GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 2, PAGES 199-202, JANUARY 15, 1998

The origin of magnetic anomalies in lower crustal rocks, Labrador

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Abstract. Mid- to lower crustal granulites near Wilson Lake in Central Labrador exhibit pronounced aeromagnetic anomalies. Areas characterized by high and low field strength correlate with the Wilson Lake allochthon and the surrounding autochthon respectively. The induced magnetization in both units has mean values of 0.34 A/m (allochthon) and 0.33 A/m (autochthon). However, the mean values of remanent magnetizations are 9.2 A/m (allochthon) and 3.3 A/m (autochthon) in directions contributing to the present geomagnetic field. Therefore, the remanent magnetization plays the main role in generating the observed magnetic anomaly. Thermal demagnetizations indicate that titanhematite is stable to 585-600 °C. The absence of significant Verwey transitions indicates that titanhematite is the predominant carrier in some rocks and a significant carrier along with magnetite in others. Any interpretation of the magnetic anomalies above these rocks must consider magnetic remanence as the principle anomaly source.

Introduction

Magnetic anomalies reflect changes in concentration and grain size of certain iron - rich minerals. Generally the most common carrier of induced magnetization in mid- to lower crustal rocks is assumed to be multidomain (MD), relatively pure magnetite (Schlinger, 1985; Williams et al, 1985; Shive and Fountain, 1988; Wasilewski and Warner, 1988; Reeves, 1989; Kelso et al, 1993). On this basis, one would expect that no significant magnetic contrast would exist over rocks in which the amount of MD magnetite does not vary. The purpose of this paper is to describe an area of high grade metamorphic rocks in central Labrador where variations in bulk rock susceptibility do not contribute significantly to observed anomalies. Instead, variations in magnetic remanence due to titanhematite seems to be the most likely cause of the anomalies.

There are relatively few areas on earth where the deepest levels of continental crust are exposed for observation. In the Redwine Mountains of central Labrador, sapphirrine-bearing gneisses are exposed over a distance of 200 km (Herd et al., 1987; Arima et al., 1986). These deep crustal rocks are within the Grenville orogenic belt and are located about 60 km south of the Grenville Front (see Figure 1). The aeromagnetic signature over much of this region is characterized by a prominent high (Figure 1) that corresponds on the ground to well-layered, quartzo-feldspathic gneisses that are resistant to weathering and erosion and thus form much of the highlands in the area. Thomas, et. al. (1993) include these rocks as part of the Hope Gneiss. Dark layers in these rocks are dominated by the metamorphic assemblage sapphirine + quartz + orthopyroxene + sillimanite along with variable amounts of plagioclase, K-feldspar, titanhematite and magnetite, whereas the felsic layers are predominantly feldspar and quartz with lesser amounts of orthopyroxene, sillimanite and titanhematite. Based on our petrographic and backscattered electron images of about 40 polished thin sections from the highlands (magnetic high), coarse grains of titanhematite are 5 to 50 times more abundant than coarse grains of magnetite. Previous petrologic studies of the area using a variety of geobarometers and thermometers indicate peak metamorphic pressures of about 10 kbar and temperatures of about 1000°C (Currie and Gittens, 1988; Arima, et. al., 1986; Morse and Talley, 1971). The mineral assemblage sapphirine + quartz + orthopyroxene + sillimanite is widespread and is diagnostic of these extreme conditions (e.g., Ellis, 1987; Harley, 1989). The abundance of titanhematite as well as high ferric iron in sapphirine (Morse and Talley, 1971; Arima, et. al., 1986), orthopyroxene (Kletetschka and Stout, 1995) and sillimanite (Fleet and Arima, 1985) suggest some degree of equilibration between oxides and silicates under relatively oxidizing conditions. The correlation of highly magnesian sapphirine and orthopyroxene with the relative abundance of titanhematite is a consequence of this equilibration. The relatively high oxygen fugacity at the time of metamorphism is thought to be inherited from the protolith of the Hope Gneiss, possibly an oxidized shale (Arima, et. al., 1986).

In contrast, the region surrounding these gneisses is characterized by an aeromagnetic low (Figure 1). The quartzo-

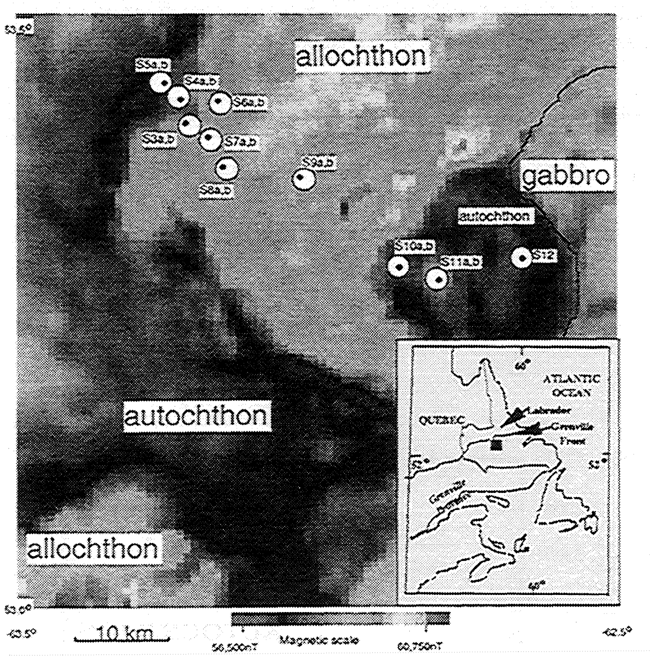

Figure 1. Magnetic anomalies in the Wilson Lake area, Labrador. Wilson Lake allochthon is a magnetic high; the autochthon is a relative magnetic low. Circles on map show both core sites and orientation of the normal remanent magnetization (NRM). Lower hemisphere projection with north-directed poles downward.

Paper number 97GL03506.
0094-8534/98/97GL-03506$05.00

feldspathic gneisses on the ground are also mapped as Hope Gneiss by Thomas, et. al. (1993). They are difficult to distinguish in hand specimen from the more resistant gneisses although they do weather more easily and thus make up much of the lowlands in the area. They are mineralogically quite similar to the more resistant gneisses with dark layers consisting of the assemblage quartz + orthopyroxene + sillimanite along with lesser and varying amounts of titanhematite, magnetite, biotite, muscovite, cordierite, and only sporadic occurrences of sapphirine. The felsic layers consist of feldspars and quartz and small amounts of titanhematite and magnetite. Our analysis of about 20 polished thin sections from the area characterized by the magnetic low indicates that coarse-grained titanhematite still predominates over coarse-grained magnetite but not as significantly as in the allochthon. Currie and Gittens (1988), Herd et al (1987), and Thomas (1993) interpret the cordierite and hydrous phases along with some magnetite as indicative of an amphibolite facies event thought to be imprinted in Grenville time. U/Pb dates on zircons yield Labradorian ages (1650-1700 Ma) which are interpreted to date the granulite-facies metamorphism (Currie and Loveridge, 1985). Rb/Sr dates on biotite are interpreted to date the retrograde event associated with Grenville emplacement (0.9-1.0 Ga) and uplift (Thomas, 1993; Currie and Loveridge, 1985).

The region of high magnetic field intensity in Figure 1 also corresponds to a tectonic unit referred to by Thomas (1993) and Rivers and Nunn (1985) as the Wilson Lake allochthon. The surrounding gneisses which underlie areas of relatively low magnetic field intensity are referred to by the same authors as paraautochthonous. The structural distinction between these units is based on differences in the regional trends of foliation and broad fold structures that are not apparent at the outcrop scale. On the broadest scale, progressively deeper-seated and more- transported rocks are encountered from north to south from the Grenville Front (Gower et al., 1990) until the most deformed and metamorphosed gneisses of the Wilson Lake allochthon are reached. For convenience, we hereafter refer to the gneisses that underlie the area of relatively high magnetic field strength in Figure 1 as the allochthon, and gneisses underlying areas of relatively low magnetic field strength as the autochthon.

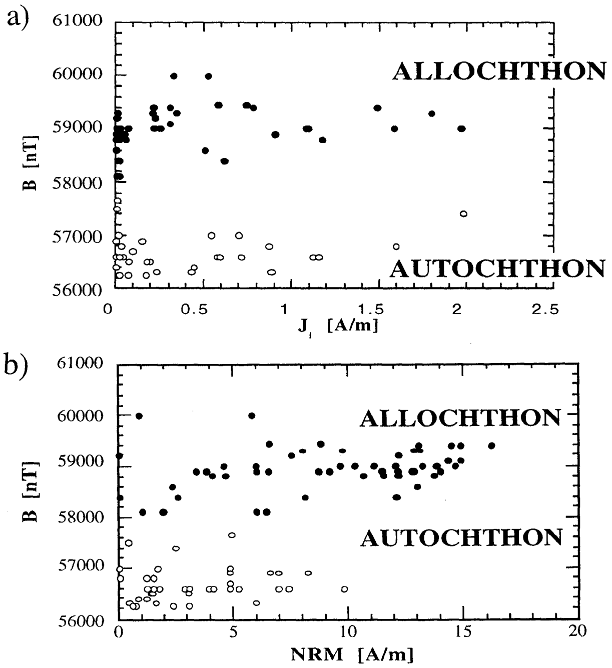

Figure 2. (a) Geomagnetic field (B) vs. induced magnetization (J_i) and (b) Geomagnetic field vs. NRM for Wilson Lake gneisses.

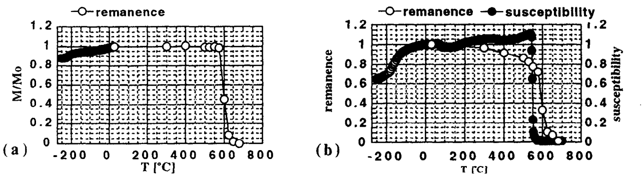

Figure 3. Typical remanence (M/M_0) dependence on temperature for samples (a) without a Verwey transition and (b) with a significant Verwey transition. Figure 4b also shows the typical susceptibility dependence on temperature with a prominent drop at the Curie temperature of magnetite.

Induced versus Remanent Magnetization

Field mapping, observation and sample collecting were done in the summers of 1994, 1995 and 1996. Bulk susceptibilities on 90 unoriented specimens collected from both the allochthon and the autochthon were measured on a Bartington Bridge. The susceptibilities were converted to induced magnetization, J_i, and plotted against field strength, B, in Figure 2a. Mean values of induced magnetization in rocks from the allochthon and autochthon are 0.33 A/m and 0.34 A/m respectively. The fact that the range in susceptibilities is the same in the two tectonic units suggests that the range in amount of magnetite in the two units is about the same. Although titanhematite is more abundant than coarse-grained magnetite in polished thin sections, the known susceptibility of magnetite is 3 to 4 orders of magnitude greater than the susceptibility of hematite and silicates (Hunt, et. al., 1995). Because all of our thin sections have visible coarse-grained magnetite, this phase is most likely the principal cause of the induced magnetization. This suspicion was confirmed by temperature-dependent susceptibility measurements (see figure 3b) which show the principle drop in susceptibility at the Curie temperature of magnetite (545 - 560^{o}C). The more abundant titanhematite in the rocks has a higher Curie temperature so its contribution at most would be represented by the susceptibility remaining above 560 ^{o}C. Our measurements (Figure 3b) show a negligible amount of susceptibility left above this temperature. We have observed no evidence of single domain magnetite, but if present, it would have a susceptibility about a factor of 5 less than that of MD magnetite.

Natural remanent magnetization (NRM) was measured in a spinner magnetometer on the same specimens. The mean measured NRM, 6.3 A/m (see Figure 2b), is more than an order of magnitude greater than the mean value of J_i (0.34 A/m). It thus seems unlikely that the magnetic anomalies in Figure 1 are generated by induced magnetization as implied by Rivers and Nunn (1985). Our data imply that the bulk magnetic susceptibility is not large enough to solely account for the observed anomalies. The positive correlation of NRM moment and field strength strongly supports the hypothesis that the aeromagnetic anomalies observed over both the allochthonous and autochthonous gneisses are controlled by stable remanence.

Remanence Carrier

Figure 1 shows the locations of five coring sites in the allochthon and five sites in the autochthon that were established in the summer of 1996. Two oriented cores were collected from each site, except for S12 where we have only one core. Thermal demagnetization of the oriented cores was measured in the Institute for Rock Magnetism (IRM) at the University of Minnesota with a Shoenstedt spinner magnetometer combined with a shielded oven. Thermal demagnetization data for these cores are shown separately for the allochthon and the autochthon in Figure 3. The two sets of

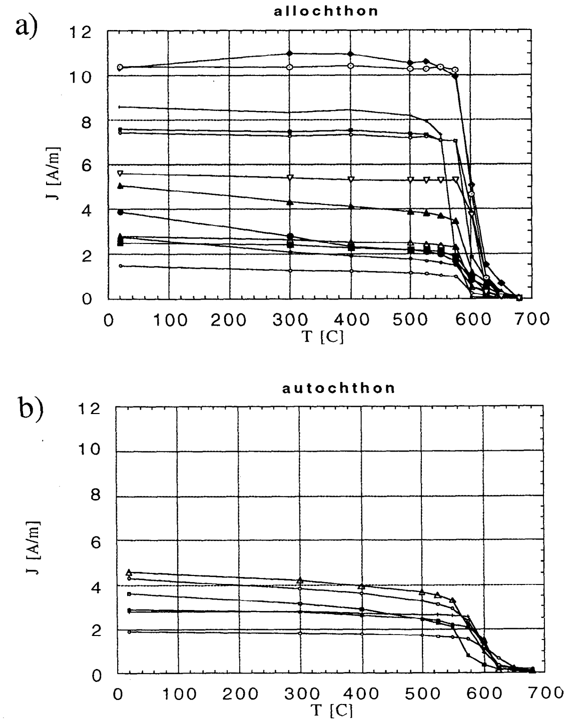

Figure 4. Thermal demagnetization of the remanence from 9 allochthonous cores (a) and 6 autochthonous cores (b).

data are not normalized in order to show the significantly higher NRM moment in the allochthon discussed above. Figure 4 shows that the stable remanence carriers have unblocking temperatures (T_0) in excess of 500°C. Both data sets are consistent with magnetite and/or titanhematite as the predominant remanence carrier. Backscattered electron images and reflected light observations of about 60 polished thin sections from both tectonic units confirm magnetite and especially titanhematite as the major coarse-grained oxides. The latter phase has an ilmenite component that varies from y=0.1 to y=0.2. This range of composition corresponds to a range of T_c from 600°C to 510°C, respectively (Hunt, et. al., 1995).

Both data sets in Figure 4 also have a 650°C component that is likely caused by fine-grained hematite observed as exsolution in orthopyroxene and in sillimanite (see also Fleet and Arima, 1985). Verwey transitions (Verwey et al., 1947) indicative of remanence-bearing magnetite are present in some cores but not in others. For example, core S9a from the allochthon (Figure 1) shows no evidence in Figure 3a of the Verwey transition. The remanence in this case is stable to 575°C. However, core S4a from the autochthon has a significant Verwey transition (Figure 3b) and a decrease in NRM beginning around 300°C and ending just below 580°C when the main, presumably titanhematite-related drop in remanence occurs. The unblocking temperature of the main magnetic phase is slightly higher than the Curie temperature of pure magnetite, indicating that titanhematite is the predominant if not exclusive remanence carrier in some rocks and a significant carrier along with magnetite in others. This observation is supported by an absent or small Verwey transition during the decay of the magnetite NRM at low temperature. In addition, Figure 3b shows a typical measurement of rock susceptibility as a function of temperature. The susceptibility dependence on temperature has a dominant drop at the Curie temperature of magnetite, indicating that magnetite is a principle carrier of susceptibility.

The thermal stability of the titanhematite remanence signal is due to the large coercivity of hematite compared to that of MD magnetite. This behavior suggests that titanhematite, like SD magnetite, could make a significant contribution at depth to observed long wavelength anomalies providing the bulk chemistry of the rocks and conditions are appropriate for hematite stability.

Remanence Direction

Thermal demagnetizations of representative gneisses from the allochthon (S9a, Figure 1) and the autochthon (S10a, Figure 1) are shown by the Zeiderweld plots in Figure 5. Both specimens, despite their difference in initial orientations, show very strong directional stability of the remanence vector at temperatures as high as 650 °C. Only at temperatures as high as 680°C were significant deflections from the original magnetization directions observed. However, the magnitude of this component is close to the noise level, and therefore the directional deflection may be an artifact. The magnetic moment and its direction stay more or less constant up to 575°C before the moment starts to decay. During this decay, the original vector direction is generally preserved to temperatures as high as 650°C. This means that magnetite, if present, has the same remanence direction as the titanhematite. Further decay above 575°C is due to a successive unblocking of the magnetic moments of titanhematite grains as the ilmenite component decreases and/or due to unblocking temperatures of characteristic grain sizes and unpinning of the domain walls of titanhematite grains.

The directional spread of NRM vectors (95° confidence cone) in the allochthon (12 vectors) and the autochthon (9 vectors) is 15 ° and 21° respectively. The bearing and plunge of the mean allochthon direction is 281° and 21° respectively. The bearing and plunge of the mean autochthon direction is 102° and 46° respectively. Figure 5 is an example of the general directional behavior during thermodemagnetization and shows the stability of the NRM directions up to 600 °C.

The correlation of the magnetite and titanhematite remanent magnetizations in the Wilson Lake gneisses is in marked contrast to the remanence magnetization of titanhematite ore bodies in the northern Adirondacks, New York, and in the Allard Lake area, Quebec (Balsley and Buddington, 1957; Hargraves and Burt, 1967). In these latter areas the direction of the remanence due to magnetite is opposite to that of titanhematite, giving rise to negative magnetic anomalies. In both areas, the remanence of magnetite is directed towards the earth's present field. Kelso et. al. (1993) showed that generally assumed variations of magnetic

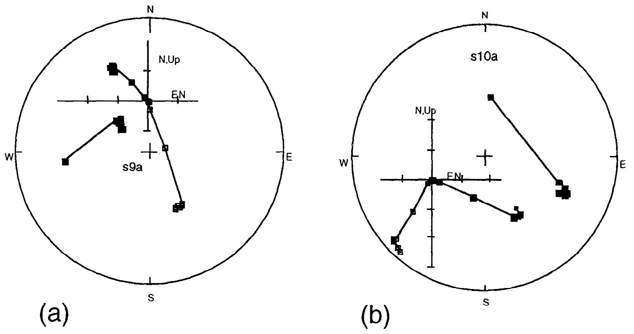

Figure 5. Magnetic remanence vector behavior for representative cores: (a) S9A from the allochthon and (b) S10A from the autochthon. Zeiderweld plots are superimposed on equal-area projection. Solid symbols in Zeiderweld plots are in the horizontal plane; open symbols are in the vertical plane. The data points relate to temperatures listed in Figure 3.

susceptibility of the bedrock could actually be variations of viscous remanence of multidomain magnetite pointing parallel to the Earth field direction. The magnetite remanence observed in the Adirondacks, Allard Lake and at Wilson Lake may well be a viscous remanence (see Kelso and Banerjee, 1993). Thus the fact that the remanence carriers near Wilson Lake are magnetized in the same direction in both the allochthon and the autochthon suggests that if the magnetization in both terranes was acquired under similar conditions the remanent signal should be indicative of the amount of remanence carriers in these granulites. This implies the anomaly high in central Labrador is caused by the relatively high titanhematite abundance in the allochthon as compared to that in the autochthon. This conclusion is consistent with field and petrographic observations.

Conclusions

We demonstrate in this paper that the magnetic contrast between allochthonous and autochthonous terranes in central Labrador is due to differences in the remanent magnetization of the underlying rocks rather than to differences in susceptibility. The mean measured NRM is more than order of magnitude greater than the mean value of induced magnetization. In the Wilson Lake area, carriers of remanent magnetization are both coarse titanhematite and magnetite; however, titanhematite seems to be the dominant carrier. Multidomain magnetite appears to dominate the susceptibility behavior of the rocks, and the same range of induced-magnetization values in both the allochthon and the autochthon indicates that the range in amounts of magnetite in both terranes is about the same. On the other hand, the amount of titanhematite is greater in gneisses of the allochthon than in the autochthon based on petrographic and field observations. This mineralogical difference is responsible for the magnetic contrast observed in the Wilson Lake area, and by extension to anomalies elsewhere in the Redwine Mountains.

Acknowledgments. The Institute for Rock Magnetism is funded by the W. M. Keck Foundation, the National Science Foundation, and the University of Minnesota. IRM contribution 9711.

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(Received August 18, 1997; revised Novemeber 17, 1997; accepted Novemeber 25, 1997.)