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Mineralogy of the sources for magnetic anomalies on Mars

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Abstract–Recent discovery of intense magnetic anomalies on Mars, which are due to remanent magnetization, requires some explanation for the possible minerals responsible for the anomalous signature. Thermoremanent magnetization (TRM) in single domain (SD) and multidomain (MD) sized magnetite, hematite, and pyrrhotite, all potential minerals, are considered. The intensity of TRM (in 0.05 mT) is in descending order: SD-sized magnetite, SD-sized pyrrhotite, MD-sized hematite, MD-sized pyrrhotite, MD-sized magnetite, SD-sized hematite. The TRM intensity is <4% of the saturation isothermal remanence (SIRM) for all but the MD hematite, which may have >50% of the SIRM. Each of these minerals and estimated concentrations of magnetic remanence carriers (assumed to be titanomagnetite) in the Shergotty–Nakhla–Chassigny martian meteorites are used in a thin sheet approximation model to reveal the concentration of each mineral required for the generation of an observed magnetic anomaly (1500 nT at 100 km altitude) assuming TRM acquisition in a 0.05 mT magnetic field.

INTRODUCTION

Attempts were made to assess the nature of the magnetic minerals in the martian soil (Viking and Pathfinder missions) by extracting magnetic particles with strong magnets that were part of the experiment package on the Viking and Pathfinder landers (Hargraves *et al.*, 1977; Madsen *et al.*, 1999, respectively). This resulted in a list of potential magnetic mineral candidates, notably metallic Fe; magnetite, titanomagnetite, or both; maghemite; and monoclinic pyrrhotite. All of these minerals have high magnetic susceptibility; consequently, lower susceptibility minerals such as hematite, ilmenite, and goethite were excluded as they would not be attracted by the magnet arrays.

The magnetic measurements by the Mars Global Surveyor (MGS) magnetometer experiment (Acuña *et al.*, 1998) revealed strong, linear crustal magnetic anomalies (~5000 × ~500 km) in the ancient heavily cratered terrain (Acuña *et al.*, 1999; Connerney *et al.*, 1999) in the martian crust. Vector measurements of the ambient magnetic field acquired by the twin fluxgate magnetometer system established that Mars does not currently possess a global magnetic field (Acuña *et al.*, 1998). Consequently, these magnetic signatures must result from remanent magnetization associated with unknown lithologies in the martian crust. The observed anomaly is more than an order of magnitude stronger than the largest anomaly (Kursk, Russia) on Earth (Connerney *et al.*, 1999). The sources of remanent magnetism do not necessarily constitute the same spectrum of magnetic minerals extracted by the lander mission magnet arrays, all of which have high susceptibility minerals that may not have a potential to hold stable remanence. It is the purpose of this report to assess the spectrum of magnetic minerals that may represent the sources of remanent magnetization for these very large planetary magnetic anomalies.

Among the common rock-forming minerals, only a few are capable of acquiring and retaining significant remanent magnetization. These minerals are among the oxides and sulfides that are commonly found on Earth (Clark, 1997). The available petrographic data for the Shergotty–Nakhla–Chassigny (SNC) martian meteorites (McSween, 1985), inferences based on soil analyses (Rieder *et al.*, 1997), magnetic experiments on the Viking and Pathfinder missions (Hargraves *et al.*, 1977; Madsen *et al.*, 1999), and inference based on the thermal emission spectrometer (Christensen *et al.*, 1999) suggest that magnetite, hematite, and pyrrhotite are candidate minerals to be considered. Other specific minerals, which are also potentially important, such as low-Ti titanomagnetites and titanohematites, are similar to the magnetites and hematites, respectively, and need not be considered separately.

We consider here that the likely cause of the martian magnetic signatures is thermoremanent magnetization (TRM), which is acquired when a mineral is cooled from above its Curie point down to ambient temperature in the presence of an external magnetic field. We must also recognize the likelihood that the intense remanent magnetization might be associated with the shock metamorphism associated with intense cratering, though the circumstances must include the presence of an ambient or shock-generated (Hood and Huang, 1991) external field. It is also possible that chemical remanence (CRM) associated with hydrothermal activity and partial TRM associated with various levels of shock heating might need to be considered. A requirement for the preservation of the remanent magnetization is time stability, the presence of large amounts of magnetic material, or both, either of which are likely explanations. Martian crustal terrane has retained magnetization for billions of years as revealed by the MGS mission. One model would have a main-field dynamo acting for a few hundred million years after accretion, before it shut down (Acuña *et al.*, 1999). It would be during this time when the remanent magnetization was acquired by portions of the crust. Resulting magnetized crust is then further modified through deep impacts, magmatic flows, and reheating above the Curie point (Acuña *et al.*, 1999).

SOURCES OF MAGNETIZATION

Intense magnetic crustal sources, detected in the Terra Sirenum region (120 to 210 W; 30 to 85 S), require an estimated magnetic moment of ~1.3 × 10^{17} A m^2 (Acuña *et al.*, 1999). For a 30 km thick magnetized layer, this moment translates to a magnetization of ~20 A/m (Connerney *et al.*, 1999). Our study assumes that initially this magnetization was acquired as a TRM, because of its high efficiency in producing an intense remanence in a relatively weak inducing magnetic field (10^{-6} to 10^{-4} T).

The TRM acquisition level for potential magnetic minerals in their pure forms is summarized in Fig. 1a, where we show ranges of TRM values acquired in a field comparable to the geomagnetic

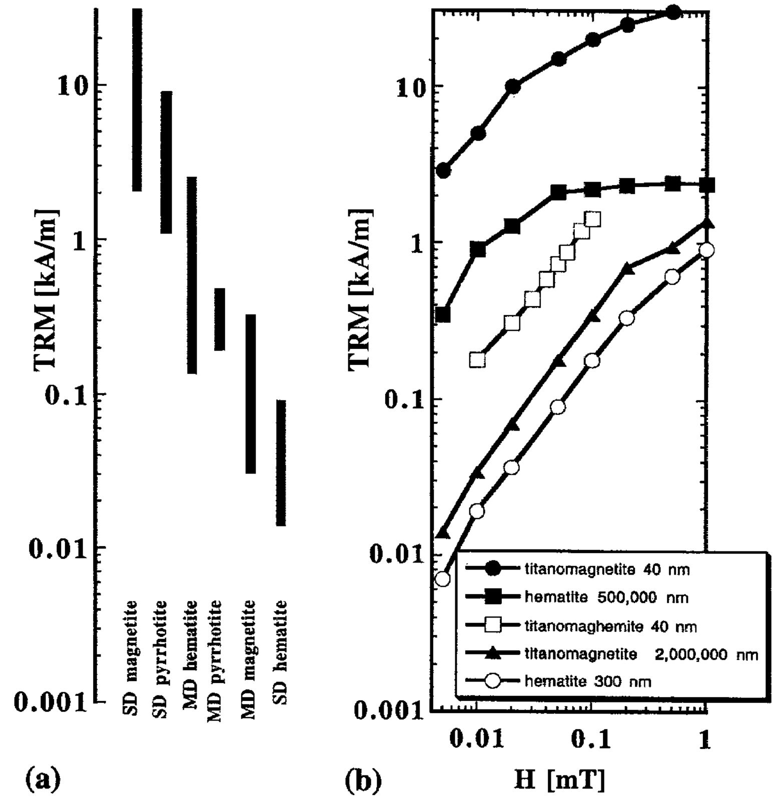

FIG. 1. Summary of TRM acquisition in small magnetic fields: (a) ranges of TRM intensities acquired in the geomagnetic field (~0.05 mT). (b) The TRM acquisition trends for variable magnetizing field intensity: single domain hematite and multidomain hematite (N115249 and N114078, respectively) were obtained from the Department of Mineral Sciences, NMNH, Smithsonian Institution, and are described in Kletetschka *et al.* (2000b). Single domain titanomaghemite data (40 nm) are from Özdemir and O'Reilly (1982). Ranges of TRM for magnetite, pyrrhotite, and hematite are from Clark (1983). Single domain (40 nm) and MD (2 mm) titanomagnetite curves are from Özdemir and Reilly (1982) and Tucker and O'Reilly (1980), respectively.

TABLE 1. Single domain limits for magnetite, titanomagnetite, pyrrhotite, and hematite.*

Mineral	Critical SD size (μm)
Magnetite	0.05–0.084
Titanomagnetite (x = 0.55–0.6)	0.2–0.6
Pyrrhotite	1.6
Hematite	15

*Data taken from Dunlop and Özdemir (1997). x is the composition parameter (Ti content).

intensity of 50 000 nT (Clark, 1983, 1997; Kletetschka *et al.*, 2000a). It is apparent that single domain (SD) magnetite and SD pyrrhotite would be more effective in acquiring TRM compared to a proposed multidomain (MD) sized hematite or pyrrhotite (Connerney *et al.*, 1999). If grains of magnetite and pyrrhotite minerals are larger (see Table 1), their effectiveness in acquiring TRM magnetization rapidly decreases. For example, an average TRM of SD magnetite (~10 kA/m) is three orders of magnitude larger than the TRM of MD-sized magnetite (~0.01 kA/m) (Dunlop, 1990; Kletetschka *et al.*, 2000b). Similarly, the average TRM of SD pyrrhotite (~4.5 kA/m) is an order of magnitude greater than the average TRM of MD-sized pyrrhotite (~0.5 kA/m) (Clark, 1997).

Insofar as the effectiveness of acquiring TRM in low magnetic fields is concerned, we want to emphasize that hematite does not behave the same way as magnetite and pyrrhotite with regard to its grain-size dependence. The REM value (defined as natural remanent magnetization (NRM)/saturation isothermal remanence (SIRM)) is almost a constant ~0.01 to 0.07 for most of the minerals (Wasilewski and Kletetschka, 1999). Multidomain-sized hematite can acquire TRM more effectively than SD hematite (Dekkers and Linssen, 1989; Uyeda, 1958; Harstra, 1982) and, in fact, it can have REM >0.5 (Kletetschka *et al.*, 2000a,b; Syono *et al.*, 1962; Harstra, 1982).

Because the strength of the martian magnetizing field is not known, we attempt to show how the TRM intensities vary with an increasing magnetizing field for selected minerals (Fig. 1b). The range of magnetic fields was chosen in the vicinity of the value for the geomagnetic field (0.05 mT). The MD hematite shows signs of saturation for stronger fields. The TRM values for other displayed magnetic minerals increase more or less linearly with increasing fields. The level of SD TRM in titanomaghemites (Özdemir and O'Reilly, 1982) is slightly below the TRM range of SD magnetite and corresponds to the range of MD hematite. It should also be noted that the TRM of millimeter-sized polycrystalline Fe-Ni spheres (not shown in Fig. 1) is low (Wasilewski, 1981) and comparable in intensity to TRM of MD magnetite and SD hematite.

The data presented in Fig. 1 form the basis for evaluating the contribution of possible magnetic minerals responsible for the remanent magnetic signature observed by the MGS magnetometer experiment. Connerney *et al.* (1999) modeled the source of magnetization as uniformly magnetized strips whose magnetic field was computed by Talwani's thin sheet approximation (Talwani, 1965), valid for plate thickness that is small compared with the distance to the observer. According to these assumptions, the magnetization of the thin sheets required to produce the observed anomalies depends on the sheet thickness (Fig. 2). The dependence comes from constraining the product of the plate thickness and the volume magnetization. Therefore, a 1 km thick plate requires 10× the volume magnetization of a 10 km thick plate (see also Connerney *et al.*, 1999). To illustrate how much stronger the magnetization required for Mars is relative to Earth, we used the same model to estimate the total magnetization required to account for the Kursk magnetic anomaly, the largest on Earth (Fig. 2).

On the basis of the analysis of the soils at the Pathfinder landing site (Rieder *et al.*, 1997), and analysis of martian meteorites (McSween, 1985), we now understand that the martian surface material has a total Fe content of ~20%. Magnetic minerals incorporate only a fraction of this Fe content. Collinson (1997) estimates that a magnetic mineral content <0.1% of the volume of SNC meteorites is responsible for their magnetic remanence signature. The presence of large amounts of magnetic material in the martian soil (Hargraves *et al.*, 1977; Madsen *et al.*, 1999) suggests lithologies with much larger amounts of magnetic material.

The TRM values of the rock-forming minerals can be used to predict concentration of these minerals required to generate the observed magnetic anomalies. These are upper limits, as we may expect the magnetic intensity to diminish with time because of viscous, shock, chemical, thermal, and randomizing effects (Dunlop and Özdemir, 1997). We compared the values required for homogeneous magnetization from Fig. 2 with the mineral-characteristic TRM values acquired in an Earth-like external magnetic field (Fig. 1a,b).

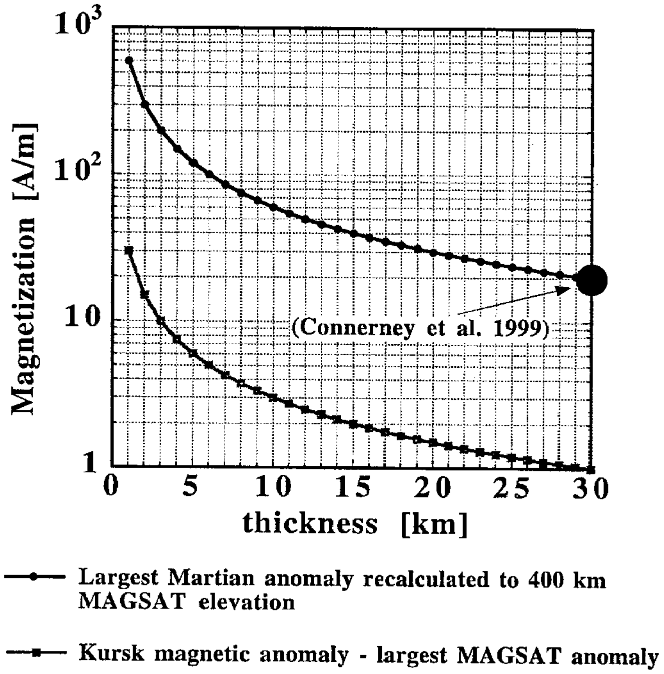

FIG. 2. Homogeneous distribution of magnetization in a thin sheet of indicated thickness required to account for the 1500 nT anomaly considered by Connerney (1999) is compared with the Kursk magnetic anomaly, the largest on Earth.

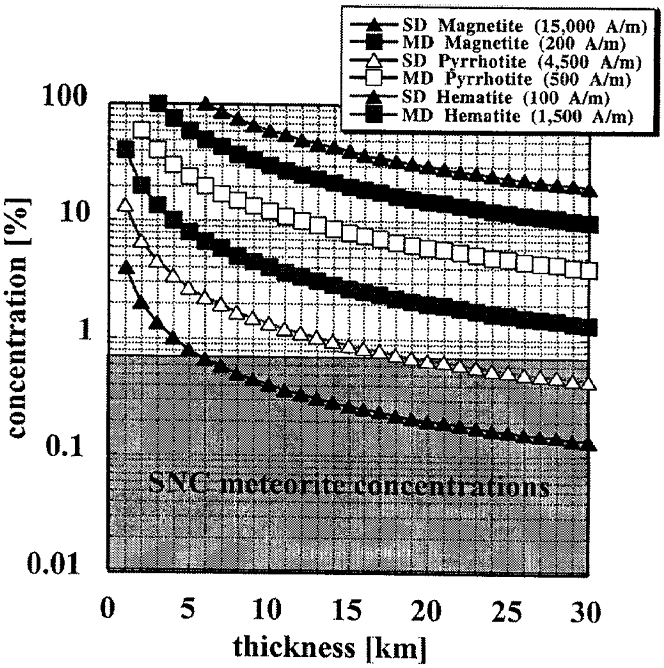

FIG. 3. Concentrations of magnetic minerals with TRM in the indicated thickness required to account for the 1500 nT anomaly considered by Connerney *et al.* (1999). The TRM values used for individual curves relate to Fig. 1a,b. The concentration range of assumed SD titanomagnetite in SNC meteorites is also shown.

The data in Fig. 1 represent pure mineral data. When we dilute these data mathematically in nonmagnetic unit volume, we can find a correlation with MGS data represented by Talwani's approximation (Fig. 2) and plot individual mineral concentration curves required to generate the observed magnetic signature (Fig. 3).

Figure 3 illustrates, for example, that a 30 km thick sheet can contain <2% of MD hematite to generate observed magnetic anomalies. Hematite was detected with near infrared (IR) Earth-based telescopic (Morris *et al.*, 1997) and Phobos-2 (Mustard and Bell, 1994) data. The red pigmentary hematite used in the mixing model experiments of Morris *et al.* (1997) to match visible and near-IR data had particle diameters <1 μm (SD range) and thus negligible magnetization (Fig. 1). However, the thermal emission spectrometer instrument on the MGS mission (Christensen *et al.*, 1999) recognized hematite grains with particle diameters >10 μm and thus permissive of MD hematite. Therefore, if circumstances allow TRM of MD-sized hematite to occur in the martian crust, this alone could derive significant magnetic anomalies and is consequently worthy of consideration.

The mineral concentrations with TRM acquired in an Earth-like magnetic field can be compared with concentrations of magnetic minerals found in SNC meteorites. In the following analysis, we will attempt to find the most "magnetic" meteorite to constrain a maximum concentration estimate for the source. Concentrations can be deduced from measurements of the saturation magnetization (J_s) of SNC meteorites and assuming magnetite as a sole mineral responsible for magnetic signature. Hysteresis parameters for six of the SNC meteorites—Allan Hills 77005, Elephant Moraine A79001, Shergotty, Governador Valadares, Zagami, and Nahkla (see Cisowski, 1986)—indicate that Nakhla and Governador Valadares have the largest J_s (0.46 A m^2 kg^{-1} and 0.38 A m^2 kg^{-1}, respectively) and would constitute concentrations of 0.51% and 0.42% of pure magnetite (J_s = 91 A m^2 kg^{-1}; Hunt *et al.*, 1995). Collinson (1997) and McSween (1985) state that magnetic carriers in Nakhla meteorites are titanomagnetites. The Ti component lowers the value of J_s (J_s = 45 A m^2 kg^{-1}; Hunt *et al.*, 1995), and therefore the maximum concentration estimate given above would increase up to 0.8–1.0% for titanomagnetite with 60% Ti content (TM60).

Our observations of Nakhla thin section (borrowed from Tim McCoy at United States National Museum (USNM), Smithsonian Institution, Washington D.C.) reveal the presence of large grains of titanomagnetite (less than ~0.3%). However, as mentioned above, from the magnetic analysis of the Nakhla meteorite, we may have maximum concentration of titanomagnetite approaching 1%. This disagreement indicates that the thin section used for this study either was not representative or there is still <0.7% of TM60 in very fine-grained form, which escaped the imaging technique. If the latter is true, these grains would possibly overlap a SD (<50 nm) range and would have much larger coercivity of remanence. Thus, we measured magnetic acquisition and demagnetization curves for actual thin sections of SNC meteorites (USNM).

The thin sections were slices of Chassigny (USNM 6245), Nakhla (USNM 42616), and Shergotty (USNM 3213). Even though SNC sections contain very small volumes of material, the magnetic signature from the magnetic minerals is detectable by superconducting rock magnetometer (SRM, superconducting technology). After measurement of initial NRM, we performed magnetic remanence acquisition measurements on each thin section up to maximum field intensity of 2 T (Fig. 4, isothermal remanent magnetization curves (IRM)). Thus, magnetic minerals acquired their SIRM. At this point, we demagnetized each section by alternating magnetic field of increasing amplitude while recording their magnetization M (Fig. 4, alternating field demagnetization (AFD) curves).

Figure 4 illustrates that the acquisition isothermal remanent magnetization saturated after application of magnetic fields

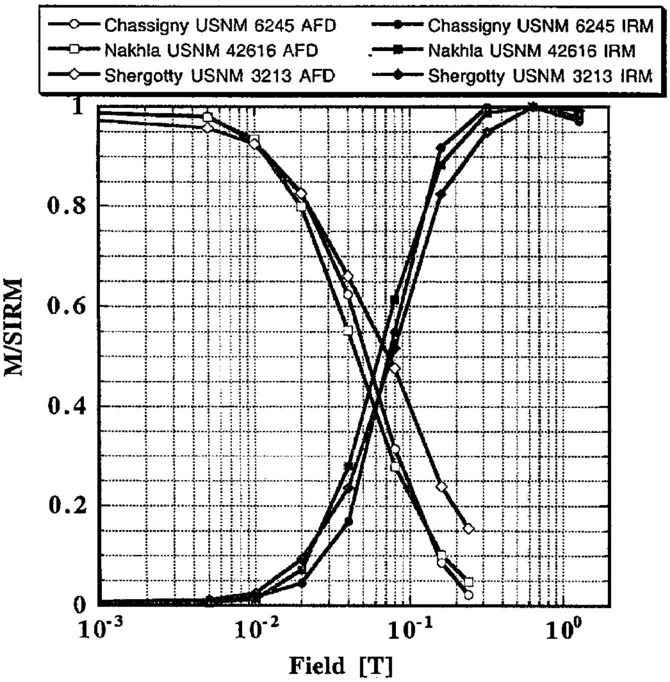

FIG. 4. Remanence acquisition efficiency and SIRM demagnetization for three SNC meteorites identified in the legend.

exceeding 0.3 T. The large coercivity is characteristic of SD carriers, fine-scale microstructure in large grains, or both. The crossover points between the acquisition curves and AFD curves are very slightly <0.5. According to the Wohlfarth–Cisowski test for interaction (Wohlfarth, 1958; Cisowski, 1981), this would indicate a slight negative interaction between the magnetic grains. This low degree of interaction suggests the presence of finely dispersed magnetic grains possibly overlapping the SD-grain size range.

According to the TRM efficiency of titanomagnetites (Fig. 1), the MD titanomagnetite fraction (<0.3%) would contribute very little to the overall TRM signature. The remaining maximum amount of possible SD titanomagnetite (<0.7%, probably a mixture of pseudosingle domain (PSD) and SD grains) would then have the potential to contribute to the anomaly signature. According to the Talwani's thin sheet approximation (see Fig. 3), the minimum thickness of homogeneously magnetized crust with SD titanomagnetite would have to exceed 5 km in order to generate the observed magnetic signal.

The SNC meteorites may not be representative of the material in the magnetic anomaly region. In fact, since most of their dates are younger than 2 Ga, and the densely cratered anomaly region is generally considered to be >3 Ga old (Acuña *et al.*, 1999), these SNC meteorites may have originated in the younger northern lowlands. Thus, their magnetic properties may not be applicable for magnetic anomaly signatures in the southern highlands.

POSSIBLE SIGNIFICANCE OF MULTIDOMAIN HEMATITE

Hematite, because of its low magnetic susceptibility and low magnetic intensity for SD sizes, which most researchers are familiar with, has to our knowledge never been considered an important contribution to magnetic anomaly signatures. Recent work (Kletetschka *et al.*, 2000a,b) emphasizes the probable importance of MD hematite and similar titanohematite wherever it is found. The petrogenetic conditions for the genesis of the magnetite–titanomagnetite compared to hematite would be contrastive, and it would therefore be appropriate to consider how the TRM would differ from the CRM that would be appropriate to remanence acquisition associated with chemical precipitation, crystal growth, and hydrothermal processes. Clark (1983) considered the available data for TRM and CRM and found that the intensity values would be essentially identical. Because CRM experiments are difficult to perform, very little experimental definitive data is available and we take the Clark database as a guideline. Consequently, CRM and TRM can be viewed as essentially identical intensity acquisition mechanisms. The real issue in the terrestrial case is where the CRM intensities are superimposed, as they are acquired, with the magnetizing field in different directions. This would randomize the magnetization.

In terrestrial rocks, fine-grained magnetite can be obtained as a result of retrogressive metamorphism (*e.g.*, metaperiodites; see Shive *et al.*, 1988). Also, mineral exsolution produces fine plates of magnetite, for example, in feldspar (Geissman *et al.*, 1988), olivine (Champness, 1970), and pyroxene (Fleet *et al.*, 1980; Schlinger and Veblen, 1989). Thus, in order to explain magnetic anomalies on Mars, we have to consider other mechanisms for fine-grained magnetite origin aside from direct crystallization.

Multidomain hematite can acquire the most intense TRM among all of the oxide and sulfide MD minerals (Fig. 1) that are presently considered important for terrestrial and martian crustal magnetization. Hematite on Earth is found in the following environments: metamorphised iron formations, redbeds, metabasites metamorphosed at low to medium grades, metasediments, and metamorphosed manganiferrous rocks (Frost, 1991b).

Titanohematite, which behaves like hematite, can occur in many rock types that have been slowly cooled or subjected to retrogressive metamorphism in relatively oxidizing conditions. Mafic rocks in granulite and amphibolite facies commonly have relatively oxidized ilmenite–hematite series minerals (Kletetschka, 1998; Kletetschka and Stout, 1998; Arima *et al.*, 1986; Thomas, 1993; Schlinger and Veblen, 1989; Braun and Reith, 1985; Peretti and Koppel, 1986; Banno and Kanehira, 1961; Kanehira *et al.*, 1964) and can be shown to contribute significant remanence intensity.

CONCLUSIONS

The effectiveness of TRM acquisition for magnetic minerals common to the earth and identified in the SNC meteorites can be arranged in the following order: SD magnetite, SD pyrrhotite, MD hematite, MD pyrrhotite, MD magnetite, SD hematite. Single domain magnetite is the mineral species most easily invoked to explain the source of the intense magnetic anomalies. However, MD hematite with its unique remanence properties must be considered for Mars as well as Earth. Even though it is mostly absent from SNC meteorites, hematite was detected on the surface of Mars by the thermal emission spectrometer instrument on MGS (Christensen *et al.*, 1999). The SD-sized titanomagnetite is the most likely candidate based on the SNC data.

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