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Introduction to special section: The Hemispheric Dichotomy of Mars

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[1] The hemispheric dichotomy is one the most fundamental and least understood features of Mars. The papers in this special section address aspects of the origin of the crustal dichotomy and the modification and evolution of the dichotomy boundary and the northern lowlands. These studies utilize new data from a variety of instruments on spacecraft operating in Mars orbit and on the surface. This special section is an outgrowth of a two-day workshop held at the Lunar and Planetary Institute in Houston, Texas.

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1. Introduction

[2] Even to the uninitiated, the contrast between the rugged heavily cratered highlands of the southern hemisphere and the smooth, sparsely cratered lowland plains of the northern hemisphere of Mars is unmistakable (Figure 1). Perhaps most dramatically reflected in the topography and the exposed cratering record, the dichotomy between the highlands and lowlands is expressed in nearly every aspect of the geology of Mars. The nature of the hemispheric dichotomy has intrigued planetary scientists since the 1970s when the first global image mosaics of Mars were returned by Mariner 9 and the Viking Orbiters. The true extent of the contrast between the hemispheres has only recently been revealed by a robotic exploration effort rivaled only by the unmanned exploration of the Moon. The Mars Global Surveyor (MGS), Mars Odyssey (MO), and Mars Express (MEX) orbiting spacecraft and the Mars Exploration Rovers (MERs) operating on the surface are returning imaging, geochemical, and geophysical data that are revolutionizing our view of the red planet. In this emerging new view, the hemispheric dichotomy stands out as perhaps the most fundamental feature of the planet's crust. Its formation may have set the course for most of the subsequent geologic evolution of Mars, including that of the Tharsis volcanic and tectonic province.

[3] Topography from the Mars Orbiter Laser Altimeter (MOLA) [*Smith et al.*, 1999, 2001] and MGS gravity data [*Zuber et al.*, 2000; *Neumann et al.*, 2004] have quantified the elevation difference and the contrast in crustal thickness between the highlands and lowlands. MOLA topography has also revealed a population of quasi-circular depressions (QCDs) in the northern lowlands interpreted to be buried impact craters and basins [*Frey et al.*, 2002] that suggest the northern lowlands crust is very old, approaching the age of the ancient southern highlands crust [*Frey*, 2006]. The long wavelength topography of the dichotomy boundary in the eastern hemisphere suggests flexure of the southern highlands lithosphere is responsible for the present-day boundary at this location [*Watters and McGovern*, 2006]. Topographic data also suggests flexure of the northern lowlands lithosphere resulted from loading by a thick accumulation of material in the Utopia basin [*McGowan and McGill*, 2006]. Gravity data indicates a positive anomaly in the northern lowlands along the dichotomy boundary in the eastern hemisphere that may indicate localized crustal thinning from edge-driven convection [*Kiefer*, 2005].

[4] High resolution imaging from the Mars Observer Camera (MOC) on MGS, the Thermal Emission Imaging System (THEMIS) on MO, and the High-Resolution Stereo Camera (HRSC) on MEX are shedding new light on the geologic evolution of the dichotomy boundary and the northern lowlands. Images from these cameras show evidence of valley glacial systems in fretted terrain along the dichotomy boundary [*Head et al.*, 2006] and debris flows that cut outflow channels into the northern lowlands [*Rodriguez et al.*, 2006].

[5] This special section of Geophysical Research Letters is a collection of 6 papers that encompasses some of the research presented at a two-day workshop held in the Fall of 2004 at the Lunar and Planetary Institute in Houston, Texas [*Watters and McGovern*, 2005]. The goal of the workshop was to discuss both observational and theoretical viewpoints and to foster future research directions.

2. Origin of the Crustal Dichotomy

[6] Debate over the nature of the crustal dichotomy has centered on two broad modes of origin, exogenic or externally-driven mechanisms and endogenic or internally-driven mechanisms. Exogenic models invoke either one giant impact [*Wilhelms and Squyres*, 1984; *McGill*, 1989] or multiple impacts [*Frey and Schultz*, 1988] to remove crust from the northern lowlands. Such models dictate that the hemispheric dichotomy must be very old (early or pre-Noachian), forming before the end of the period of heavy bombardment. Endogenic (internally-driven) models generate thinner crust through either removal of the basal lowlands crust by mantle convection [*Wise et al.*, 1979; *McGill and Dimitriou*, 1990; *Zhong and Zuber*, 2001; *Zuber*, 2001] or by plate tectonics [*Sleep*, 1994, 2000].

[7] Predictions from planetary accretion models and isotope data from Shergottites, Nakhlites, and Chassigny (SNC) meteorites suggest that the crust of Mars formed very early in the geologic history of the planet, possibly only 50 My after the formation of the solar system [*Solomon et al.*, 2005]. Although an early phase of plate recycling [*Lenardic et al.*, 2004] or early subcrustal transport by

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degree-one mantle convection [*Zhong et al.*, 2004] could have formed a lowlands crust slightly younger than the highlands crust, these mechanisms operate on timescales on the order of several hundred million years [*Solomon*, 2004; *Solomon et al.*, 2005]. Heterogeneous development of a magma ocean could account for an early-rapid formation of the crustal dichotomy [*Solomon*, 2004; *Solomon et al.*, 2005], or crystallization of an early magma ocean may have resulted in a gravitationally unstable mantle that rapidly overturned and triggered the formation of the crustal dichotomy by subcrustal transport [*Elkins-Tanton et al.*, 2003, 2005].

[8] *Frey* [2006] presents evidence based on the populations of QCDs that the lowlands are as old as the exposed highlands but not as old as the total highlands (exposed plus buried highlands). His results indicate that while the crater retention ages for very large QCDs (diameters >1000 km) in Utopia, Acidalia, and Chryse Planitiae are older than the average buried lowlands, they are still younger than the total highlands. Based on model absolute ages, *Frey* [2006] suggests that the age difference between the total highlands and the formation of the lowlands could be as little as ~100 million years. He suggests this argues against endogenic models that require extended periods of time to form the lowlands and supports an exogenic origin for the dichotomy. *Frey* [2006] notes that the expanse of lowlands in Amazonis Planitia has no associated very large QCD and the geology and crustal thickness there is different than other areas within the lowlands.

3. Erosion, Deposition, and Glacial Modification of the Boundary

[9] Recent geologic mapping efforts supported by the vast new resource of image and topographic data suggest that the present-day dichotomy boundary has a long and complex history evolving from an ancient, poorly understood transition zone between the highlands and lowlands [*Skinner et al.*, 2004; *Tanaka et al.*, 2005]. Fretted terrain along the dichotomy boundary in Aeolis Mensae, thought to be erosional remnants of highland materials, may have formed in aeolian sediments deposited along the dichotomy boundary in the late Noachian-early Hesperian when fluvial activity was declining [*Irwin et al.*, 2004]. *Head et al.* [2006] report on a detailed study of the fretted terrain along Deuteronilus-Portonilus Mensae, a region where the dichotomy boundary extends to the highest northern latitudes. They describe evidence in the fretted valleys indicative of glacial processes. These include localized alcoves that are the source for concentric-ridged flows, likely remnants of debris-covered glaciers, horseshoe-shaped ridges upslope of topographic obstacles, convergence and merging of lineated

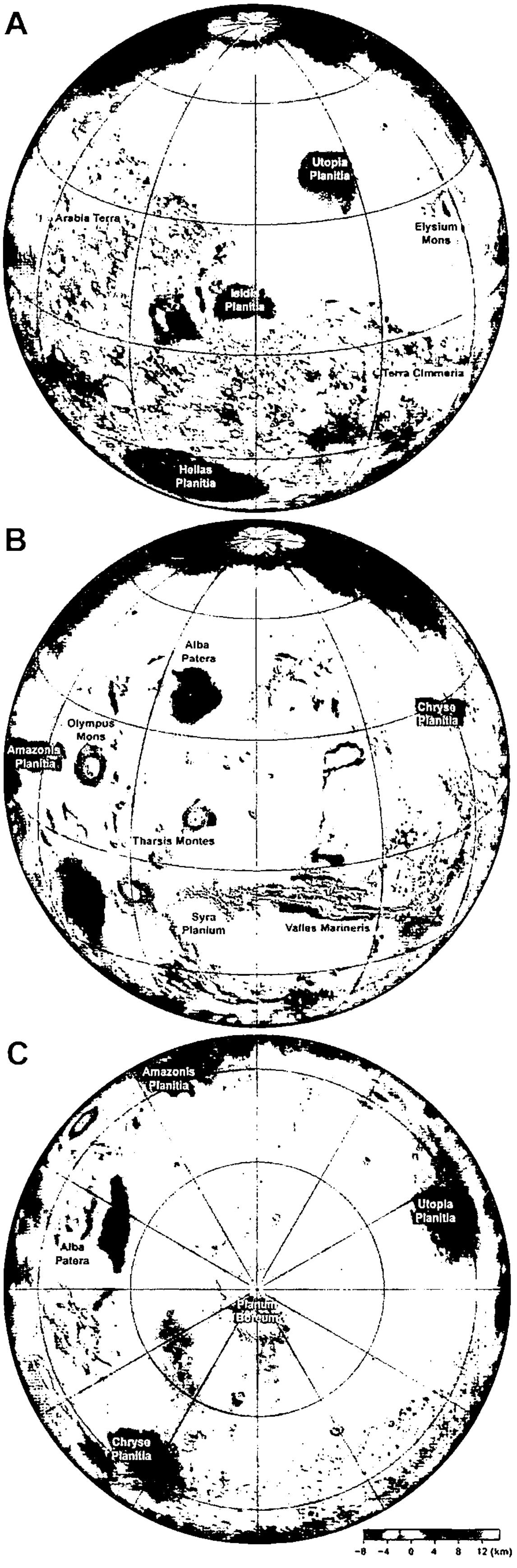

Figure 1. Topographic maps of Mars: (a) the eastern hemisphere centered at 20°N, 90°E, (b) the western hemisphere centered at 20°N, 270°E, and (c) the northern hemisphere centered at 90°N. The topographic maps were derived from MOLA $^1/_{128}$ degree per pixel resolution gridded data. The Martian crustal dichotomy is expressed by the change in elevation between the highlands of the southern hemisphere and the lowlands of the northern hemisphere.

valley fill material in the down-valley direction consistent with glacial-like flow, and lobe-shaped termini where valley fill material emerges into the northern lowlands. Based on the broad occurrence of glacial-like features in the region's fretted valleys, *Head et al.* [2006] conclude that glaciation is a major erosional process along the dichotomy boundary, causing significant retreat of the boundary in the Amazonian.

[10] *Rodriguez et al.* [2006] report on a study of the Simud and Tiu outflow channels that cut across the dichotomy boundary in Chryse Planitia. In the higher levels of the channels, where highland materials are deeply incised, erosion was driven by flood waters from Hydaspis Chaos. They conclude that the lower elevation sections of the channels, by contrast, were cut by debris flows from Hydraotes Chaos. *Rodriguez et al.* [2006] propose that instabilities in individual debris flows may have resulted in multiple surges with variable volatile content. They also conclude these multistage debris flows emplaced extensive sedimentary deposits both in the lower channel floors and throughout the northern lowlands.

4. Lithospheric Flexure at and Near the Boundary

[11] The elevation change across the dichotomy boundary is the greatest in the eastern hemisphere (Figure 1), and tectonic features express crustal shortening in the highlands along the boundary and crustal extension in the adjacent lowlands [*McGill and Dimitriou*, 1990; *Watters*, 2003]. The morphometry of the dichotomy boundary in the eastern hemisphere is also distinctive, generally consisting of a broad rise and an arching ramp that slopes down into the lowlands and often terminates in an escarpment. Two approaches have been taken to explain the long wavelength topography of the dichotomy boundary, crustal relaxation and lithospheric flexure. Relaxation models invoke lateral flow of the lower crust to account for the boundary topography, and associated stresses are roughly consistent with the location of the tectonic features [*Nimmo*, 2005; *Guest and Smrekar*, 2005]. *Watters and McGovern* [2006] account for the long wavelength topography of the boundary through lithospheric flexure. They model flexure of the southern highlands for both a continuous and broken plate boundary with the northern lowlands lithosphere and find the best fits to the topography are obtained for a broken lithosphere. *Watters and McGovern* [2006] suggest that flexure is in response to vertical loading along the dichotomy boundary from the emplacement of volcanic material in the northern lowlands. Stresses resulting from flexure are consistent with the location of tectonic features along the boundary. They suggest the lithosphere at the boundary was weakened during the formation of the crustal dichotomy.

[12] Flexure may also be responsible for the long wavelength topography of the northern lowlands in Isidis Planitia. *McGowan and McGill* [2006] report on the result of analysis and modeling of the southwest slope of Isidis Planitia which is counter to the general northward slope of the northern lowlands. They model flexure of the lowlands lithosphere in response to a uniformly distributed load from a thick accumulation of sediments or volcanic material in the Utopia basin. The resulting peripheral bulge matches the location of the high elevation point between the Isidis basin and the Utopia basin and accounts for the observed southwest tilt.

5. Gravity Anomalies and Edge-Driven Convection at the Boundary

[13] Along with the change in elevation, there is also a distinct change in crustal thickness across the dichotomy boundary in places, particularly in the eastern hemisphere [*Neumann et al.*, 2004]. Large lateral gradients in lithospheric thickness and thermal structure can give rise to edge-driven mantle convection [*King and Redmond*, 2004]. *Kiefer* [2005] reports on a gravity anomaly in the northern lowlands that extends along a 3000 km long segment of the dichotomy boundary in the eastern hemisphere. He interprets the anomaly to be the result of buried, high density material along the boundary. The most likely source of the anomaly is mantle material that has replaced crust due to localized crustal thinning. *Kiefer* [2005] attributes the crustal thinning along the dichotomy boundary to edge-driven convection. Because edge-driven convection requires rapid development of lateral variations in lithospheric thermal gradients, *Kiefer* [2005] concludes a likely mechanism to create such conditions is the formation of a large impact basin like the Utopia basin.

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