Magnetic properties of anorthosites: A forgotten source for planetary magnetic anomalies?

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[1] Anorthosites, igneous rocks very rich in plagioclase, rarely considered to be strongly magnetic, are common on Earth, and the Moon, and inferred to be on other planets. Magnetic properties of anorthosites could be important in investigating associated mineral deposits and in studying magnetic anomalies, especially on Mars. Here we investigate three late Proterozoic anorthosites in Rogaland, Norway, for magnetic and petrographic properties. Two of the anorthosites have large natural remanent magnetization (NRM), with intensities comparable to Tertiary basalts. Susceptibility, NRM and hysteresis properties provide information about the magnetic minerals present and their response to inducing fields. Microscopic observations show ubiquitous hemo-ilmenite in the anorthosites, whereas magnetite is common in the Håland-Helleren, but rare in the Åna-Sira and Egersund-Ogna bodies. This study illustrates that anorthosites can be important sources of magnetic anomalies, and can retain a remanent field over geologic time. It also supports the recently described property of 'lamellar magnetization'. **Citation:** Brown, L. L., and S. A. McEnroe (2008), Magnetic properties of anorthosites: A forgotten source for planetary magnetic anomalies?, *Geophys. Res. Lett.*, *35*, L02305, doi:10.1029/2007GL032522.

1. Introduction

[2] Anorthosite, a plutonic igneous rock composed almost entirely of plagioclase feldspar, is found in a number of geologic settings on Earth. These range from Archean calcic anorthosites to Proterozoic massifs to bodies associated with layered intrusions, and from orogenic to non-orogenic environments. The origin of anorthosites has been debated for many years, and although now a magmatic source is accepted, the location of that source in the mantle or crust is still in question [*Ashwal*, 1993; *Schiellerup et al.*, 2000; *Longhi*, 2005]. Besides their ancient existence on Earth and the problems as to their origin, anorthosites host economic deposits, including ilmenite, magnetite, chromite, and platinum group elements, making them objects of continued interest. Anorthosite is also a common rock on the Moon [*Papike et al.*, 1998; *Hawke et al.*, 2003; *Takeda et al.*, 2006] and has been suggested as a possible rock type on other planets such as Mars and Mercury [*Ashwal*, 1993; *Blewett et al.*, 2002]. Due to the typical composition of over 90% plagioclase feldspar, anorthosites generally have been ignored by the magnetic community and considered to be "non-magnetic" or treated predominantly as "paramagnetic crust." In this paper we investigate the magnetic properties of three related, but distinct, anorthosites from southern Norway, all marked by notable aeromagnetic anomalies and documenting a wide variety of magnetic properties. Two of the anorthosite bodies have average NRM values $\sim$4–6 times higher than 1 A/m, a value typically cited for volcanic rocks [*Dunlop and Özdemir*, 1997]. Here we examine the magnetic properties of the three anorthosites, and evaluate their contribution to magnetic anomalies on Earth, and as a possible source for anomalies on other planets.

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2. Geologic and Geophysical Settings

[3] The Rogaland Province of southwestern Norway is one of the youngest of the massif-type anorthosites of Proterozoic age. It consists of three large massif-type anorthosite bodies; Egersund-Ogna, Håland-Helleren, and Åna-Sira, emplaced into granulite facies terrain. Associated with the anorthosites is the 230 km^2 Bjerkreim-Sokndal layered intrusion, the smaller Garsaknatt and Hidra leuconorites, and the Farsund charnockite [*Marker et al.*, 2003]. The province represents a post-orogenic intrusion into migmatic gneisses of Sveconorwegian age ($\sim$1 Ga) with U-Pb zircon ages of 931 $\pm$ 3 Ma on the anorthosites [*Schärer et al.*, 1996]. These rocks have been studied for decades [*Michot and Michot*, 1969; *Duchesne*, 2001] with continued interest stimulated by the presence of economic hemo-ilmenite ore and natural stone deposits [*Korneliussen et al.*, 2000; *Duchesne*, 2001]. A recent geologic map of the region has been compiled by the Geological Survey of Norway [*Marker et al.*, 2003].

[4] The Egersund-Ogna massif is the largest of the three anorthosites, composed of coarse (1–3 cm) homogeneous plagioclase of composition An_{40-45} with local megacrysts of Al-rich orthopyroxene and plagioclase. The margin of the dome-shaped body is more leuconoritic in composition. The other bodies have similar compositions, with the megacrysts of orthopyroxene being limited to the Helleren massif. Economic deposits of hemo-ilmenite ore are found in the Åna-Sira massif.

[5] The Rogaland Igneous Province has distinct aeromagnetic signatures with large negative and sporadic positive anomalies over the anorthosite bodies [*McEnroe et al.*, 1996, 2001], as well as positive and negative anomalies over the layered intrusion, with a distinct large negative anomaly greater than 10,000 nT [*McEnroe et al.*, 2004a, 2004b]. The Åna-Sira anorthosite has a negative anomaly of nearly 3000 nT below background, while the Håland-

Table 1. Means of Rock and Magnetic Properties for Rogaland Anorthosites[a]

Body	S/s	X SI	Jr, A/m	Ji, A/m	NRM Inc	NRM Dec	Q	Q_v	Den, gm/cc
Åna-Sira	15/110	5.43×10^{-3}	3.81	0.24	−77.7	330.1	36.6	16.0	2.71
Egersund-Ogna	13/78	4.88×10^{-4}	0.58	0.02	−79.2	327.5	61.1	26.7	2.70
Håland-Helleren	6/43	2.40×10^{-2}	5.88	0.96	−70.5	301.7	25.9	6.0	2.73

[a]Abbreviations are S/s, number of sites/number of samples; X, magnetic susceptibility; Jr, natural remanent magnetization; Ji, induced magnetization from mean X using ambient field in southern Norway of 39.8 A/m; NRM Inc and NRM Dec, directions of remanent magnetization; Q, ratio of Jr to Ji; Qv, ratio of Jr to Ji using vector components; and Den, density in gm/cc.

Helleren and Egersund-Ogna show both negative and positive anomalies of a more subdued nature.

3. Samples and Methods

[6] Oriented samples from each anorthosite body were collected as part of a larger magnetic investigation of the Rogaland area involving the aeromagnetic response of the hemo-ilmenite ores [*McEnroe et al.*, 1996, 2001, 2002], and paleomagnetism [*Brown and McEnroe*, 2004]. Between 9 and 15 sites were collected per anorthosite, providing 231 individual samples for study. Magnetic susceptibility, density, NRM, alternating field (AF) and thermal demagnetization were determined in the magnetic laboratories at the University of Massachusetts and NGU. Hysteresis properties were measured on Princeton Measurements micro vibrating sample magnetometers in a maximum field of 1.5T at the Institute of Rock Magnetism, University of Minnesota and at NGU.

4. Oxide Mineralogy

[7] Millimeter size hemo-ilmenite grains are a common accessory phase in all three anorthosites. Hemo-ilmenite is a primary phase that crystallized as discrete grains of ferrian ilmenite which exsolved hematite lamellae upon cooling to below solvus temperatures. Inclusions of hemo-ilmenite are also in plagioclase grains. Thin section observations on petrographic and scanning electron microscopes show the hemo-ilmenite grains contain two or more generations of hematite exsolution lamellae, ranging from a few microns to submicron size. Hemo-ilmenite-rich cumulates in the Åna-Sira anorthosite have been studied by transmission electron microscope and the lamellae were found to continue down to a few nanometers in thickness [*McEnroe et al.*, 2002]. It is likely that the exsolution lamellae in the hemo-ilmenite grains in the anorthosites contain the same nanoscale exsolution because of the same cooling and oxidation history. Magnetite that crystallized as a primary mineral phase is rare in the Egersund-Ogna anorthosite [*Brown and McEnroe*, 2004], and locally present in the Åna-Sira anorthosite [*McEnroe et al.*, 1996]. Samples from the Egersund-Ogna are the most oxidized and show minor late alteration to hemo-ilmenite grains. Håland-Helleren anorthosite samples contain more magnetite than the other anorthosite bodies. These magnetite grains are usually >50 μm and contain oxidation-exsolution lamellae of ilmenite and spinel needles. A late-stage alteration of ilmenite to rutile can be found in some samples from all three anorthosite bodies. Overall the Åna-Sira and Håland-Helleren oxide mineralogy shows little alteration and exsolution features indicate the remanent magnetization was acquired by cooling from high temperatures soon after emplacement of the anorthosites. The Egersund-Ogna anorthosite is locally altered, and some hemo-ilmenite grains show evidence for oxidation of ilmenite to hematite + rutile likely occurring during cooling As shown by *Brown and McEnroe* [2004] the paleomagnetic directions are consistent through out this intrusion with little difference between unaltered and slightly altered sites. The directions are consistent with other late Proterozoic data from Baltica, supporting primary magnetization.

5. Magnetic Properties

[8] Magnetic susceptibility and NRM were measured on all samples and mean values are given in Table 1. Egersund-Ogna samples have the lowest susceptibilities, with a mean of 5×10^{-4} SI, and the lowest NRM values, with a mean of 0.6 A/m (range 0.002 to 3.94 A/m). The Koenigsberger ratios, Q (ratio of remanent magnetization to induced magnetization), range from 1 to over 400, with a mean of 61; all samples plot in the region of remanence dominant on Figure 1. The highest values of susceptibility and NRM are from the Håland-Helleren anorthosite, with an average susceptibility of 2×10^{-2} SI, and an NRM of 6 A/m, with NRM ranges of 0.8 to 15.1 A/m. Q values range from 0.4 to >200, with over 90% of the samples values >1. The Åna-Sira body has intermediate susceptibility values, with a mean of 6×10^{-3} SI, and NRM average value of 3.8 A/m (range 0.3 to 9.3 A/m); 51 samples have NRMs of 3 A/M or greater. Q values for this body are higher than for the Håland-Helleren, averaging 37.

[9] Mean NRM directions are steeply negative with northwest declinations for all the bodies (Table 1), similar to demagnetized remanent magnetizations found in the Egersund-Ogna anorthosite [*Brown and McEnroe*, 2004]. By contrast, the local induced vector is steeply positive. Both the Egersund-Ogna and Åna-Sira, with low susceptibilities have little scatter in the undemagnetized directions (NRM), with σ_{95} (95% confidence circle) of 5.6° and 4.6° respectively. The Håland-Helleren, with highest susceptibility, shows greater scatter in directions, represented by σ_{95} of 11.1°. To further investigate the contribution of induction to remanence, vector Q (Qv) values were calculated for each intrusion. This calculation takes the direction of the NRM vector, the intensity (the length of the vector), and the scatter of the vectors, into consideration, yielding a more accurate indication of the contribution of remanence to the magnetic anomaly. In all cases Qv will be lower than standard Q values. For the Egersund-Ogna and Åna-Sira Qv are 26.7 and 16.0, respectively. These values are comparable, or higher than Qv for young volcanic rocks and are impressive values for rocks that obtained their remanent magnetization nearly 1 Ga ago. The remanence carriers in these anorthosites are robust and show little magnetic relaxation that would result in a higher VRM contribution. For the magnetite-richer Håland-Helle-

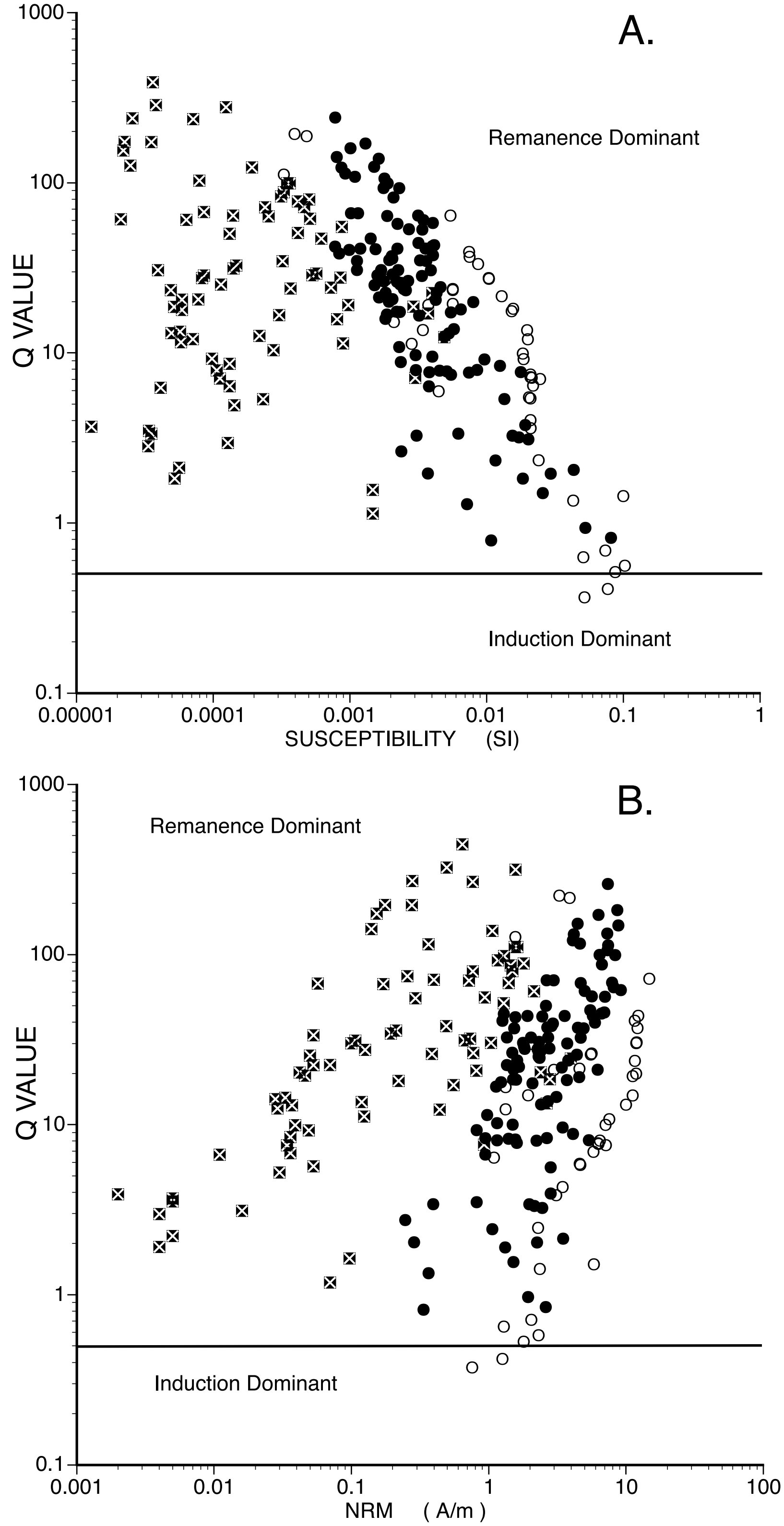

Figure 1. Bulk magnetic properties for individual samples from the three anorthosite bodies in the Rogaland Igneous Complex. (a) Log-log plot of Koenigsberger ratio (Q) vs. susceptibility (SI units). (b) Q versus natural remanent magnetization (NRM) in A/m. Symbols represent individual samples from each body: cross-box, Egersund-Ogna; open circle, Håland-Helleren; and solid circle, Åna-Sira.

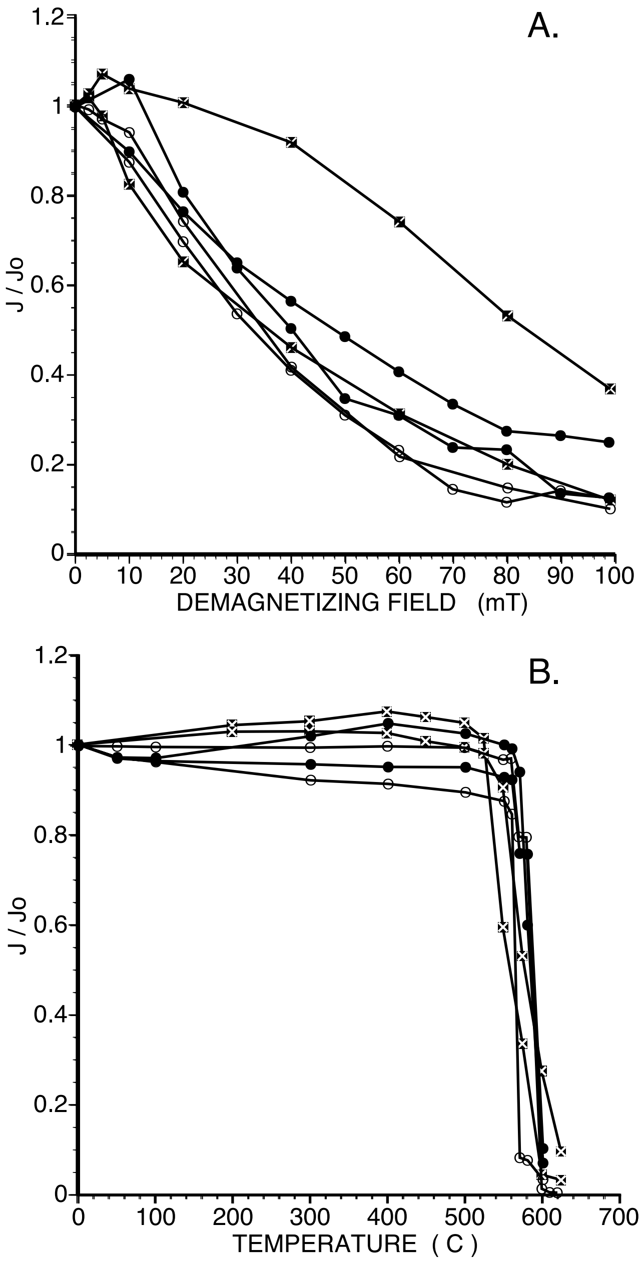

Figure 2. Plots of stepwise demagnetization versus normalized remanent intensity. (a) Alternating field demagnetization in steps from 2.5 to 100 mT for two samples from each anorthosite. (b) Thermal demagnetization from room temperature to 630°C for companion samples to those shown in Figure 2a. Symbols are the same as in Figure 1.

ren anorthosite the Qv is 6.0, significantly lower than the standard Q calculation due to the scatter in the NRM directions partly resulting from an added VRM component. However the Q values indicate that the remanence carriers strongly contribute to the magnetic anomaly.

[10] Demagnetization behavior was measured using both AF and thermal techniques (Figure 2). All anorthosites have high coercivity on AF demagnetization, with mean destructive fields ranging from 35 mT to 85 mT (Figure 2a). Thermal demagnetization shows little decay before 550°C (Figure 2b), with 10% of the intensity remaining by 630°C. Håland-Helleren samples lose intensity rapidly, with at least 80% of their intensity destroyed by 580°C, whereas, both Egersund-Ogna and Åna-Sira samples require higher temperatures to unblock, with nearly 80% remaining at 580°C and 30% by 600°C. The higher thermal unblocking temperatures for the Egersund-Ogna and Åna-Sira samples indicate little magnetite is present in the samples.

[11] Hysteresis properties on 36 samples are dependent on magnetic mineralogy, with the Håland-Helleren samples reflecting the contribution from MD magnetite whereas the Åna-Sira and Egersund-Ogna are dominated by hemo-ilmenite. Ratios of remanent magnetization to saturation magnetization (Mr/Ms) range from 0.03 to 0.33 with the Håland-Helleren samples having the lowest mean Mr/Ms of 0.08. The Åna-Sira and Egersund-Ogna samples have higher Mr/Ms ratios and coercive remanence to coercive force ratios (Hcr/Hc) similar to previously studied hemo-ilmenite samples [*McEnroe et al.*, 2002; *Dyar et al.*, 2004]. These samples are not completely saturated in a 1.5T field, therefore the Mr/Ms values are slightly biased toward the high end. Mean coercivity values for Håland-Helleren (6.0 mT) are ~50% lower than Hc values for Åna-Sira (11.5 mT) and Egersund-Ogna (15.2 mT).

6. Discussion and Conclusions

[12] Though the magnetic properties of the three anorthosites differ considerably, this study shows that anorthosites can contribute significantly to the magnetic signature of Earth's crust. Susceptibility values range from levels of paramagnetic rocks 10^{-4} SI [*Clark*, 1997], to those more indicative of magnetite (10^{-2} SI). NRM values for Åna-Sira and Håland-Helleren are similar to those found in Late Tertiary basalts of 4 to 6 A/m [*Brown et al.*, 2004], while the more oxidized Egersund-Ogna samples have lower NRMs. The wide range of NRM and susceptibility values encountered in this study indicates that oxide abundance must vary in these otherwise similar plagioclase-rich rocks. The significantly larger NRM values compared to susceptibility in these samples produce Q values 99% of which are above 0.5, and 70% above 10, indicating that NRM directions dominate the local aeromagnetic anomalies.

[13] To evaluate the contribution of magnetite in the samples, an estimate of the percent magnetite can be calculated using the relationship $K = 2.6\ V^{1.33}\ 10^{-3}$ cgs [*Balsley and Buddington*, 1958], where K is the magnetic susceptibility and V is the volume percent magnetite, which gives results of less than 1% for all three bodies. Based on this calculation, the Åna-Sira, with the largest negative anomalies, would contain <0.2% magnetite. However, because hemo-ilmenite accounts for a significant part of the susceptibility, the calculated amount of magnetite is lower. Using mean measured densities for each anorthosite and average densities for plagioclase (2.67 gm/cc) and hemo-ilmenite (4.7 gm/cc) we calculate the maximum oxide content by assuming only plagioclase and hemo-ilmenite in the samples. Based on petrography this is a reasonable approximation for the Åna-Sira and the Egersund-Ogna. This yields a maximum oxide content of 1.6% for the Åna-Sira, and 1.4% for the Egersund-Ogna massifs. Though minor magnetite can be present in these samples, the amount is so small that the effect on the density calculation is trivial.

For Håland-Helleren the density of magnetite is considered and the calculation yields a maximum of ~2.2% oxide which is a mixture of magnetite and hemo-ilmenite.

[14] Though the anorthosite samples contain only ~1–2% of oxides, NRM signals are strong, even when little, or none, of the oxide is magnetite. These bodies produce negative remanent anomalies, which interact with, and commonly dominate the present field. The ability of micron-and nanoscale lamellae in hemo-ilmenite and ilmeno-hematite to produce strong remanence has been described previously [*Frandsen et al.*, 2007; *McEnroe et al.*, 2001, 2002, 2004a, 2007a, 2007b; *McEnroe and Brown*, 2000; *Kasama et al.*, 2004] and is now referred to as lamellar magnetism [*Robinson et al.*, 2002, 2004; *Harrison*, 2006]. Remanent anomalies on Earth, which have persisted for nearly a billion years in a magnetic environment that is harsher than that on a planet without a frequently reversing magnetic field, are prime targets for further research, to aid in understanding the mechanism of magnetic memory on planetary bodies which no longer have an active dynamo to generate a planetary magnetic field.

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