

THE DICHOTOMY-FORMING IMPACT ON MARS: EVIDENCE AND IMPLICATIONS. J. C. Andrews-Hanna^{1,2} and M. T. Zuber¹, ¹Dept. of Earth, Atmospheric, and Planetary Sciences, MIT ²now at the Dept. of Geophysics, Colorado School of Mines, jhanna@mit.edu.

Introduction: The topography and crustal structure of Mars is dominated by the hemispheric crustal dichotomy, dividing the planet between southern highlands and northern lowlands. Recent work revealed evidence that this dichotomy was produced in a giant basin-forming impact, making the northern lowlands of Mars the largest impact basin in the solar system [1-3]. While all of the terrestrial planets likely experienced similar mega-impacts at some stage in their formation, the importance of the dichotomy-forming impact on Mars is heightened by the fact that it post-dated planetary differentiation. We review evidence for the impact basin, and explore the implications for Mars evolution.

Borealis Basin – Evidence for an impact: The primary evidence for an impact origin for the dichotomy lies in the near-perfect elliptical shape of the lowlands, as revealed in a recent analysis of the topography and gravity that removed the superposed Tharsis volcanic rise [1]. The elliptical lowlands shape is strikingly similar to other elliptical impact basins, including Hellas, Utopia, and South Pole-Aitken. The bimodal crustal thickness distribution between the lowlands and highlands is also similar to the bimodal distribution between the Hellas basin floor and surrounding crust. Simulations found that an impacts of 1600-2700 km diameter objects at angles of 30-60° produce basins matching the elliptical lowlands [2]. The impact may also explain the demagnetization of a broad region antipodal to the basin [3].

Borealis Basin – Possible basin-related features:
Arabia Terra: A partial multi-ring structure. Arabia Terra is the one ancient Noachian province that does not match the characteristics of typical highlands crust [4]. Arabia Terra slopes gently northwards, and is separated from both the lowlands and highlands by distinct breaks in slope [1]. Based on profiles of the Orientale, Hellas, and Argyre basins [1], we propose a topographic definition of a multi-ring structure as an inwards facing slope at ~1.4 radii from the basin center that is separated from the main excavation rim of the basin by a gently sloping to concave upwards bench at intermediate elevation. By this simple observational definition, Arabia Terra is a partial basin ring, though the mechanism responsible for the origin of both Arabia Terra and other multi-ring structures is uncertain.

Highlands ejecta textures. The lowlands forming impact would have buried the primordial highlands crust beneath a thick ejecta blanket [2]. The nearly uniform thickness of the highlands crust suggests ei-

ther an even distribution of ejecta or viscous relaxation of thickness variations in the hot ejecta blanket. Preservation of the basin rim requires that the ejecta be largely solid upon impacting the surface. Structures in the highlands are likely a result of either textures in the ejecta blanket or subsequent modification processes. In some regions of the highlands, the crust exhibits long wavelength undulations, which do not appear consistent with a volcanic or tectonic origin. This texture may represent the highly relaxed and eroded signature of hummocky or blocky portions of the ejecta blanket.

Impact fractures and fretted terrain. The crust surrounding a crater or basin is intensely fractured at scales ranging from microfractures to large breccia-filled tear faults. Many portions of the dichotomy boundary are characterized by fretted terrain – an intersecting network of valleys with semi-rectilinear plan form [5]. The valleys have been erosionally enlarged, though a clear structural control is evident. Focused groundwater discharge along the dichotomy boundary in the Noachian and Hesperian could have fueled fluvial and glacial erosion, which would naturally concentrate in zones of weakness or high porosity. This fretted terrain may thus represent erosionally enlarged impact-induced faults around Borealis.

Implications for Mars evolution: Early crustal structure. The ancient highlands basement is the only crust on Mars dating back to planetary differentiation. The crustal thickness [6] histogram of the highlands

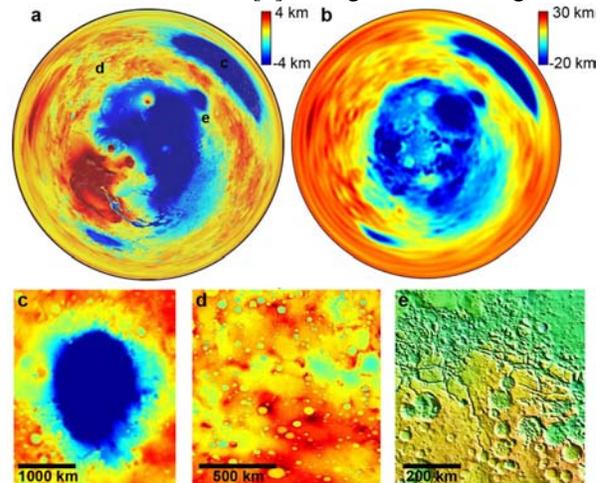


Figure 1. Polar plots of the Borealis basin in the topography (a) and modeled isostatic roots, representing the pre-Tharsis crust (b), show a clear similarity with the Hellas basin (c). Hummocky textures in the highlands (d) may represent ejecta. Fretted terrain (e) may reveal eroded basin fractures.

(excluding Arabia Terra and regions of volcanic/impact modification [1]) is sharply peaked at a thickness of 65 km and a full width at half max of 7 km. This suggests that the pre-dichotomy crust exhibited a nearly uniform thickness, with implications for the mechanism of primary crustal formation.

Timing of the impact. If the crust of Mars was near the solidus temperature after differentiation [7] (likely within ~20 Myr of solar system formation [8]), this would require substantial cooling prior to the dichotomy-forming impact in order to maintain the abrupt dichotomy boundary against relaxation. For a 50 km thick crust, the thermal diffusion timescale is ~65 Myr, suggesting that the impact likely occurred one to several hundred Myr after accretion.

Climate and atmosphere. Mars is thought to have acquired its volatiles through accretion of carbonaceous asteroids (accounting for less than 1% of the mass of the planet) in the first 20 Myr of solar system formation [9]. Formation of the atmosphere then resulted from outgassing during differentiation and late-stage accretion of volatile-rich projectiles. The Borealis impact clearly occurred after the main phase of crustal formation and outgassing. Large impacts are thought to strip the atmosphere above the plane tangent to the impact basin [10], suggesting removal of a minimum of 40% of the primordial atmosphere by the dichotomy-forming impact. Above a critical energy, complete atmospheric ejection by the shock wave and expanding silicate vapor plume is possible [11]. The estimated energy of the impact [2] exceeds that required for total atmospheric removal by a factor of 10.

An impact more than 100 Myr after accretion would have been long after Jupiter had cleared the asteroid belt of large bodies [12], suggesting a water poor projectile from the vicinity of Mars. Alternatively, a carbonaceous projectile would likely have been differentiated and may have lost much of its initial volatile inventory before impact. In either case, the impact would have resulted in a net loss of water. Mars may have had a thicker outgassed CO₂-H₂O atmosphere that was lost during this late-stage mega-impact. Subsequent atmospheric replenishment by degassing of the impact-generated local magma ocean, volcanic outgassing at Tharsis, and accretion of a late-stage veneer of volatile-rich projectiles would have partially restored the atmosphere, allowing a short-lived clement climate before loss to solar wind and small impact erosion led to the present cold and arid conditions.

Surface composition. The dichotomy-forming projectile represents the largest post-differentiation contribution of meteoritic material to Mars. Estimated projectile sizes [2] correspond to a global equivalent layer (GEL) of 14-71 km of meteoritic material, dwarfing

the combined contribution from the Hellas, Utopia, Argyre, and Isidis impacts (~0.6-6 km GEL).

The highlands is likely blanketed in ejecta from the lowlands-forming impact up to several 10's of km in thickness [2,3], composed of a mixture of excavated crust, mantle, and projectile material. The lowlands crust likely differentiated from the local impact-generated magma ocean, and was later covered in a thin veneer of volcanic and sedimentary material. These two provinces roughly correlate with the spectral surface types 1 and 2, with the more mafic surface type associated with the highlands (possibly consistent with a physical mixture of crust and mantle ejecta). However, the lowlands and highlands are of different provenance regardless of the mechanism of dichotomy formation, and existing observations do not disambiguate impact and endogenic mechanisms. It has been suggested that the characteristic red color of Mars may be due to oxidized meteoritic Fe in the dust [13]. The vast majority of post-differentiation meteoritic iron would have been delivered to Mars in the Borealis impact.

Analyses of isotopic ratios in the martian meteorites suggest that the martian interior includes two compositionally distinct mantle reservoirs [8]. This result is surprising in light of evidence for likely plume-sourced volcanism, and theoretical arguments for whole-mantle convection on early Mars [14]. A distinct mantle reservoir could have been produced by the Borealis impact, in the form of a local magma ocean composed of a mixture of martian and foreign projectile material. The roughly even division of known martian meteorites between the two compositional groups is consistent with the similar sizes of the highlands and lowlands.

Summary: The dichotomy-forming impact on Mars affected all aspects of Mars' evolution, particularly given its timing after planetary differentiation. While there is much uncertainty regarding the effects of the impact, this much is clear: the fundamental nature of Mars and the course of its evolution were changed dramatically by this single event.

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