A SOURCE FOR THE MARTIAN CRUSTAL MAGNETIC FIELD.

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Summary: The magnitude of the martian magnetic crustal field requires intensities of magnetization of large volumes of the martian crust to be stronger than any comparable volumes on Earth [1, 2]. The Martian magnetic field at 4.0 Gyr was about one order smaller than the present geomagnetic field [3-5], and because the generating volume for the martian dynamo is considerably smaller than that for the geodynamo, it seems unlikely that the martian dynamo would ever have been much stronger than the geodynamo. In the absence of evidence for such a strong field on Mars, there is a need for a special model to account for the intensity of magnetization of the source rocks of the Martian anomalies. One potentially relevant feature of early Mars is the presence of water that reacts with atmospheric carbon dioxide to form acidic solutions. These fluids can dissolve igneous rocks in the crust and precipitate iron-rich carbonates, as observed in the older martian meteorites. Here we suggest that thermal decomposition of such iron-rich carbonates due to magmatic intrusions could give rise to plentiful single-domain magnetite and generate a potent source for the martian crustal field.

Magnetization of Martian Crust: The spectacular magnetic crustal field observed on Mars with the fluxgate magnetometer and the electron reflectometer on the Mars Global Surveyor spacecraft differs from the terrestrial crustal field in its intensity and distribution [1, 2]. On Earth, the magnetic features in the crust are distributed more or less uniformly over the planet, but on Mars, the features are much stronger and are largely confined to a band that covers two-thirds of the southern highlands.

The strength of a magnetic crustal field depends upon the distance to the source rocks, the geometry of the source and its intensity of magnetization. Since the geometry of the source is unknown the tendency has been to set up models in terms of discs, or layers, of variable thickness and magnetization. Given this approach one matches the crustal field at altitude by varying the thickness of the disc, or layer, and the intensity of magnetization. These procedures indicate that the outermost ten kilometers or more of crust must have intensities of magnetization that are of order 10 A m^{-1} [2, 6]. Since there is no significant active martian dynamo at present, this magnetization is a remanent magnetization and is an order of magnitude larger than the intensity of remanent magnetization seen in comparable volumes of terrestrial source rocks.

The intensity of remanent magnetization acquired by a rock depends upon (1) the field in which magnetization was acquired, (2) its mechanism of magnetization, and (3) the magnetic material it contains. Constraints on the intensity of the Martian magnetic field can be derived from theoretical considerations and measurements on Martian meteorites. The strongest constraint comes from studies of Allan Hills 84001. Earlier work on ALH84001 suggested that it acquired its magnetization in a field about one order smaller than the Earth's field [3]. Later work confirmed this estimate and showed that the field was recorded around 4.0 Gyr [4, 5]. Thus at that time, the intensity of the martian field was not as large as the Earth's field is now. As noted above, given the smaller size of the generating volume for a martian dynamo, it seems unlikely that it was ever much larger than the geodynamo. Hence it does not seem likely that the intensity of magnetization of the source rocks can be explained by very high magnetic fields on Mars.

Mechanism of magnetization: Most authors have assumed that the mechanism of magnetization for the strongly magnetized source rocks on Mars must be thermal remanent magnetization (TRM). This is indeed an efficient magnetization mechanism giving rise to an intensity of magnetization about one part in 100 of saturation isothermal remanent magnetization [7]. However, when fine grain secondary magnetite is formed in sediments, the process of chemical (or crystallization) remanent magnetization (CRM) is comparable in efficiency with TRM and again gives a magnetization about 1 part in 100 of saturation isothermal remanent magnetization [8]. Hence TRM or CRM would be comparably efficient processes of magnetization to order of magnitude.

Magnetic material: The most potent magnetic material that might produce these strongly magnetized rocks is single-domain magnetite [9]. Given the saturation magnetization of magnetite of 4.9 x10^5 A m^{-1}, the saturation remanent magnetization of a 1% dispersion of uniaxial, single-domain magnetite will be of order 10^3 A m^{-1} and the CRM (or TRM) will be 10 A m^{-1}, as required by the models for the crustal fields. We therefore only need 1% of single-domain magnetite in the source rock to meet the requirements of the models. The key point is that the 1% must be single-domain magnetite.

Single-domain magnetites, which are mostly 30-200 nm in length, do not crystallize from molten rock unless cooling is exceptionally rapid, as in the glassy, quenched margins of basalt flows. Since intrusive rocks are much more abundant in the Earth's crust than extrusive rocks [10], it is unlikely that the martian crust was strongly magnetized as a result of rapid crystallization of basalts. Nimmo has suggested instead that large Ti-bearing magnetites crystallized in intruded dikes and were converted during slow cooling into single-domain magnetites as a result of oxidation and exsolution of ilmenite lamellae [11]. On Earth, these and related processes appear to contribute significantly to sea-floor magnetism [12], but further oxidation by hydrothermal fluids destroys magnetite and reduces the magnetization. Fine-grained magnetites can also form by exsolution from plagioclase, and other igneously formed silicates [e.g., 13]. However, such exsolution has not been reported in martian meteorites and does not appear to be a plausible mechanism for large volumes of the martian crust.

Magnetization model: Our model for the martian crustal magnetic field is derived from studies of the martian meteorite, ALH84001. The single-domain magnetites in ALH84001 are an especially potent source of magnetization as they are remarkably similar to those formed by magnetotactic bacteria, which have the optimal shapes, sizes and orientation for strong remanent magnetization [14]. Magnetotactic bacteria are not responsible for the ALH84001 magnetites [15, 16] and could not have been the source of the crustal magnetic fields as remanent magnetization from detrital grains is much weaker than chemical or thermal remanent magnetization [7]. The magnetites in ALH84001 were formed instead by thermal decomposition and exsolution from iron-bearing carbonate [15, 16], which originally crystallized from aqueous or hydrothermal solutions percolating through the martian crust [17]. Under appropriate conditions, such a process is a most effective means of making single-domain magnetite.

Several lines of evidence suggest that iron-rich carbonate was a likely alteration product in the martian crust. Given that large volumes of carbon dioxide were probably converted into carbonates and that carbonates have not been detected in the surface by remote sensing, hydrothermal or aqueous fluids mayy have deposited a few percent of carbonates in the upper few kilometers of the crust [18]. Geochemical models show that provided the martian atmosphere had >0.1 bar CO_2, siderite would have been the first major carbonate to precipitate during evaporation at the surface [19]. The martian meteorites provide direct evidence for siderite formation by alteration. In ALH84001, ~1 vol.% iron-rich carbonate formed around 4.0 Gyr and in the nakhlites, siderite precipitated $\leq$1 Gyr [17, 20]. Very limited alteration of silicates in these rocks indicates that the hydrothermal fluids or low-temperature brines from which the iron-rich carbonates formed were only present briefly or intermittently [21].

In ALH84001, only a small part of the carbonate ($<10^{-2}$) was converted into magnetite, probably as a result of impact-induced heating [15]. However, laboratory heating at 450°C can completely convert siderite crystals into porous aggregates of magnetite crystals that closely resemble magnetites in ALH84001 in size and shape [16, 22]. The reaction products and temperature of decomposition depend on the ambient atmosphere and pressure, but given a CO_2 atmosphere on Mars, magnetite should form from the thermal decomposition of carbonates. In the martian crust, heating from magmatic intrusions was probably more important than impact heating. In the Earth's crust, single-domain magnetites are commonly destroyed by alteration, but ALH84001 shows that they can survive on Mars for over 4 Gyr.

Distribution of magnetic anomalies: Finally we address whether the proposed scenario is consistent with the distribution of magnetic crustal field features. In the southern highlands there is a correlation between the locations of the magnetic anomalies and the valley networks, which was attributed to magmatic heat sources that melt ice in the permafrost and crystallize magnetic minerals [23]. We suggest instead that the released water may have percolated through the fractured crust causing siderite to form. In the northern plains, which are virtually devoid of magnetic anomalies, we infer that the chain of events – the intermittent flow of fluid, the precipitation of siderite, and the thermal decomposition of siderite – was broken. An obvious possibility is that the water draining into the northern plains (possibly forming an ocean) saturated the fractured crust beneath so that the alteration conditions were quite different from those in the southern highlands. Higher water/rock ratios or longer reaction times may have prevented the formation or survival of siderite or magnetite.

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