

EVIDENCE FOR A SECOND MARTIAN DYNAMO FROM ELECTRON REFLECTION MAGNETOMETRY. R.J. Lillis^{1,3}, M. Manga², D.L. Mitchell¹, R.P. Lin^{1,3} and M.H. Acuña⁴. ¹Space Sciences Laboratory, ² Dept. of Earth and Planetary Sciences, ³ Dept. of Physics, University of California, Berkeley CA 94720 and ⁴ NASA Goddard Space Flight Center, Greenbelt, MD 20711. (EMAIL: rlillis@ssl.berkeley.edu)

Introduction: Present-day Mars does not possess an active core dynamo and associated global magnetic field. However, the discovery of intensely magnetised crust in Mars' Southern hemisphere [1] implies that a Martian dynamo has existed in the past [2,3]. Resolving the history of the Martian core dynamo is important for understanding the evolution of the planet's interior. Moreover, because the global magnetic field provided by an active dynamo can shield the atmosphere from erosion by the solar wind [4], it may have influenced past Martian climate.

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 the distribution of those electrons reflected from the surface, the increase in the magnetic field strength can be determined. Here ~2 million measurements of 191 eV electrons over 5 years have been combined to produce a map of the field magnitude $|B|$, due to *crustal* sources only, at 170km altitude (near the stopping altitude for ~191 eV electrons). It has an r.m.s. error of 30%, an intrinsic resolution of ~150km or ~2.5 degrees of latitude and a 1- σ detection threshold for crustal fields of ~2.5nT at 170km [5].

Magnetic Signatures of Volcanoes & Basins:

The heating and shock from a large meteorite impact can demagnetise the entire depth of crust over an area comparable to the final size of the impact basin [6,7]. Similarly, prior magnetisation of the crust in the vicinity of the magma chamber beneath an active volcano can be erased by the heating of the magnetic minerals above their Curie temperature [8]. As the volcanic complex or impact basin cools, its magnetic minerals acquire a magnetisation aligned to the local ambient magnetic field. This magnetisation (or lack thereof) is preserved in the crust and can be detected by spacecraft measurements.

Data: Most of the volcanoes have magnetic fields below 10 nT inside the volcano radius, implying that no strong magnetic field was present during their last significant magmatic activity. Arsia Mons and Biblis Patera lie near the boundary between the magnetised southern edge of the Tharsis province and its demagnetised bulk and have somewhat stronger magnetic

signatures though these do not suggest that a global field was present when they last erupted (see fig. 3)

In contrast, Tyrrhena, Nili and Mereo Paterae display magnetic signatures of 20-40nT at their centers, high compared with the aforementioned volcanoes but still low compared to their surroundings. If their magmatic activity completely erased any pre-existing crustal magnetisation, then the signatures would imply the presence of a significant ambient field at the time of these volcanoes' last significant magmatic activity. An alternative explanation, however, is that these volcanoes only partially removed the pre-existing magnetisation.

Finally, the Hadriaca Patera volcano shows a maximum in B_{170} of 43nT at the center, dropping to 20nT at 1.3 radii, a distance of ~220km (see figs. 1, 2). The simplest explanation for this signature is that Hadriaca's magmatism erased much of the prior crustal magnetisation (leading to the low of 20 nT at 1.3 radii), and that the crust in or near the magma chamber was then magnetised by a substantial ambient magnetic field when it cooled below its Curie point. Hadriaca's large gravity anomaly, presumably due to a buried magma chamber, has been modeled by Kiefer [9] as 2 disks, the first of diameter 500km and composition-dependent minimum thickness of 4.7-7.8km, located beneath the volcanic edifice, and the second of diameter 300km and minimum thickness 3.9-6.4km, located 5° to the east, in a data gap. It is likely that such an intrusion would demagnetise the entire crust.

The location of Hadriaca Patera on the North-East slope of the Hellas Basin implies that its last eruption occurred after the Hellas impact, which post-dated the cessation of the early dynamo [10]. Fig. 3 plots the mean value of B_{170} over the centers of 7 ancient impact basins and 10 of the oldest volcanoes, versus age as determined by crater-counts (see Methods). Starting at 4.2 Gyr ago, the ancient Daedalia & Ares basins are in strongly magnetised regions, indicating that those impacts occurred before the cessation of an early core dynamo. The two lowland-forming basins Chryse & Utopia [10] and the three large visible basins Isidis, Hellas & Argyre, dated between ~4.2 and 3.9 Gyr ago, all have very weak magnetic signatures, implying that there was no significant global field at that time. The Peneus & Amphitrites

volcanoes similarly show weak magnetic signatures (4, 7nT) and are dated between 3.8 & 3.95 Gyr. Then a sharp rise in B_{170} occurs over ~50 Myr for Mereo and Nili Paterae (25-30nT), followed by a high of 40-43nT for Hadriaca and Tyrrhena Paterae, dated between 3.65 and 3.8 Gyr, and then a sharp fall to 2-4nT for Hecates Tholus, Elysium Mons and Uranius Patera, dated at 3.4-3.7 Gyr and Alba Patera, dated at 2.9-3.2Gyr. The remainder of the large volcanoes do not possess a sufficient number of large craters to obtain a reliable age, but all are younger than 3.7 Gyr and have weak magnetic signatures, implying low ambient fields. The plot strongly suggests a second period of dynamo activity, approximately 300 Myr after the the early dynamo, with all four of the volcanoes with enhanced magnetic fields occurring after 3.85 Gyr and before 3.65 Gyr. It also shows that, if Hadriaca's signature were an accident, its emplacement would have be fortuitous not only in space (as mentioned earlier) but also in time to suggest the second dynamo episode.

An active dynamo requires a convecting core. Convection can be maintained when the core-to-mantle heat flux exceeds the limit of adiabatic conduction[11]. Schubert et al [12] propose that this additional heat flux is derived from the latent heat of core solidification, and could power a dynamo that starts several hundred Myr after accretion and lasts at least 1Gyr -- not quantitatively in agreement with our results. Another possibility is large mantle plumes, which remove heat from the lower mantle and increase the heat flux out of the core. Thermal plume simulations[13] show that heat flow from the core should increase by approximately a factor of two immediately following the first formation of plumes, sufficient to restart a dynamo that ceased due to cooling of an initially superheated core[14]. Continued cooling of the core, combined with the decay of heat producing radioisotopes, would then decrease the heat flow out of the core, causing the dynamo to cease a second time.

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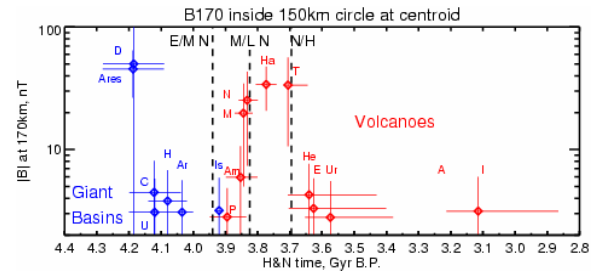


Figure 1: Magnetic signatures of 7 giant impact basins and 10 volcanoes plotted against Hartmann & Neukum [15] age with crater-counting uncertainties. B_{170} is plotted as a mean with standard deviation of all measurements inside a 150-km circle (size of the intrinsic resolution) at the center of the basin or volcano, where the effect of the impact/eruption is assumed to be greatest. The dashed lines separate the early, mid, late Noachian (E/M/L/N) and Hesperian (H) periods of Martian history. The blue labels are basins: Daedalia (D), Ares, Chryse (C), Utopia (U), Hellas (H), Argyre (Ar) and Isidis (Is). Volcanoes are red: Peneus (P), Amphitrites (Am), Mereo (M), Nili (N), Hadriaca (Ha) & Tyrrhena (T) Paterae, Hecates Tholus (He), Elysium Mons (E), Uranius (Ur) and Alba (Al) Paterae. The implied second dynamo epoch occurs from ~3.85 to 3.7-3.45 Gyr ago.

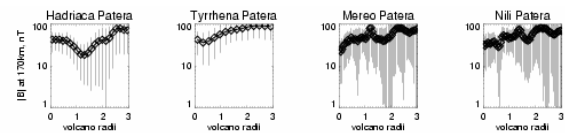


Figure 2: B_{170} (averaging measurements in 30 km-wide concentric rings) is plotted vs. radial distance measured in average volcano radius. The error bars are standard deviations within each ring.

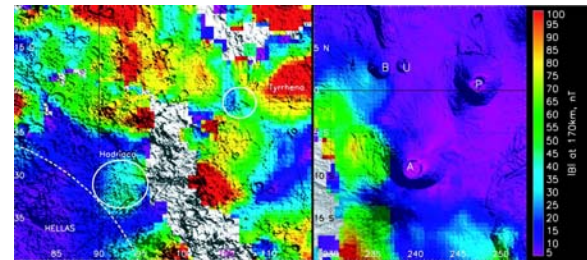


Figure 3: B_{170} over (left panel) north-eastern Hellas and Terra Tyrrhena with Hadriaca Patera & Tyrrhena Patera highlighted by white circles and (right panel) the southwestern region of Tharsis showing Arsia (A) and Pavonis (P) Montes and Biblis (B) & Ulysses Paterae. White are data gaps.