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Earth analog for Martian magnetic anomalies: remanence properties of hemo-ilmenite norites in the Bjerkreim-Sokndal intrusion, Rogaland, Norway

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Abstract

To explain the very large remanent magnetic anomalies on Mars, which no longer has a global magnetic field, it is important to evaluate rocks on Earth with the necessary properties of high natural remanent magnetization (NRM) and coercivity. Here, we describe a possible analog from the 230-km^2 930 Ma Bjerkreim-Sokndal layered intrusion (BKS) in Rogaland, Norway. In the layered series of the BKS, fractional crystallization of jotunitic magma was punctuated by influx and mixing of more primitive magmas, producing six megacyclic units, each typically with early plagioclase-rich norites, intermediate hemo-ilmenite-rich norites and late magnetite norites with subordinate near end-member ilmenite. Following each influx, the magma resumed normal crystallization and, following the last, near the base of Megacyclic Unit IV, crystallization continued until norites gave way to massive fayalite-magnetite mangerites and quartz mangerites in the upper part of the intrusion. The Megacycles are marked on a regional aeromagnetic map by remanent-controlled negative anomalies over ilmenite norites and induced positive anomalies over magnetite norites and mangerites. A prominent negative anomaly (with amplitude −13,000 nT in a high-resolution helicopter survey, down to −27,000 nT below background in ground magnetic profiles) occurs over the central part of Megacyclic Unit IV. The anomaly is centered on ilmenite norite Unit IVe and is most intense where cumulate layering is near vertical at the southeast edge of the Bjerkreim Lobe of the intrusion at Heskestad. Here, Unit IVe is flanked to the east by magnetite norite of Unit IVc and country-rock gneisses (group E) and to the west by Unit IVf magnetite norite and mangerites (group W). Magnetic properties were measured on 128 oriented samples. Susceptibilities are similar for all three sample groups at $\sim 8\times10^{-2}$, but Koenigsberger ratios are very different, with average values of 7.7 for IVe, and <1 for groups E and W. The IVe samples, with only a few percent of oxides, have the highest NRMs measured from the BKS, up to 74 A/m, with an average of 30.6 A/m, making them prime candidates for consideration as Mars analogs. The mean direction for IVe samples is D=17.6°, I=−79.9, a_{95}=10°, almost opposite the present field. Evidence on origin of the strong NRM in IVe as compared to groups E and W, include greater abundance of hemo-ilmenite and of orthopyroxene with hemo-ilmenite exsolution, and the strong lattice-preferred orientation of both in a relationship favorable for "lamellar magnetism". Massive magnetite-free hemo-ilmenite ores in anorthosite from the

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same district also produce negative magnetic anomalies. They have a substantial but much lower NRM, suggesting that there are special oxide properties in the IVe rocks at Heskestad.

Keywords: Magnetic anomalies; Mars; Hemo-ilmenite; Hematite; Aeromagnetic

1. Introduction

1.1. Martian magnetic anomalies

Large magnetic anomalies have been mapped by the Mars Global Surveyor in the area above the ancient cratered crust of Mars (Acuña et al., 1998, 1999). The strongest anomalies measured at elevations of 100–200 km have amplitudes up to 1500 nT, though the magnetic anomalies observed over the younger Martian terranes are much weaker. These measurements (Connerney et al., 2001) have renewed early speculation (Russell, 1978, 1980) that Mars possessed an internal magnetic field at an early time in its history. Acuña (2001) speculated that the planetary magnetic field was present during crust formation shortly after the planet accreted ~4.5 billion years ago. Thermal modeling indicates that a core dynamo may have existed early in Martian history (Stevenson et al., 1983; Schubert and Spohn, 1990) and could have been a source for an early magnetic field. Today, there is no appreciable magnetic field; however, small surface magnetizations of <50 nT have been measured (Acuña, 2001). The magnetic anomalies, with the lack of a global magnetic field, indicate the magnetization measured is due to memory of an ancient magnetic field, i.e. remanent magnetization. Reasonable models of the large anomalies on Mars require intensely magnetized rocks with average natural remanent magnetization (NRM) of 20 A/m and very large volumes of rock, in 100 km wide and 30 km thick crustal slabs (Acuña et al., 1999; Sprenke and Baker, 2000). For the volumes of magnetic rock to be smaller, the magnetic intensity must increase.

The rocks that produce these anomalies are required to preserve their magnetic properties over billions of years. For that to happen, the magnetic mineral or minerals holding the remanent memory need to have a relatively high stability (coercivity). It is difficult to use anomalies on Earth as analogs for Mars, because of Earth's strong present internal magnetic field, such that many Earth magnetic anomalies have a large component due to the interaction of the magnetic mineralogy with the inducing field. In rocks with multidomain (MD) magnetite, this interaction commonly dominates over the permanent memory of the ancient magnetic field acquired when the metamorphic or igneous rocks cooled through their Néel or Curie temperatures, or grew chemically at still lower temperatures. Another important variable, though still unknown, is the strength of the Martian magnetic field when the rocks were magnetized. On Earth, except for times of field reversals, values range from 20,000 to 70,000 nT, much higher than available estimates for an early Martian field from 100 to 10,000 nT (Collinson, 1986; Cisowiski, 1986).

Given these different planetary conditions, is it likely that there are rocks on Earth to study that have a magnetic mineralogy analogous to rocks on a planet like Mars? Could remanent anomalies of this magnitude exist on Earth, where an inducing magnetic field and rocks with large NRM values can interact to produce anomalies composed of induced and remanent components? Because exploration of planets like Mars without planetary magnetic fields will become more likely in the future, and because of the need to exploit local resources (Purucker and Clark, 2000), it is important to study anomalies on Earth that are remanent-dominated as possible Mars analogs (McEnroe et al., 2002a). From this perspective, a good Martian analog rock must have both an intense NRM and relatively high coercivity (Hargraves et al., 2001). Recently, Proterozoic rocks, ~1 billion years old, that have faithfully retained a large part of their magnetic memory and are associated with sizeable magnetic anomalies, have been studied in detail for their magnetic properties, mineralogy, chemistry, and magnetic responses. Mid-Proterozoic high-grade metamorphic rocks from the Adirondack Mts., USA (Balsley and Buddington, 1958; McEnroe and Brown, 2000), granulite-facies metamorphic rocks from Sweden (McEnroe, 1995; McEnroe et al., 2001a) and igneous rocks in southern Norway (McEnroe, 1997; McEnroe et al., 1996, 1998, 2001b, 2002a,b; Robinson et al., 2001, 2002a,b) and Quebec, Canada (Hargraves and Burt, 1967) are all from areas where the magnetic response is strongly influenced or dominated by an NRM vector that is reversed compared to the Earth's present-day magnetic field. For this type of response to occur, the ancient magnetic memory must contribute strongly or dominate over the present-day induced response of the rock body. If the Earth's magnetic field were to be turned off, these negative magnetic anomalies would increase, because the induced normal component, parallel to the present field would no longer subtract from the anomaly.

In this paper, we present data from a rock unit that has very intense magnetizations and produces a large remanent negative magnetic anomaly. If rocks such as these could be found in the required volumes, then they would be excellent analogs for Martian anomalies. Whether there is a geological setting on Earth that could produce the rock types in the required volumes to produce the anomalies mapped on Mars is a matter of speculation and outside the scope of this paper. The large negative anomaly discussed is produced from one unit in a Proterozoic layered igneous intrusion in southern Norway. We refer to it as the Heskestad anomaly, named after the small hamlet at the southern end of the anomaly.

1.2. Geology

Our example is from the ~930 Ma Mid-Proterozoic Egersund anorthosite-norite province (Schärer et al., 1996) within the Baltic shield in south Norway (Fig. 1). These igneous rocks intrude ~980 Ma granulite-facies metamorphic rocks (Bingen and van Breemen 1998). The province is dominated by six bodies of "massif-type" anorthosite-leuconorite and the 230 km^2 Bjerkreim-Sokndal (BKS) norite-mangerite-quartz mangerite layered intrusion (Wilson et al., 1996; Robins and Wilson, 2001) that contains the Mars analog rocks discussed here.

The layered series of the BKS Intrusion was precipitated from jotunitic magmas in which the dominant early primary precipitate minerals were intermediate plagioclase, orthopyroxene 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 six megacyclic units (0, 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. 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 continued until norites gave way to extremely fractionated, more massive fayalite-bearing mangerites and quartz mangerites in the upper part of the intrusion. The six megacyclic units (MCU 0, IA, IB, II, III, IV) are individually subdivided into zones (a–f), based on assemblages of cumulus minerals (Robins and Wilson, 2001). The megacyclic sequence is marked on the regional aeromagnetic map by remanent-controlled negative anomalies over the ilmenite norites and induced positive anomalies over the more evolved magnetite norites and mangerites.

The layered intrusion is folded into a large doubly plunging syncline (Fig. 1). The Bjerkreim lobe occupies the southeast-plunging northern end; the Sokndal lobe occupies the north-plunging southern end. The layered intrusion is floored by anorthosite on the southeastern and southwestern sides, and by granulite-facies gneisses on the northern and northeastern sides. A seismic reflection profile (Deemer and Hurich, 1997) and gravity modeling (Smithson and Ramberg, 1979) indicate that the base of the intrusion lies at a depth of 4–5 km.

The area of the Heskestad anomaly is at the southeastern corner of the Bjerkreim lobe on the east limb of the syncline. Here, the layering strikes north–northeast and the dip is vertical to 80°W. At

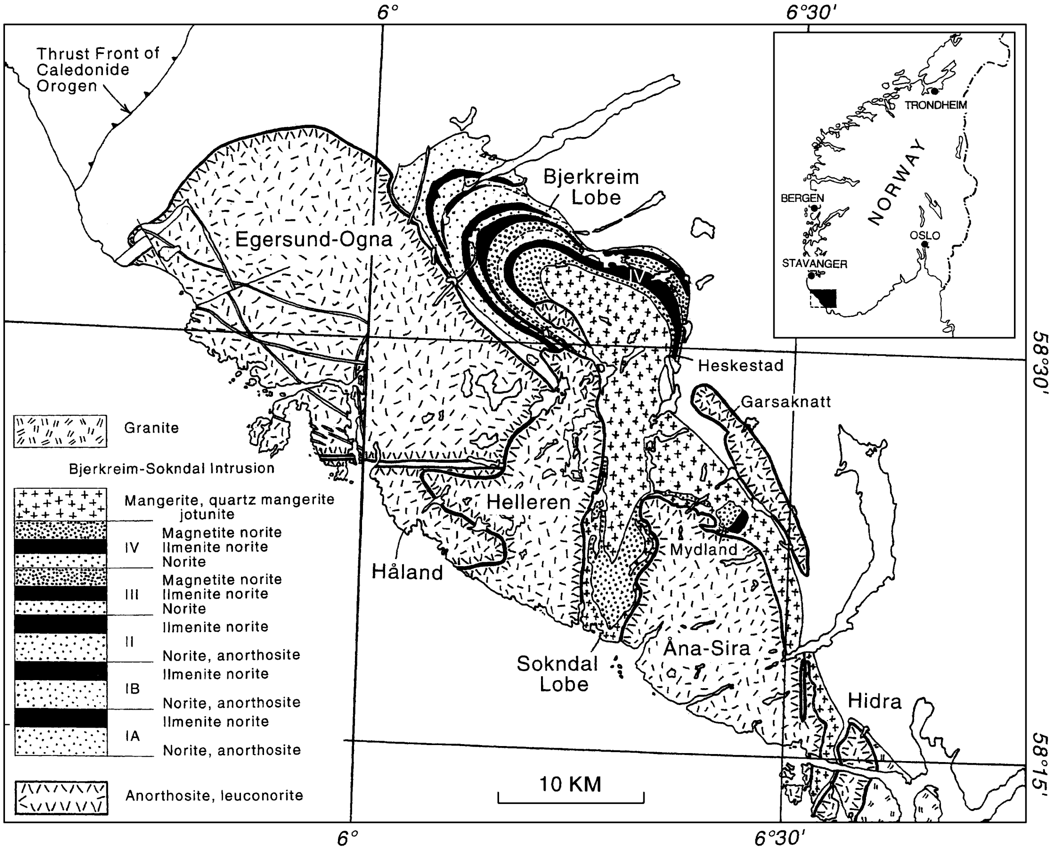

Fig. 1. Regional geological map showing the major intrusive units of the province including the megacyclic units 1A, 1B, II, III and IV of the BKS intrusion (from McEnroe et al., 2001b). Dashed outline shows area of high-resolution helicopter aeromagnetic survey.

Heskestad, the layered series pinches out between the underlying gneiss and the transition zone (TZ) so that the only exposed layered rocks of Unit MCU IV belong to IVc, IVe and IVf.

2. Heskestad geology and magnetic data

2.1. Regional aeromagnetic map

This region is considered rich in mineral resources of ilmenite, vanadium, magnetite and apatite (see Korneliussen et al., 2000). Over the years, numerous airborne magnetic surveys have been flown for mineral exploration. Fig. 2 is an image-enhanced regional aeromagnetic map of the Egersund igneous province made from older fixed wing surveys by the Norwegian Geological Survey (NGU). The surveys were flown at an elevation of 150 m with 0.4–0.5 km line spacing and used visual navigation. Subtraction of the 1965 IGRF values converted the total intensity measurements to anomaly values. Fig. 2 shows distinct positive and negative magnetic anomalies with magnetic contrasts of over 6000 nT (see McEnroe et al., 2001b for an overview). The positive magnetic anomalies are predominantly over granulite-facies country rocks and over magnetite norites and overlying mangerites of the BKS layered intrusion. The negative magnetic anomalies are over hemo-ilmenite-rich norites of the BKS layered intrusion, ilmenite norite ores and the massif anorthosites including the Åna-Sira, the large Egersund-Ogna and the smaller Håland, Helleren and Garsaknatt bodies (Fig. 1). The Åna-Sira, Egersund-Ogna and Håland bodies contain some internal areas with local positive magnetic anomalies.

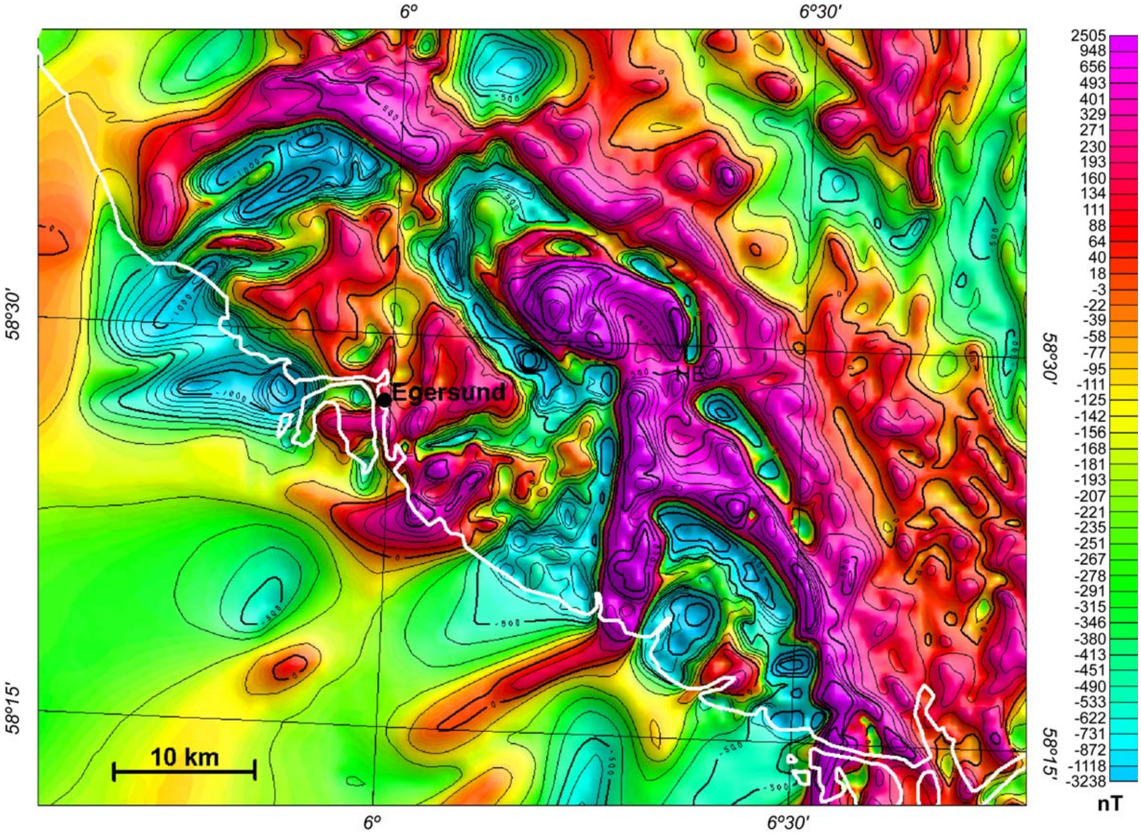

Fig. 2. Regional aeromagnetic anomaly map. These older data have been image-enhanced using Geosoft, on a 500×500-m grid, with illumination from the northeast. The magnetic total field was reduced to anomaly values by subtracting the IGRF (1965) from total field values (modified from McEnroe et al., 2001b). The contour interval is 100 nanoteslas (nT). Color shades: pink = positive anomalies, blue = negative anomalies, green and yellow = intermediate.

Distinct negative anomalies occur over hemo-ilmenite-bearing cumulates near the fold hinge of the Bjerkreim lobe and there is a prominent negative anomaly at the southeastern tip at Heskestad. Reviews of flight-line details for the older aeromagnetic map, and recent ground-magnetic profiles, indicate different contouring for the regional map is essential and show that there is a continuous negative magnetic anomaly from the center of MCU IV at the hinge of the Bjerkreim lobe to Heskestad, everywhere centered on Unit MCU IVe. This anomaly extends along strike for at least 20 km and at its widest is ~1.2 km.

2.2. Heskestad geology and mineralogy

To understand the geology of the rocks exposed at Heskestad, it is essential to understand the nature of the megacyclic (MCU) units of the layered series as exemplified by MCU IV and the overlying massive rocks. Their essential mineralogy as given by Robins and Wilson (2001) is set out in stratigraphic order (top to bottom).

Quartz Mangerite (QMG)—plagioclase, Ca-poor pyroxene, Ca-rich pyroxene, fayalite, ilmenite, magnetite, apatite, mesoperthite, quartz
Mangerite (MG)—plagioclase, Ca-poor pyroxene, Ca-rich pyroxene, fayalite, ilmenite, magnetite, apatite, mesoperthite
Transition Zone (TZ)—plagioclase, Ca-poor pyroxene, Ca-rich pyroxene, fayalite, ilmenite, magnetite and apatite
Megacyclic Unit MCU IVf—plagioclase, pigeonite, Ca-rich pyroxene, ilmenite, magnetite and apatite

Megacyclic Unit MCU IVe—plagioclase, Ca-poor pyroxene, Ca-rich pyroxene, hemo-ilmenite, ilmenite, ilmenite, magnetite and apatite
Megacyclic Unit MCU IVd—plagioclase, Ca-poor pyroxene, hemo-ilmenite, magnetite
Megacyclic Unit MCU IVc—plagioclase, Ca-poor pyroxene, hemo-ilmenite
Megacyclic Unit MCU IVb—plagioclase, olivine, ilmenite, magnetite
Megacyclic Unit MCU IVa—plagioclase, Ca-poor pyroxene, hemo-ilmenite

At its base, Megacyclic Unit IV rests above evolved magnetite-rich cumulates of Unit IIIe that are similar to Unit IVf. Unit IVa represents the beginning of contamination of the magmas by a new more primitive magma influx. This is marked by a regression zone in the composition of silicate and oxide phases, notably the disappearance of Ca-pyroxene, magnetite and apatite, and the appearance of ilmenite-rich cumulate layers believed to have precipitated during magma mixing. Unit IVb represents the most primitive composition of the magma achieved during the influx. Overlying layers IVc, IVd, IVe and IVf represent a return to a normal course of fractional crystallization with progressive loss of olivine, return of magnetite, clinopyroxene and apatite, respectively, as primary precipitate minerals. The distinction between the IVe and IVf layers has been made on the occurrence of orthopyroxene, or of inverted pigeonite, as the Ca-poor pyroxene, but at Heskestad we also report a significant change in the oxides.

The local geology at Heskestad is depicted in Fig. 3. It shows a region close to the steeply plunging edge of the layered series where first IVc, IVe and then IVf pinch out against the basement floor (GN)*. Just south of the map area the transition zone and the overlying mangerite come in contact with the basement. The cumulate layer at Heskestad that causes the anomaly is IVe and has been traced along strike for over 20 km. MCU IV has a maximum thickness of ~1800 m, but in the Heskestad map area IVe narrows to about 400 m thick as it approaches the edge of the intrusion. The contrast in mineralogy between the MCU IVe rocks, layer IVc and country rock gneiss east of Heskestad, and the overlying layer IVf, transition zone, mangerite and quartz mangerite, west of Heskestad, contains the origin of the Heskestad anomaly.

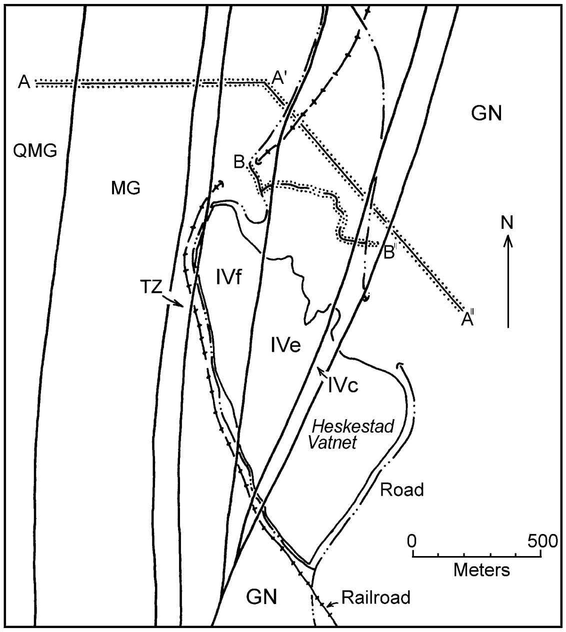

Fig. 3. Detailed geological map of the Heskestad area showing the base of the Bjerkreim-Sokndal layered intrusion where the upper part of Megacyclic Unit IV (IVc, IVe, IVf) pinches out between the country rock gneisses and the overlying transition zone. Lines with dots give the location of magnetic profiles A–A″ (Fig. 7) and B–B″ (Fig. 8) also shown in Fig. 6. For explanation of rock units, see text.

- *The uppermost Unit IV layers at Heskestad were indicated as IVd and IVe until re-interpreted recently as IVe and IVf (Brian Robins, per comm., 2003). The lowest layer still retains the designation of IVc, though our work shows it contains substantial magnetite more like IVd as outlined above.

A transmitted-light photomicrograph of the Heskestad norite (MCU IVe) is shown in Fig. 4a. Orthopyroxene and plagioclase are the dominant silicates; discrete minor clinopyroxene, biotite, quartz and rare apatite are present. Hemo-ilmenite and magnetite are the dominant opaque phases and minor pyrite locally rimmed by secondary goethite is also present. Hemo-ilmenite grains contain multiple generations of very fine (0001) hematite exsolution (Fig. 4b), minor sulfide 'inclusions' and aluminous spinel plates. Up to 4% discrete MD-magnetite is present

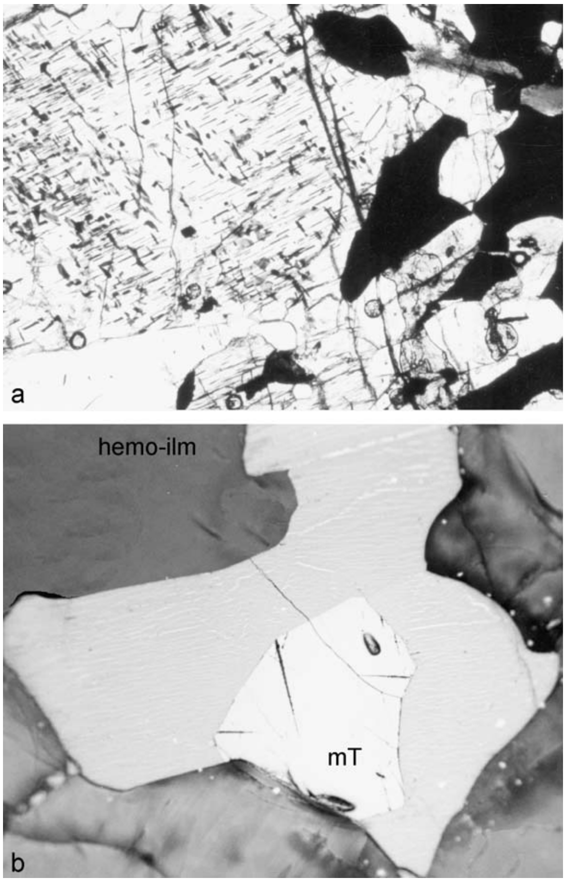

Fig. 4. (a) Transmitted-light photomicrograph of the Heskestad IVe norite. Large cumulate orthopyroxenes, with hemo-ilmenite exsolution and plagioclase are the dominant silicates. Quartz, biotite (brown), apatite, magnetite and hemo-ilmenite (black) are also shown. (b) The reflected-light photomicrograph shows large discrete hemo-ilmenite with abundant hematite exsolution. Magnetite is an accessory mineral and commonly has spinel exsolution. Both the magnetite and ilmenite grains are large. All observed discrete magnetite grains are in the multidomain range.

with minor aluminous spinel exsolution and rare oxidation–exsolution lamellae of ilmenite. Spinel-magnetite-ilmenite symplectites (Duchesne, 1972) decorate some contacts of ilmenite and magnetite though they are not so well developed as in other norites in the intrusion. Orthopyroxenes show abundant hemo-ilmenite exsolution as blades parallel to b of the host as well as rods and blades parallel to c (Fig. 4a). The hematite lamellae in the hemo-ilmenite exsolution are less than a micron wide. Clinopyroxene grains, though rare (<1%), contain exsolved blades and rods of both hemo-ilmenite, and, magnetite with ilmenite lamellae. Detailed magnetic force microscopy studies on the clinopyroxene grains showed the oxide exsolution ranges from PSD to MD size (Frandsen et al., 2004). The primary differences between the norites of Units IVe and IVf near Heskestad are the reduced amount or absence of oxide exsolution in the pyroxenes, and the much poorer amount of hematite component in the hemo-ilmenite in Unit IVf compared to IVe.

2.3. Detailed aeromagnetic maps—Sokndal region

A detailed high-resolution helicopter survey was flown by NGU, covering an area of approximately 250 km^2 in the Sokndal region of 58°25′N latitude, 6°15′E longitude. The local geomagnetic field has declination of 357°6′, inclination of 71°6′ and magnitude of 50,032 nanoteslas (nT). Aeromagnetic data were acquired at 45 m above the ground using a Scintrex Vapour MEP 410 high-sensitivity magnetometer at a 100-m line-spacing. For details of the data acquisition and original processing, see Rønning (1995). The measured total field magnetic intensity ranged from 54,240 to 38,650 nT.

To highlight the magnetic anomalies, a 3D image was created using software from Geosoft (Fig. 5a). Illumination is from the east, with a sun inclination just above the horizon. This image shows positive anomalies as topographically high mountains (in red) due to induced magnetization from the magnetite-bearing and magnetite-rich rocks, and several large negative anomalies, shown in blue. In contrast to most magnetic surveys, the amplitudes of the negative anomalies are larger than the induced anomalies. To highlight the very large negative amplitude of the Heskestad anomaly, a low angle 3D image of the survey is shown in Fig. 5b.

Fig. 6 is a detailed magnetic contour map prepared from flight data in the helicopter survey. It shows a north–northeast-trending magnetic low with a minimum contour at 39,000 nT, flanked to northwest and southeast by a moderate magnetic high reaching ~52,5000 and 50,000 nT, respectively. Unfortunately, because the Heskestad anomaly lies at the northeast corner of the high-resolution helicopter survey, neither the northern extension of the low, nor the extent of the high to the east, is shown on this map. However, these

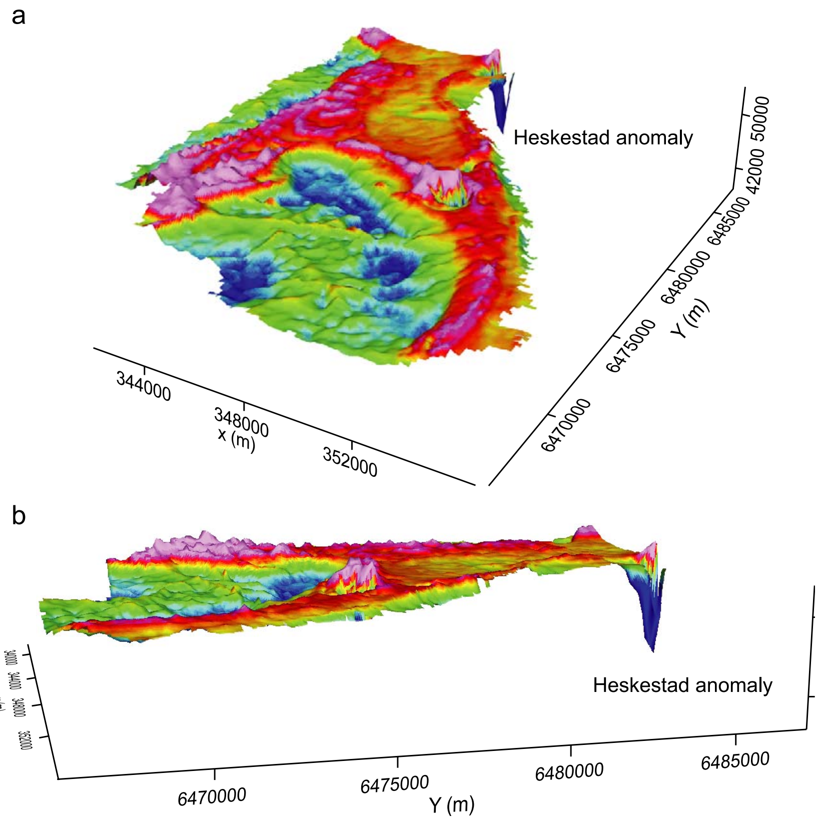

Fig. 5. (a) 3D image made from the high-resolution helicopter data of the southern part of the Bjerkreim-Sokndal region. In this image, the illumination is from the east with an inclination of 25°. (b) Low angle 3D image of the area to highlight the negative anomaly mapped at Heskestad.

overall features can be seen on the older regional map (Fig. 2). A ground-magnetic profile on the southwest margin of the Heskestad lake shows a sharp magnetic low and helps constrain the southwest extension of Unit IVe in Fig. 3. Whether the positive anomaly is somehow paired with the main Heskestad negative anomaly, or is just due to a greater than average thickness of Units IVf and TZ is uncertain. However, the Heskestad negative anomaly obviously requires a strong remanent component to overwhelm any anomaly induced by the present Earth field.

A profile taken from the flight line data shows the ~13,000-nT amplitude anomaly (Fig. 7). The very steep magnetic gradients of this anomaly reflect the contrast in magnetic response between Unit IVe and other BKS units and country rock, and indicates that the source rocks lie at or near the surface. In this profile, the apparent width of the anomaly at the half minimum of 45,500 nT is 390 m.

2.4. Ground magnetic survey

The magnetic variations recorded in the aeromagnetic surveys were investigated in greater detail in 10 ground-magnetic traverses. Measurements were made on the ground in the Heskestad area using a hand-held nuclear-precession total field magnetometer (Uni-Mag G-836 proton magnetometer). Survey lines were run along existing public and farm roads in the area of Heskestad, as well as across fields and along the lakeshore. Fig. 8 shows the results of two traverses along line B–B′, one with a spacing of 15.2 m (Fig. 8a) and one with a closer spacing of 1.52 m (Fig. 8b). This line was collected just north of Heskestad lake along a narrow paved road (Fig. 3). It passes across the southern trough of the helicopter aeromagnetic anomaly about 150 m south of the lowest measurement on profile A–AA′ (Fig. 6). The profile runs from MCU IVc in the east, across MCU

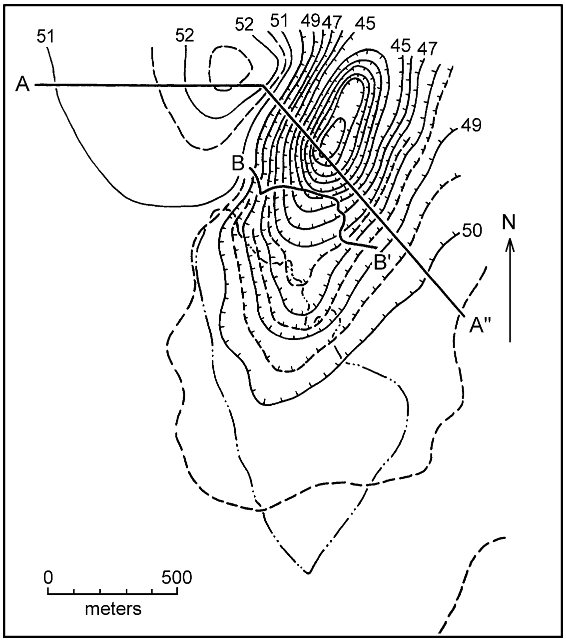

Fig. 6. Detail of the magnetic contour map prepared from flight-line data of the northeast corner of the helicopter survey covering the same geographic area as the geological map of Fig. 3. Solid contours are at 1000-nT intervals with a few additional dashed contours at 500-nT intervals. Dash-dot pattern shows outline of Heskestad Lake. A–A″ is the line of profile from the helicopter survey in Fig. 7. The eastern part of the profile is oriented to include as much as possible of the magnetic high directly east of the Heskestad magnetic low that was outside the helicopter survey area. B–B″ is the line of the ground-magnetic profile in Fig. 8.

IVe and into the magnetic high region of Unit MCU IVf to the west.

The negative anomaly is clearly related to the rocks in MCU IVe ("IVe" on Fig. 3). The shorter-spaced data mimics the wide-spaced data but shows more variability over short distances indicating that these variations are caused by the different layers exposed at the surface. Measured field values range from a high of nearly 53,500 nT on the west to a low of 23,000 nT in the center of the line. Although the collected data in this traverse only extends slightly outside of the mapped regions of Unit MCU IVe, it still indicates a large variable negative magnetic anomaly in a confined area. This narrow anomaly, despite its moderate surface extent, is negating more than half the Earth's field at this latitude. In the 10 ground-magnetic traverses, the lowest measurement of 19,000 nT was made on a bedrock exposure. Using the simple half-width rule, the source of this anomaly must be at or very near the ground surface. Comparison of the helicopter aeromagnetic anomaly and ground-magnetic traverses shows the increased detail apparently related to primary layering of magnetite, hemo-ilmenite and pyroxene cumulates in layer MCU IVe.

3. Rock properties

Rock samples were collected from natural outcrops related to the prominent magnetic low in the Heskestad area and the associated magnetic highs. Six sites are located in a several square kilometer area in Heskestad from layer MCU IVe and the other 11 sites are in layers MCU IVc, IVf, the transition zone, mangerite and metamorphic gneisses. Samples were collected either as individual oriented cores drilled in the field, or as oriented blocks that were later drilled in the laboratory. Usually several specimens of 2.5 cm length were cut from each core. Samples were divided into three groups: the magnetic low area (MCU IVe),

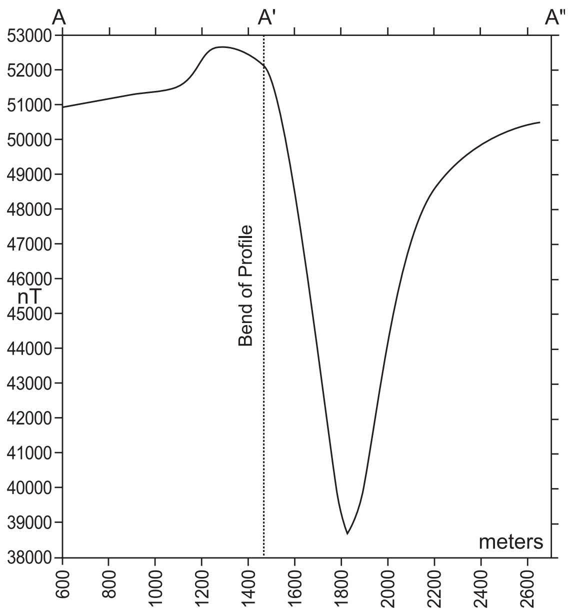

Fig. 7. Magnetic intensity profile taken from helicopter survey data along line A–A″ of Fig. 6, with a bend of section. Even though the Heskestad anomaly appears very steep, the vertical scale is compressed to about one-third.

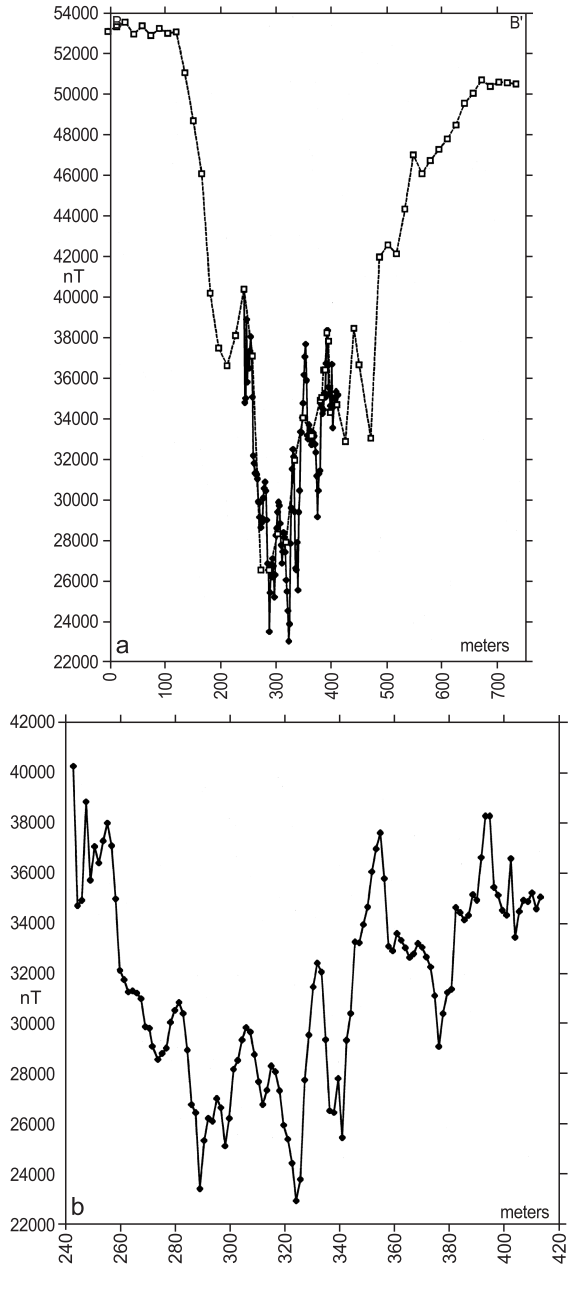

Fig. 8. (a) Ground-magnetic profile along B–B″ (Figs. 3 and 6) from unit IVf to left, through unit IVe to unit IVc on right. Open squares are readings at 15.2-m spacing (50 ft). (b) Detailed shorter ground-magnetic profile along B–B″ solid circles are readings at 1.5-m spacing (5 ft). The variation in layering that is at a steep angle to the traverse is shown by the variation in magnetite content resulting in higher magnetic readings.

the eastern magnetic high area (MCU IVc, metamorphic gneisses) and the western magnetic high area (MCU IVf, TZ, MG).

3.1. Laboratory techniques

NRM was measured using a 2 G cryogenic magnetometer, or a Molspin Spinner Magnetometer at the University of Massachusetts (UMASS), or a JR-5 9 Hz Spinner Magnetometer at the Norwegian Geological Survey (NGU). Many samples were subjected to either AF or thermal stepwise demagnetization as part of a regional paleomagnetic study of southern Norway. Susceptibility values were measured on a Sapphire susceptibility coil at the University of Massachusetts, or a susceptibility bridge at NGU. A Princeton Measurements Alternating Gradient Force Magnetometer at the Institute for Rock Magnetism at the University of Minnesota was used to collect hysteresis properties. Isothermal remanent magnetization (IRM) up to fields of 1.0 T was made on an ASC Pulse Magnetizer.

3.2. Results

NRM directions were obtained from 128 specimens representing all 17 sites, with the results plotted in Fig. 9. Samples from the Heskestad magnetic low area (N=64) carry predominantly reversed directions (92%), with steep negative (upwards) inclinations. These samples have a large range in NRM intensities, from 1 to 74 A/m, that reflects the internal layering of minerals (i.e. variations in modal mineralogy) in this unit. The average NRM value is substantial at 30.6 A/m. Remarkably, there are only two samples with NRM values less than 5 A/m and 65% of the samples have NRM values above 20 A/m. The majority of samples from the most negative part of the anomaly have intensities above this average. A mean direction for these samples, prior to any demagnetization, is $I=-79.9^\circ$ and $D=17.6^\circ$ with a 10.0° circle of confidence at the 95% level (α_{95}). With alternating field (AF) demagnetization, magnetic directions change at low levels of AF with the removal of a soft component carried by the MD magnetite, resulting in a steepening of the negative inclinations and a declination swing towards the northwest.

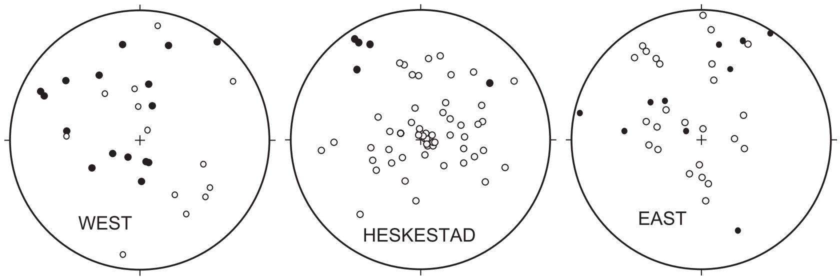

Fig. 9. NRM directions of individual samples from the Heskestad area plotted on an equal area diagram. Data are divided into West, Heskestad and East groups as discussed in the text. Open symbols indicate upward (negative) inclinations; solid symbols represent downward (positive) inclinations.

Susceptibility values vary from 0.007 to 0.143 (SI) with an average of 0.085. Because magnetite has a significantly higher susceptibility than hematite, as a first approximation susceptibility values can be used to calculate the magnetite content of a sample. The calculated magnetite contents in Unit IVe are from 0.2% to 4.1%, with an average magnetite content of 2.4%, in good agreement with optical observations.

The rocks to the west of the Heskestad anomaly (MCU IVf, TZ zone and mangerite) have markedly lower NRM intensities with an average of 3.8 A/m. NRM directions are both negative and positive, as seen on Fig. 9. A mean direction for the group of 27 samples is I=21.9° and D=357.7°, representing a combination of normal and reversed polarity directions. The extremely large α_{95} of 107° attests to the random scatter of the NRM directions. The range in susceptibilities is 0.06–0.14 (SI), with an average of 0.083. Samples have a range in magnetite contents from 1.6 to 4%, with an average of 2.4.

Samples from the area east of the negative anomaly (MCU IVc and country rock gneisses) have a range in NRMs from 0.003 to 9 A/m, with an average of 2.7 A/m. Though the NRM directions are mixed, the majority are negative and have an average direction of I=−47.7° and D=338.5°, α_{95}=26.0°. Susceptibilities of the country rocks are highly variable ranging from a low of 0.00004 to a high of 0.23 (SI) with an average of 0.09. Excluding the metamorphic gneiss samples, the range is from 0.04 to 0.17 and calculated magnetite contents from 0.2% to 6.1%.

Distinctions can be drawn between the two sample sets from the magnetic high regions. The samples from the eastern anomaly area are more consistent in NRM directions than those from the west and the predominant NRM direction is negative. Forty-two percent of the magnetic high samples have positive inclinations, though directions do not mimic the present Earth's magnetic field for southern Norway, indicating a remanent contribution to the NRM.

Samples from the positive and negative magnetic anomaly regions are suspected of responding differently to applied laboratory fields. Results from IRM experiments on three samples from the magnetic low (sites BK34, BK38 and BK42) and one sample from the magnetic high (site BK 43) are shown in Fig. 10.

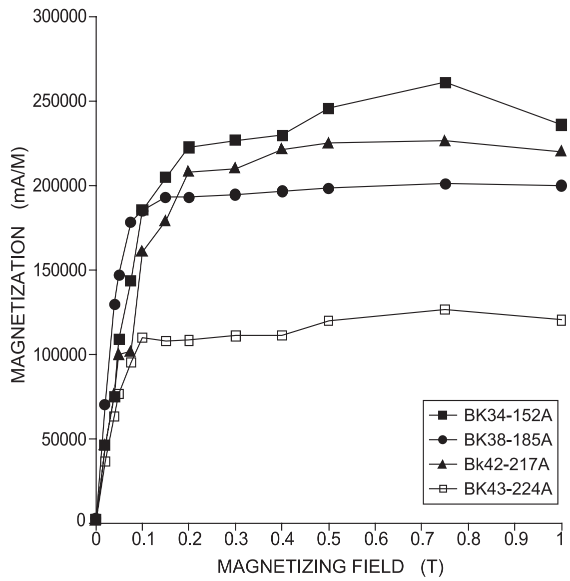

Fig. 10. Plot showing isothermal remanent magnetization for four samples from Heskestad, three from the magnetic low area (BK34, BK38 and BK 42) and one from the magnetic high area (BK43). Magnetization, in mA/m^2, plotted against magnetizing field from 0 to 1.0 T.

The sample from the magnetic high area saturates in a field of 0.1 T and has a total saturation magnetization around 100 A/m, whereas samples from the magnetic low area show variable saturation fields, with one sample saturating by 0.15 T and the other two samples showing continued saturation to 0.4 T or greater with total saturation of 200–250 A/m. Subsequent AF demagnetization of the saturated samples shows two kinds of behavior when compared to AF demagnetization of the NRM on the same sample. BK 43, from the magnetic high area, has nearly identical demagnetization curves for both the IRM and the NRM, with the medium destructive field (MDF) below 5 mT. Samples from the magnetic low area show a softer IRM demagnetization than the corresponding NRM demagnetization, with MDFs of the IRM 10 mT or less, while the MDFs for the NRM ranges from 20 to 40 mT. Samples from the magnetic high region appear to be dominated by MD magnetite, whereas in MCU IVe samples there is a higher coercivity phase in addition to the MD magnetite. Additional information on the saturation and coercivity properties of IVe rocks is provided by room-temperature hysteresis measurements made on seven chips from samples in the magnetic low area. After paramagnetic corrections, samples have a range of saturation magnetization (M_s) from 740 to 3700 mA m^2/kg with normalized saturation magnetization values from 2220 to 11,100 A/m. Saturation remanence (M_{rs}) measurements were far lower, ranging from 56 to 112 mA m^2/kg with a mean value of 85 mA m^2/kg. All M_{rs}/M_s ratios are less than 0.1. Coercivity measurements also reflect the presence of MD magnetite in the samples, with mean coercivity (Hc) of 3.8 and coercivity of remanence (Hcr) of 18. Ratios of Hcr to Hc range from 3 to 10 and many plot within the MD magnetite field on a day plot (Day et al., 1977) where the samples from the magnetic high region also plot.

Excluding the low susceptibility gneiss samples, the three groups of samples yield similar susceptibility values, around 10^{-2} SI, indicating that each group contains nearly the same amounts of magnetite. Because of the coexistence in the samples of similar magnetite contents, most strong field rock magnetic experiments show similar results, and it is difficult to obtain useful information from them. However, there are noticeable differences between the magnetic 'high rocks', both east and west of the anomaly, and the samples from the magnetic 'low' regions.

The primary differences between samples from sites in the magnetic high and low regions are in their initial NRM intensities and in their response to demagnetization experiments. Samples from the magnetic low region have an order of magnitude higher mean NRM value of 30.6 A/m, compared to a mean of 3.1 A/m for samples from the magnetic high region. Demagnetization experiments show higher resistance to AF and significantly more magnetization remaining at higher temperatures in thermal demagnetization in the samples from the magnetic low regions. Demagnetization of the IRM indicates that the magnetic behavior of the samples from the magnetic high region is dominated by MD magnetite while the samples from the magnetic low regions contain an additional component that has a higher coercivity. Given these differences, how do the different rock properties affect the magnetic response of the rock units? To answer this question, it is worthwhile to examine the parameters that produce an induced or remanent magnetic signature.

4. Discussion

To evaluate the different magnetic responses of these igneous layers in magnetic anomalies on Earth, NRM and susceptibility values are the two most important magnetic parameters. From these two parameters a Koenigsberger ratio (Q value) is calculated by dividing the NRM by the induced magnetization (susceptibility$\times$ambient field). For our calculations, we used a value of 50,032 nT (corresponding to a magnetizing force of 39.8 A/m) for the ambient field in Rogaland, southern Norway.

In areas where Q values are <0.5, the magnetic response should be primarily from the induced magnetization of the rocks, whereas in areas with Q values >1 remanent magnetization is a major contributor to the anomaly, provided the remanence directions are reasonably consistent. Where Q>10 and NRM directions are consistent; the NRM should dominate the magnetic response of the rock, far exceeding the induced response. Because samples typically contain 2–4% MD magnetite, the expected magnetic response is that of an induced magnetization, plus a subordinate, subparallel viscous component and possibly a small remanent component resulting in overall low Q values. Though there is a similarity in magnetite content for the igneous rocks Q values range from $\ll 1$ to 29.

Samples from the western region have a low ratio of NRM to susceptibility with an average Q of only 0.09. Q values from the eastern region are also highly variable ranging from 0.12 to 4.5, with an average of 0.8, significantly higher than the samples from the western magnetic high region.

Heskestad samples from the negative anomaly region all have Q values >1; 91% have Q>5 and 21% have >10 with an average of 7.7. The NRM directions, measured by the 10° circle of confidence at the 95% level, are well clustered. The high Q values and persistent remanence directions indicate that the NRM vector significantly affects the shape of the anomaly so that the direction and intensity of the NRM must be known to model this anomaly successfully.

In Fig. 11, NRM, induced magnetization (susceptibility*magnetic field), and Q values are plotted to evaluate the relative contributions of susceptibility and remanence to the anomaly. Fig. 11a shows induced magnetization (Ji) and NRM values plotted in A/m. Excluding four very low susceptibility country rock gneiss samples, there is remarkably little variation in induced magnetization data amongst the samples. When Ji is plotted against Q values (Fig. 11b), it shows very little change in susceptibility with increasing Q value except for the samples with the highest Q values. These samples show a relative decrease in susceptibility relative to NRM values. The general invariance in susceptibility between units indicates similarity in magnetite contents. Given the relative consistency in susceptibility values, the large range in Q values is surprising. When we evaluate the relationship

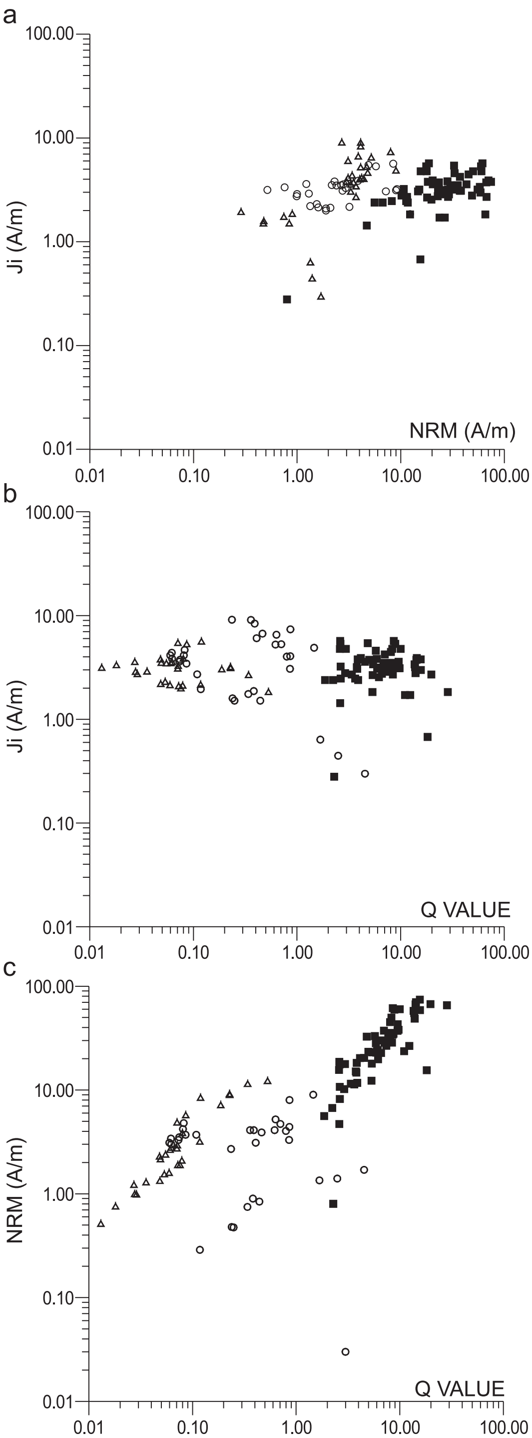

Fig. 11. Log–log plots of magnetic properties of 128 cores from Heskestad and associated rocks. Solid squares are samples from the Heskestad area of the magnetic low; open triangles are samples from rocks on the west side of the magnetic low area; open circles are from rocks on the east side of the magnetic low area. (a) Plot of natural remanent magnetization in A/m versus Ji (induced magnetization in A/m). (b) Koenigsberger ratio (Q) versus Ji. (c) Koenigsberger ratio (Q) versus natural remanent magnetization in A/m.

between Q and NRM (Fig. 11c), three trends of increasing NRM with increasing Q are evident. Heskestad IVe samples show an almost linear trend of increasing NRM correlating with higher Q values. Overall, the samples from the western magnetic high area (open triangles) have lowest Q; however, these show a good correlation between NRM and Q. Samples from the Eastern positive magnetic area (open circles) can be subdivided into two groups: (1) higher NRM values that plot between the Heskestad IVe samples and the western samples, falling on a trend of increasing NRM with increasing Q value; (2) lower NRMs, but similar Q values. There is an overall trend from low NRM and Q values for the positive anomaly samples, toward high NRM and Q values for samples from the Heskestad negative anomaly area. In Fig. 12, NRM is plotted against Q value in a mixed linear-log plot to emphasize the large NRM component that distinguishes the Heskestad IVe samples from all others. From this plot, it is clear that the NRM values are the cause of the high Q values and that the MD magnetite has limited effect on NRM intensities. Based on the limited variation in susceptibility, we conclude that the range

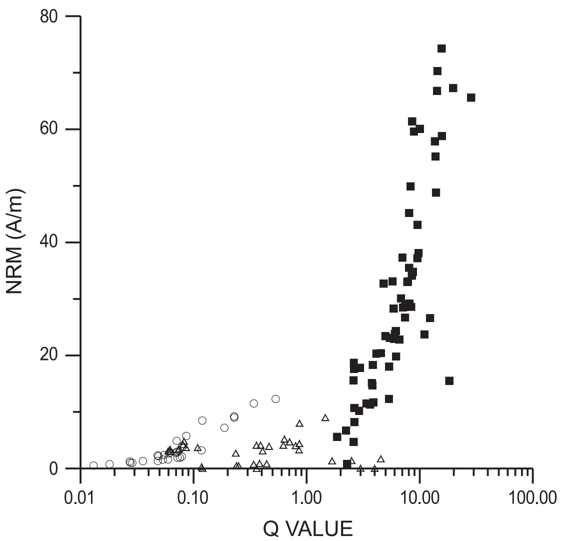

Fig. 12. Semi-log plot of Koenigsberger ratio (Q) versus NRM in A/m for samples from Heskestad and surrounding areas. Solid squares are samples from the Heskestad magnetic low area; open circles are samples from rocks on the west side of the magnetic low area; open triangles are from rocks on the east side of the magnetic low area.

in NRM values in Unit IVe is a function of hemo-ilmenite and the amount of oxide exsolution in the pyroxenes.

Assuming that the sample collection is representative of the distribution of magnetic properties, a rigorous estimation of the average remanent magnetization of the unit can be made, allowing for variations in the NRM directions (Fig. 9). This entails calculation of the vector mean NRM (sum of NRM vectors/number of vectors). The vector mean NRM from eastern sites (positive anomaly) is NRM=1.7 A/m, D=333, I=−53 and a vector Q value of 0.3. Rocks from the western side of the Heskestad anomaly have NRM=0.9 A/m, D=358, I=45 and a vector Q value of 0.09. The large scatter at the NRM level in data sets from the two magnetic high regions significantly reduces the vector NRM intensities from 3.7 to 0.4 and 2.8 to 1.7 A/m, respectively, resulting in greatly reduced Q values compared to those derived from Fisherian statistical data. In the Heskestad IVe samples, the resultant vector NRM is characterized by: intensity of 25.1 A/m, D=83.2°, I=−73.8° and a calculated vector Q value of 5.9. Though the induced magnetic response from 2% to 4% magnetite is significant, on average 85% of the magnetization in the Heskestad IVe samples is composed of remanence producing a magnetic response dominated by their remanent memory.

Earlier work in the region by McEnroe et al. (2000, 2001b) concluded that in the BKS layered intrusion the primitive magmas produced rocks rich in hemo-ilmenite. These rocks have negative magnetic anomalies related to magnetic remanence. The more evolved magmas produced rocks rich in magnetite and Ti-rich ilmenite and are related to positive induced magnetic anomalies. The mineralogical differences that resulted in the change from remanent-dominated to induced-dominated response of the rock layers occurred as a result of crystallization-differentiation in the layered series following the last of five influxes of more primitive magmas. In the Heskestad IVe layer, more ferri-ilmenite and higher temperature pyroxenes crystallized out of the magma producing more discrete hemo-ilmenite, and pyroxenes with oxide exsolution, than in the adjacent MCU IVc and IVf layers. One of the surprising results of the present study is the identification of a significant amount of discrete MD magnetite in the Heskestad IVe layer so that these samples have similar magnetite contents to the immediately adjacent MCU layers. In this sense, the simplified explanation on Fig. 1 is misleading because both the ilmenite norites and the magnetite norites contain MD magnetite and the chief explanation of their very different magnetic properties is more complicated. There are three obvious differences that characterize the IVe ilmenite norites: (1) more ilmenite than the magnetite norites, (2) Unit IVe is dominated by highly exsolved hemo-ilmenite, whereas the magnetite norites contain predominately near end member ilmenite with little or no exsolution, and (3) the pyroxenes, especially the orthopyroxenes, have abundant hemo-ilmenite exsolution, whereas the pyroxenes of the magnetite norites, have little or no exsolution.

The anomaly produced by the Heskestad IVe layer and surrounding rocks, though narrow, is large. The maximum vertical magnetic anomaly associated with a vertical magnetization contrast M at a geological contact is μM/2. The Heskestad IVe layer NRM corresponds to an anomaly of −15,700 nT, in relatively good agreement with the observed magnetic anomaly. Though the amplitude of this anomaly and high NRM make these rocks a good Martian analogue, are these rocks somehow special?

In previous magnetic studies of deep crustal rocks, it was generally assumed that high magnetizations are restricted to rocks with magnetite (Shive et al., 1990). In deep and moderate crustal levels, Shive et al. (1988) concluded that remanent magnetization contributes far less than the induced magnetization and that the total magnetization is not significantly greater than the induced magnetization. Inherent in this conclusion is that, if magnetite is the dominant magnetic mineral at depth, then the induced magnetization should predominate over remanent magnetization, unless magnetite is in the single- or pseudo-single domain state.

The rocks at Heskestad contradict this assumption. These rocks have high susceptibilities, and very high NRMs, implying the presence of magnetic phases that can carry high NRM intensities and memory for geological time periods. To try to understand further the cause of the high NRMs in the hemo-ilmenite rich Heskestad rocks, McEnroe et al. (2002b) studied samples from ‘nearly pure hemo-ilmenite layers’ in the Åna-Sira Anorthosite. The hemo-ilmenite samples have high NRMs and stability. However, when these properties are ‘normalized’ to the modal hemo-ilmenite content in the Heskestad IVe layer, only 10% of the NRM could be account for by the discrete hemo-ilmenite grains. Rare clinopyroxene grains (<0.05% of the rock) contain exsolved blades and rods of both hemo-ilmenite and magnetite. Based on the MFM study (Frandsen et al., 2004), the calculated contribution from the PSD magnetite in the clinopyroxene grains is estimated to be ~2% of the total NRM.

In the BKS layered series, there is a striking contrast between rocks crystallized from less evolved magmas with the negative magnetic anomalies and those crystallized from more evolved magmas related to positive induced magnetic anomalies. The large negative anomaly at Heskestad was easy to spot because the remanent vector is at a large angle to the inducing vector. However, if the remanent vector had been closer to the inducing vector the response would be to produce a very large magnetic high and as a first approximation, would be attributed to induced magnetization of a magnetite-rich layer. This case study shows that induced magnetization is not the sole cause of large magnetic anomalies and reinforces the opinion that remanence can be an important contributor to deep crustal anomalies (McEnroe and Brown, 2000; McEnroe et al., 2001a,b, 2002a,b; Worm, 1989). Clark (1999) has also concluded that remanence could be important in many mafic plutons. Are the high NRMs and Q values unusual from high-grade metamorphic and intrusive rocks?

Magnetite-bearing Proterozoic granulites from southern Sweden also have a high ratio of NRM to susceptibility and high Q values. The strong and extremely stable NRM is carried by highly exsolved hemo-ilmenite and ilmeno-hematite grains (McEnroe, 1995; McEnroe et al., 2001a). Instead of a regional magnetic high over the granulite terrane, there are subdued magnetic anomalies because of the strong influence of a negative remanent vector. High-grade metamorphic rocks in the Adirondack Mountains, New York, also have strong negative remanent-dominated anomalies associated with certain rock types. Balsley and Buddington (1958) recognized that these anomalies were unusual, and they combined oxide petrography, rock and mineral chemistry with susceptibility and NRM measurements to interpret them. They concluded that the rocks containing magnetite had positive anomalies, and those that contained hematite-ilmenite yielded negative anomalies and suspected a self-reversal mechanism in the hematite-ilmenite bearing rocks. Later, McEnroe and Brown (2000) made a detailed study of the geophysical and rock-magnetic properties of the Russell Belt in the Adirondack Mountains and showed that highly exsolved ilmeno-hematite was the remanence carrier, and clearly correlated the magnetic properties with the negative magnetic anomaly. Though McEnroe and Brown (2000) did not find evidence for self-reversal in the ilmeno-hematite grains they could not disprove the possibility.

There are still too few detailed magnetic studies on metamorphic and high-temperature igneous terranes. Too commonly, when the magnetic response of these bodies is that of a magnetic low, these areas are interpreted as 'non-magnetic crustal regions'. An alternative explanation is that highly magnetic rocks, which have a strong remanent component at a large angle to the inducing field, produce some of these anomalies.

The distinguishing feature of the studies discussed above is that the rocks all contain exsolved members of the hematite-ilmenite solid solution. Robinson et al. (2002a, 2004) proposed that the high magnetization and stability in exsolved hematite-ilmenite grains is due to "contact layers" at the interfaces of small exsolution lamellae producing a ferrimagnetic moment. Many metamorphic and high-temperature igneous terranes provide slow cooling, which is one of the necessary conditions for creating very abundant exsolution lamellae in oxides and in silicates. In all the geological regions described above, prolonged cooling over millions of years took place.

However, the Heskestad IVe layer is still distinguished from these other studies in that it has higher NRM values for similar oxide contents. This difference could be due to the abundant hemo-ilmenite exsolution in the pyroxene grains that have a strong preferred orientation in the IVe layer as compared to the other rocks studied that do not have this strong preferred orientation.

On Mars, where anomalies are attributed to a remanent magnetization acquired billions of years in the past, the main requirements for source rocks are high NRM intensities, and high Q values, that would reflect the relatively high coercivity needed to preserve the magnetic memory for billions of years. These conditions are met at Heskestad. The setting of the BKS intrusion is not unique on Earth where there are many layered intrusions, a few with similar characteristics. There is no reason to suspect that they could not exist on Mars. We believe that if the Heskestad hemo-ilmenite norite occurred in large enough volumes it would produce an anomaly of Martian proportions.

To compare accurately the Heskestad anomaly to Martian conditions, we would need to model the anomaly with the induced component subtracted from the remanent component, in which case this anomaly would have greater negative amplitude. Models for Martian anomalies given by Sprenke and Baker (2000) used a 20 A/m magnetization for a slab of 100 km width and 30 km thickness. The Heskestad norite IVe layer with a magnetization of 30 A/m could create the necessary anomaly with only 24 km thickness because of the higher magnetization. However the BKS intrusion has a maximum thickness of only 7 km. To create the large anomalies on Mars a rock body like the Heskestad norite IVe layer would have to be much larger. It is possible that enhanced contrast between magmatic layers of opposite magnetic polarity could reduce the required thickness to as little as 12 km. At present, we do not know of an ilmenite norite layer this thick on Earth, but subcrustal magmatic underplating is a realistic way to get large amounts of mafic material and if it had similar magnetic properties to the Heskestad norite then it could produce anomalies of the necessary magnitude. Previously cited studies on granulites on Earth are other good candidates due to their high magnetic stability and NRMs produced from a few percent oxides. We see no reason to assume that conditions to form granulite-facies rocks at depth or layered intrusions could not have occurred during early Martian evolutionary history.

5. Conclusions and future work

A large negative anomaly of nearly 13,000 nT was mapped by a high-resolution aeromagnetic survey in the Heskestad region of southern Norway. It occurs over hemo-ilmenite norite unit IVe of the Bjerkreim-Sokndal layered intrusion. Other negative anomalies in the BKS intrusion associated with hemo-ilmenite are known, however the Heskestad anomaly is the largest of the negative anomalies, traceable for nearly 20 km along strike. Samples from this rock unit have high NRM and Q values, and dominantly steep negative inclinations. Rocks both to the east and west of the Heskestad anomaly have similar susceptibilities to the Heskestad rocks, but notably lower NRM and Q values, and more scattered NRM directions. Remarkably, the ilmenite norites of unit IVe contain similar amounts of magnetite to adjacent layers but differ from them in three ways: (1) they contain more hemo-ilmenite than the magnetite norites; (2) are dominated by highly exsolved hemo-ilmenite, whereas the magnetite norites contain predominantly near-end-member ilmenite with little or no exsolution; and (3) contain orthopyroxenes with abundant hemo-ilmenite exsolved on (100) of the host. In addition, there is the strong lattice-preferred orientation of both ilmenite and orthopyroxene in a position favorable for "lamellar magnetism". The relationship between the norite mineralogy and the high NRM values will be further investigated by rock-magnetic experiments on mineral separates combined with transmission electron microscopy and chemical analyses of the different magnetic phases and lattice-preferred orientation studies.

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