Magnetic anomalies, layered intrusions and Mars

S. A. McEnroe,[1,2] J. R. Skilbrei,[1] P. Robinson,[1,2] F. Heidelbach,[3] F. Langenhorst,[3] and L. L. Brown[2]

Received 1 June 2004; revised 26 July 2004; accepted 8 September 2004; published 2 October 2004.

[1] Studies of remanence-controlled magnetic anomalies on Earth provide possibilities to interpret the nature of crustal rocks that cause the large remanent anomalies on Mars. What types of conditions on Earth can create large remanent magnetic anomalies? Such an anomaly, extending for 20 km centered over a norite layer in the Bjerkreim-Sokndal (BKS) Intrusion, shows a minimum −13000 nT below background in the helicopter survey. Modeling of the anomaly requires a natural remanent magnetization (NRM) value of 24 A/m, similar to values measured in norite samples and to values invoked to explain the anomalies on Mars. Preliminary magnetic assessment considers the roles of hemo-ilmenite, magnetite, and oxide exsolution in clino- and orthopyroxene, and high-temperature ductilely induced lattice-preferred orientation. *INDEX TERMS:* 1517 Geomagnetism and Paleomagnetism: Magnetic anomaly modeling; 1519 Geomagnetism and Paleomagnetism: Magnetic mineralogy and petrology; 3902 Mineral Physics: Creep and deformation; 6225 Planetology: Solar System Objects: Mars. **Citation:** McEnroe, S. A., J. R. Skilbrei, P. Robinson, F. Heidelbach, F. Langenhorst, and L. L. Brown (2004), Magnetic anomalies, layered intrusions and Mars, *Geophys. Res. Lett.*, *31*, L19601, doi:10.1029/2004GL020640.

1. Introduction

[2] Fascination with the nature and origin of the large Martian crustal magnetic anomalies has continued since their discovery by the Mars Global Surveyor spacecraft [*Acuña et al.*, 1999]. Because Mars no longer has a global magnetic field, models of the Martian lithosphere require NRMs from 12–30 A/m [*Acuña et al.*, 1999; *Connerney et al.*, 1999; *Langlais et al.*, 2004]. A way to obtain a high NRM in rocks is to have a large magnetic field during NRM acquisition. However, due its smaller core size, Mars is estimated to have had a field only 0.1 to 1 of Earth's [*Collinson*, 1986].

[3] Mars, like Earth, likely contains several minerals responsible for magnetic anomalies, with varied microstructures, oxidation states and geological settings. These must carry a high NRM and relatively high coercivity to retain a magnetic memory for ~4 billion years. The scale of the anomalies implies a relatively coherent vector direction. On Earth, studies of large-scale crustal anomalies have focused on those created by interaction of magnetic minerals with the present field, thus a combination of induced and viscous remanent magnetization. Without a magnetic field, such anomalies decrease substantially and only remanent anomalies persist. To understand the stability of remanent magnetization with time, studies of ancient remanent anomalies on Earth are needed as Martian analogs. There are few rigorous case studies of such anomalies and some show that members of the ilmenite-hematite solid solution can produce significant remanence-controlled magnetic response [*McEnroe et al.*, 2001a, 2001b, 2002, 2004; *McEnroe and Brown*, 2000]. By examining the geological setting and magnetic mineralogy/petrology that produce these, and making accurate magnetic models of amplitude and dimensions of sources, these localities can be used in understanding the magnetic response of Martian rocks. Though the limited sample of Martian crust in SNC achondrite meteorites [*McSween and Treiman*, 1998] lacks a precise match with rocks reported here, ilmenite with up to 5% hematite solid solution is reported.

[4] Here we examine a large-amplitude aeromagnetic anomaly of regional significance and model it using petrophysical data. It is centered over a noritic layer in the Bjerkreim lobe of the BKS layered intrusion in the Proterozoic part of the Fennoscandian Shield, South Norway, and is traced for over 20 km. We model a distinct part of the anomaly where it narrows near the edge of the intrusion, and has an amplitude of −13000 nT at 60 m above ground. Upward continuation of the data to 300 m is considered, and the dimensions of the rock bodies are increased to test if these types of rocks could be analogs for those producing the large anomalies on Mars.

2. Geology

[5] *Wilson et al.* [1996] described the regional geology of the Proterozoic Egersund anorthosite province and BKS intrusion. The BKS consists of 230 km^2 of norite, mangerite and quartz mangerite folded into a complex syncline. The norites of the ~7-km-thick layered series, at the base, precipitated from jotunitic magmas in which early primary minerals were plagioclase, orthopyroxene and ferri-ilmenite that exsolved to hemo-ilmenite during cooling. As the magma evolved, the oxide cumulates changed to titanomagnetite with subordinate end-member ilmenite [*McEnroe et al.*, 2001b]. Influxes of new more primitive magma into more evolved resident magma produced six Megacyclic units (MCU's 0, IA, IB, II, III, IV) each subdivided into layers a–f (absent in some MCUs), with early plagioclase-rich norites, intermediate hemo-ilmenite-rich norites and later magnetite norites, each with distinctive magnetic properties.

[6] This anomaly lies at the SE extremity of the synclinal Bjerkreim lobe (Figure 1), near where MCU IV hemo-ilmenite-rich layer IVe pinches out (Figure 2). This norite contains plagioclase, orthopyroxene, hemo-ilmenite, magnetite and minor clinopyroxene, biotite, apatite and sulfide.

[1]Norges Geologiske Undersøkelse, Trondheim, Norway.
[2]Department of Geosciences, University of Massachusetts, Amherst, Massachusetts, USA.
[3]Bayerisches Geoinstitut, Universität Bayreuth, Bayreuth, Germany.

0094-8276/04/2004GL020640$05.00

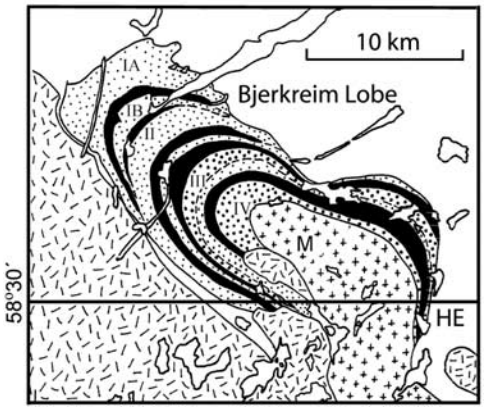

Figure 1. Simplified geologic map showing the Bjerkreim Lobe of the BKS Intrusion and location of cumulate MCU layers (IA-IV) and Heskestad (HE). Key to patterns: Cumulates of layered series: plagioclase-rich = fine dots, hemo-ilmenite-rich = solid, magnetite-rich = heavy dots; massive jotunite, mangerite and quartz mangerite (M) at top of intrusion = crosses, country rock anorthosite, leuconorite = tick pattern; country-rock gneisses, later dikes, and lakes = unpatterned.

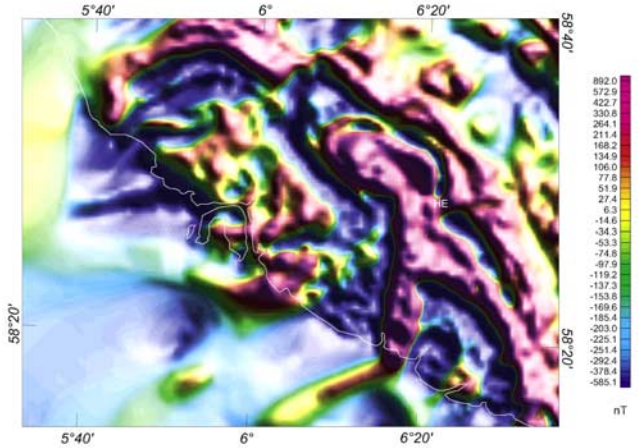

Figure 3. Aeromagnetic map of the Rogaland region from fixed wing data flown at 150 m. The magnetic total field was reduced to anomaly values by subtracting the International Geomagnetic Reference Field from the total field (1965). Color shades: pink- large positive magnetic anomalies, blue- strong negative anomalies. Heskestad anomaly is directly north of symbol HE. Negative anomaly continues north for ~20 km. Coastline outlined in white.

The petrology, mineral chemistry and remanence carriers are discussed elsewhere [*McEnroe et al.*, 2001b, 2004].

3. Geophysical Data and Anomaly Interpretation

[7] A fixed-winged aeromagnetic survey of the region (Figure 3) was drape flown at 150 m elevation, using 500 m line separations and visual navigation. The BKS shows a range of positive (induced) and negative (remanent) magnetic anomalies with contrasts up to ~16000 nT, controlled by oxide mineralogy. Early fractional crystallization products rich in plagioclase and hemo-ilmenite show negative anomalies. Later layered-series norites and overlying mangerites and quartz mangerites, dominated by titanomagnetite, show positive anomalies. Aeromagnetic data shows a southward offshore extension of the Egersund anorthosite province, covering an area 80–100 km long and ~30 km wide, to the NE of the Sorgenfrei-Tornquist Zone [*Aalstad*, 1971].

[8] The negative anomaly centered over layer MCU IVe reaches extreme lows on the east limb of the Bjerkrem Lobe at Heskestad. A later exploration helicopter survey was drape flown at ~60 m and line spacing of 200 m. The aeromagnetic map (Figure 4) combines both data sets and shows the location of the profile modelled in Figure 5. In combining the two, the helicopter data were upward-

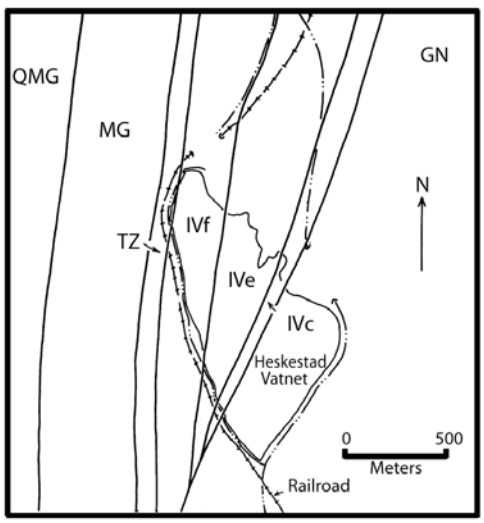

Figure 2. Geological map of Heskestad area showing the base of the BKS intrusion where the upper part of MCU IV (c, e, and f) pinches out between metamorphic gneisses and the overlying transition zone and mangerites.

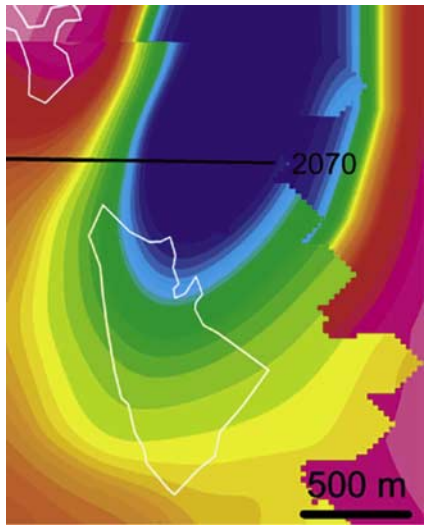

Figure 4. Heskestad anomaly map made from the helicopter data upward continued to 150 m combined with the older regional aeromagnetic data. Flight line 2070 (Black) is modelled in Figure 5. Lakes outlined in white.

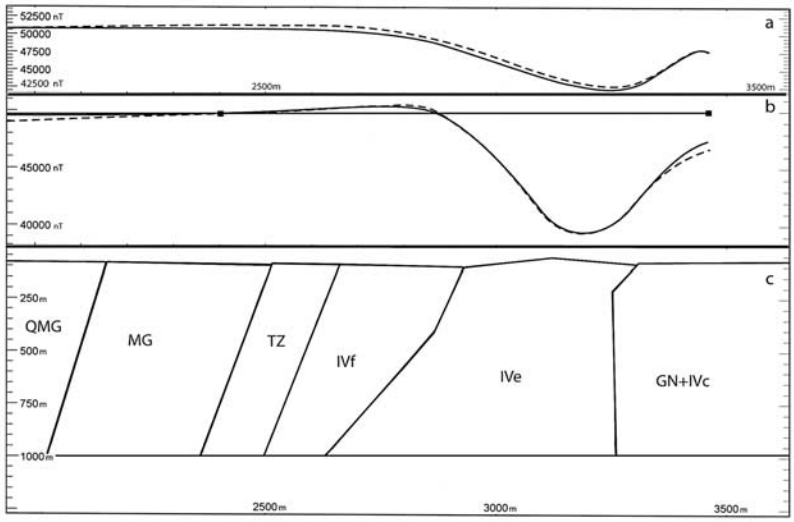

Figure 5. Magnetic model along line 2070. Panel (a) shows magnetic anomaly upward continued to 300 m. Panel (b) shows magnetic anomaly at 150 m. The bold line is observed anomaly, modelled profile is shown with dashed line, and regional field straight line with filled box symbols. Panel (c) shows geological units. Distances in meters, and anomaly in nanoteslas (nT). Horizontal scale is twice vertical scale, so true contact dips are steeper than shown. The model is very sensitive to the upper parts of the bodies, while the depth extent of the model is uncertain.

continued to 150 m, still leaving differences between them, due to inadequate positioning and instrument systems, and manual contouring of the older fixed-winged study. No additional efforts were made to level the two at the edges of the helicopter survey.

[9] The helicopter survey shows amplitude of −13000 nT. Ground profiles collected in Heskestad show more variation due to local layering, and total amplitude of −30900 nT, canceling more than half the regional field. Although norite layer IVe contains 2 to 3% MD magnetite, the magnetic response is strongly controlled by the remanence carriers which comprise less than 5% of the rock.

4. Magnetic Models

[10] In computing the magnetic model we used the Modelvision program [*Encom Technology Pty Ltd.*, 2001]. The model comprises 2 1/2-dimensional bodies of polygonal cross-section and finite length in the strike direction. Constraints for modelling include geological maps (Figure 2), ground-magnetic profiles and petrophysical data. Selection of applied width and strike length of the bodies was based both on magnetic data and geological maps. The profile radar altimetry from the helicopter was studied together with the profile magnetic data to analyze variations in anomalies and terrain clearance. Because the rock units are highly magnetic, changes in flying height of ±10 m affect the anomaly curve to some degree. This sensitivity was tested during forward modelling.

[11] Line 2070 (Figures 4 and 5b) was chosen because it has a high angle to the main anomaly. The helicopter profiles do not extend into the positive flank southeast of the negative anomaly and here older fixed-wing data was used. The trend of the anomaly in the fixed-winged data was useful for interpreting the regional magnetic field as applied in the forward model. The magnetic properties used are listed in Table 1.

[12] The profile is dominated by the pronounced negative anomaly coincident with unit IVe. The unit and the anomaly pinch out about 500 m southwest of Heskestadvatnet. The main part of the negative anomaly and the positive anomaly on the northwest flank can be modelled using unit IVe only. Adding other bodies improves the fit, though the interpreted regional field had to be lowered between the observed and the calculated magnetic field. The upper surface of the bodies is reasonably well modelled because it represents the distance between the magnetic sensor and the ground surface as measured by on-board altimeter. The lower boundaries of the bodies are difficult to estimate. Using measured magnetic properties and variations in flight elevation, a fit was easily obtained.

[13] When the induced component of the magnetic anomaly is removed, the magnetic low decreases to 38482 nT, increasing amplitude to −14000 nT at helicopter levels, in good agreement with the calculated induced magnetisation of 3.3 A/m based on susceptibility measurements. Upward continuation of the data to 300 m (Figure 5a) shows the negative anomaly dominates the magnetic field, producing a wider anomaly with amplitude of −10,000 nT. Additional magnetic models were made to study sensitivity of the modelled anomaly to body dimensions. With a thickness of 5 km, and width of 3.5 km, the magnetic low decreases to 36293 nT, (−14600 nT, below 50900 nT background), and the width is equal to the dimension of the body. In data

Table 1. Magnetic Properties of Rock Units Used in Model

Unit	X (SI)	Q ratio	NRM (A/m)	Dec	Inc
QM	0.061	0.02	0.15	33	−14.4
M	0.059	0.56	1.63	140	−33.0
TZ	0.085	0.31	1.31	266	−11.0
IVf	0.086	0.32	1.39	265.0	21.0
IVe	0.075	6.30	23.70	84.1	−53.2
IVc + GN	0.090	0.37	1.70	333.0	−53.0

continued upward to 300 m, this anomaly has a low at 37700 nT (−13200 nT below background).

5. Discussion and Conclusions

[14] The NRM and susceptibility values of samples from unit MCU IVe near Heskestad account for the anomaly. Contributions to the NRM from matrix hemo-ilmenite are estimated to be ~2 A/m, and from magnetite in the Ca-pyroxenes ~4 A/m [*Frandsen et al.*, 2004]. Other magnetic phases are discrete MD-size magnetite and orthopyroxene with hemo-ilmenite exsolution. MD magnetite contributes primarily to induced magnetization, leaving orthopyroxene for further consideration in explaining the remanence.

[15] The Heskestad anomaly is part of the longer negative magnetic anomaly following unit MCU IVe for >20 km around the large syncline hinge, maintaining a similar mineralogy. At Heskestad the calculated vector NRM is 25 A/m; to the north, half-way to the hinge, it decreases to 10 A/m; and near the hinge to 7 A/m. Why does layer IVe achieve such a high NRM only near the edge of the intrusion at Heskestad?

[16] The BKS has a solid-state deformation fabric in the syncline, varying in intensity; weakest at the hinge, strongest on the limbs [*Paludan et al.*, 1994]. The modeled aeromagnetic line is over an area with foliation nearly parallel to cumulate layering and a steep lineation of elongated pyroxenes. Electron backscatter diffraction measurements of crystallographic orientation of orthopyroxene demonstrate a very strong lattice-preferred orientation (LPO) with (100) parallel to the dominant foliation and **c**-axes parallel to the steep lineation. Hemo-ilmenite also has a modest LPO with (001) parallel to foliation. Some hemo-ilmenites contain minor magnetite inclusions. The LPO's were induced ~800–600°C after igneous crystallization, but above temperatures of exsolution in the oxides ~600–400°C. Optical and transmission electron microscopy of the orthopyroxenes, including electron diffraction, show they contain coherent rods and blades of ilmenite with exsolved hematite, where (001) ilmenite is epitaxially intergrown on (100) pyroxene, and **a** ilmenite is parallel to **c** pyroxene. Rods are elongate parallel to **c** of pyroxene; blades are elongate parallel to either **b** or **c**. We are currently exploring whether the LPO of elongate orthopyroxene may produce a high magnetic moment by extreme orientation, shape, or lattice strain of the enclosed hemo-ilmenite.

[17] Part of the "lamellar magnetism" theory for the ilmenite-hematite series is that if (001) planes of ilmenite are oriented parallel to the magnetizing field at lamellar separation and further if **a**-crystallographic axes are also parallel to the field, lamellae will form magnetically "in phase", with resulting very strong magnetic moment [*Robinson et al.*, 2002, 2004]. At Heskestad the steep foliation and lineation are both quasi-parallel to the early Neo-Proterozoic magnetizing field [*Brown and McEnroe*, 2004], fulfilling these requirements, and the LPO intensity appears to increase from the fold hinge to the limb at Heskestad.

[18] Although understanding of individual contributions to total magnetization of the norite is incomplete, it remains a clear example of a rock, with a very high NRM, producing a large remanent anomaly, ~1 billion years old. The norite is in a common Earth setting of a layered intrusion, not requiring an unusually high magnetic field or large abundance of oxides. Though the Heskestad anomaly has the largest amplitude where narrow due to pinch out of the rocks, we can show that a very large remanent anomaly could be produced by increasing the layer to a width of 3 km with thickness of 5 km.

[19] **Acknowledgment.** NFR to SM, EU Contr. HPRI-1999-CT-00004, Universität Bayreuth to D. Rubie. P. Schmidt and Y. Yu are thanked for constructive reviews.

References

Aalstad, I. (1971), NGU Aeromagnetiske målinger over kontinentalsokkelen, *Teknisk Ukeblad*, *118*, 25–27.

Acuña, M. H., et al. (1999), Global distribution of crustal magnetization discovered by the Mars Global Surveyor MAG/ER Experiment, *Science*, *284*, 790–793.

Brown, L. L., and S. A. McEnroe (2004), Paleomagnetism of the Egersund-Ogna anorthosite, Rogaland, Norway, and the position of Fennoscandia in the late Proterozoic, *Geophys. J. Int.*, *158*, 479–488.

Collinson, D. W. (1986), Magnetic properties of Antarctic meteorite EETA 79001 and ALHA 77005: Possible relevance to a Martian magnetic field, *Earth Planet. Sci. Lett.*, *77*, 159–164.

Connerney, J. E. P., M. H. Acuña, P. Wasilewski et al. (1999), Magnetic lineations in the ancient crust of Mars, *Science*, *284*, 794–798.

Encom Technology Pty Ltd. (2001), Geophysical data display, analysis and modeling, in *Encom Modelvision Reference Manual*, 361 pp., Milsons Point, Australia.

Frandsen, C., S. L. S. Stipp, S. A. McEnroe et al. (2004), Magnetic domain structures and stray fields of individual elongated magnetite grains revealed by Magnetic Force Microscopy (MFM), *Phys. Earth Planet. Intrum.*, *141*, 121–124.

Langlais, B., M. E. Purucker, and M. Mandea (2004), Crustal magnetic field of Mars, *J. Geophys. Res.*, *109*, E02008, doi:10.1029/2003JE002048.

McEnroe, S. A., and L. L. Brown (2000), A closer look at remanence-dominated anomalies: Rock-magnetic properties and magnetic mineralogy of the Russell Belt microcline-sillimanite gneisses, Northwest Adirondacks Mountains, New York, *J. Geophys. Res.*, *105*, 16,437–16,456.

McEnroe, S. A., R. Harrison, P. Robinson et al. (2001a), The effect of fine-scale microstructures in titanohematite on the acquisition and stability of NRM in granulite facies metamorphic rocks from southwest Sweden: Implications for crustal magnetism, *J. Geophys. Res.*, *106*, 30,523–30,546.

McEnroe, S. A., P. Robinson, and P. Panish (2001b), Aeromagnetic anomalies, magnetic petrology and rock magnetism of hemo-ilmenite- and magnetite-rich cumulates from the Sokndal Region, South Rogaland, Norway, *Am. Mineral.*, *86*, 1447–1468.

McEnroe, S. A., R. Harrison, P. Robinson, and F. Langhorst (2002), Nanoscale hematite-ilmenite lamellae in massive ilmenite rock: An example of "lamellar magnetism" with implications for planetary magnetic anomalies, *Geophys. J. Int.*, *151*, 890–912.

McEnroe, S. A., L. L. Brown, and P. Robinson (2004), Earth analog for Martian magnetic anomalies: Remanence properties of hemo-ilmenite norites in the Bjerkreim-Sokndal Intrusion, Rogaland, Norway, *J. Appl. Geophys.*, *56*(3), 195–212.

McSween, H. Y., and A. H. Treiman (1998), Martian meteorites, *Rev. Mineral.*, *36*, 1–53.

Paludan, J., U. B. Hansen, and N. Ø. Olsen (1994), Structural evolution of the Precambrian Bjerkreim-Sokndal intrusion, Norway, *Norsk Geol. Tid*, *74*, 185–198.

Robinson, P., R. J. Harrison, S. A. McEnroe, and R. B. Hargraves (2002), Lamellar magnetism in the hematite-ilmenite series as an explanation for strong remanent magnetization, *Nature*, *418*, 517–520.

Robinson, P., R. Harrison, S. A. McEnroe, and R. B. Hargraves (2004), Nature and origin of lamellar magnetism in the hematite-ilmenite series, *Am. Mineral.*, *89*, 725–747.

Wilson, J. R., B. Robins, F. Neilsen et al. (1996), The Bjerkreim-Sokndal layered intrusion, southwest Norway, in *Layered Intrusions*, edited by R. G. Cawthorn, pp. 231–256, Elsevier Sci., New York.

L. L. Brown, Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA.

F. Heidelbach and F. Langenhorst, Bayerisches Geoinstitut, Universität Bayreuth, D-95440 Bayreuth, Germany.

S. A. McEnroe, P. Robinson, and J. R. Skilbrei, Norges Geologiske Undersøkelse, N-7491 Trondheim, Norway. (suzanne.mcenroe@ngu.no)