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Grain size dependent potential for self generation of magnetic anomalies on Mars via thermoremanent magnetic acquisition and magnetic interaction of hematite and magnetite

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Abstract

Early in the history of planetary evolution portions of Martian crust became magnetized by dynamo-generated magnetic field. A lateral distribution of the secondary magnetic field generated by crustal remanent sources containing magnetic carriers of certain grain size and mineralogy is able to produce an ambient magnetic field of larger intensity than preexisting dynamo. This ambient field is capable of magnetizing portions of deeper crust that cools through its blocking temperatures in an absence of dynamo. We consider both magnetite (Fe_3O_4) and hematite (α-Fe_2O_3) as minerals contributing to the overall magnetization. Analysis of magnetization of magnetic minerals of various grain size and concentration reveals that magnetite grains less than 0.01 mm in size, and hematite grains larger than 0.01 mm in size can become effective magnetic source capable of magnetizing magnetic minerals contained in surrounding volume. Preexisting crustal remanence (for example ∼250 A/m relates to 25% of multi-domain hematite) can trigger a self-magnetizing process that can continue in the absence of magnetic dynamo and continue strengthening and/or weakening magnetic anomalies on Mars. Thickness of the primary magnetic layer and concentration of magnetic carriers allow specification of the temperature gradient required to trigger a self-magnetization process.

Keywords: Magnetic mineralogy; Self-magnetization; Blocking temperature; Martian crust; Temperature gradient

1. Introduction

The detection of strongly magnetized ancient crust on Mars is one of the most surprising outcomes of recent Mars exploration, and provides an important

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insight about the Mars core. The iron-rich liquid core was associated with magnetic dynamo (limited in duration to several hundred million years) and probably formed during the hot accretion of Mars 4.5 billion years ago and subsequently cooled at a rate dictated by the overlying mantle (Stevenson, 2001). Presently, Mars probably has a liquid, conductive outer core and might have a solid inner core like Earth, however, no evidence of magnetic sources (Voorhies et al., 2002).

The self-magnetization of Martian crust (Arkani-Hamed, 2003) can produce a thermoremanent magnetization (TRM) of the Martian lithosphere. The process assumes that the upper part of the lithosphere acquired TRM in the early history of the planet and in the presence of the core field (the primary magnetization), whereas the lower part has been gradually magnetized by the magnetic field of the upper part as it has cooled below the Curie temperature (secondary magnetization). In Arkani-Hamed's model, the secondary magnetization from the layer that underlies the upper lithosphere magnetized by Martian dynamo is relatively weak. In this contribution we show conditions where magnetization from the deep layers can be significant, contrary to Arkani-Hamed's model. The main reason why the Arkani-Hamed's model does not generate significant contribution to the overall magnetic anomaly is because he assumed that the source layer, the upper lithosphere, is similar to that of the extrusive basalt near the oceanic ridge axes on Earth and contains constant magnetization on the order of 25 A/m. The field from the upper lithosphere, considered as a source field, allows providing ambient magnetic field for the underlying layers of contrasting magnetization factor, reflecting magnetic properties of the rocks. It is this assumption of the magnetizing layer with constant strength of 25 A/m that is different from our model where we allow this magnetization to be within 100–1000 A/m. In our model the primarily magnetized crust has high concentration (10–100%) of the magnetic material and the thermal magnetization acquisition process involves titanohematite (solid solution Fe_2O_3-$FeTiO_3$) magnetic carrier rather than titanomagnetite (solid solution Fe_3O_4-Fe_2TiO_4) as assumed for oceanic ridges on Earth.

Titanohematite rich rocks have sharply contrasting magnetic acquisition properties than titanomagnetite (Kletetschka et al., 2002; Robinson et al., 2002). Titanohematite resembles magnetic acquisition of pure hematite, which has been shown to increase with magnetic grain size (Dunlop and Kletetschka, 2001; Kletetschka et al., 2000a, 2000c), allowing massive hematite rich formation to possess magnetizations close to its saturation, exceeding 1000 A/m.

Most of the magnetic anomalies detected by MGS are located in the Southern Hemisphere within the Southern Highlands (Connerney et al., 2001). The amplitude of many of the Southern Highland anomalies (~250 nT) is over 10 times what is observed on Earth (<20 nT) at the same 400 km altitude. The presence of coherent magnetic anomalies occupying large regions indicates the past existence of magnetic dynamo in the Martian core. However, the regions where the magnetism is small or absent may be due either younger crustal masses or more complex magnetic history (Hood et al., 2003; Kletetschka et al., 2004b). Perhaps the absence/presence of magnetism is due to the underlying crust that was either formed and/or modified (igneous and/or metamorphic) after the magnetic dynamo had ceased. These events may represent remelting and/or re-heating of large portions of the crust by rock forming processes or by impact related demagnetization or physical removal of magnetized crustal material. The small or absent magnetic anomalies may also indicate magnetic minerals that are not suitable for self-magnetization of the Mars crust.

The magnetic anomaly distribution outlines two different age epochs of Mars crust. The oldest crust (>3 billion years) is associated with the significant magnetic anomalies (greater than 15–20 nT at 400 km altitude) and the younger modified crust with anomalies less than 15 nT and below the instrument detection threshold (±4 nT) (Acuna et al., 1999; Kletetschka et al., 2003b). However, if the crustal rock on Mars has self-remagnetization potential, the absence of magnetic anomalies does not necessarily indicate the crustal age but absence of conditions for self-magnetization.

2. Magnetizing mechanisms

Minerals contained within the Martian crust were magnetized, by cooling, within the ambient preexisting magnetic field. There are two distinct mechanisms that allow homogenous magnetizations of large volumes of rocks within the crust at temperatures dependent on the particular mineral—commonly around 500 °C. Mechanism 1 is acquisition of thermo-remanent magnetization (TRM) by the magnetic minerals cooling and passing through the mineral-specific blocking temperatures. Mechanism 2 is acquisition of chemical remanent magnetization (CRM) which can occur also during cooling. However, in the case of CRM the magnetic minerals are formed below their blocking temperatures as a result of the new phase precipitation, for example, during the phase exsolution processes (McClelland, 1996).

Both of these processes are very efficient and comparable to TRM intensity (Clark, 1983, 1997) acquired just below the blocking temperature of the grains. Stacey pointed out in his theory of multidomain TRM (Stacey, 1958), since the demagnetizing energy falls off more slowly with temperature than any other, the condition under which TRM is first acquired is the minimization of the internal field. This guarantees that at least at this temperature the TRM is related only to the magneto static energy and the demagnetizing energy (Kletetschka et al., 2004a).

At the blocking temperatures the magnetic moment of the grain is forced by the ambient magnetic field to be parallel to the applied field. When cooling several degrees below this temperature, the stability of the magnetic moment against magnetic changes increases exponentially (Dunlop and Özdemir, 1997) and information about the ambient field is frozen within the mineral grains. In the case of CRM, the new magnetic phase starts to nucleate at a sub-nanometer size. In this state, the magnetic moment of the grain is perturbed by thermal fluctuations and the blocking temperature of the grain is very low. With increasing size of the growing grain, the blocking temperature rises, and the grain records the ambient field when this temperature reaches the ambient temperature.

3. Available magnetic minerals

There are only a few magnetic minerals that can be responsible for magnetic anomalies on Mars. Attempts were made to assess the nature of the magnetic minerals in the Martian soil (Viking and Pathfinder missions) by collecting small magnetic particles with strong magnets that were part of the experiment packages on the Viking (1976), Pathfinder (1996), Spirit (2004), and Opportunity (2004) landers. This resulted in a list of potential magnetic mineral candidates, notably metallic iron, magnetite and/or titanomagnetite, maghemite (γ-Fe_2O_3), and monoclinic pyrrhotite (Fe_7S_8). All of these minerals have high magnetic susceptibility and yield no information about the presence of remanence carrying minerals, such as hematite and goethite as they would not be attracted by the magnet arrays. Therefore, the sources of remanent magnetism do not necessarily constitute the same spectrum of magnetic minerals sampled by the lander-mission magnet arrays.

Among the common rock-forming minerals only a few are capable of acquiring and retaining significant remanent magnetization (Kletetschka et al., 2003b, 2000b). These minerals are among the oxides and sulfides, which are commonly found on Earth. The available petrographic data for the SNC meteorites (McSween, 1985), high pressure experiments on sulphites (Rochette et al., 2003), magnetite (Gilder et al., 2002), 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., 2000) suggest that magnetite, hematite, and pyrrhotite are the primary candidate minerals to be considered.

4. Analysis of potential minerals for sources of Martian magnetic anomalies

Intense magnetic crustal sources, detected in the Terra Sirenum region (120°W–210°W; 30°S–85°S), require an estimated magnetic moment of $\sim 1.3 \times 10^{17}$ A m^2 (Connerney et al., 1999). For a 30 km thick magnetized layer this moment translates to a magnetization of ∼20 A/m. It can be assumed that initially this magnetization was acquired as a TRM/CRM, because these are the only remanence acquiring mechanisms operating in the deep crustal rocks (Kletetschka et al., 2002). The data from magnetizations of common terrestrial rocks (Kletetschka et al., 2003a) indicates that it is a quite exceptional (except for iron ores) for terrestrial rocks to have a magnetization of 20 A/m, apart from the large volumes required (30 km thick layer) with uniform magnetization.

The magnetization of hematite, magnetite and pyrrhotite in their pure form changes according to grain

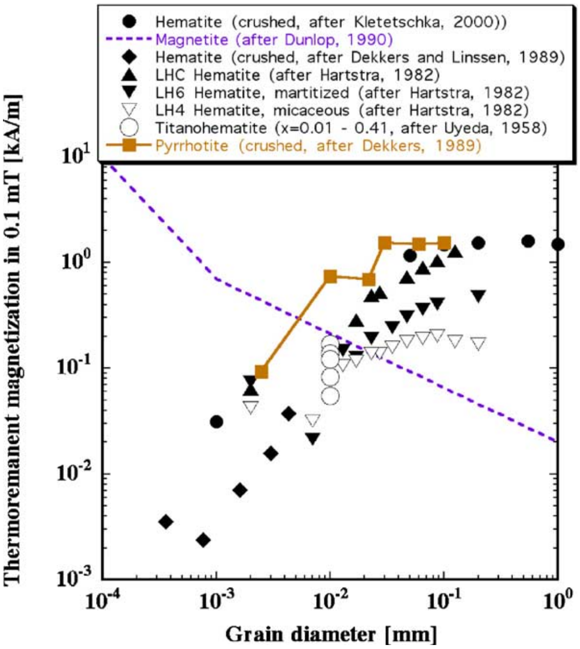

Fig. 1. TRM magnetizations for the three main candidate minerals, magnetite (Dunlop and Argyle, 1990), hematite (Dekkers and Linssen, 1989; Hartstra, 1982; Kletetschka et al., 2000c; Uyeda, 1958) and pyrrhotite (Dekkers, 1989) that can constitute the source of the magnetic anomalies on Mars.

size (Fig. 1, note that the unit is kA/m). The diagram (the acquisition field is 0.1 mT) indicates that the maximum possible TRM of large grains of hematite and pyrrhotite is a little over 1000 A/m. Magnetization for small grains of magnetite is close to 10,000 A/m. Both hematite and pyrrhotite can acquire strong magnetizations while in large grain size. Thus, maximum intensity per volume of the rock formation occurs when hematite and pyrrhotite accumulate by ore forming processes. In such a case the concentration of hematite and/or pyrrhotite can be >50% (by volume) and magnetization of the entire rock can be greater than 500 A/m.

Magnetite can be more magnetic (by almost an order of magnitude) but only when small in grain size. There are only few mechanisms that can preserve the small grain size of magnetite in deep crustal rocks. One mechanism is an exsolution from silicate minerals. Exsolution of fine grained magnetite permits only about a half percent (by volume) concentration due to problems of fitting magnetite in the host-phase crystal-lattice defects and due to a change from the phase hosting Fe that has to be compensated. This limits the maximum overall magnetization of rocks with magnetite (0.5% by volume) to about 50 A/m, an order of magnitude lower than magnetizations of hematite and pyrrhotite. Another mechanism is thermal decomposition of iron rich carbonates, as observed in the older Martian meteorites (Scott and Fuller, 2004). However, there is no yet evidence for wide spread amount of iron rich carbonate on Mars.

All three minerals, magnetite, hematite and pyrrhotite can generate enough magnetization to produce the observed magnetic anomalies. There must be a way to enhance the concentration of one of these minerals within large volumes of Martian crust while keeping a uniform magnetizing direction. As discussed before, ore deposits are one way of making possible large volumes of large magnetization regions. This is directly connected to the early history formation of the crust and choosing one of these minerals over the other will have major impact on the evolution path of Martian crust. Hematite presence in lower crustal Martian rocks would imply high oxidation levels. The titanohematite is also suggested from large coercivities deduced from the decay of magnetic anomalies near Prometheus impact basin on Mars (Kletetschka et al., 2004b).

The occurrence of hematite bearing lower crustal rocks on Earth may be attributed to the orogenic recycling of oxidized surface material. On the other hand both magnetite and pyrrhotite have been detected in SNC meteorites (Antretter et al., 2003; Rochette et al., 2001; Weiss et al., 2002). Lower crust with large concentration of magnetite requires a special mechanism to disperse fine-grained magnetite, and/or produce complex textures so the magnetization can be stable and survive more than 3 billion years. Pyrrhotite rich crust would imply large hydrothermal flows accumulating enough pyrrhotite concentration in a massive form.

Magnetite grains have large intrinsic demagnetizing fields (2.6 mT) causing low efficiency of an acquired remanence and multidomain magnetic structures for grains larger than 1000 nm (Dunlop and Kletetschka, 2001; Kletetschka et al., 2000c, 2004a). This property suggests that magnetite is less likely responsible for magnetic anomalies on Mars. More promising minerals are pyrrhotite and hematite grains with 1–2 orders of magnitude lower demagnetizing field (0.5 and 0.012 mT), allowing preservation of SD-like behavior for grain diameters reaching 0.2 mm (Fig. 1, Kletetschka and Wasilewski, 2002). Because the nature of the magnetic source is most likely intrusive and/or metamorphic rocks with predominantly coarse-grained granular texture, magnetic source should include pyrrhotite and/or ilmenite-hematite composition.

5. Self-magnetization model

Magnetic minerals with stable magnetic remanence generate magnetic flux density proportional to the reciprocal distances from their surfaces. The existence of magnetic anomalies on Mars indicates that magnetic field generated by global process inside the Mars core magnetized portions of the Martian crust. The thickness of the primary magnetic crust was controlled by thermal flux escaping from the cooling of primitive planet. In our model we can choose arbitrarily initial crust thickness to see if such a layer would have self-magnetizing potential.

Fig. 2 establishes grain size regions with significant spatial extent of magnetic flux density. Such grains are illustrated in Fig. 3 using magnetic simulation software "Finite Element Method Magnetics" written by David Meeker and freely available at http://femm.berlios.de. The contour lines indicate magnetic intensity that would be detectable at various locations near the magnetic grain and near the combination of several magnetic grains. The TRM is acquired at 0.05 mT. TRM of

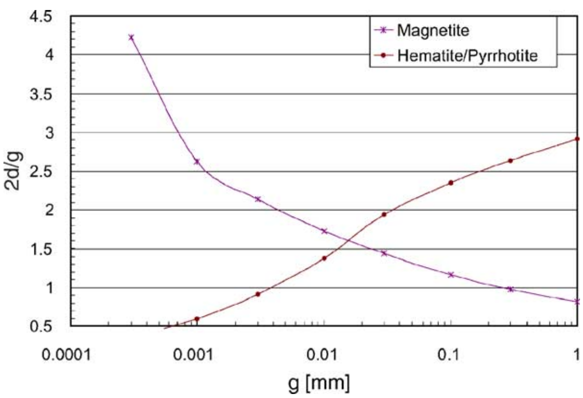

Fig. 2. Normalized distance d between the surface of the magnetic mineral and the field of $1e-4$ T generated by mineral's thermal remanence (TRM) acquired at field of $1e-4$ T. d is normalized by grain radius $g/2$. Pyrrhotite and hematite data are combined into one curve based on information in Fig. 1.

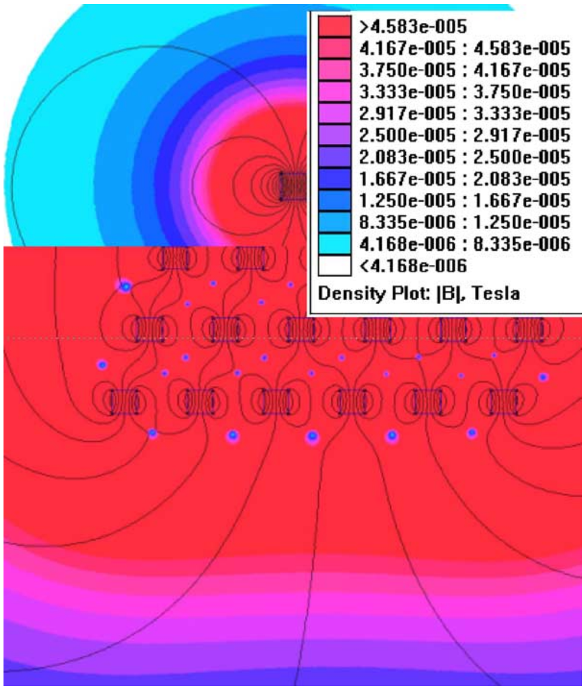

Fig. 3. Magnetic field from hematite with magnetization of 1500 A/m in vertical direction. Top: single grain 0.2 mm in size. Bottom: combination of grains with the bottom size 2.8 mm and 11% hematite concentration.

hematite and possibly pyrrhotite are close to saturation in the ambient field of this intensity (Kletetschka et al., 2004a, 2003a, 2003b, 2000a, 2000c). TRM magnetizations would not change in intensity for more intense TRM acquisition fields and the crustal intensity would stay constant.

Our TRM acquisition model explores the likelihood that individual grain magnetic fields (Fig. 3, top) could be configured such a way (Fig. 3, bottom) to provide the "ambient field", either in absence or in addition to existing dynamo generated magnetic field, in which proximate grains could be magnetized as they cool through their blocking temperatures. Primary magnetization of thin crust in radial direction provides a positive interaction and the overall magnetization would continue to increase as the underlying rock cools. A negative interaction (a decrease of the crustal magnetization) will occur when a primary TRM magnetization is acquired parallel to the planet surface.

One can imagine a hypothetical 50 km thick layer of 25% ilmenite hematite to provide the "ambient field"

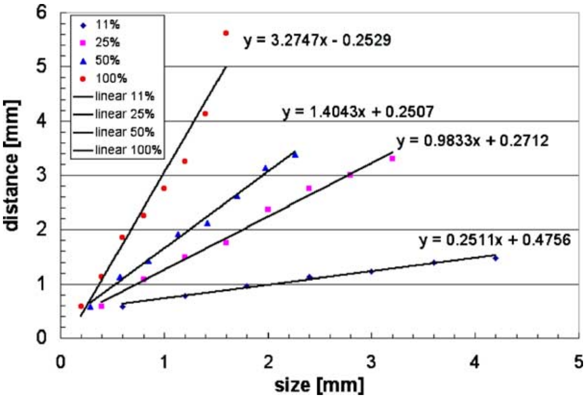

Fig. 4. Spatial magnetic field extent (distance from the modeled rock surface) for increasing volumes of rock (size of the rectangular body) containing various concentrations (11, 25, 50, 100%) of hematite carriers. Calculated data are fitted with the straight line by least-square method.

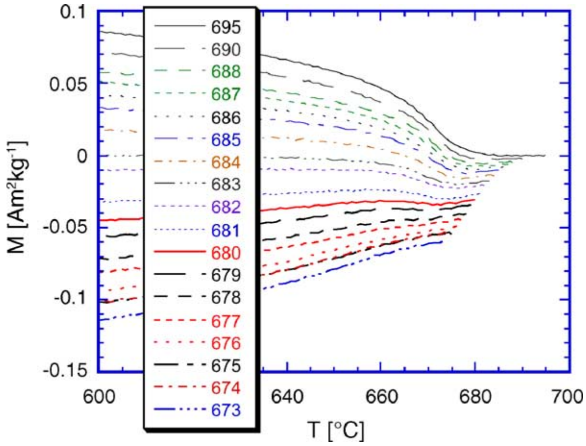

Fig. 5. Pure hematite grain (0.2 mm) with saturated remanence in negative direction is brought to various temperatures, in vicinity of the hematite blocking temperature, and cooled while applying positive field of 0.05 mT. The data establish sharpness of the hematite's blocking temperature window (∼20 °C) for single domain grain, 0.2 mm in size.

at levels up to 0.05 mT to depths of 50 km. Such concentration would be quite exceptional compared with terrestrial standards where such rock occurs only locally (Hargraves and Burt, 1967; Kletetschka and Stout, 1998; McEnroe et al., 2001, 2002). This information derives from Fig. 4, where we plot results from numerical modeling of various block sizes and concentrations (one such block configuration is illustrated in Fig. 3, bottom). In Fig. 4 the distance between the magnetic surface and the predefined field intensity (we chose 0.05 mT) increases linearly with size of the magnetic source. Because there is no an apparent physical reason why the larger scale bodies of our mineral TRM acquisition model should deflect from the linear behavior obtained by our modeling we consider extrapolation to kilometer scale as a realistic approximation. Unfortunately, the model, combining the individual sub-millimeter sized magnetic grains into the kilometer size objects, is beyond our present computation limits. Therefore, an extension of the block volume (magnetized in the Martian dynamo ambient field) to several kilometers in size and containing 25% of hematite concentration generates field exceeding the 0.05 mT to depths of additional several kilometers (Fig. 4).

In order to estimate a thermal gradient that would accommodate our model of slow cooling we tested stability of hematite's magnetic remanence near the blocking temperature. Fig. 5 represents multiple heating and cooling cycles of multidomain hematite grain. During beginning of each cycle the hematite grain was given TRM in negative ambient magnetic field (−0.05 T). Then after cooling to 23 °C the field was reversed to positive (+0.05 T) and sample was exposed to slow heating to variable temperatures near the blocking temperature. After reaching the target temperature the magnetization was measured continuously as the grain cooled in a positive magnetic field. Fig. 5 shows that the initial thermally blocked magnetization is completely remagnetized over a temperature difference of ∼20 °C. Hematite bearing rock held at the temperature only 20 °C below its blocking temperature would likely preserve its stable magnetization acquired from the magnetic dynamo. The blocking temperature is 20 °C higher than the hematite's remagnetizing temperature. For the rock to acquire magnetization at 0.05 mT, generated from the cold block above, it has to be in sufficient proximity to the cold block (Fig. 3). By combining the *x* km distance of magnetizing field from magnetized body *x* km thick with 25% of hematite in Fig. 4 with the temperature interval necessary for acquiring stable magnetic remanence at 0.05 mT (Fig. 5) we obtain a thermal gradient >20 °C/*x* km that fully accommodates our model of slow cooling. Based on currently estimated small thermal gradient of 5–15 °C/1 km (Hood and Zakharian, 2001) initially magnetized layer >1 km thick would be sufficient to trigger the self magnetizing process if the concentration of magnetic carriers of favorable grain size would be et least 25%.

The existence of this mechanism in Mars crust would mean that the prevalence of radial direction of magnetization in the source rock generates magnetization in rock below that is parallel to the source. However, the horizontal magnetizations of the source rock create magnetizations of the rock below that is anti-parallel to the source rock. Thus, for the purpose of a magnetic anomaly detection, horizontally magnetized rocks generate field of lower intensity than rocks magnetized radially (Arkani-Hamed, 2003). The future detailed magnetic surveys of Mars will verify this.

6. Conclusions

Assuming that the magnetic source of the middle and lower Martian crust has magnetite, ilmenite-hematite and/or pyrrhotite composition of specific grain size, the magnetic anomalies can be amplified during slow cooling of the planet's surface, while producing a variable thermal gradient. Variation of magnetic anomalies may localize areas with abundant suitable magnetic mineralogy, radial versus horizontal initial magnetization, and/or places where the historical heat flow exceeded 20 °C per distance that equals to a depth of the primary crust magnetized by dynamo. The future altitude dependent magnetic survey should test our model by searching for crustal magnetic sources with magnetization predominantly in radial direction.

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