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A hybrid origin of the Martian crustal dichotomy: Degree-1 convection antipodal to a giant impact

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ABSTRACT

The Martian crustal dichotomy is the stark ∼5 km difference in surface elevation and ∼26 km difference in crustal thickness between the northern lowlands and southern highlands that originated within 100s of Myr of Mars' formation. The origin of the dichotomy has broad implications for the geodynamic history of Mars, but purely exogenic or endogenic theories so far cannot explain all of the large scale geophysical observations associated with dichotomy formation. A giant impact can produce the shape and slope of the dichotomy boundary, but struggles to explain Mars' remanent crustal magnetic signatures and the ultimate formation of Tharsis. Degree-1 mantle convection can relate the crustal dichotomy to the formation of Tharsis, but does not explain the elliptical dichotomy shape and must be initiated by a large pre-existing viscosity jump in the mantle. We propose a hybrid model of dichotomy formation in which a giant impact induces degree-1 convection with an upwelling antipodal to the impact site. In this scenario, a giant impact in the northern hemisphere excavates crust, creating an initial difference in crustal thickness and possibly composition between the two hemispheres. Over 10s to 100s of Myr, the dominant upwelling(s) would migrate to be under the thicker, insulating crust in the southern hemisphere, generating melt that further thickens the southern crust. We examine this process using 3-D mantle convection simulations, and find that a hemispherical difference in crustal thickness and composition caused by a giant impact can induce degree-1 convection with the upwelling(s) antipodal to the impact site in <100 Myr.

1. Introduction

1.1. Constraints on dichotomy formation

One of the oldest observable features on Mars is the crustal dichotomy, an approximately hemispheric difference of ∼5 km in surface elevation and ∼26 km in crustal thickness between the northern lowlands (Borealis basin) and southern highlands (*e.g.*, Neumann et al., 2004). The formation of the dichotomy is generally attributed to either an exogenic event such as a giant impact (*e.g.*, Marinova et al., 2008), or an endogenic process such as mantle convection (*e.g.*, Roberts and Zhong, 2006). There are several important constraints or potential constraints on the formation mechanism, including the timing of dichotomy formation, boundary shape, magnitude of variation in crustal thickness, distribution/strength of remanent crustal magnetism (residual magnetization retained in crustal rocks after cessation of the dynamo), and formation of Tharsis on the dichotomy boundary.

Crater retention ages for buried and visible craters suggest that the dichotomy likely originated within 100s of Myrs of Mars' formation (*e.g.*, Frey, 2006), and geochemical arguments also suggest an early formation time ∼4.5 Ga (Bottke and Andrews-Hanna, 2017; Brasser and Mojzsis, 2017). Relatively early formation of the dichotomy is consistent with a giant impact during the late stages of planetary accretion (Brasser and Mojzsis, 2017), but limits endogenic theories because it constrains the timescale for mantle convection to evolve to a degree-1 pattern. Solid–solid phase changes in the mantle have been successful at producing degree-1 convection, but only on Gyr timescales and require a constant or weakly temperature dependent viscosity (Harder, 2000; Roberts and Zhong, 2006). Degree-1 convection can arise on shorter timescales (100s of Myr) if Mars had a temperature dependent, layered viscosity with a factor of 25 increase in the mid-mantle (Roberts and Zhong, 2006). It is unclear what process would cause such a large viscosity jump in the mantle, but it could be the result of a solid–solid phase transition, compositional vari-

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ation from an early magma ocean, or a transition from diffusion to dislocation creep (*e.g.*, Roberts and Zhong, 2006). Compositional layering due to magma ocean solidification has been proposed as a mechanism to generate asymmetrical overturn on timescales <10 Myr (*e.g.*, Elkins-Tanton et al., 2005), however, more recent work has shown that degree-1 structures are unlikely to result from mantle overturn on Mars (Scheinberg et al., 2014).

The elliptical shape of the dichotomy boundary has been used as evidence for a giant impact because Borealis-scale impacts produce elliptical basins due to the effects of planet curvature (Andrews-Hanna et al., 2008) and the scale of the impact (Collins et al., 2011). An elliptical basin could also be the result of an impact megadome, which occurs when an impact is large enough to cause widespread crust production and magmatism in the impacted hemisphere, a scenario that could potentially result in a Borealis-like depression in the hemisphere opposite the megadome (*e.g.*, Golabek et al., 2018). An elliptical boundary shape would not be an expected result of degree-1 convection, but migration of a single upwelling and the resulting crust production could result in asymmetries in the dichotomy boundary (Šrámek and Zhong, 2012). An elliptical dichotomy shape could result from one-ridge convection, where the upwelling planform is a single ridge spread over half of Mars (Keller and Tackley, 2009). Furthermore, although the dichotomy boundary appears elliptical, the pre-Tharsis boundary computed by removing Tharsis depends on the elastic plate thickness (Andrews-Hanna et al., 2008) and contributions of lateral or temporal elastic thickness variations are unexplored (Šrámek and Zhong, 2010).

The extent of crustal thickness variation between the northern and southern hemispheres of Mars, as inferred from gravity and topography data (*e.g.*, Neumann et al., 2004), is possible with both exogenic and endogenic dichotomy formation mechanisms. Coupling of melt/crust production with mantle convection models can produce crust in one hemisphere of similar thickness to the present-day highlands (Šrámek and Zhong, 2012; Keller and Tackley, 2009), however, such crust production depends on the vigor of convection and not all plumes produce melt (Sekhar and King, 2014). The required crustal thickness variation can also be produced by magmatism resulting from an impact megadome (Golabek et al., 2011). For a Borealis-scale impact, numerical impact simulations show that the resulting crustal thickness variation is generally consistent with present observations (Marinova et al., 2008; Nimmo et al., 2008). An additional effect of excavating crust in the northern hemisphere via a giant impact is the formation of a circum-Mars debris disk that could explain the formation of the Martian moons Phobos and Deimos (*e.g.*, Rosenblatt et al., 2016). The sharp dichotomy boundary expected from an impact could also induce edge driven convection, possibly explaining the buried mass anomalies on the eastern dichotomy boundary (Kiefer, 2005).

Another constraint on dichotomy formation is the remanent crustal magnetic signatures that are observed over the entire planet, indicating another global process active early in Martian history (Acuna et al., 1999). The remanent magnetic signatures are significantly stronger in the southern hemisphere, and also contain a unique pattern of lineations of alternating polarity (Connerney et al., 2005). The emplacement of the magnetic signatures most likely occurred prior to the cessation of the Martian dynamo $\sim$4.1 Ga (Lillis et al., 2013), although it is uncertain if the magnetic signatures were emplaced before, during, or after dichotomy formation. The magnetic signatures must post-date a giant impact because a Borealis-scale impact could have completely erased magnetic signatures in the northern lowlands, and the thick ejecta blanket could have demagnetized the entire southern crust as well (Citron and Zhong, 2012). Even if an impact occurred in the presence of a strong magnetic field, the pattern of magnetic lineations of alternating polarity is difficult to reconcile with Borealis-scale impact/ejecta generated melt or magmatism associated with an impact megadome (*e.g.*, Golabek et al., 2018), which would have cooled on a short timescale in the vertical direction. The alternating polarity of the lineations could be explained by crust production radiating from a single large plume in a reversing magnetic field, which might explain why the geometry of the lineations roughly corresponds to concentric circles centered around a single pole that is <300 km from the centroid of the thickened southern crust (Citron and Zhong, 2012). However, the melting history is likely more complex than the simple model of Citron and Zhong (2012), and could involve multiple migrating plumes and more complex melt extraction and crust evolution. Furthermore, the pattern of lineations observed from orbit does not necessarily represent the distribution of magnetized material at depth. Still, emplacement of the magnetic signatures during thickening of the southern crust could at least explain the higher strength and concentration of remanent magnetic signatures in the southern hemisphere, particularly if degree-1 convection promotes the development of a hemispherical dynamo (Stanley et al., 2008).

The formation of Tharsis on the dichotomy boundary also favors the endogenic theory of dichotomy formation. If degree-1 convection sufficiently thickens the southern crust, it would create a layer of highly viscous melt residue under the thickened crust. This lateral variation in viscosity could cause differential rotation of the lithosphere or migration of the degree-1 upwelling, until the plume reaches the dichotomy boundary and creates Tharsis (Zhong, 2009; Šrámek and Zhong, 2010, 2012). Plume migration from the south pole to Tharsis' location is supported by observations of volcanic resurfacing, demagnetization, and increased crustal thickness along that path (Hynek et al., 2011; Cheung and King, 2014), and is consistent with the creation of Tharsis within a few hundred Myrs of dichotomy formation (*e.g.*, Nimmo and Tanaka, 2005, and references therein).

1.2. A hybrid origin

Neither a purely exogenic nor endogenic model can easily or obviously explain all geophysical observations related to dichotomy formation. Because of this, we examine a hybrid model in which a giant impact forms the Borealis basin, producing an initial nearly hemispherical difference in crustal thickness and composition that induces degree-1 convection with the upwelling centered under the thicker, enriched (in radiogenic-heat producing elements) crust opposite the impact site (Fig. 1). Although initially an upwelling should develop under the impact site, such an upwelling should dissipate relatively quickly (*e.g.*, Roberts and Arkani-Hamed, 2017), allowing for the composition and structure of the crust/lithosphere to control the convection pattern over longer timescales (100s of Myr). We expect the northern and southern post-impact crusts to differ in composition, specifically the concentration of radiogenic-heat producing elements, because of the depletion of such elements from the mantle over time. During Mars' initial crust formation, radiogenic-heat producing elements would be partitioned into the crust, creating an ancient crust enriched in such elements and depleting the mantle of the same elements. The giant impact would strip the northern hemisphere of its original, enriched crust, and the new crust in the northern hemisphere would be derived from an already depleted mantle, resulting in a new northern crust that is depleted in radiogenic-heat producing elements relative to the southern crust. The compositional difference between the newer depleted crust in the northern hemisphere and the ancient crust in the southern hemisphere could persist for billions of years (Ruedas and Breuer, 2017). On early Mars, the thicker, enriched crust in the hemisphere opposite the impact should have an insulating effect that increases the mantle temperature and promotes hot spot and plume formation under the thicker, enriched