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Magnetization of Martian lower crust: Revisited

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[1] This paper examines the magnetization that can be acquired by the lower crust of Mars in the absence of a core field but in the presence of the magnetic field of the upper crust that is magnetized by the core field. A uniformly magnetized vertical prism of a square horizontal cross section is considered to be a magnetic source in the upper crust for simplicity. Three thicknesses of 40, 60, and 80 km and six horizontal dimensions of 180, 300, 600, 900, 1200, and 1500 km are considered for the prism. To estimate the upper limit for the contribution of the lower crust to the observed magnetic anomalies, a potentially magnetic layer of 100 km thickness is adopted. Coarse-grain hematite is uniformly distributed in the lower crust with 4, 10, 20, or 30% concentration of hematite. The first is equivalent to the oceanic extrusive basalt as far as its thermo-remanent magnetization (TRM) is concerned. It is shown that the magnetization of the lower crust has minor effects on the strong magnetic anomalies of Mars over the southern hemisphere. However, if the lower crust has 20 to 30% coarse-grain hematite, which is highly unlikely, it may have appreciable contributions to small magnetic anomalies of Mars with horizontal dimensions smaller than 200 km.

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1. Introduction

[2] Attempts have been made in the last 7 years to determine the magnetization of the Martian crust that is responsible for the strong magnetic anomalies detected by Mars Global Surveyor over the southern hemisphere of Mars [*Acuna et al.*, 1999]. The anomalies require bulk (vertically integrated) magnetization of $(6-10) \times 10^5$ A [e.g., *Connerney et al*, 1999; *Arkani-Hamed*, 2002; *Langlais et al.*, 2004; *Whaler and Purucker*, 2005], which is one to two orders of magnitude stronger than the bulk magnetization of the Earth's crust. The strong magnetization of the Martian crust must be largely of remanent origin because no core field presently exists on Mars.

[3] Among the factors that control the magnetization of the Martian crust, i.e., the core field strength, the thickness of the magnetic crust, the concentration of magnetic minerals, and the minerals with strong remanent magnetization, the latter seems more effective. On the basis of magnetostrophic balance scaling, where Coriolis force is balanced by Lorentz force, it can be argued that the core field of Mars at the surface was weaker than the present core field of the Earth at the surface [*Arkani-Hamed*, 2005a]. Rock magnetic measurements may also provide constraints on the intensity of the Martian core field. Allan Hills meteorite AH84001 has acquired its magnetization in a field 0.1–1 times that of the present Earth's field [e.g., *Weiss et al.*, 2002; *Antretter et al.*, 2003]. However, it is not clear whether it was magnetized by the core field or by the local crustal field and after the cessation of the core dynamo [*Weiss et al.*, 2002]. Nevertheless, many rock magnetic and paleomagnetic investigators favor a weaker field for Mars [*Weiss et al.*, 2002; *Antretter et al.*, 2003]. A thickness of 35–50 km has been estimated for the magnetic crust of Mars at present on the basis of possible demagnetization of the crust by impacts [*Nimmo and Gilmore*, 2001] and the statistical characteristics of the power spectra of spherical harmonic models of the Martian magnetic field [*Voorhies et al.*, 2002]. *Nimmo* [2000] suggested an upper limit of 60 km for the magnetic layer of Mars at 4 Gyr ago assuming *Longhi et al.*'s [1992] estimate of the radioactive abundance of Mars. The thermal evolution models of Mars based on parameterized convection calculations in the Martian mantle overlain by stagnant lithosphere [*Arkani-Hamed*, 2005b] imply that the depths to the Curie temperatures of magnetite and hematite, i.e., the potentially magnetic layer of Mars, were about 80 and 100 km during the active period of the Martian core dynamo, before 4 Gyr ago. There is no firm estimate of the concentration of magnetic minerals in the Martian crust. The entire crust of the southern hemisphere appears to be basaltic with iron content higher than that of the Earth's crust [*McSween et al.*, 2003]. However, the oxidation state of iron in the Martian crust is poorly understood, partly because only a fraction of iron usually goes into magnetic oxides. The major magnetic minerals suggested for the Martian magnetic lithosphere are magnetite, hematite, and pyrrhotite [e.g., *Kletetschka et al.*, 2000, 2004; *Dunlop and Kletetschka*, 2001; *Rochette*

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et al., 2001; *Dunlop and Arkani-Hamed*, 2005]. Although pyrrhotite occurs in most of the shergottite-nakhlite-chassigny (SNC) Martian meteorites [*Rochette et al.*, 2001], its remanence-carrying role is less clear [*Weiss et al.*, 2002; *Antretter et al.*, 2003]. Moreover, the low Curie temperature of pyrrhotite, 230°C, and the temperature gradients of 7–10°C/km estimated in the crust [e.g., *Arkani-Hamed*, 2000; *Zuber et al.*, 2000; *Ruiz et al.*, 2006] limit the magnetic layer of Mars to less than 30 km thick if pyrrhotite is the major magnetic carrier. On the other hand, the lack of appreciable demagnetization of the crust beneath some freshly looking impact craters with diameters as large as 300 km [e.g., *Nimmo and Gilmore*, 2001; *Hood et al.*, 2003; *Mohit and Arkani-Hamed*, 2004] is convincing evidence that pyrrhotite may not be a major magnetic carrier in the Martian crust. This is because impact heating and shock waves associated with such impacts that created the craters are expected to demagnetize pyrrhotite-bearing rocks within the upper 40–50 km of the crust [*Shahnas and Arkani-Hamed*, 2006].

[4] Single-domain magnetite is by far the most magnetic mineral that acquires magnetization by at least an order of magnitude stronger than other minerals [e.g., *Dekkers and Linssen*, 1989; *Hartstra*, 1982; *Dunlop and Özdemir*, 1997]. The magnetite particles must be single-domain or pseudo-single-domain to be the major magnetic carrier in the Martian crust [*Dunlop and Arkani-Hamed*, 2005] because the multidomain magnetite is weakly magnetic [e.g., *Dunlop and Özdemir*, 1997]. There is a distinct difference between the magnetic particles nucleated deep in the crust that slowly cool from an initially high temperature and those nucleated inside a thin volcanic flow at the surface. The former produces multidomain magnetic particles, whereas in the latter case, lava cools very rapidly and can result in single-domain/pseudo-single-domain particles with strong thermo-remanent magnetization. Many evidences that the upper parts of the Martian crust has been constructed by volcanism [see *Zhong and Roberts*, 2003 and many references there] led *Arkani-Hamed* [2005a] to argue that magnetite can exist deep in the crust as single-domain or pseudo-single-domain particles. The author demonstrated that subsequent burial heating of the lava layer, as it is overlain by successive lava flows, does not enhance its temperature beyond the magnetic blocking temperature range of magnetite, 480–580°C, until the layer reaches a depth of 30–45 km. The magnetite particles can remain single-domain/pseudo-single-domain and retain a major part of their initially strong magnetization. The recent experimental results of the magnetic properties of olivine basalt and Mossbauer spectroscopy data from Gusev crater on Mars by *Gunnlaugsson et al.* [2006] further support the possibility of single-domain magnetite produced in a volcanic layer. The authors attribute the appreciable increase of the natural remanent magnetization (NRM) intensity of olivine basalt to the oxidation of olivine in the cooling period of volcanic lava and exsolution of magnetite in a single-domain state. *Brachfeld and Hammer*'s [2006] experimental results show that the magnetic properties of synthetic iron-rich basalt strongly depend on the oxygen fugacity. Iron-rich melts that crystallize under quartz-fayalite-magnetite (QFM) buffer contain stable single-domain and pseudo-single-domain titanomagnetite and acquire magnetization of about 200 A/m in a magnetic field of 50,000 nT, similar to the magnetic field of the Earth.

[5] Unlike magnetite, hematite is more magnetic at multi-domain state [e.g., *Dekkers and Linssen*, 1989; *Hartstra*, 1982; *Kletetschka et al.*, 2000], though it is still weaker by an order of magnitude than single-domain magnetite. This implies that intrusive rocks deep in the Martian crust can acquire appreciable magnetization if they contain a high concentration of hematite.

[6] The lower boundary of the potentially magnetic layer established during the active period of the core dynamo has changed since. The lower crust that was hotter than the Curie temperature of magnetic minerals has gradually cooled since the cessation of the core dynamo and has acquired thermo-remanent magnetization (TRM) in the presence of the magnetic field of the upper crust. This possibility was first investigated by *Arkani-Hamed* [2003], who assumed that the lower part of the crust beneath the southern hemisphere is basaltic on the basis of petrological investigations by *McSween et al.* [2003]. It was shown that the TRM of the lower crust has minor contributions to the observed magnetic anomalies. *Kletetschka et al.* [2005] recently suggested that deep seated coarse-grain hematite bearing intrusive rocks can acquire appreciable magnetization in the presence of the magnetic field of the upper crust after the cessation of the core dynamo and can have appreciable contributions to the observed magnetic anomalies of Mars. The present paper examines this scenario in detail by considering a potentially magnetic layer of 100 km thickness at present. The upper part of the layer is magnetized by the core field and the lower part is magnetized by the magnetic field of the upper part. The thick magnetic layer adopted provides an upper limit for the thickness of the lower crust and thus for the contribution of the lower crust to the observed magnetic anomalies.

[7] I consider a vertical prism of square horizontal cross section as a magnetic source body in the upper crust that was uniformly magnetized by the core field. The lower crust is assumed to be magnetized by the magnetic field of the prism, similar to the example by *Kletetschka et al.* [2005]. The actual shape of the magnetic source bodies of Mars is likely complicated. Although a square prism is a very rough estimate for an actual body, it is sufficient for the feasibility study considered in this paper. Using a rectangular prism introduces two extra parameters, the aspect ratio of the rectangle and the orientation of the horizontal component of the magnetization of the prism, without producing significantly different results as far as the comparison of the magnetic fields of the upper and lower crust are concerned. The core field intensity probably changed by about 5% in the upper crust, from the surface to a depth of about 50 km, and its direction changed by a few degrees over the entire volume of a magnetic body, assuming that the field was dipolar. The adopted uniform magnetization represents the magnetization at the center of the body. A few percent variations in the magnetization inside the body relative to the magnetization at the center have no appreciable effects on the results presented in this paper. I also use a rectangular coordinate rather than a spherical one, for simplicity. Bearing in mind that altitude of Mars Global Surveyor during its mapping phase is only 10% of the radius of the

planet, using a flat model may not introduce a significant error [*Arkani-Hamed et al.*, 1984].

[8] Although the magnetic field of the prism can easily be determined by a space-domain technique, the magnetization acquired by the lower crust is too complicated to use a space-domain method to calculate its magnetic field. Therefore I adopt a Fourier domain method. For this feasibility study, it is only required to produce a magnetic anomaly that is similar, though not identical, in size and amplitude to the observed magnetic anomalies of Mars at 400 km altitude over the southern hemisphere.

[9] The upper crust of Mars is taken to be as thick as the vertical dimension of the prism. It contains no magnetic body other than the prism. The lower crust contains uniformly distributed coarse-grain hematite, but it is magnetized heterogeneously because of spatial variations of the magnetic field of the prism. For numerical purposes, the lower crust is subdivided into five sublayers of equal thickness, and magnetization is assumed to be depth-independent inside each sublayer. The magnetization inside a given sublayer is calculated on the basis of the magnetic field of the prism at the middle of the sublayer. The lower crust has been gradually magnetized as it has cooled below the magnetic blocking temperatures of the magnetic particles. Therefore the lower parts of the lower crust have acquired magnetization in the presence of the magnetic field of the upper crust, which was magnetized by the core field, and the magnetic field of the upper parts of the lower crust that had been magnetized by the time the lower parts cooled below the magnetic blocking temperatures. This complicated magnetization history was investigated by *Arkani-Hamed* [2003]. It was concluded that the magnetization acquired by the lower parts of the lower crust due to the magnetic field of the upper parts of the lower crust is actually very small and can be neglected for this feasibility study.

[10] The magnetic potential of the prism at the middle of the jth sublayer of the lower crust is calculated in the Fourier domain following *Arkani-Hamed* [2002]

$$\mathbf{V}_{\mathrm{p}}(\xi,\eta,h_j) = \left(2\pi/k^2\right)\mathrm{e}^{-kh_j}(\boldsymbol{\gamma}\bullet\mathbf{M}_{\mathrm{u}})\left(1-\mathrm{e}^{kH}\right);\; k=\left(\xi^2+\eta^2\right)^{1/2} \quad (1)$$

where $V_{\mathrm{p}}(\xi, \eta, h_j)$ is the Fourier transform of the magnetic potential of the prism, ξ and η are the wave numbers in the x and y directions, respectively, h_{j} is the depth to the middle of the jth sublayer, $\mathbf{M}_{\mathrm{u}}$ is the Fourier transform of the magnetization vector of the upper crust due to the prism, and H is the thickness of the prism. ($\boldsymbol{\gamma}$) is a complex vector defined as

$$\boldsymbol{\gamma} = (i\xi, i\eta, -k) \quad (2)$$

and i is the square root of -1. The Fourier transform of the magnetic field at the middle of the jth sublayer is

$$\mathbf{B}_j = -\mathbf{V}_{\mathrm{p}}\boldsymbol{\gamma} \quad (3)$$

and the Fourier transform of the magnetization of the jth sublayer is

$$\mathbf{M}_j = \chi\mathbf{B}_j \quad (4)$$

where χ is the magnetization factor, which is assumed to be the same for all sublayers for simplicity. The value χ includes both TRM acquired when the sublayer cooled below the magnetic blocking temperatures of the magnetic minerals and the induced magnetization presently acquired at the presence of the magnetic field of the prism. The induced magnetization is likely much weaker than the remanent magnetization. The bold letters in the equations denote vector quantities. The top of the prism and the origin of the coordinate system are assumed to be at the surface of Mars. The x, y, and z axes of the coordinate system are toward east, north, and up, respectively. Knowing the dimensions and magnetization vector of the prism, equations (1)–(4) yield the magnetization of the jth sublayer.

[11] The magnetic potential of the entire crust at the satellite altitude of z is determined by combining the magnetic potential of the prism and those of the sublayers

$$\mathbf{V}(\xi,\eta,z) = (2\pi/k^2)\mathrm{e}^{-kz} \times\left\{(\boldsymbol{\gamma}\bullet\mathbf{M}_{\mathrm{u}})\left(1-\mathrm{e}^{kH}\right) + \textstyle\sum_j\left[(\boldsymbol{\gamma}\bullet\mathbf{M}_j)\left(\mathrm{e}^{kd(j)}-\mathrm{e}^{kd(j+1)}\right)\right]\right\} \quad (5)$$

where $d(j)$ and $d(j+1)$ are depths to the bottom and top of the jth sublayer, respectively. The Fourier transform of the magnetic field of the entire crust $\mathbf{F}(\xi, \eta, z)$ is then calculated using a relationship similar to equation (3),

$$\mathbf{F}(\xi,\eta,z) = -\mathbf{V}(\xi,\eta,z)\boldsymbol{\gamma} \quad (6)$$

[12] We note that for a given wavelength, the ratio of the magnetic field of the lower crust to that of the prism is independent of the altitude of observation. Therefore the conclusions of this study are also applicable to future low-altitude magnetic observations.

2. Results

[13] The potentially magnetic layer of Mars in the southern hemisphere is assumed to be 100 km thick at present. It is probably the upper limit for the actual magnetic crust of Mars and likely overestimates the contribution of the lower crust to the observed magnetic anomalies. The thermal evolution models of Mars, calculated using parameterized convection inside the Martian mantle with a stagnant lithosphere at the top [*Arkani-Hamed*, 2005b], indicate that the depths to the Curie temperatures of magnetite and hematite were respectively about 80 and 100 km during the active period of the core dynamo. Recent study of the early thermal and magnetic states of the Martian crust has concluded that the depth to Curie temperature of magnetite or hematite did not exceed 40 km during the early history of Mars [e.g., *Ruiz et al.*, 2006]. It is worth mentioning that the potentially magnetic layer thus determined may not necessarily represent the actual Martian crust defined in terms of density contrast relative to the upper mantle. The gravity and topography data suggest a globally averaged crustal thickness of about 50 km and a crustal thickness of about 60 km beneath Cimmeria and Sirenum Terrae [*Neumann et al.*, 2004; *Wieczorek and Zuber*, 2004]. *Turcotte et al.* [2002] suggested that the crust beneath the Terrae is about 90 km thick. These estimates are based on

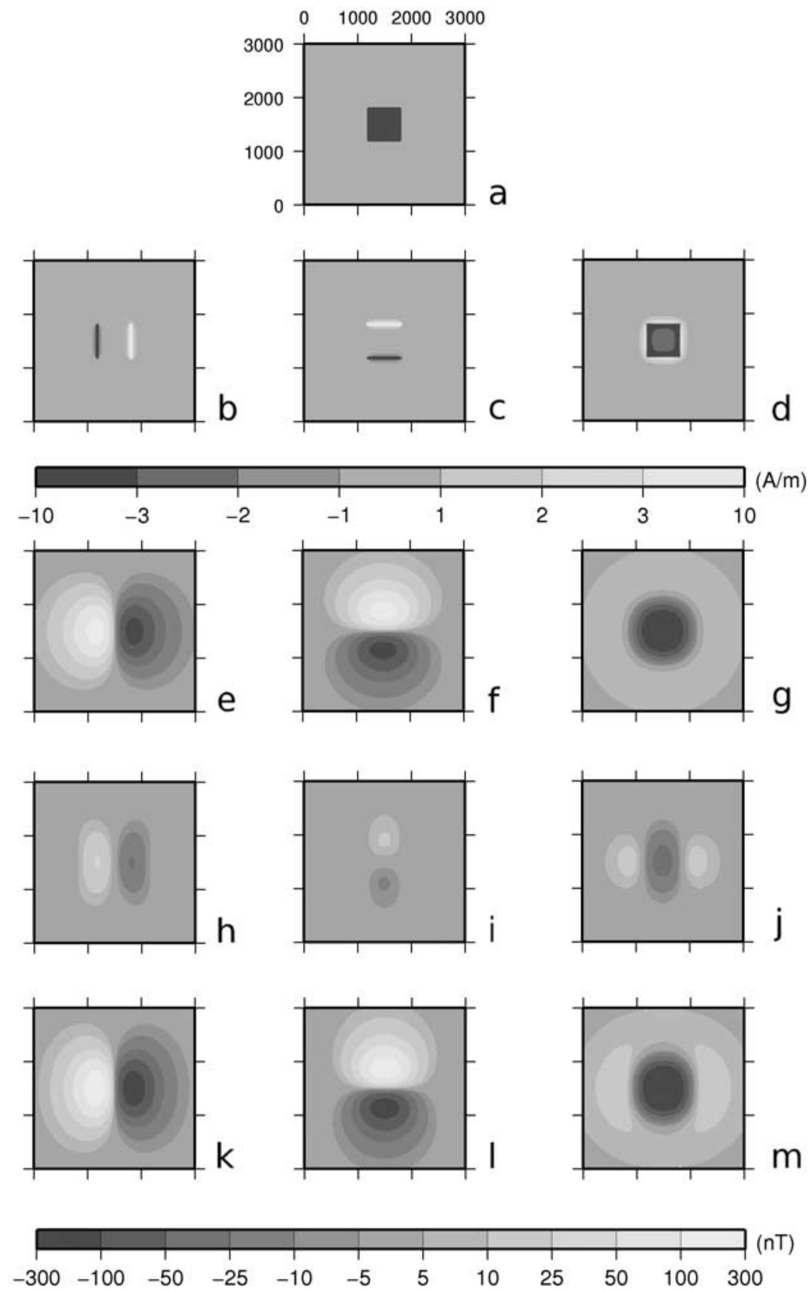

Figure 1. (a) The magnetization of the prism in vertical direction. (b), (c), and (d) The *x*, *y*, and *z* components of the magnetization of the uppermost sublayer, directly beneath the upper crust. (e), (f) and (g) The *x*, *y*, and *z* components of the magnetic field of the prism at 400 km altitude. (h), (i) and (j) The *x*, *y*, and *z* components of the magnetic field of the lower crust at 400 km altitude. (k), (l) and (m) The *x*, *y*, and *z* components of the magnetic field of the entire crust at 400 km altitude.

the assumption of uniform density of the crust on a global scale, which may not be the case. On Earth, the average crustal density of oceans are about 10% higher than that of the continents, and there are appreciable lateral variations of density in the continental crust. There is no information whether the uppermost mantle of Mars is magnetic. The uppermost mantle of Earth beneath continents is probably nonmagnetic [*Wasilewski et al.*, 1979]. If the uppermost mantle of Mars is also nonmagnetic, then the potentially magnetic layer must be confined to the actual crust of Mars. It is also possible that the uppermost mantle of Mars is highly magnetic, if a possible ilmenite-rich layer, produced in the later stages of magma ocean solidification, did not sink into the mantle (possibly because of fast cooling of the upper parts of Mars). The hematite-ilmenite lamellae have magnetic properties similar to single-domain magnetite [*Robinson et al.*, 200]. This scenario was also examined by *Arkani-Hamed* [2003], who added a highly magnetic layer between 60 and 75 km depths with a magnetization factor of 10^{-2} Am/nT, equivalent to that of pure coarse-grain hematite, and allowed it to be magnetized by the magnetic field of the upper crust. Because of its great depth, the magnetic field produced by the

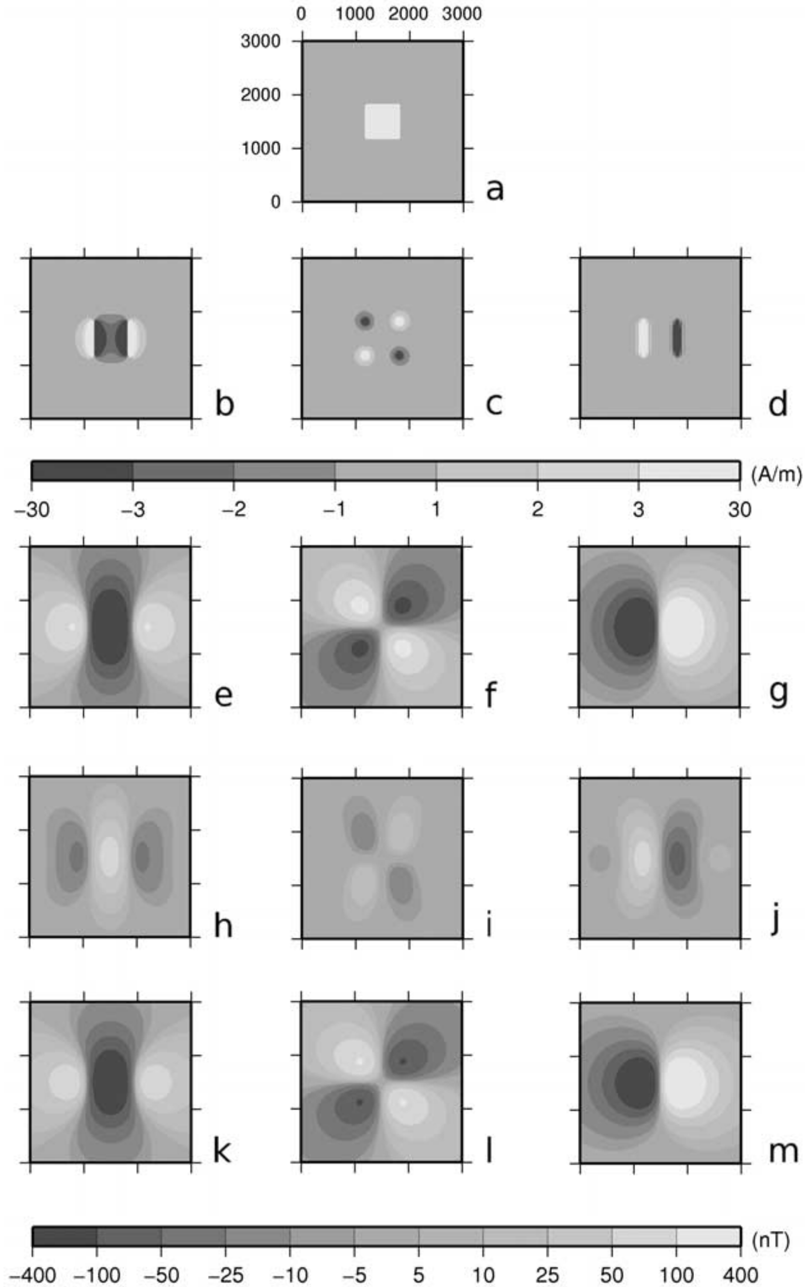

Figure 2. (a) The magnetization of the prism in *x* direction. For the rest of the panels, see Figure 1 caption.

hematite-rich layer at satellite altitude was appreciably weaker than that of the upper crust.

[14] Three different thicknesses, 40, 60, and 80 km, are considered for the prism in this study. The high altitude of Mars Global Surveyor limits the resolution of the magnetic anomalies. The horizontal extent of the major magnetic anomalies of Mars in the southern hemisphere varies typically between 400 and 1500 km at 400 km altitude. Accordingly, six different values are examined for the size of the square cross section of the prism, 180, 300, 600, 900, 1200, and 1500 km. The lower value of 180 km corresponds to the half wavelength of the spherical harmonics of degree 55 on the surface of Mars. Such a magnetized body can have appreciable contributions to magnetic anomalies of Mars specified by spherical harmonics of degrees 50 to 60 which are well resolved by Mars Global Surveyor data [e.g., *Cain et al.*, 2003; *Arkani-Hamed*, 2004]. The upper values of 1200 and 1500 km are meant to model the three large and strong magnetic anomalies sandwiched in the north-south direction, negative-positive-negative from north to south, envisaged as a positive anomaly with the two negative lobes if they arise from a single source body occupying a region between 160–190 east longitudes and 45–60 south latitudes.

Table 1. The Models Examined in This Study[a]

T	W	M	H	Ratio
40	180	V	4	0.05
40	180	V	10	0.11
40	180	V	20	0.19
40	180	V	30	0.26
40	300	V	4	0.04
40	300	V	10	0.10
40	300	V	20	0.19
40	300	V	30	0.26
40	600	V	4	0.04
40	600	V	10	0.09
40	600	V	20	0.17
40	600	V	30	0.23
40	900	V	4	0.03
40	900	V	10	0.08
40	900	V	20	0.14
40	900	V	30	0.21
40	1200	V	4	0.03
40	1200	V	10	0.08
40	1200	V	20	0.15
40	1200	V	30	0.21
40	1500	V	4	0.04
40	1500	V	10	0.09
40	1500	V	20	0.16
40	1500	V	30	0.23
60	180	V	4	0.03
60	180	V	10	0.07
60	180	V	20	0.13
60	180	V	30	0.19
60	300	V	4	0.03
60	300	V	10	0.07
60	300	V	20	0.13
60	300	V	30	0.18
60	600	V	4	0.03
60	600	V	10	0.06
60	600	V	20	0.12
60	600	V	30	0.17
60	900	V	4	0.02
60	900	V	10	0.05
60	900	V	20	0.10
60	900	V	30	0.14
60	1200	V	4	0.02
60	1200	V	10	0.05
60	1200	V	20	0.10
60	1200	V	30	0.15
60	1500	V	4	0.02
60	1500	V	10	0.06
60	1500	V	20	0.11
60	1500	V	30	0.16
80	180	V	4	0.01
80	180	V	10	0.04
80	180	V	20	0.07
80	180	V	30	0.10
80	300	V	4	0.01
80	300	V	10	0.04
80	300	V	20	0.07
80	300	V	30	0.10
80	600	V	4	0.01
80	600	V	10	0.03
80	600	V	20	0.06
80	600	V	30	0.09
80	900	V	4	0.01
80	900	V	10	0.03
80	900	V	20	0.05
80	900	V	30	0.08
80	1200	V	4	0.01
80	1200	V	10	0.03
80	1200	V	20	0.05
80	1200	V	30	0.08
80	1500	V	4	0.01
80	1500	V	10	0.03
80	1500	V	20	0.06
80	1500	V	30	0.08
40	180	h	4	0.08
40	180	h	10	0.21
40	180	h	20	0.51
40	180	h	30	1.09
40	300	h	4	0.07
40	300	h	10	0.20
40	300	h	20	0.51
40	300	h	30	1.02
40	600	h	4	0.06
40	600	h	10	0.17
40	600	h	20	0.41
40	600	h	30	0.79
40	900	h	4	0.06
40	900	h	10	0.15
40	900	h	20	0.36
40	900	h	30	0.67
40	1200	h	4	0.05
40	1200	h	10	0.15
40	1200	h	20	0.34
40	1200	h	30	0.61
40	1500	h	4	0.05
40	1500	h	10	0.14
40	1500	h	20	0.33
40	1500	h	30	0.59
60	180	h	4	0.05
60	180	h	10	0.13
60	180	h	20	0.30
60	180	h	30	0.52
60	300	h	4	0.05
60	300	h	10	0.12
60	300	h	20	0.28
60	300	h	30	0.50
60	600	h	4	0.04
60	600	h	10	0.11
60	600	h	20	0.24
60	600	h	30	0.41
60	900	h	4	0.04
60	900	h	10	0.10
60	900	h	20	0.21
60	900	h	30	0.36
60	1200	h	4	0.05
60	1200	h	10	0.09
60	1200	h	20	0.20
60	1200	h	30	0.33
60	1500	h	4	0.03
60	1500	h	10	0.09
60	1500	h	20	0.19
60	1500	h	30	0.32
80	180	h	4	0.02
80	180	h	10	0.06
80	180	h	20	0.13
80	180	h	30	0.20
80	300	h	4	0.02
80	300	h	10	0.06
80	300	h	20	0.12
80	300	h	30	0.20
80	600	h	4	0.02
80	600	h	10	0.05
80	600	h	20	0.11
80	600	h	30	0.17
80	900	h	4	0.02
80	900	h	10	0.05
80	900	h	20	0.10
40	900	h	30	0.15
80	1200	h	4	0.02
80	1200	h	10	0.04
80	1200	h	20	0.09
80	1200	h	30	0.14
80	1500	h	4	0.02
80	1500	h	10	0.04
80	1500	h	20	0.09
80	1500	h	30	0.14

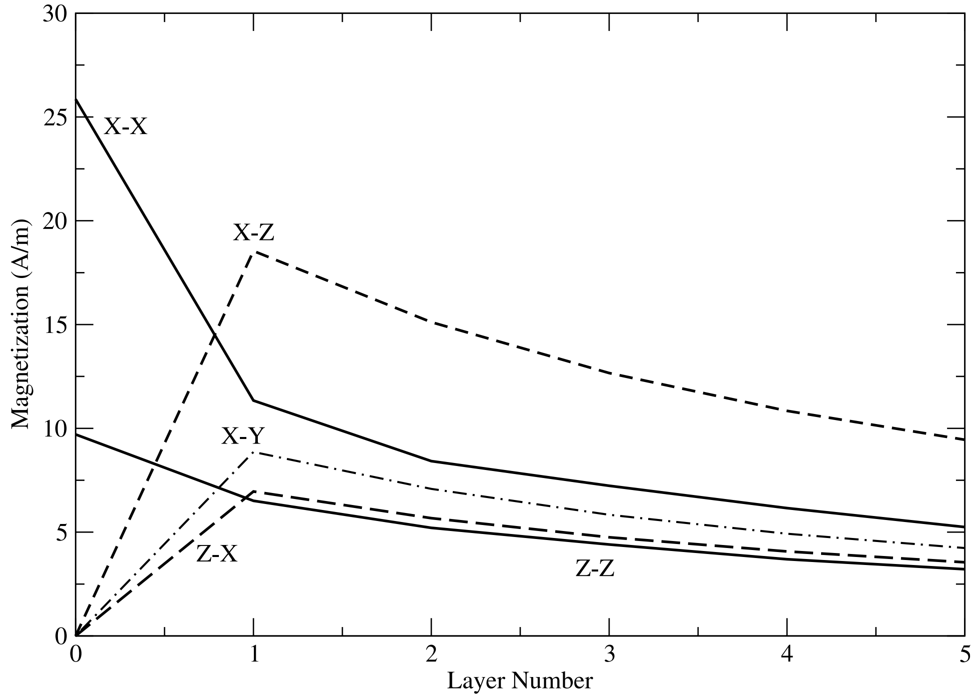

Figure 3. The magnetization of the upper crust (the prism) and that of the sublayers of the lower crust. The prism is 60 km thick and has a 600 × 600 km horizontal cross section. The lower crust has 20% coarse-grain hematite. The first letter on a curve denotes the magnetization of the prism, and the second is the magnetization component of the sublayer. When the prism is vertically magnetized, the magnetizations of the sublayers in the *x* and *y* directions are identical, and their curves overlap.

[15] The prism is uniformly magnetized either vertically or horizontally along the *x* direction. This allows us to investigate the effects of different magnetization directions on the magnetization of the lower crust and the resulting magnetic field. A uniform magnetization may not be adequate for a large 1200- or 1500-km prism over which the core field inclination may change by as much as ±12 degrees relative to that at the center of the prism. Nevertheless, such a change in the core field inclination has minor effects on the main conclusions of this paper, that the magnetic field of the lower crust at satellite altitudes is much weaker than that of the upper crust. The magnetization of the lower crust depends on the concentration of magnetic minerals besides the strength of the magnetic field of the upper crust. A pure coarse-grain hematite acquires about 1000 A/m TRM in a 0.1-mT magnetic field [e.g., *Kletetschka et al.*, 2000; *Dunlop and Kletetschka*, 2001], corresponding to a magnetization factor of χ = 0.01. Although localized mineralization may produce a high concentration of coarse-grain hematite, it is unlikely that the average hematite concentration in a layer of several tens of kilometers thick and several hundred-kilometer horizontal dimensions can be high. In an example, *Kletetschka et al.* [2005] assumed a body with 25% coarse-grain hematite and acknowledged that such a concentration is extraordinary on a terrestrial scale. Here I assume that the lower crust contains 10, 20, or 30% coarse-grain hematite that is uniformly distributed. The corresponding magnetization factors are 0.001, 0.002, or 0.003. Freshly produced oceanic extrusive basalt acquires about 20 A/m magnetization in the geomagnetic field of about 50,000 nT [e.g., *Bliel and Petersen*, 1983]. This was the model adopted by *Arkani-Hamed* [2003] for estimating the TRM of the lower crust of Mars. Its magnetization factor is about χ = 0.0004, equivalent to that of rock with only 4% coarse-grain hematite. This magnetization factor is also included in the present models for comparison.

[16] A given model is required to produce a magnetic field with a maximum intensity of 300 nT at 400 km altitude, comparable to the strong magnetic anomalies over the southern hemisphere of Mars. For smaller anomalies elsewhere, the results can easily be scaled by a multiplying factor.

[17] A total of 144 models are calculated. Table 1 lists their physical parameters. I select a prism with a 60-km thickness and 600 × 600 km horizontal dimensions that contains 20% hematite as the nominal model for illustration purposes. The magnetic anomaly created by this nominal model is comparable to those in the southern hemisphere in both amplitude and horizontal dimension. The magnetic characteristics of the nominal model are illustrated in Figures 1 and 2. The top panel in Figure 1 shows the magnetization of the upper crust, solely delineating the

Notes to Table 1.

[a]The column T denotes the thickness of the prism in km, W is the horizontal dimension of the prism in km, and M is the magnetization of the prism Where V is vertically magnetized and h is horizontally magnetized in the *x* Direction. H is the percentage of hematite content of the lower crust. The 4% concentration is equivalent to a basaltic lower crust. Ratio is the ratio of the maximum magnetic field intensity of the lower crust to that of the upper crust.

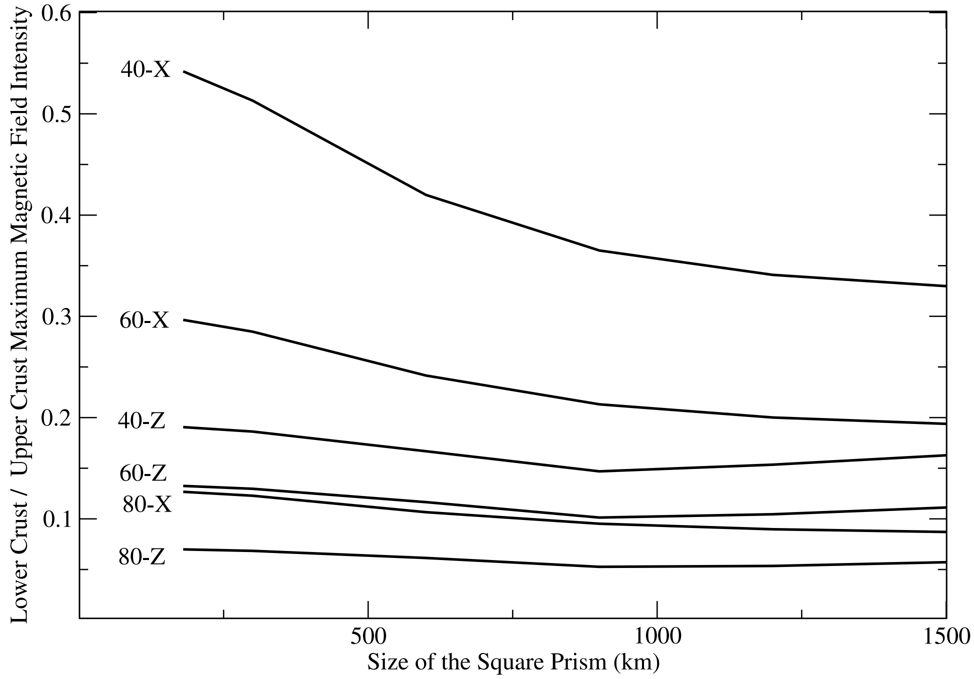

Figure 4. The ratio of the maximum magnetic field intensity at 400 km of the lower crust to that of the prism. The lower crust has 20% coarse-grain hematite. The numbers on the curves are the thicknesses of the prism. The letters on the curves denote the directions of magnetization of the prism.

square prism that is vertically magnetized. The panels in the second row are, from left to right, the *x*, *y*, and *z* components of the magnetization vector of the sublayer immediately beneath the upper crust. The computation domain is a square of 256 × 256 grid points, with grid intervals of 30 km. Only the central part of the computation domain is displayed. The sublayer is magnetized in all three directions even though the prism is only vertically magnetized. Such is also the case for other sublayers. Because of large horizontal dimension of the prism, sublayers are mainly magnetized by the edge effects of the prism. The sublayer magnetization in the *x* direction (left to right) is identical to that in the *y* direction (top to bottom) because of the symmetry of the vertical magnetization of the prism. Included in the figure are the *x*, *y*, and *z* components of the magnetic fields created at 400 km altitude by the prism (the third row), the lower crust (the fourth row), and the entire crust (the last row). Because the magnetized zones of the sublayers are very localized, their magnetic fields decay faster with altitude than the magnetic field of the prism. Also, the depth of the lower crust further reduces its magnetic field at 400 km altitude to less than 20% of that of the prism. Figure 2 is similar to Figure 1, except for the magnetization of the prism which is horizontal in the *x* direction. Although the magnetic anomalies in Figure 2 are different from those in Figure 1, similar conclusions can be drawn for their amplitudes and horizontal extent.

[18] Figure 3 shows the vertical distribution of the maximum magnetization of the nominal model. Layer 0 denotes the prism, i.e., the upper crust. Two letters specify each curve. The first letter is the imposed magnetization direction of the prism, *Z* vertical, *X* eastward. The second letter denotes the direction of magnetization of each sublayer, including the upper crust. For example, the curve *Z*-*X* is the *x* component of the magnetization created by the vertically magnetized prism. Note that this curve shows zero *x* component of the magnetization in the upper crust, as expected because of the imposed vertical magnetization there. Similarly, the curves *X*-*Z*, *X*-*Y*, and *Z*-*Y* show zero values for the prism. The latter overlaps the *Z*-*X* curve because of the symmetry when the prism is vertically magnetized. The magnetizations of the sublayers decrease with depth but gently. Note that to produce a similar magnetic anomaly at 400 km altitude, the horizontally magnetized prism requires more magnetization than the vertically magnetized prism. This is partly because, with the same strength of magnetization, a horizontally magnetized body creates a weaker magnetic field than a vertically magnetized body and partly because the magnetic field of the lower crust is in direct opposition to the magnetic field of the horizontally magnetized prism. The ratio of the maximum magnetic field intensity of the lower crust to that of the prism increases almost linearly with the increase in the amounts of hematite concentration in the lower crust.

[19] Figure 4 displays the ratio of the maximum magnetic field intensity of the lower crust at 400 km altitude to that of the prism as a function of the horizontal dimension of the prism. The prism is similar to the nominal one otherwise. For a given magnetization of the prism, the ratio is highest for the smallest prism. This is because the lower crust is now magnetized by almost the entire prism rather than by its edge effects. The ratio decreases asymptotically with the increase of the prism size and becomes very small when the prism is larger than 600 km. This is because the edge effects of the prism do not change significantly once the size of the prism becomes large.

[20] Included in Table 1 are the ratios of the maximum magnetic field intensity at 400 km altitude of the lower crust

to that of the prism for all 144 models examined. The ratios are generally lower than 0.2 except for a few models with very high concentration of hematite in the lower crust.

[21] No attempt is made in this short article to investigate the mechanism that can produce coarse-grain hematite in the lower crust. This mechanism remains as an outstanding problem. The paper is concerned with the effects of a concentrated coarse-grain hematite on the observed magnetic anomalies of Mars if it exists at all. The models presented suggest that high concentration of hematite in the lower crust may have appreciable effects on the small magnetic anomalies but not on the large and strong anomalies in the southern hemisphere if they indeed are due to extended magnetic bodies. Comparison of aeromagnetic anomalies with satellite magnetic anomalies of Earth observed at about 400 km altitude reveals that the satellite anomalies generally arise from coalescing of the magnetic fields of small but strongly magnetic bodies. This may also be the case for the extended magnetic anomalies over the southern hemisphere of Mars. Low-altitude magnetic data are required to test this scenario.

[22] It is more likely to produce significant mineralization within a small body rather than in a body of several hundred km horizontal directions and several tens of km thickness. There is no direct evidence for high concentration of hematite in the Martian crust, especially the lower parts of the crust. The coarse-grain hematite deposits discovered in Sinus Meridiani by the Thermal Emission Spectrometer (TES) instrument of the Mars Global Surveyor (MGS) [*Christensen et al.*, 2000] are most likely formed by postdepositional near-surface diagenesis [*Squyers et al.*, 2006; *Bibring et al.*, 2006]. The coarse-grain hematite concentrations of 20 and 30% in the lower crust examined in this study are quite extraordinary and hard to produce. Such high concentrations are examined in order to demonstrate that the lower crust that is magnetized in the absence of the core field cannot have a dominant contribution to the observed magnetic field of Mars even if it contains a very unreasonably high concentration of coarse-grain hematite. The anomalies are essentially due to the magnetization of the upper crust that was acquired during the active period of the core dynamo.

3. Conclusions

[23] Under the assumption that the upper crust of Mars was magnetized by the core field and the lower crust was magnetized by the magnetic field of the upper part, I investigated the contribution of the lower crust to the strong magnetic anomalies over the southern hemisphere of Mars. A vertical prism of a square cross section with uniform magnetization represented the magnetization of the upper crust. A total of 144 models were examined depending on the size of the prism and the concentration of coarse-grain hematite in the lower crust. Three different thicknesses of 40, 60, and 80 km and six different horizontal dimensions of 180, 300, 600, 900, 1200, and 1500 km were considered for the prism. The lower crust was assumed to contain 4, 10, 20, or 30% coarse-grain hematite. In all of the models with horizontal dimensions of the prism larger than about 300 km, the lower crust was essentially magnetized by the edge effects of the prism. The magnetized zones were localized, and their magnetic fields decayed substantially with altitude. The magnetic field of the lower crust at 400 km altitude was found to be always less than 20% of the magnetic field of the prism, except for the 180-km prism with the magnetic field intensity about 40% of that of the prism. I concluded that a lower crust with a reasonable concentration of coarse-grain hematite, less than 20%, has minor contributions to the strong magnetic anomalies observed over the southern hemisphere of Mars. However, localized mineralization in the lower crust with higher concentration of hematite can have appreciable contribution to the small magnetic anomalies.

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