WHY ARE THERE SO FEW MAGNETIC ANOMALIES IN MARTIAN LOWLANDS AND BASINS?

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Introduction. The discovery of large areas of strongly magnetized crust on Mars [1,2] provides important information on the timing of both crustal and deeper interior processes on that planet. Critical to an understanding of that timing, as well as to the processes that have contributed to the magnetization and demagnetization of crustal materials, is the geographical distribution of magnetic anomalies discernible from spacecraft orbit. The paucity of resolved magnetic anomalies in the northern lowlands and within and surrounding the best-preserved major impact basins has been noted since the crustal field was first globally mapped [1], but no straightforward explanation of that full pattern has yet been offered. Here we suggest that ancient hydrothermal alteration of magnetic carriers in Martian lowlands and basins may have contributed to the magnetization distribution observed today.

Timing of the Martian Magnetic Dynamo. Two scenarios have been put forward for the timing of the core dynamo implied by magnetization of the Martian crust. In the first, the dynamo was active in the early to middle Noachian and ceased prior to or near the end of heavy bombardment [1]. In the second, dynamo onset postdated the youngest impact basins [3]. Arguments favoring an early Noachian dynamo include the pronounced concentration of regions of high magnetization in the ancient southern uplands [1,2], a general lack of correlation of magnetic anomalies with Hesperian and younger volcanic units or impact structures, and the inferred magnetization of carbonates at least 3.9 Gy old in Martian meteorite ALH84001 [4]. While the absence of large volumes of strongly magnetized crust within and near the youngest impact basins can be attributed to the effects of shock and heating of previously magnetized crust [e.g., 5] at a time following dynamo shut-off, the detection of smaller-amplitude magnetic anomalies within the Hellas basin [6] suggests that a global field may still have been present at the time of that impact event. Theoretical models for dynamo shut-off as a result of insufficient heat transport from the core to the mantle [7] or thinning of the fluid outer core [8] are permissive of a range of times for the end of a global magnetic field.

Magnetization of the Northern Lowlands. The sparse magnetic anomalies of modest amplitude in the northern lowlands of Mars might be due to one or more of the following reasons: (1) the northern crustal province [9] may postdate the dynamo; (2) magnetization may have been largely removed as a result of burial by sediments and post-dynamo lavas; (3) reheating by volcanism and intrusion may have demagnetized crustal material; (4) the northern lowlands crust may be magnetic but only at wavelengths shorter (< 200 km) than those detectable from orbit; or (5) hydrothermal activity may have altered magnetization.

The first explanation can be discounted on the basis of the topographic identification of numerous largely buried impact structures suggesting that the northern lowlands crust had formed by the early Noachian [10]. That such impact features are still detectable limits the thickness of sedimentary and volcanic infill subsequent to the early Noachian to be generally no more than 1-2 km [10]. Under the assumption that the base of a magnetized layer beneath the northern lowlands was at the Curie temperature prior to burial, the effect of such burial is to attenuate the discernible magnetic anomaly by an amount that is a function of wavelength and altitude of observation. As long as the thickness of magnetized material (tens of kilometers in the southern uplands [2, 11]) was greater than the thickness of infill, early Noachian magnetization at wavelengths seen in the southern uplands should be detectable by orbiting spacecraft, so the second explanation is most likely a minor contribution. The third explanation is probably also at most a small contributor, on the grounds that cooling of thin flows occurs rapidly without deep penetration of heat, and intrusions are unlikely to have demagnetized crust on spatial scales comparable to the dimensions of the northern lowlands. The fourth explanation is somewhat ad hoc in the absence of a specific mechanism for the hemispherical difference in scale lengths, but at least it is testable with future low-altitude or surface magnetic observations.

Possible Hints from Terrestrial Oceanic Crust. While the nature of the magnetic carriers and the range in specific magnetizations of Noachian crustal material on Mars are not known, the behavior of remanent magnetization in terrestrial oceanic crust may provide clues to the evolution of magnetization on Mars. Along mid-ocean ridges, the amplitude of the central magnetic anomaly is generally greater than that of older anomalies, at least in part the result of off-axis hydrothermal oxidation of magnetic titanomagnetite grains to titanomaghemite and a consequently lower specific magnetization [e.g., 12, 13]. The hydrothermal alteration is generally enabled by penetration of seawater along fissures and faults [12], and the time scale for magnetization change is short, on the order of tens of thousands of years [13]. Axial hydrothermal vent areas can be sites of particularly low magnetization [14]. The magnetization of the uppermost crust dominates the contributions to magnetic anomalies in the oceans, but there is strong evidence from oxygen isotopes in ophiolites [15] and the depth of brittle faulting beneath mid-ocean ridge axes [16] that hydrothermal circulation along fault systems can extend to depths equivalent to at least 300 MPa pressure.

Hydrothermal Alteration of Crustal Magnetization on Mars. Guided by the processes in terrestrial oceanic crust, we suggest that hydrothermal circulation along deep faults within the Martian crust may have led to oxidation of magnetic carriers and a reduction in magnetization. The preferred sites for this hydrothermal circulation would have been the generally lower-lying areas of major drainage basins, on the grounds that such areas would have been persistent traps for crustal fluids as a result of episodic flooding and lesser discharge events throughout Martian history. Deep circulation of water would have been driven by deep-seated heat, including that associated with the formation of major impact structures and that associated with local and regional magmatism. The effects of hydrothermal alteration would have been both to lessen the specific magnetization of crustal rocks and to change the spatial scale of magnetization coherence (e.g., to horizontal scales comparable to the depth of water circulation). If circulation extended to pressures comparable to that demonstrated in terrestrial oceanic settings, the depth of alteration would be at least 25 km.

Others have suggested links between hydrothermal activity on Mars and crustal magnetic anomalies. It has been proposed, for instance, that multi-domain titanohematite formed by hydrothermal alteration of titanomagnetite might carry a high specific magnetization [17]. A postulated explanation for a suggested correlation between large-amplitude crustal magnetic anomalies and Martian valley networks [18] is that the valley networks formed as a result of hydrothermal discharge accompanying the formation of major crustal intrusions that acquired thermoremanent magnetization during the time of a global field [19]. The hypothesis put forward here differs from earlier suggestions, in that the effects of hydrothermal circulation are concentrated in drainage basins and tended to reduce, rather than enhance, the detectability of magnetization.

Discussion. There are several testable consequences of the scenario we propose. First, there should be a strong correlation between at least the central regions of major drainage basins and an absence or paucity of strong magnetic anomalies observable from orbit. This correlation is observed [1, 20].

Second, magnetic anomalies should tend to be suppressed or unresolvable from orbit within topographically well-preserved impact basins, whatever the relative timing of basin formation and dynamo shut-off, because of the tendency of large basins to collect water and the deep circulation that would have been driven by impact heating of the interior [21].

Third, there should be shorter-wavelength magnetic anomalies throughout the northern lowlands of Mars than can be resolved from orbit. Such anomalies would be detectable at the surface or at low elevations.

There are important additional implications of this hypothesis. The deep hydrothermal circulation necessary to alter the magnetization to depths of several tens of kilometers [2, 11] would have accelerated the cooling of the Martian crust and lithosphere, helping to preserve the variations in crustal thickness observed today [9, 22]. Further, dynamo shut-off can postdate the time of formation of the youngest impact basins. In particular, the conditions favoring an active dynamo in the Martian core may have persisted until at least latest Noachian or early Hesperian times.

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