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Unusual magnetic signature of the Hadriaca Patera Volcano: Implications for early Mars

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[1] Typically, Martian volcanoes show either a total absence of crustal magnetism or a local magnetic mimimum. Hadriaca Patera is the only volcano on Mars with a clear positive magnetic anomaly directly over the volcanic edifice, as determined by electron reflection magnetometry. Hadriaca's topography, lava flow crater ages, gravity anomaly, position relative to the Hellas rim and past aqueous environment provide geological constraints on possible scenarios to explain this unusual magnetic signature. The two most probable scenarios are a) pre-Hellas thermoremanent magnetization (TRM) of a deep-seated magma body followed by post-Hellas intrusive partial thermal demagnetization and b) post-Hellas emplacement of the volcano and TRM in a global magnetic field. It is thus likely that Mars had at least one of the following: highland volcanism in pre-Hellas times (older than any datable volcanic feature on the planet) or an active dynamo some time after the Hellas impact.

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1. Introduction

[2] The history of a planet's dynamo provides information on its thermal evolution and interior structure. On Mars, evidence for an early dynamo has been used to postulate an early episode of plate tectonics [e.g., *Nimmo and Stevenson*, 2000], an initially superheated core [e.g., *Hauck and Phillips*, 2002; *Williams and Nimmo*, 2004] and compositional stratification of the mantle [e.g., *Wenzel et al.*, 2004; *Elkins-Tanton et al.*, 2005].

[3] Determining the history of the dynamo on Earth relies on measuring the magnetization and age of rocks. On Mars, we are limited to measuring the magnetic field with spacecraft and relating measured anomalies to datable surface features such as impact craters and volcanoes. The absence of a magnetic anomaly above the large impact basins Hellas and Argyre, and over large volcanic provinces Tharsis and Elysium, has been the basis for arguing that the dynamo was active only during the early Noachian [*Acuna et al.*, 1998; *Arkani-Hamed*, 2004].

[4] To gain more information about the possible history of the Martian dynamo, we use a global map of crustal magnetic field magnitude at 170km, as derived from electron reflection magnetometry [*Lillis et al.*, 2004; D. L. Mitchell et al., A global map of Mars' crustal magnetic field based on electron reflectometry, submitted to *Journal of Geophysical Research*, 2005, hereinafter referred to as Mitchell et al., submitted manuscript, 2005], to analyze and interpret the magnetic signature above smaller datable volcanic landforms. We focus on Hadriaca Patera, a large highland volcano located on the northeastern margin of the Hellas Basin which, unlike any other large volcano on Mars, displays a local magnetic maximum directly over the volcanic edifice.

2. Electron Reflectometry and the Magnetic Signature of Martian Volcanoes

[5] Electron reflection (ER) magnetometry is based on the magnetic mirror effect, that is, the reflection of charged particles from regions of increased magnetic field strength. By comparing the pitch angle distribution of electrons moving toward the planetary surface with that of electrons reflected from it, we can determine the field strength at altitudes where the electrons are absorbed [*Anderson et al.*, 1976, *Acuna et al.*, 1992].

[6] For this study, ~2.6 million nightside measurements of 90–400 eV solar wind electrons over 6 years (1999–2005) from the Magnetometer/Electron Reflectometer (MAG/ER) on Mars Global Surveyor have been combined to produce a map of the field magnitude $|\boldsymbol{B}|$, due to crustal sources only, at 170 km altitude, hereafter referred to as B_{170} [*Lillis et al.*, 2004, Mitchell et al., submitted manuscript, 2005]. Within a pixel, the standard deviation of measurements is ~30%, the map's intrinsic resolution is 150 km or 2.5 degrees of latitude and it has data gaps at locations where all field lines within 75km of the pixel are permanently closed (i.e., do not connect to the solar wind) at the spacecraft altitude of 400 km, which occurs mostly, though not always, in regions of strong crustal magnetic field. It has a small selection bias (averaging 9nT) toward crustal fields which, at 170km, are approximately parallel to the dominant direction of the draped Martian magnetotail field because weak anti-parallel crustal fields tend to be cancelled out by this draped field. Its spatial resolution is a factor of 2–2.5 better, and its sensitivity to crustal fields is at least a factor of 7 better, than the map of radial component of nightside magnetic field at ~400 km published by *Acuna et al.* [2001].

[7] Using this global map, we can examine the magnetic signatures of the major Martian volcanoes identified by *Plescia* [2004]. We first note that, in general, anomalies are

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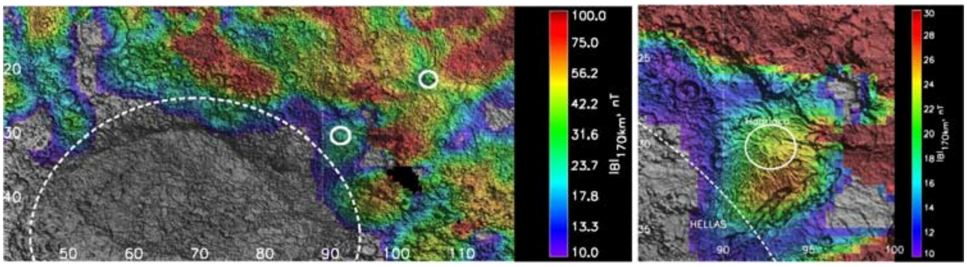

Figure 1. Electron reflection magnetometry map overlayed on MOLA topography. Grey indicates fields weaker than 10 nT and black indicates data gaps. (left) Magnetic anomalies around the northern rim of the Hellas basin (dashed circle). The small circles indicate the locations of two volcanoes: Hadriaca Patera (lower left) and Tyrrhena Patera (upper right). (right) is a close-up of Hadriaca's vicinity. Note that the Figures 1(left) and 1(right) have different color scales (left is logarithmic), chosen to highlight weak features, and that both saturate in places.

weak in the vicinity of volcanoes. The median value of all measurements over volcanic edifices is 5.1 nT compared to a median value of 15.2 nT for the planet as a whole. The statistical robustness of this difference is confirmed by a Kolmogorov-Smirnov test.

[8] Most volcanoes display either a total lack of crustal magnetic field (e.g., those in Elysium, most of Tharsis and Malea Planum) or local magnetic minima suggestive of thermal demagnetization by magmatic intrusion and/or underplating (e.g., Syrtis Major, Arsia Mons, and Tyrrhena Patera) (Mitchell et al., submitted manuscript, 2005). Apollinaris Patera, located in a region of moderate crustal magnetic field as identified in the ~400-km map of *Acuna et al.* [2001] and associated by *Whaler and Purucker* [2005] with magnetized crust, falls in a closed-field region data gap in the ER map and so cannot be commented upon here. The other signatures are in general consistent with an early Martian dynamo, possibly reversing periodically [*Whaler and Purucker*, 2005], and likely ceasing by the time of the Hellas impact in the early Noachian [*Acuna et al.*, 1998], as they do not show evidence of magnetization since that time. One exception to this pattern is Biblis Patera, a small volcano in Tharsis on the boundary between strong and weak magnetic regions [*Johnson and Phillips*, 2005; Mitchell et al., submitted manuscript, 2005] which, given the intrinsic resolution of our technique, is difficult to identify with either region unambiguously. The large highland volcano Hadriaca Patera is the other notable exception with a local magnetic maximum directly over the volcanic edifice. Given this unusual magnetic signature, we examine it and the volcano's geological context in more detail.

3. Hadriaca Patera

3.1. Magnetic Signature

[9] Hadriaca Patera is located on the northeastern margin of the Hellas Basin. Figure 1(left) shows a map of B_{170} over the whole northern and eastern rim of the Hellas basin, an area with strong and variable magnetic fields. Assuming an early dynamo, the early Noachian crust that forms the northern rim of Hellas cannot have been demagnetized by the Hellas impact because strong anomalies occur (e.g., at 75°E, 20°S and 97°E, 40°S) around the entire rim. Some anomalies may have been caused by impact demagnetization (e.g., the Huygens basin magnetic low at 15°S, 55°E), volcanism (e.g., the Tyrrhena Patera local minimum at 22°S, 106°E), or perhaps by fluvial modification as proposed by *Solomon et al.* [2005] (e.g., at Dao and Harmahkis Valles, directly south of Hadriaca).

[10] Figure 1(right) shows B_{170} in the near-vicinity of Hadriaca and Figure 2 shows the radial magnetic profile of the volcano in quadrants. Although the magnetic maximum is ~120 km south of the caldera, the profile is somewhat symmetric from the caldera to ~1 volcano radius with the field strength decreasing from 28 nT to 17 nT. Beyond 1 radius, the strength then increases in the NE, SE and NW quadrants and continues to decrease in the SW quadrant, which extends into the demagnetized Hellas Basin. A 150 km-diameter circle centered on Hadriaca contains 846 data points with a mean of 27 nT and a standard deviation of 13 nT, corresponding to an error in the mean value of ~0.5 nT. Comparing ER maps from different segments of the mission shows that sources smaller than ~150 km are not reproducible due to noise in the data [*Lillis et al.*, 2004; Mitchell et al., submitted manuscript, 2005]. This is consistent with the expected resolution of remote magnetic maps [*Connerney et al.*, 2004]. In comparison, Hadriaca's magnetic feature is ~400 km across, is consistent across mission segments, and may be connected to larger magnetic feature to the east at ~100°E, 31°S.

[11] We therefore conclude that Hadriaca's anomaly is due to crustal magnetization beneath the volcanic edifice and perhaps extends to the east some distance.

3.2. Geological Context

[12] Hadriaca Patera occurs just inside the topographic rim of the Hellas Basin. Its visible edifice must thus be

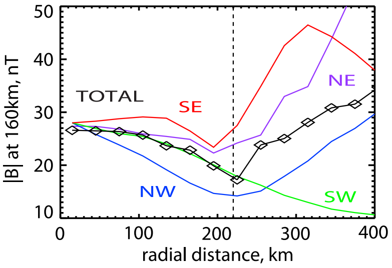

Figure 2. The mean magnetic field at 170 km in 30-km wide concentric rings centered around the caldera, totaled and divided into quadrants. The vertical dotted line is the mean radius of the volcanic edifice.

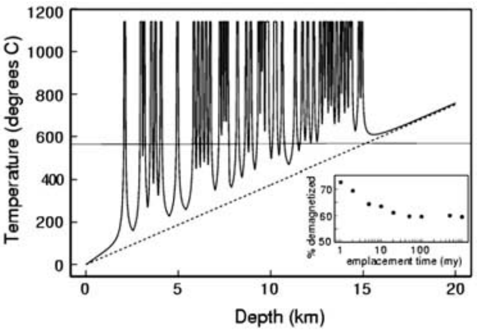

Figure 3. Maximum temperature ever reached as a function of depth for the case in which 50 sills, 100 m thick, are randomly intruded over a 500 m.y. period. The dashed curve shows the temperature in the absence of instrusion and the horizontal line is the Curie temperature of magnetite. Inset shows the percentage of the upper 15 km of crust that is heated above 570°C as a function of the emplacement time of the 50 sills.

younger than the Basin, although a 'proto-Hadriaca' could have existed as a volcanic center before the Hellas impact. It is a large volcano (~330 × 550km) with low relief (1.2 km), deeply dissected flanks with shallow slopes (<0.8° and a large shallow caldera (90km wide, 700m deep) [*Plescia*, 2004]. The edifice may have been formed primarily by pyroclastic flows [e.g., *Crown and Greeley*, 1993].

[13] Crater counts performed by *Williams et al.* [2005] on images of Hadriaca Patera taken by the High Resolution Stereo Camera (HRSC) on Mars Express imply ages of ~1.1 Ga to ~3.5 Ga inside the caldera, indicating at least some volcanic activity over a long period of Martian history. However, outside the caldera ages are no less than 3.3Ga for both the smooth flanks to the north and the fluvially-dissected flanks whose channels run to the south, mostly into Dao Vallis. *Williams et al.* [2005] conclude that the earliest shield-building events occurred ~3.7–3.9 Ga, prior to the end of the Noachian era.

[14] *Kiefer* [2003] infers the presence of a large high-density body beneath Hadriaca from a gravity anomaly too large to be explained by the edifice itself. Similar anomalies exist at other highland volcanoes [*Kiefer*, 2004]. He infers a 500 km diameter cylinder of minimum thickness 4.7 to 7.8 km at 93.5E, 32.5S and another 300 km diameter cylinder of thickness 3.8 to 6.2 km closeby at 98.5E, 32.5S, perhaps corresponding to the magnetic feature further to the east. The spatial distribution of the mass anomalies (sills, dikes, or even a solidified magma chamber) is not well constrained because of the limited spatial resolution of gravity data and inherent model non-uniqueness; thicknesses are poorly constrained because density anomalies are not known. Nevertheless, intruded magma thicknesses estimated by Kiefer seem quite reasonable given our knowledge about Earth's volcanoes. The ratio of intrusive to extrusive volumes at ocean hotspots, perhaps the most analogous volcanic setting, is between 3 and 5 [*Crisp and Baloga*, 1990]; in other settings, such as volcanic arcs, the ratio is larger, with a ratio of 10 for the Cascade volcanic arc [*Ingebritsen et al.*, 1989]. Assuming a volcanic edifice height of 1–2 km, we expect a thickness of 3–10 km of intruded magma.

3.3. Magnetization of Crust Beneath Hadriaca

[15] Although there is considerable uncertainty in the dimensions of the magma bodies, we can use B_{170} to roughly constrain their average magnetization. Using the radii and minimum thicknesses of the 2 disk-shaped bodies fitted to the Hadriaca gravity anomalies, and assuming uniform magnetization in both bodies, the observed magnetic anomaly signature of ~28 nT at 170km, above a 'background' of ~17nT, can be produced by maximum crustal magnetizations of 1.3–4.2 A/m depending on the orientation of the magnetization, comparable to magnetizations producing strong magnetic anomalies on Earth [*Fedorova and Shapiro*, 1998].

[16] A crustal field is unlikely to have magnetized Hadriaca. The field at Hadriaca due to its nearest strong crustal source is <20 nT, compared with ~5,000 nT due to a dynamo field one tenth as strong as Earth's, which has been proposed as a lower bound for an early Martian dynamo from studies of meteorite ALH84001 [*Weiss et al.*, 2002]. Given the general consensus that the most strongly magnetic regions on Mars were magnetized in a global field, it seems implausible that a crustal field ~250 times weaker could magnetize Hadriaca to even 10% of the 20–30 A/m magnetization inferred for Terra Sirenum/Cimmeria from magnetometer measurements [*Connerney et al.*, 1999].

4. Explanations and Implications of the Positive Magnetic Anomaly at Hadriaca

[17] We suggest 3 possible scenarios for the unusual magnetic signature at Hadriaca. First, the magma body and volcano were emplaced after the Hellas impact and after the cessation of an early dynamo, at almost the precise location of a pre-existing positive magnetic anomaly. Aqueous hydrothermal alteration and/or the volcanic activity which built up the volcano in the late Noachian may then have partially demagnetized the crust and reduced the amplitude of the anomaly, resulting in what we see today: a weaker anomaly than others in the region.

[18] To quantify the expected thermal demagnetization by magmatic intrusion, we model the construction of a dense cooled magma body beneath a volcano using a one-dimensional simulation in which heat transfer occurs only by conduction in the vertical direction and neglect the latent heat of crystallization. 50 sills, each 100 m thick (similar in thickness to the dolerite sills in the Antarctic Dry Valleys), are emplaced over a 500 m.y. time interval. Their depth is randomly assigned between 2 and 15 km, and we assume the magma temperature is 1140°C. The background heat flow is 60 mW/m^2, and we use a thermal conductivity of 1.6 W/mK [*Ingebritsen et al.*, 1989]. Figure 3 shows the maximum temperature ever reached at a given depth compared to the temperature if there were no intrusions. For this particular simulation, 60% of the crust with temperatures that would otherwise stay below 570°C (near the Curie temperature for magnetite) is heated above this temperature. As shown in the inset of Figure 3, analogous simulations with differing recurrence intervals show that if 5 km of intrusives accumulate over intervals greater than a few tens of m.y., 60% of the crust will experience temperatures above 570°C. Shorter accumulation times result in higher temperatures, and a greater extent of demagnetization.

[19] We do not favor this first hypothesis due to the low probability of forming a volcano almost precisely at a location with a pre-existing magnetic anomaly.

[20] Second, a proto-Hadriaca was emplaced before the Hellas impact, and was magnetized by TRM in an early pre-Hellas dynamo magnetic field. When the Hellas impact occurred, the collapse of the transient cavity erased any surface manifestation of the volcano, but the crust beneath it remained magnetized because shock demagnetization did not extend as far as Hadriaca. Subsequent volcanic and hydrothermal activity, mostly in the late Noachian, built up the current volcano, and partially demagnetized the crust beneath it (Figure 3). The volcano, however, was still left with a greater magnetization than its surroundings, creating the positive magnetic anomaly directly over the volcano.

[21] Third, the bulk of Hadriaca was emplaced after the Hellas impact, in a region that, at least locally, was not strongly magnetized. The sills and dikes that formed the high-density body beneath the volcano [*Kiefer*, 2004] cooled and acquired TRM in a post-Hellas global magnetic field. After the cessation of the dynamo, subsequent volcanic and hydrothermal activity may have reduced this magnetization but still left the volcano more strongly magnetized than its surroundings, producing today's positive anomaly. This interpretation is consistent with the hypothesis of *Schubert et al.* [2000], who argue for a long-lived (>1Gyr) dynamo driven by core solidification, and with *Lillis et al.* [2005], who raised the possibility of 2 separate dynamo episodes, both pre- and post-Hellas. The process that might restart a dynamo is unclear. The surface age of Hadriaca, however, is not much different from the period over which the bulk of Tharsis was emplaced [*Phillips et al.*, 2001]. Perhaps the formation of Tharsis by a mantle plume removed enough heat from the lower mantle to increase the heat flux out of the core sufficiently to restart a dynamo, as by *Stegman et al.* [2003]. This hypothesis is, in our opinion, not as strong as hypothesis 2 due to the apparent lack of magnetism associated with unambiguously young crust elsewhere on Mars.

[22] Distinguishing between hypotheses 2 and 3 has important implications for the evolution of the dynamics and structure of the Martian interior. Hypothesis 2 implies highland volcanism older than the surface age of any volcano on Mars, while hypothesis 3 implies an active dynamo in the late Noachian. From our analysis, at least one of these is likely to be true. Either would be a new insight into the thermal and magnetic evolution of early Mars. These hypotheses can be tested by finer spatial resolution of magnetic field measurements, so that more datable features can resolve the history of the dynamo, or by analyzing samples collected on future missions, which additionally allows the carrier of magnetization to be identified.

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