NEW INSIGHTS INTO THE THERMAL HISTORY AND CRUSTAL EVOLUTION OF MARS FROM MARS GLOBAL SURVEYOR.

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Introduction. The subject of the thermal history of Mars ties together the evolution of the crust, mantle, core, and atmosphere as well as the history of magmatic and tectonic activity on the planet [1]. Recent results from the Mars Global Surveyor (MGS) mission [2] constitute important new information pertinent to planetary evolution. These results include the detection of substantial magnetization anomalies in the martian crust [3-5], new high-resolution topography both on a global scale and for features sensitive to the properties of the underlying lithosphere [6-9], and new information from imaging on martian magmatic processes [10].

Crustal Magnetic Anomalies. The demonstration from the magnetometer experiment on the MGS spacecraft that Mars presently lacks a global magnetic field [3] resolves a long-standing controversy and poses an important constraint on the present characteristics of the martian core. More importantly, the magnetometer has detected crustal magnetic anomalies of surprisingly high magnitude interpreted as evidence of an early vigorous hydromagnetic dynamo [3-5]. The largest magnetic anomalies are confined to the southern highland crust, and because anomalies are generally absent near large southern-hemisphere impact basins, a rapid decay in the strength of the dynamo and the global magnetic field in the first 500 My of martian history is inferred [4-5]. An early vigorous dynamo is consistent with isotopic evidence from martian meteorites for very early core-mantle separation [11, 12], a process that should have resulted in a molten core with sufficient excess thermal energy to drive internal motions. The era of most vigorous dynamo activity should have been accompanied by significant heat flux from the core to the base of the mantle, a flux that would have helped to fuel mantle convection and pressure-release partial melting of the upper mantle.

The form of early mantle convection is less well constrained. One suggestion [13] is that the earliest phase of martian crustal history was one of crustal formation by a martian analog of plate tectonics, with the crust of the younger and lower northern hemisphere of Mars formed during the final stages of that era. That the magnetic anomalies in a portion of the southern hemisphere of substantial areal extent are arranged in linear zones of coherent magnetization of alternating polarity (or at least alternating magnetization magnitude) has been taken as supportive of a plate-tectonic origin for the southern highland crust during a time when a strong global magnetic field underwent dipole polarity reversals [5]. The magnitude of the fields measured at spacecraft elevation demands that the product of the magnitude and the depth extent of coherent crustal magnetization be 1-2 orders of magnitude greater than for crustal rocks on Earth [3-5]. For magnetizations similar to the terrestrial upper oceanic crust, the dominant contributor to marine magnetic anomalies, the depth extent of coherent magnetization in the southern highlands of Mars must be about 30 km [5]. To achieve this outcome, the crust must attain temperatures lower than the Curie temperature of the dominant magnetic minerals throughout this depth interval on a time scale shorter than the characteristic interval between reversals. Under the crustal spreading hypothesis, such temperatures are reached at 30 km depth only after a cooling time of about 50 My if thermal conduction is the controlling heat transport process. This figure is about two orders of magnitude longer than the typical reversal interval on Earth, so some combination of higher magnetization than shallow oceanic crust, a longer characteristic time between reversals than on Earth, or more efficient heat transport (e.g., through the circulation of water to greater equivalent pressures than in the Earth's oceanic crust) would be required to sustain the crustal spreading hypothesis.

While the global magnetic field of Mars by the time of formation of the Hellas, Argyre, and Isidis impact basins was evidently substantially less than earlier [4-5], the dynamo need not have ceased entirely by that time. The detection of crustal magnetic anomalies in the northern hemisphere [4] and the remanent magnetization of martian meteorites [14] are consistent with a less vigorous dynamo that persisted to times considerably younger than 4 Gy, a feature of thermal evolution models for the martian core [1].

Topography of Impact Basins. The Mars Orbiter Laser Altimeter (MOLA) experiment on MGS has yielded topographic information for a variety of features on Mars at unprecedented resolution [6]. Topographic relief on the largest impact basins provides important information on the mechanical properties of the martian crust and lithosphere. The 9 km of present relief displayed by Hellas, the largest identified impact structure on Mars, implies that the lithosphere at the time of basin formation was at least locally of substantial thickness and long-term strength [9]. The stress differences supported by the martian lithosphere at Hellas exceed those for the South Pole-Aitken basin on the Moon, and would be larger still if the 2-to-3-km of younger deposits in the floor of Hellas were removed [9]. A basin relaxation model [15] indicates that the elastic lithosphere was approximately 30 km thick at the time of Hellas basin formation [9], a result in agreement with a 30-km depth to the Curie isotherm in the southern hemisphere crust predating Hellas [4, 5].

That the mechanical lithosphere of the southern hemisphere may have been as thick as 30 km at the time of formation of the Hellas basin suggests that the thermal structure of Mars at that time was strongly aspherical. Thermal evolution models suggest that the global average lithosphere thickness should have been substantially less than that figure 4 Gy ago [1]. An aspherical thermal structure is also implied by the much younger crater retention age for the northern lowlands than the southern highlands as well as by the evidence for widespread post-Noachian volcanic (and sedimentary) resurfacing in the northern hemisphere [16] and the partial to complete burial of such ancient northern impact structures as the Isidis and Utopia basins. Whether the asphericity in temperature and magmatic flux is the product of the pattern of mantle convection [e.g., 17] or the result of the waning stages of plate tectonics [13] is an open issue.

Topographic Evidence for Lithospheric Flexure. The thickness of the mechanical lithosphere on a planet is a measure of the reciprocal of the vertical thermal gradient in the lithosphere and thus of interior heat flow [18]. Most commonly the lithosphere thickness is estimated from the flexural deflection of the lithosphere in response to loading, but for Mars that methodology was hindered prior to MGS by the lack of accurate topographic information. Instead the earliest estimates of the thickness of the elastic lithosphere on Mars were derived from the radial distances of circumferential graben inferred to be the result of flexural stresses near axisymmetric loads or from the absence of such graben around a known load [19].

MOLA data now permit the question of whether a topographic signature of flexure is present to be answered for all the major features likely to constitute a load on the martian lithosphere. These include large volcanic constructs, impact basins displaying positive gravity anomalies analogous to mascon maria on the Moon, and polar deposits. Most large volcanoes lack discernible flexural signatures in altimeter profiles, implying that any flexural depressions must be filled by some combination of volcanic and sedimentary material [6]. For the large Alba Patera construct, circumferential graben previously interpreted as the result of flexure in response to the volcano load [19] are now known from MOLA data to lie well up the volcanic edifice. Quantitative models for both the regional and edifice graben require a combination of edifice loads, lithospheric uplift by a buoyant basal load, and regional extensional stresses and are most consistent with a lithosphere of modest thickness (10-25 km) at the time of graben formation [20].

For the north and south polar deposits, including both the residual ice and the associated layered terrain, accounting for the effects of flexure of the lithosphere increases substantially the estimated volumes of these deposits. For neither polar region can topographic profiles resolve well the thickness of the underlying lithosphere, but geological mapping and MOLA data for the northern hemisphere suggest a flexurally-derived circumpolar depression largely filled with sediments and consistent with an elastic lithosphere thickness in the range 60-120 km [8].

While much work remains to be completed on the implications of the latest altimetry data for lithospheric properties, the results to date are consistent with a lithosphere that has generally thickened with time but that at any given time is spatially heterogeneous, with the lowest values found in the vicinity of major volcanic centers.

Imaging Constraints on Volcanic Flux. Images by the Mars Orbiter Camera [21] have documented layering to depths of at least 8 km in the walls of the Valles Marineris canyon system [10]. The layered units, ascribed to the Upper Noachian stratigraphic series [16], have been interpreted as dominantly volcanic in origin, on the basis of the morphology of the overlying plains, the spectral properties of the plains and wall rocks, the layer thicknesses, and the cliff-forming topography [10]. This interpretation is consistent with a large role for volcanic construction in the evolution of the Tharsis rise [22] and will require upward revisions to regional and global estimates for the martian volcanic flux in the Late Noachian [16]. Such an upward revision will likely eliminate the apparent peak in volcanic flux in the Early Hesperian given by some earlier estimates [16] in favor of flux histories that decline more monotonically through the Noachian and Hesperian, as the most straightforward of the global thermal evolution models [1] would predict.

Summary. The MGS mission has yielded a rich and still growing return of important findings regarding interior and surface processes on Mars. Integrating these new results into an emerging framework for global evolution poses a continuing challenge to the planetary science community.

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