GEOPHYSICAL OBSERVATIONS OF HADRIACA PATERA AND TYRRHENA PATERA, MARS: IMPLICATIONS FOR MAGMA CHAMBER STRUCTURE AND FOR THE END OF THE MARTIAN MAGNETIC DYNAMO

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Introduction

Hadriaca, Tyrrhena, and Apollinaris Paterae on Mars are all volcanos formed primarily by pyroclastic eruptions in the Late Noachian and Early Hesperian, after the Hellas impact basin. All three have positive gravity anomalies indicative of high density cumulate minerals in a solidified magma chamber. Hadriaca and Apollinaris both have magnetic anomalies that are correlated with the gravity anomaly. A likely explanation is that hot ground water associated with the pyroclastic activity caused hydrothermal alteration of iron-bearing minerals in the cumulate chamber, resulting in the formation of minerals such as magnetite and hematite. These magnetic anomalies indicate that the martian dynamo may have survived at least briefly beyond the end of the impact basin bombardment era on Mars.

Hadriaca Patera

Hadriaca Patera is 330 by 550 km across, with a summit relief of 1.1 km. The caldera complex is 90 km across and 0.7 km deep [1]. Based on the erosional morphology of the volcano and the friable nature of deposits on the flanks, it is likely that pyroclastic activity played a dominant role in the formation of Hadriaca [2]. The volcano is located close to the rim of the Hellas impact basin and clearly post-dates the Hellas impact. Crater densities indicate that early shield building occurred during the late Noachian, with a model crater age of 3.7-3.9 Ga. Volcanic activity continued into the Hesperian, with caldera formation complete by a model age of 3.5 Ga. Minor resurfacing, possibly due to fluvial activity, continued into the Amazonian [3]. Electron reflectometer measurements with a horizontal resolution of ~200 km show the presence of a distinct magnetic anomaly associated with Hadriaca, centered on the south flank of the volcano [4, 5].

Hadriaca is also a major gravity anomaly (Figure 1). The solid black line shows the free-air gravity anomaly in a north-south profile across Hadriaca. The profile is based on gravity model MRO110B [6] up to spherical harmonic degree 90, corresponding to a half-wavelength resolution of 120 km. A preliminary gravity model was presented for Hadriaca in 2003 [7] but the significant improvements in gravity field resolution in the intervening years permits the geophysical details to be studied at nearly twice the earlier resolution. Moreover, it is now possible to assess the correlation between the gravity anomaly and recent magnetic anomaly maps for this region [4, 5]. The maximum gravity amplitude occurs over Hadriaca's caldera, but the gravity is elongated toward the south and south-east. The magnetic anomaly is also nominally centered south of the caldera [4, 5].

The dashed black line in Figure 1 shows the expected free-air gravity anomaly for topography supported by a 30 km thick elastic lithosphere, which is a reasonable value for a volcano forming primarily in the Late Noachian and Early Hesperian [8]. Clearly, the surface topography can not account for much of the observed gravity anomaly, and a significant quantity of high density material must be present in the subsurface. A likely interpretation is that this dense material is dense cumulate minerals concentrated in a now-solidified magma chamber, similar to structures at Syrtis Major [9] and Apollinaris Patera [10].

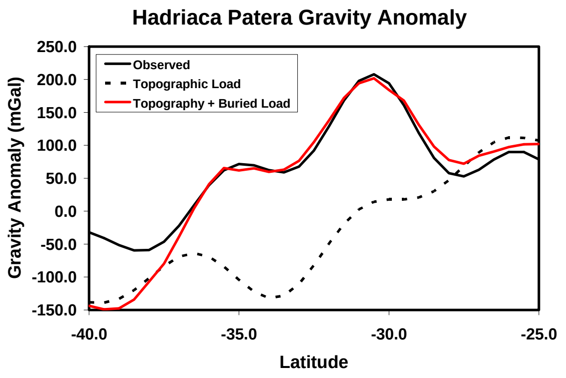

Figure 1. Gravity results for Hadriaca Patera along 93 East longitude. The solid black is the observed free-air gravity, the dashed black line is the model gravity due to flexurally supported topography alone, and the red line is the model gravity due to both flexurally supported topography and the buried load caused by the high density cumulate chamber.

We have modeled the Hadriaca gravity anomaly using the DISKGRAV modeling program [9]. DISKGRAV models buried structures as finite thickness spherical caps, which permits the spatial structure of an anomaly to be modeled with a minimum number of free parameters. If necessary, multiple disks can be used to model more complex shapes. The DISKGRAV results are always filtered to match the resolution of the observed gravity model. Figure 1 (red line) shows that a model combining both the surface topographic load and a high density buried load can reproduce the observed free-air anomaly. The buried load is approximately 600 km across. If it is composed of Chassigny-like cumulate olivine, the disk is up to 7 km thick. For the more realistic case of mixed olivine and pyroxene cumulates, a thicker load is required.

Tyrrhena Patera

Tyrrhena Patera is 215 by 350 km across, with a summit relief of 1.5 km. The caldera complex is 41 by 55 km across and 0.6 km deep [1]. The erosional morphology of much of Tyrrhena suggests that it consists primarily of friable material emplaced in pyroclastic eruptions [11, 12]. The bulk of the volcano was emplaced at model crater ages between 3.7 and 4.0 Ga, with some minor volcanism at later times [13]. This is comparable to the age of activity at Hadriaca, but given the typical 100 Ma uncertainty in the cratering ages, it is impossible to assess if one volcano might be older than the other. Although a magnetic anomaly is present at Tyrrhena, it is a local minimum in the field strength, suggesting that the volcano may have caused thermal demagnetization of a pre-existing crustal magnetic field [5, 14]. The topography at Tyrrhena can explain at most only half of the observed gravity anomaly, leaving at least a 125 mGal signal unexplained. However, a dense cumulate layer a few km thick centered near the caldera can explain the free-air gravity anomaly.

Comparison with Apollinaris Patera

Like Hadriaca and Tyrrhena, Apollinaris Patera formed primarily by explosive volcanic emplacement [15] with a model crater age for emplacement of 3.7-3.8 Ga [16]. Also like Hadriaca and Tyrrhena, its large free-air gravity anomaly requires the presence of a disk of high density material such as igneous cumulates that is several kilometers thick [10]. Like Hadriaca, Apollinaris is strongly magnetized in a disk about 360 km across centered on the volcano's caldera [17]. Thus, at both Hadriaca and Apollinaris, there are 3 correlated structures: the pyroclastic volcano, the gravity anomaly, and the magnetic anomaly. The existence of these 3-way correlations at two different volcanos is unlikely to be due to random chance and instead indicates a genetic relationship between the volcanos and their gravity and magnetic anomalies. A likely explanation is that the magnetic anomaly is carried by minerals such as magnetite or hematite, which formed by hydrothermal processing of the original olivine and pyroxene cumulates in the magma chamber. The hot ground water required for such hydrothermal processing is consistent with the history of pyroclastic volcanism. Only a small amount of magnetite (0.3 volume % for a 5 km thick layer) is needed to produce the Apollinaris magnetic anomaly [17]. Although magnetite is quite dense, the abundance required by the magnetic data can only explain a small fraction of the gravity anomaly at Apollinaris.

Implications for Magnetic Dynamo History

Based on the strength of crustal magnetization observed at various impact basins, it has been proposed that the martian dynamo died prior to the formation of the five youngest large (> 1000 km diameter) impact basins: from oldest to youngest North Polar, Utopia, Hellas, Argyre, and Isidis [18]. Based on the cratering ages cited above, it is possible that both Hadriaca and Apollinaris are younger than all of the large impact basins on Mars. These cratering ages do not necessarily rule out a much earlier starting age for volcanism and the associated magnetized crust at Apollinaris. However, Hadriaca is located on the rim of Hellas and clearly post-dates the formation of Hellas. These observations imply that the dynamo may have persisted on Mars at least somewhat longer than previously thought. These observations also imply that models which attribute the end of the martian magnetic dynamo to the thermal effects of large impacts [19, 20] are unlikely to be the only mechanism responsible for ending dynamo activity, although they may certainly play a role in at least weakening the dynamo. An alternative model for ending the dynamo involves changes in the strength of mantle convection associated with loss of volatiles from the interior [21].

References [1] Plescia, JGR 109, 2002JE002031, 2004. [2] Crown and Greeley, JGR 98, 3431-3451, 1993. [3] Williams et al., JGR 112, 2007JE002924, 2007. [4] Lillis et al., GRL 33, 2005GL024905, 2006. [5] Lillis et al., Icarus 194, 575-596, 2008. [6] Konopliv et al., Icarus in press, 2011. [7] Kiefer, 7th Int. Mars Conference, 2003. [8] McGovern et al., JGR 109, 2004JE002286, 2004. [9] Kiefer, EPSL 222, 349-361, 2004. [10] Kiefer, GSA Annual Meeting, abstract 92-12, 2010. [11] Greeley and Crown, JGR 95, 7133-7149, 1990. [12] Gregg and Farley, J. Volcan. Geotherm. Res. 155, 81-89, 2006. [13] Williams et al., JGR 113, 2008JE003104, 2008. [14] Lillis and Kiefer, this conference. [15] Robinson et al., Icarus 104, 301-323, 1993. [16] Werner, Icarus 201, 44-68, 2009. [17] Hood et al., Icarus 208, 118-131, 2010. [18] Lillis et al., GRL 35, 2008GL034338, 2008. [19] Roberts et al., JGR 114, 2008JE003287, 2009. [20] Arkani-Hamed and Olson, JGR 115, 2010JE003579, 2010. [21] Sandu and Kiefer, this conference.