, producing a strong negative remanent anomaly that has been followed along strike for at least 20 km by ground-magnetic measurements. The highly varied magnetic properties of this intrusion, caused by varied magmatic crystallization of combinations of opaque minerals, illustrate some of the possibilities to be considered in evaluating crustal magnetic anomalies.



## 1. Introduction

Geopotential research is in an unprecedented period, with the recent launches of Oersted in 1999, SAC-C in 2000, and CHAMP in 2000 satellites and the planned launch of a new magnetic field constellation mission, SWARM, in 2010 (Mandea, 2006). The SWARM mission will have three satellites in two different polar orbits between 400 and 550 km altitude. Each satellite will make high-precision and high-resolution measurements of the Earth's magnetic field. Together they will provide observations of the geomagnetic field needed to model its various sources, with particular interest in the magnetic character of the Earth's lithosphere. However, potential-field data, though extremely valuable, are not sufficient to constrain models to a unique distribution of magnetic sources. Therefore, to make the maximum use of magnetic data obtained from satellites and high-resolution aeromagnetic surveys, petrophysical data from well characterized samples and well documented geologic settings will be necessary (McEnroe and Brown, 2000; McEnroe et al., 2001a, 2006). Here we present a detailed study combining oxide mineralogy with petrophysical measurements, and relate the resulting data to the magnetic anomalies measured by fixed-wing and high-resolution helicopter aeromagnetic surveys, and ground-magnetic surveys, over the BKS layered intrusion.

Archean to Tertiary layered intrusions found in many locations around the globe have long been a topic of interest to petrologists and geochemists (Cawthorn, 1996). Layers of varying mineral composition, commonly recurring, due to recharge events in the magma chamber, and commonly associated with economic mineralization, occur in intrusions such as the Bushveld, Skaergaard and Stillwater. Despite detailed studies by petrologists, only a little is known about the magnetic properties of these interesting bodies. Paleomagnetic studies have yielded stable directions from layered intrusions (e.g. Tanczyk et al., 1987), but basic magnetic and petrophysical properties within the layered systems remain unstudied. Local magnetic anomalies over such intrusions have been used to help delineate the bodies, such as the Dufek Intrusion in Antarctica (Ferris et al., 1998) and the Sept Iles

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0040-1951/$ – see front matter 
doi:10.1016/j.tecto.2008.11.021

layered intrusion in Quebec (Loncarevic et al., 1990), although no attempt was made in either study to link specific rocks with discrete parts of the magnetic anomalies. In support of paleomagnetic results, Xu et al. (1997) studied 10 samples from the Banded Series in the Stillwater Complex, investigating stability of magnetic remanence; however a comprehensive study of the magnetic properties remains to be done. Recently, Ashwal et al. (2005), using samples from a deep drill core, measured magnetic susceptibility through a section of the Northern Lobe of the Bushveld Complex. Our primary aim here is to investigate the magnetic character of the 7-km-thick Bjerkreim-Sokndal Layered Intrusion with reference to magnetic remanence, susceptibility and the magnetic anomalies over the body.

The Bjerkreim-Sokndal (BKS) layered intrusion is the largest in Europe (Fig. 1), and has been studied for over 100 years from the perspective of economic deposits and magmatic processes (Michot, 1965; Schiellerup et al., 2001; Meyer et al., 2002). Hemo-ilmenite rich layers within the BKS intrusion have pronounced remanence-controlled anomalies. In particular, the norite in Megacyclic Unit (MCU) zone IVe has been studied in detail and proposed as an analog for Martian anomalies due to the large negative anomaly (maximum −13,000 nT below background at 60 m above ground) centered over it (McEnroe et al., 2004a,b). The Sokndal lobe of the BKS also has been studied from the perspective of magnetic anomalies and economic deposits (McEnroe et al., 1996, 1997, 2001b; Robinson et al., 2003).

## 2. Geologic setting

The Bjerkreim-Sokndal (BKS) norite – quartz mangerite layered intrusion (Wilson et al., 1996; Robins and Wilson, 2001; Wilson and Overgaard, 2005) is part of the early Neoproterozoic Rogaland Anorthosite Province intruded into the Fennoscandian shield in south Norway (Fig. 1) at ~930 Ma (Schärer et al., 1996). The BKS intruded into ~980 Ma granulite-facies metamorphic rocks (Bingen and Van Breemen, 1998) during the youngest phase of post-orogenic anorthosite and associated plutonic activity. The areal extent of the BKS is estimated to be 230 km$^2$ with a thickness of ~7000 m.

The layered series of the BKS Intrusion, best exposed in the Bjerkreim Lobe (Fig. 2), was precipitated from jotunitic magmas in which the dominant early primary precipitate minerals were plagioclase ($An_{52-44}$), orthopyroxene ($En_{75-65}$), and ferri-ilmenite that produced hemo-ilmenite by exsolution during cooling. The course of fractional crystallization was punctuated by the influx and mixing of more primitive magmas, producing five Megacyclic Units (MCUs). From the base to the top these have been numbered: IA, IB, II, III, and IV, typically with early plagioclase-rich norites, intermediate hemo-ilmenite-rich norites, and late magnetite norites with subordinate near end-member ilmenite (Fig. 3). Following each influx and mixing, the magma resumed normal fractional crystallization, though each time with a more melanocratic trend. Following the last major influx, recorded near the base of Megacyclic Unit IV, fractional crystallization

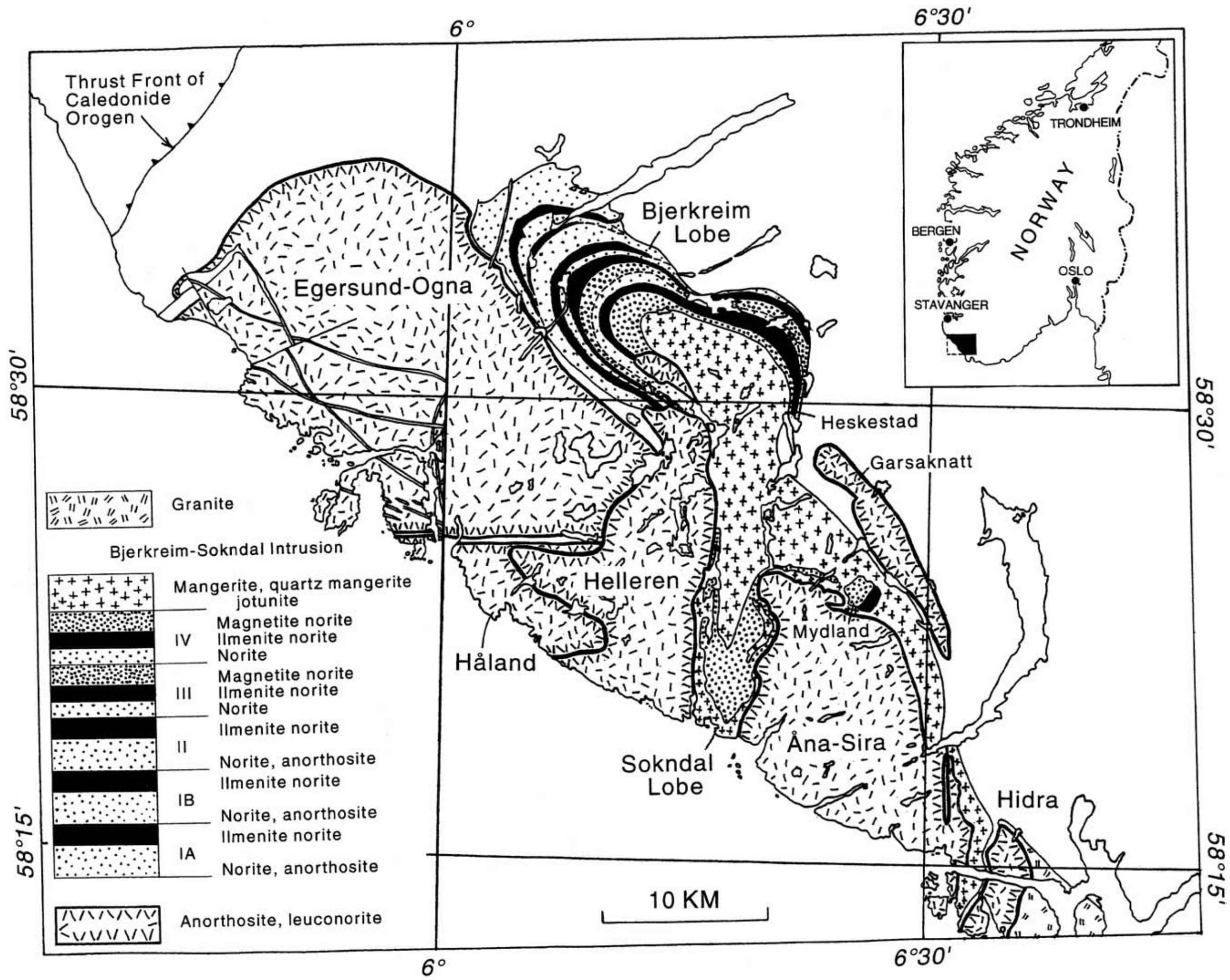


**Fig. 1.** Regional geological map of the early Neoproterozoic Rogaland Anorthosite Province in southwestern Norway from McEnroe et al. (2001b). Shown are the Bjerkreim-Sokndal layered intrusion with megacyclic units IA, IB, II, III AND IV, associated mangerites and quartz mangerites, and the Egersund-Ogna, Håland-Helleren, and Åna Sira anorthosites. White areas are metamorphic country rock and dikes. Inset shows the locations of Figs. 1 and 3 in southwestern Norway.