

# Multidomain Hematite: A Source of Planetary Magnetic Anomalies?

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**Abstract.** Thermoremanent magnetization (TRM) in hematite is larger than TRM in magnetite for grain sizes  $\geq 10 \mu\text{m}$ . We show that hematite's weak spontaneous magnetization  $M_s$  causes its strong TRM, since the self-demagnetizing field  $H_d$  opposing large domain wall displacements is proportional to  $M_s$ . In hematite,  $H_d$  is comparable to the Earth's magnetic field but in magnetite,  $H_d$  is 1000 times larger. As a result, Earth's field TRM of MD hematite ( $\approx 0.3 \text{ Am}^2/\text{kg}$ ) outweighs TRM and induced magnetization of MD magnetite ( $\approx 0.01\text{-}0.02 \text{ Am}^2/\text{kg}$ ) and rivals TRM of single-domain and PSD magnetite as a source of magnetic anomalies on Earth and perhaps on Mars.

## Introduction

Hematite ( $\alpha\text{Fe}_2\text{O}_3$ ) is antiferromagnetic with superimposed weak ferromagnetism. Its spontaneous magnetization  $M_s$  is  $\approx 0.5 \text{ Am}^2/\text{kg}$ , compared to  $\approx 90 \text{ Am}^2/\text{kg}$  for magnetite ( $\text{Fe}_3\text{O}_4$ ). The coercivity of hematite is very large for fine grain sizes (260-405 mT; Table 1) and remains substantial even for  $>200 \mu\text{m}$  multidomain (MD) sizes (4-13 mT; Table 1). Hematite has a "blocky"  $M_s(T)$  curve (Fig. 1), retaining its magnetism at high temperature more efficiently than magnetite. The Curie temperature  $T_C$  is 670-680°C (Table 1), so that hematite is a potential deep source of magnetic anomalies in planetary crusts.

Uyeda [1958] and Syono et al. [1962] discovered that MD hematite acquires near-saturation thermoremanent magnetization (TRM) in weak fields. Kletetschka et al. [2000a] showed that for grain sizes  $\geq 10 \mu\text{m}$ , hematite has a larger Earth's field TRM than magnetite. The TRM of 100- $\mu\text{m}$  hematite is 0.2-0.3  $\text{Am}^2/\text{kg}$ , 20 times the TRM of 100- $\mu\text{m}$  magnetite ( $M_{tr}=0.01\text{-}0.015 \text{ Am}^2/\text{kg}$ ). The hematite TRM is nearly saturated, while magnetite's TRM is  $<1\%$  of saturation remanence  $M_{rs}$ .

We will show that the contrast in TRM intensities for the two minerals is due mainly to the internal demagnetizing field  $H_d = -NM$  ( $N$  is demagnetizing factor and  $M$  is magnetization). At saturation,  $H_d \approx 200 \text{ mT}$  for magnetite, but for hematite,  $H_d \approx 1 \text{ mT}$ , making it much easier for a small field like the Earth's to push magnetic domain walls to their limiting positions.

TRM of coarse-grained minerals in an MD state has largely been ignored in paleomagnetism and magnetic anomaly interpretation because TRM of single-domain (SD) and pseudo-single-domain (PSD) grains is usually much stronger. However, MD grains are volumetrically dominant in most rocks, and TRM of MD hematite rivals both TRM of PSD magnetite and induced magnetization of

MD magnetite. The 4-13 mT coercivities of MD hematite are 80-260 times the Earth's field strength of  $\approx 50 \mu\text{T}$ . Coarse-grained hematite therefore deserves serious consideration as an anomaly source and a carrier of primary paleomagnetic information.

## Theory of TRM Acquisition

TRM is frozen in at the blocking temperature  $T_B$  during cooling from  $T_C$  to room temperature  $T_0$  in an applied field  $H_0$ . The TRM of SD grains of volume  $V$  and coercive force  $H_c$  is [Néel, 1949]

$$M_{tr} = M_{rs} \tanh(\mu_0 V M_s(T_B) H_0 / kT_B), \quad (1)$$

with  $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$  and  $k = 1.38 \times 10^{-23} \text{ J/K}$ . On a time scale  $t = 60\text{-}100 \text{ s}$ ,  $T_B$  is given by

$$\mu_0 V M_s(T_B) H_c(T_B) / 2kT_B = \ln(f_0 t) \approx 25, \quad (2)$$

$f_0$  being  $\approx 10^9 \text{ s}^{-1}$ . Combining (1) and (2), and introducing  $H_c(T_0) = H_{c0}$  and  $\beta(T) = H_c(T) / H_{c0}$ ,

$$M_{tr} = M_{rs} \tanh[50 H_0 / H_{c0} \beta(T_B)]. \quad (3)$$

In the Néel [1955] theory of TRM in MD grains, blocking occurs at  $T_B$  when barriers to wall motion, described by  $H_c(T)$ , grow high enough to pin domain walls against the demagnetizing field  $H_d = -NM$ . A crucial parameter is the index  $n$  in

$$\beta(T) = H_c(T) / H_{c0} \approx [M_s(T) / M_{s0}]^n, \quad (4)$$

which determines  $T_B$  and thus the TRM  $M_{tr}$ :

$$M_{tr} = n(n-1)^{1/n-1} H_{c0}^{1/n} N^{-1} H_0^{1-1/n}. \quad (5)$$

However,  $M_{tr}$  given by (5) is reduced by "magnetic screening". Loosely pinned walls are moved by  $H_d$  and their negative induced  $M$  reduces the TRM by the screening factor [Stacey, 1958]

$$\alpha = (1 + N \chi_i)^{-1}. \quad (6)$$

Internal field susceptibility  $\chi_i$  is related to observed susceptibility  $\chi_0$  by [Dunlop and Özdemir, 1997]

$$\chi_0 = (1 + N \chi_i)^{-1} \chi_i, \quad \chi_i = (1 - N \chi_0)^{-1} \chi_0. \quad (7)$$

Table 2 gives measurements of  $\chi_0$  for MD hematite N115249 and several MD magnetites [Parry, 1965], with values of  $\chi_i$  and  $\alpha$  calculated from (7) and (6) using  $N=0.31$  (SI), appropriate for large grains in rocks [Stacey, 1963]. For MD hematite,  $\alpha$  is 0.944, but  $\alpha$  is only 0.067-0.182 for the MD magnetites. Screening of  $M_{tr}$  by induced  $M$  of soft walls thus reduces the TRM of MD magnetite by a factor 6-15 but is unimportant in MD hematite.

**Table 1.** Properties of hematite and magnetite samples.

Sample	Description	Grain size ( $\mu\text{m}$ )	$T_C$ ( $^\circ\text{C}$ )	$M_s$ ( $\text{Am}^2/\text{kg}$ )	$M_{rs}$ ( $\text{Am}^2/\text{kg}$ )	$H_{c0}$ (mT)
L2	$\alpha\text{Fe}_2\text{O}_3$ , Labrador	>200	670	0.42	0.28	4
NR17174	$\alpha\text{Fe}_2\text{O}_3$ , Arizona	>200	670	0.47	0.35	8
N115249	$\alpha\text{Fe}_2\text{O}_3$ , Brazil	>200	670	0.39	0.33	13
N114078	$\alpha\text{Fe}_2\text{O}_3$ , Iran	0.5–3	670	0.465	0.345	260
H6	$\alpha\text{Fe}_2\text{O}_3$ , synthetic	0.2–0.7	679	0.245	0.15	405
90LP12	$\text{Fe}_3\text{O}_4$ , Adirondacks	>200	580	82.4	1.92	1
M3	$\text{Fe}_3\text{O}_4$ , synthetic	0.03 $\times$ 0.2	585	89.5	33.1	31

$T_C$  is Curie temperature;  $M_s$  and  $M_{rs}$  are saturation magnetization and remanence;  $H_{c0}$  is room-temperature coercive force.

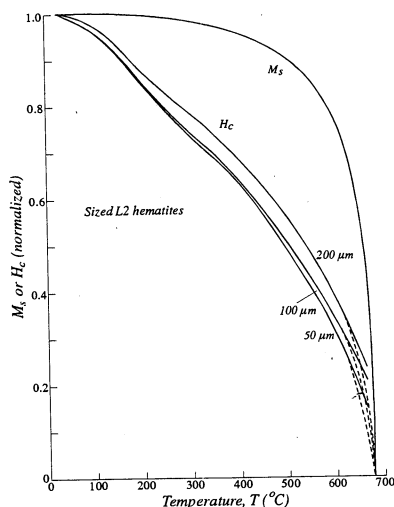
## Experimental TRM Data Compared With Theory

Hysteresis and thermomagnetic properties of the experimental samples appear in Table 1. These did not change appreciably after TRM heatings. X-ray diffraction,  $T_C$  and  $M_s$  data confirm the high purity of the hematites and magnetites used. H6 and M3 are synthetic SD samples [Dunlop, 1968, 1971; Dunlop and West, 1969]. The others are museum samples used by Kletetschka et al. [2000a,b]. L2 is from a metamorphosed banded iron formation in Labrador.

The powerful demagnetizing effect of  $H_d$  in MD magnetite, which causes low  $\alpha$  values (Table 2), also causes low  $M_{rs}/M_s$  values: 0.023 for 90LP12 compared to 0.370 for SD magnetite M3. By contrast,  $M_{rs}/M_s = 0.546$  to 0.748 for coarse as well as fine hematites. Walls in MD hematite can move far from their demagnetized positions because  $H_d$  is weak and so  $M_{rs} \rightarrow M_s$ . The high TRM of MD hematite has a similar cause.  $M_s$  and thus  $H_d$  are even smaller at  $T_B$  than at  $T_0$  (Fig. 1), so that walls move almost unhindered to their limiting positions and  $M_{tr} \rightarrow M_{rs}$  for  $H_0 \approx 50 \mu\text{T}$  (Figs. 2, 3).

Experimental TRM data for MD and SD hematites and magnetites N115249, H6, 90LP12 and M3 appear in Fig. 2. Also shown are theoretical TRM curves for MD hematite and magnetite, calculated from (5) using values of  $H_{c0}$  and  $\alpha$  from Tables 1 and 2, with  $n = 3$  for hematite [Flanders and Schuele, 1964] or  $n = 2.5$  for magnetite [Heider et al., 1987].

The theoretical TRM curve for MD magnetite matches the data for 90LP12 quite well. The theoretical MD hematite curve matches



**Figure 1.** Hysteresis parameters of 3 sieve fractions from hematite L2 measured on a vibrating-sample magnetometer at high temperature. Dashed lines are hypothetical continuations of the  $H_c$  curves to the Curie point  $T_C$ .

the initial rise of the experimental TRM curve for N115249 but saturates around  $H_0 \approx 0.07$  mT. The observed approach to saturation is more gradual because of distributed coercivities, i.e., successive Barkhausen jumps of the wall(s). Halgedahl [1995, 1998] showed that in MD hematite crystals,  $H_{c0}$  is usually determined by the first major jump of a wall but there is a series of further jumps producing a gradual approach to saturation in hysteresis.

In Fig. 2, the TRM of SD hematite is completely overshadowed by TRM of SD magnetite. However, TRM of MD hematite is much larger:  $\approx 1/5$  of TRM of SD magnetite in the Earth's field. SD magnetite is rare in nature because of its restricted size range, and TRM intensity falls rapidly with increasing grain size in the magnetite PSD range, decreasing an order of magnitude between 0.1 and 1  $\mu\text{m}$ . Therefore TRM of MD hematite is potentially important as an anomaly source.

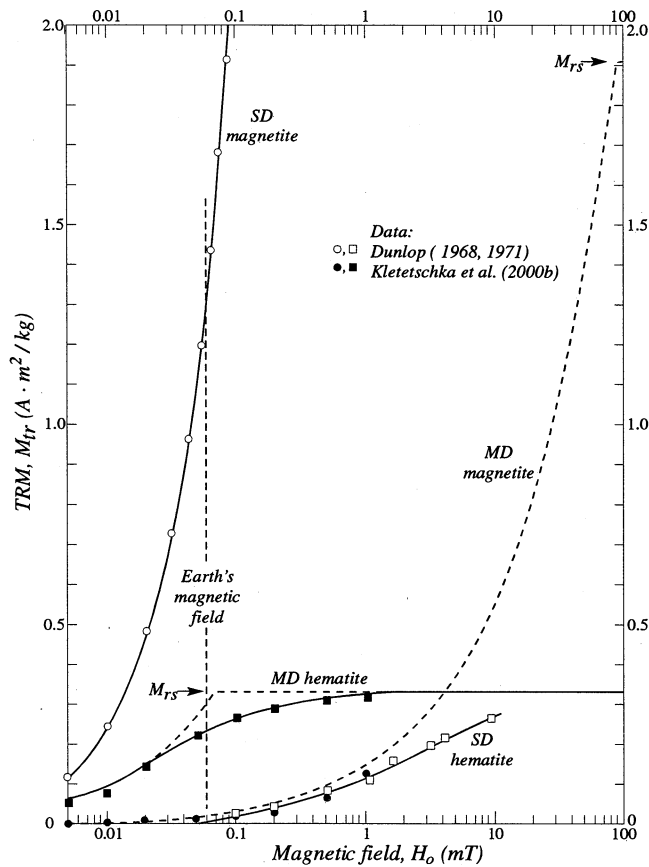
The reason MD hematite is a major contender, while MD magnetite is not, is clear in Fig. 2. The TRM of MD hematite is almost saturated in the Earth's field but the TRM of MD magnetite, which ultimately reaches a higher level, only saturates in  $H_0 \approx 100$  mT. In both cases, the saturation field of TRM is comparable to  $H_d$ , which in turn is governed by  $M_s$  in the two minerals. Strongly magnetic minerals in an MD state are thus handicapped in their TRM carrying capacity compared to weakly magnetic minerals.

A reasonable numerical match between experimental and theoretical curves results from TRM modeling for MD  $\alpha\text{Fe}_2\text{O}_3$  sample NR17174 ( $H_{c0} = 8$  mT,  $n = 3$ ; Fig. 3). The experimental rise to saturation is almost complete by 60  $\mu\text{T}$ . The TRM data for SD  $\alpha\text{Fe}_2\text{O}_3$  sample N114078 (Fig. 3) also agree well with theoretical predictions. We substituted  $H_{c0} = 260$  mT in eqn. (3) for SD TRM, as well as  $\beta(T_B) = 0.2$  for  $T_B = 640$ – $660^\circ\text{C}$  (Fig. 1 and Kletetschka et al. [2000a, Fig. 4]).

Kletetschka et al. [2000a] reported TRM data for 5 sieve fractions from MD hematite L2.  $M_s(T)$  and  $H_c(T)$  data for these fractions (Fig. 1) determine  $n$  in (4). We used various combinations of  $n$  (2.5 or 3) and  $H_{c0}$  (4 and 13 mT, the limits for the MD hematites) in predicting TRM from (5). The theoretical curves (Fig. 4) bracket the TRM data in the 1–50  $\mu\text{T}$  range. The approach to saturation indicates a range of coercivities rather than a single  $H_{c0}$ , but MD theory is successful in its main objective of predicting numerical values of TRM for fields like the Earth's.

**Table 2.** Experimental susceptibility  $\chi_0$  for MD hematite and magnetite, and calculated internal field susceptibility  $\chi_i$  and screening factor  $\alpha$  (susceptibilities are SI values).

Sample	Description	$\chi_0$	$\chi_i$	$\alpha$
N115249	$\alpha\text{Fe}_2\text{O}_3$ , >200 $\mu\text{m}$	0.18	0.19	0.944
Parry7	$\text{Fe}_3\text{O}_4$ , 120 $\mu\text{m}$	3.01	45.0	0.067
Parry8	$\text{Fe}_3\text{O}_4$ , 88 $\mu\text{m}$	2.64	14.5	0.182
Parry9	$\text{Fe}_3\text{O}_4$ , 58 $\mu\text{m}$	2.76	19.1	0.144



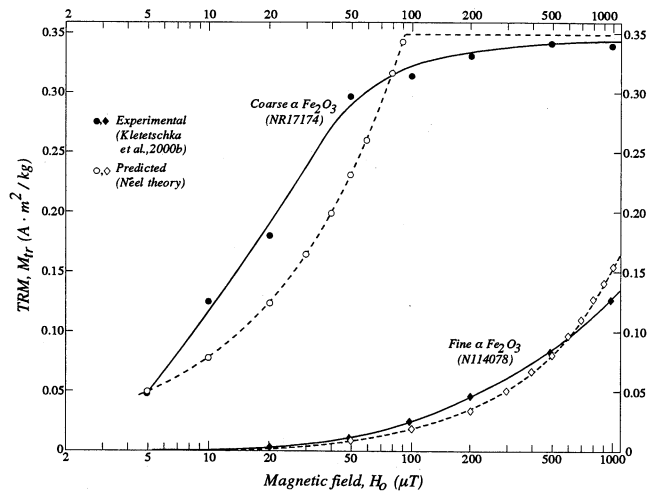
**Figure 2.** Experimental (points and solid curves) and theoretical (dashed curves) TRM values over an extended field range. Very different demagnetizing fields  $H_d$  cause hematite and magnetite to reach TRM saturation ( $M_{tr} = M_{rs}$ ) in fields differing by 3 orders of magnitude.

A calculation similar to the one for SD hematite N114078 was made for SD magnetite M3, substituting  $\beta(T_B) = 0.3$  [Stacey, 1958],  $H_{c0} = 30.5$  mT (Table 1) and  $H_0 = 50$   $\mu$ T in eqn. (3). The predicted  $M_{tr}/M_{rs}$  is 0.267, whereas the measured value is 0.026, 10 times lower. Dunlop and West [1969] explained similar discrepancies in terms of grain interaction fields, which play an analogous role to  $H_d$  in MD TRM.  $M_s$  is so low in hematite that interaction effects are negligible. The success of eqn. (3) in explaining the TRM in SD hematite (Fig. 3) is a natural consequence of hematite's weak magnetism.

## Discussion

Multidomain hematite is remarkable in several ways. Bitter pattern observations reveal only one or two major walls in large ( $\geq 200$   $\mu$ m) crystals [Halgedahl, 1995, 1998]. Walls typically move in a few large Barkhausen jumps, at fields that match  $M$  jumps in hysteresis, and approach limiting positions or disappear in fields of 3–5 mT. When  $H_0$  is removed, walls remain greatly displaced or fail to renucleate, leaving the crystal almost saturated (i.e.,  $M_{rs} \rightarrow M_s$ ). Magnetites of this size contain a dozen or more domain walls, which undergo many small Barkhausen jumps but fail to preserve their displacements when the field is zeroed unless strongly pinned by defects, leading to  $M_{rs} \ll M_s$  [Özdemir et al., 1995; Özdemir and Dunlop, 1997].

These results are explained by the contrast in  $M_s$  and  $H_d$  between the two minerals. Low  $M_s$  leads to a large critical SD size and large wall spacing [Dunlop and Özdemir, 1997, Chap. 5], as seen in  $\alpha$ - $Fe_2O_3$ , while high  $M_s$  demands more finely divided domain structure,

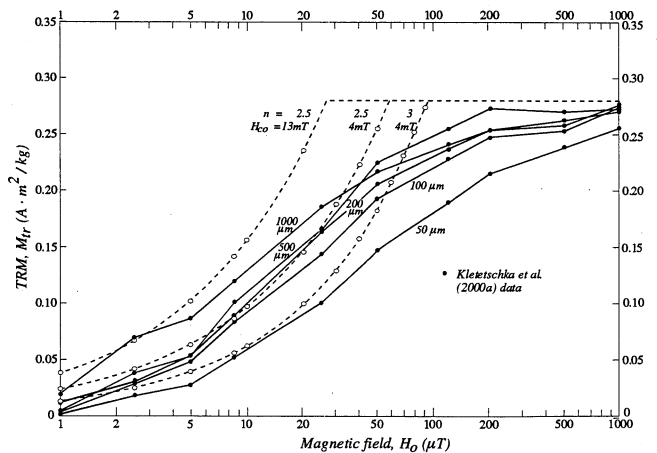


**Figure 3.** Comparison of experimental TRM data for SD and MD hematites with the predictions of Néel's [1949, 1955] SD and MD theories. Note the "inversion" of TRM intensities (MD > SD) and the near-saturation of MD TRM in the Earth's field ( $\approx 50$   $\mu$ T).

as observed in  $Fe_3O_4$ . Small self-demagnetizing fields in hematite, resulting from its low  $M_s$ , permit large, permanent wall jumps, while magnetite's large  $H_d$  limits wall movements to small increments which are largely reversed when  $H_0$  is removed. Wall renucleation is also made difficult by the small  $H_d$  in hematite. Thus both domain observations and hysteresis in hematite are well accounted for by its low  $H_d$ .

Domain observations in the TRM blocking range are technically daunting. One would expect little real difference in TRM blocking compared to room-temperature wall motion and pinning.  $H_d$  and  $H_c$  are both reduced at  $T_B$ , but their relative magnitudes in  $\alpha$ - $Fe_2O_3$  and  $Fe_3O_4$  remain unchanged. Wall displacements in  $\alpha$ - $Fe_2O_3$  will be even larger at  $T_B$  because  $H_d$  decreases with heating but  $H_0$  does not. This is why the TRM saturation field in Figs. 2–4 is substantially less than  $H_d$  at  $T_0$ .

In magnetite, thermal fluctuations can cause unblocking of TRM below the field-blocking  $T_B$  [Néel, 1955], as can domain wall nucleation below  $T_B$  [McClelland and Sugiura, 1987]. This may explain why the measured TRM of MD magnetite (Fig. 2) is



**Figure 4.** Comparison of experimental TRM data for 5 sized fractions from MD hematite sample L2 with curves predicted by Néel's [1955] MD theory for different values of  $n$  and  $H_{c0}$ .

somewhat less than predicted by (5). In hematite, the major Barkhausen jumps seen in hysteresis involve volumes too large to be readily activated thermally, while nucleation is unlikely because  $H_d$  is too small.

Our original objective was to explain quantitatively observed intensities of TRM in hematite over a broad range of fields  $H_0$ . Néel's [1955] MD theory of TRM gave quite encouraging numerical matches to the data for N115249, NR17174 and sized fractions of L2, particularly for fields  $\leq$  the Earth's field (Figs. 2, 3, 4). Néel's [1949] SD theory gave a good first-order prediction of measured TRM data for  $\approx 1 \mu\text{m}$  grains of  $\alpha\text{Fe}_2\text{O}_3$  (N114078, Fig. 3), in contrast to the indifferent matches of Néel's and other theories to TRM data for magnetite [Dunlop and Argyle, 1997]. The minor role of demagnetizing, interaction and screening effects in hematite account for the success of theoretical modeling and suggest that hematite is the mineral of choice for future investigations of TRM and partial TRM behavior.

A final question is the one posed in the title: is multidomain hematite a viable source of planetary magnetic anomalies? Major concentrations of massive MD hematite on Earth are in iron ores such as banded iron formations, which may also contain disseminated SD hematite and MD magnetite. The TRM will be dominated by the MD hematite (Fig. 2), but any MD magnetite will contribute to magnetic anomalies through its induced  $M$ . Using an average magnetite  $\chi_0$  of 2.8 SI (Table 2) and  $H_0 = 50 \mu\text{T} / \mu_0 = 39.8 \text{ A/m}$  gives  $M_{\text{in}} = 112 \text{ A/m} = 0.0215 \text{ Am}^2/\text{kg}$ , compared to  $M_{\text{tr}} = 0.2\text{--}0.3 \text{ Am}^2/\text{kg}$  (Figs. 2, 3) or 1100–1600 A/m. TRM of MD hematite is thus 10–15 times stronger than induced  $M$  of an equal mass of MD magnetite.

The Labrador banded iron formations from which sample L2 derives have stratigraphic thicknesses from 30–300 m and areal extents of several km. They are a potent source of remanent magnetic anomalies. On Mars, the situation is less clear. Connerney et al. [1999] modeled intense southern hemisphere anomalies assuming  $M_r = 20 \text{ A/m}$  or  $4 \times 10^{-3} \text{ Am}^2/\text{kg}$  over a depth of 30 km. Only magnetite and hematite have sufficiently high  $T_C$  to be magnetic at such depths. About 2% of MD hematite or 0.5% of SD magnetite would be needed. PSD magnetite is more plausible, however, and would be required in a concentration similar to that of MD hematite.

## Conclusions

1. Néel's [1949, 1955] theories of TRM predict quite well the measured field dependence of TRM in both SD and MD hematites.
2. TRM in MD hematite reaches near-saturation in the Earth's field and is an order of magnitude or more larger than TRM or induced  $M$  of MD magnetite.
3. Hematite's weak magnetism ( $M_s \approx 0.4 \text{ Am}^2/\text{kg}$ ) results in weak demagnetizing and interaction fields and no magnetic screening, thus explaining 1 and 2.
4. TRM of MD hematite rivals induced magnetization of MD magnetite and TRM of PSD magnetite as a source of magnetic anomalies on Earth and perhaps Mars.

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