Impact origin for the martian crustal dichotomy: Half-emptied or half-filled?

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Introduction Excavation of a northern lowland basin by a single giant impact is a long-standing hypothesis for martian dichotomy formation [1] that has received much attention [2-4]. An alternative hypothesis suggests that impact generated melt can be sufficiently voluminous to flood the excavated cavity, produce thickened crust, and generate a topographic basin centered on the opposite side of the planet [5]. Retention of an excavated cavity after a giant impact depends on several factors including thickness of existing crust (i.e., degree of mantle depletion) and impact size. In the case of thick pre-existing crust, depleted mantle, and relatively small impact, the amount of melt produced by the impact may be small and confined to the basin [4]. For thinner initial crust, less depleted mantle and larger impact, impact melt can produce thicker crust within the basin and thus a more subdued topographic low. Apparently, with increasing impact energy, there is eventually a transition to complete flooding of the basin.

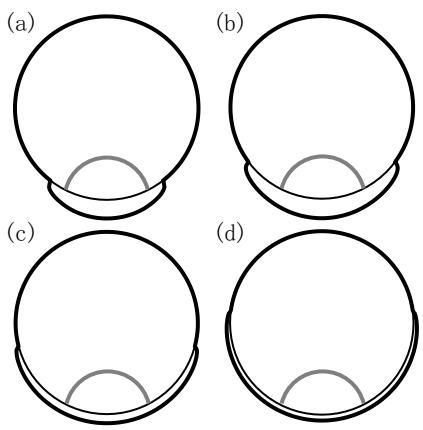

Figure 1: Height profiles of spreading layer as a function of time. Vertical exaggeration is 200x. The gray line shows the boundary of the initial impact generated melt region.

Lateral spreading of impact melt: Antipodal basin formation Fluid dynamical considerations [5] suggest that the melt region first rapidly crystallizes to a partially molten state. Subsequent to crystallization, isostatic adjustment causes the partial melt to rise up producing a layer which spreads laterally at the surface of the planet. Further cooling causes spreading to slow. Depending on partial melt volume and deformation mechanism, the partial melt layer may not spread entirely around the planet. Differentiation of the layer would result in thickened crust near the impact and a topographic "basin" antipodal to the impact.

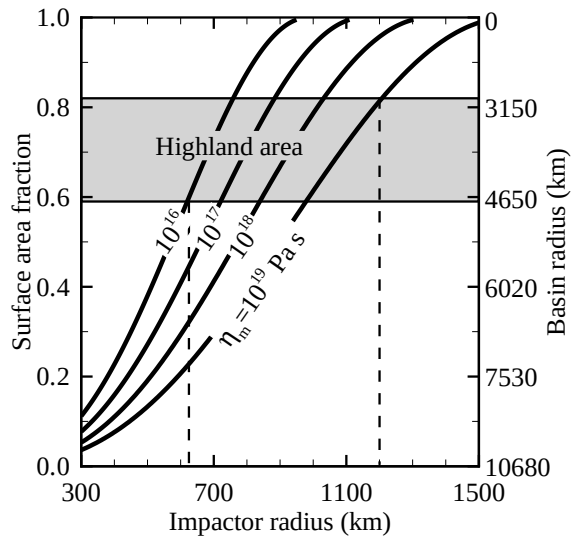

Figure 2: Planetary surface area fraction covered by the partial melt layer at the end of spreading versus impactor size (impact velocity is 10 km/s). Curves are labeled by partial melt viscosity controlling spreading, η_m. The southern highland area range corresponds to a lowland basin of radius 3000-4800 km [4]. Depending on partial melt layer viscosity, the impactor radius required to generate a layer with appropriate area varies from $\sim$ 600 - 1200 km.

Our isostatic adjustment model is based on viscous deformation of solid mantle outside the partial melt region [5]. We model lateral spreading by adapting the case of viscous fluid spreading on a planar surface to spreading on a spherical surface. Results indicate that as isostatic adjustment proceeds, the layer spreads laterally (Fig. 1a) until nearly all partial melt is at the surface (Fig. 1b). After this, the spreading rate decreases significantly (Fig. 1c). Spreading is assumed to stop when the thermal diffusion lengthscale is of the order of the layer thickness (Fig. 1d).

Implications for dichotomy formation The antipodal basin size depends on impact energy (which determines partial melt volume) and the viscosity controlling lateral spreading of the partial melt layer. A partial melt layer of the appropriate area can be generated by an impactor with radius $\sim$ 600 - 1200 km where the lower and upper bounds correspond to a range of partial melt viscosity 10^{16} Pa s - 10^{19} Pa s (Fig. 2).

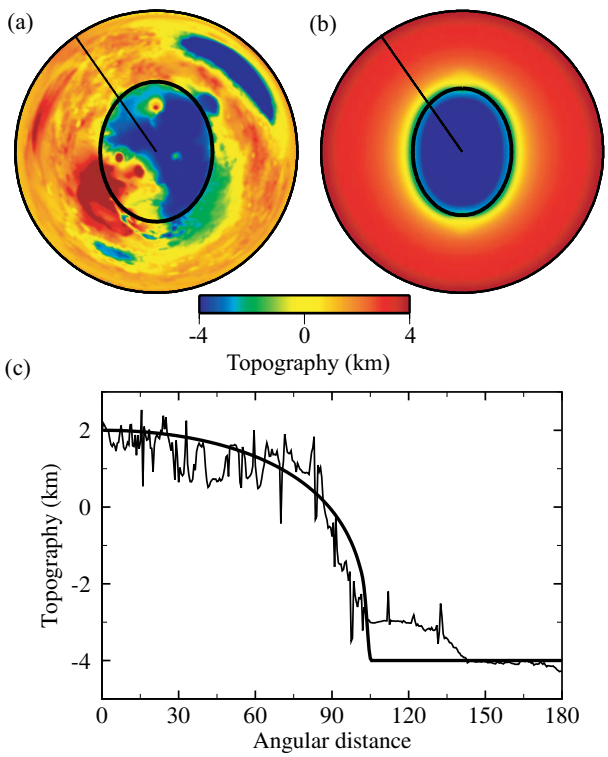

Figure 3: (a) Polar projection of martian topography around the northern lowland basin center. The solid line shows the best-fit ellipse of [2]. (b) Model result for case described in the text. Colors scale with partial melt layer thickness (c) Observed (thin line) and model (thick line) topography along a great circle transect from the basin center to the antipode (shown in (a) and (b)).

In Fig. 3, a case with impactor radius $\sim$ 900 km, impact velocity $\sim$ 10 km/s, and partial melt viscosity $\eta_m \sim 3 \times 10^{18}$ Pa s is compared to martian topography and the best-fit northern lowland basin ellipse of [2]. In this model, deviation from circularity depends on the initial asymmetry of the impact melt region which can be due to impact obliquity.

Another useful comparison is model topography at the margin of the flow. In the topographic sense, an impact crater margin is concave-up while a flow margin is concave-down. The model flow profile is compared to topography away from areas of obvious dichotomy boundary modification. We consider a great circle transect from the basin center to the basin antipode (Fig. 3c). In order to focus on the shape of the profile at the boundary, model topography is adjusted to a lowlands value of -4 km, assumed to scale with the flow thickness, and prescribed a total offset of 6 km.

The basin excavation and antipodal basin hypotheses for origin of the dichotomy are directly opposed in terms of the sign of the age difference between crustal terrains. In the impact excavation model, lowland crust is younger than highland crust. In the model we propose, highland crust is younger than lowland crust. Our model age difference depends on the timescale for emplacement of southern highland crust. Numerical results suggest that spreading of a partial melt layer takes $\sim$ 1-10 Myr while differentiation occurs on a longer timescale of $\sim$ 20 - 60 Myr. The observed age difference between lowland basement crust and highland crust based on visible and buried craters is small while uncertainties associated with the estimates are large [6]. Thus, the two hypotheses for the origin of the martian crustal dichotomy are testable with sufficiently high resolution measurements of martian crustal terrain ages.

Models for the origin of the crustal dichotomy must also address the distribution of the crustal remnant magnetic field [e.g., 7]. In the single giant impact hypothesis for lowland basin excavation, it is assumed that pre-existing crust is magnetized and that the dynamo had ceased by the time of the impact [4]. In the hypothesis that we suggest here, we assume that crust formed prior to the impact is not magnetized and thus require that the magnetic field turns on after formation of lowland crust. Recently, it has been suggested that a giant impact might induce a dynamo by delivering impact heated impactor iron to the core [8].

References [1] Wilhelms and Squyres 1984, *Nature, 309*, 138-140. [2] Andrews-Hanna et al. 2008, *Science, 453*, 1212-1216. [3] Marinova et al. 2008, *Science, 453*, 1216-1219. [4] Nimmo et al. 2008, *Science, 453*, 1220-1224. [5] Reese and Solomatov 2006, *Icarus, 184*, 102-120. [6] Frey 2006, *J.G.R., 111*, E08S91. [7] Langlais 2004, *J.G.R., 109*, E02008. [8] Reese and Solomatov 2009, *Icarus*, 10.1016/j.icarus.2009.10.016.