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Constraints on the formation of the Martian crustal dichotomy from remnant crustal magnetism

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ABSTRACT

The Martian crustal dichotomy characterizing the topographic difference between the northern and southern hemispheres is one of the most important features on Mars. However, the formation mechanism for the dichotomy remains controversial with two competing proposals: exogenic (e.g., a giant impact) and endogenic (e.g., degree-1 mantle convection) mechanisms. Another important observation is the Martian crustal remnant magnetism, which shows a much stronger field in the southern hemisphere than in the northern hemisphere and also magnetic lineations. In this study, we examine how exogenic and endogenic mechanisms for the crustal dichotomy are constrained by the crustal remnant magnetism. Assuming that the dichotomy is caused by a giant impact in the northern hemisphere, we estimate that the average thickness of ejecta in the southern hemisphere is 20–25 km. While such a giant impact may cause crustal demagnetization in the northern hemisphere, we suggest that the impact could also demagnetize the southern hemisphere via ejecta thermal blanketing, impact demagnetization, and heat transfer from the hot layer of ejecta, thus posing a challenge for the giant impact model. We explore how the pattern of magnetic lineations relates to endogenic theories of dichotomy formation, specifically crustal production via degree-1 mantle convection. We observe that the pattern of lineations roughly corresponds to concentric circles about a single pole, and determine the pole for the concentric circles at 76.5° E and 84.5° S, which nearly overlaps with the centroid of the thickened crust in the southern hemisphere. We suggest that the crustal magnetization pattern, magnetic lineations, and crustal dichotomy (i.e., thickened crust in the highlands) can be explained by a simple endogenic process; one-plume convection causes melting and crustal production above the plume in the southern hemisphere, and strong crustal magnetization and magnetic lineations are formed in the southern hemisphere as crustal production fronts spread radially out from the plume center and as the newly created crust cools in the presence of a dynamo with polarity reversals.

1. Introduction

The origin of the Martian crustal dichotomy, ~5 km difference in surface elevation and ~26 km difference in crustal thickness (Fig. 1a) between the plains in the northern hemisphere and the highlands in the southern hemisphere (Smith et al., 1999; Zuber, 2001; Neumann et al., 2004; Watters et al., 2007), remains controversial. The formation is generally attributed to either an exogenic event such as a giant impact (Wilhelms and Squyres, 1984; Frey and Schultz, 1988; Marinova et al., 2008; Nimmo et al., 2008; Andrews-Hanna et al., 2008), or an endogenic process such as plate tectonics (Sleep, 1994) or degree-1 mantle convection (Zhong and Zuber, 2001; Elkins-Tanton et al., 2005; Ke and Solomatov, 2006; Roberts and Zhong, 2006; Keller and Tackley, 2009; Šrámek and Zhong, 2010, 2012). Other theories of dichotomy formation have also been proposed, such as an impact megadome produced in the same hemisphere as a giant impact (Reese et al., 2011), or impact induced core formation and subsequent mantle evolution (Lin et al., 2011). Determining which of these processes formed the crustal dichotomy is critical to understanding the evolution of Mars, yet observations of crustal thickness and surface features alone have been unable to decisively determine the origin of the Martian crustal dichotomy. Further constraints are necessary to distinguish different theories of dichotomy formation. In this work, we compare various mechanisms of dichotomy formation by examining a process that can be influenced on a global scale by both exogenic and endogenic processes: remnant crustal magnetism.

Widespread magnetic signatures were observed with the magnetic field experiment/electron reflectometer on the Mars Global Surveyor mission (Acuña et al., 1999; Connerney et al., 1999). Though the magnetic anomalies are spread over the entire planet

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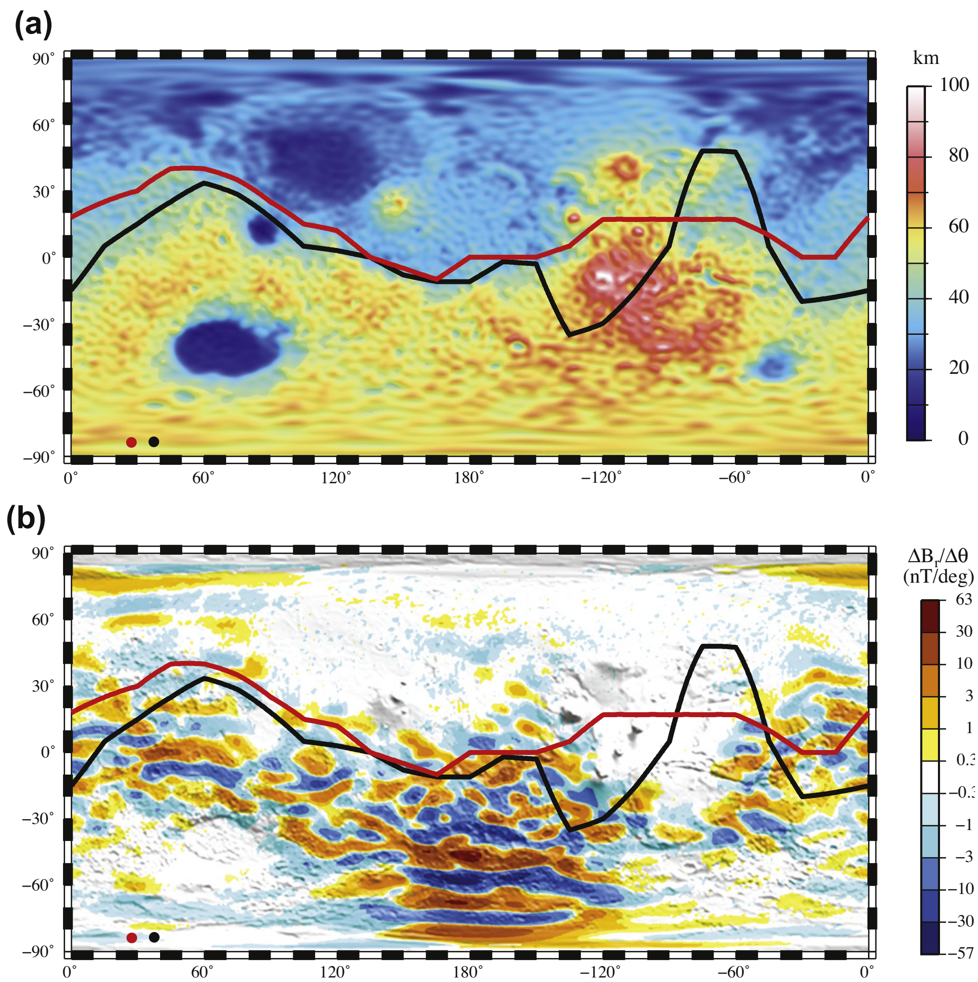

Fig. 1. Martian crustal thickness computed from the Mars Global Surveyor (Neumann et al., 2004) (a) and the map of the magnetic field of mars from the Mars Global Surveyor (Connerney et al., 2005) overlain on MOLA topography (b). Boundaries from Roberts and Zhong (2007) trace the dichotomy edge connecting either side of Tharsis with a straight line (red) or excluding the western portion of Tharsis but tracing the northeastern edge (black). Centroids of a uniformly thick southern crust are plotted as red and black circles, corresponding to the respective boundary used for the calculation.

(Fig. 1b), the crustal magnetization in the northern hemisphere is much weaker than that in the southern hemisphere (Acuña et al., 1999). Additionally, the signatures display a unique pattern of east–west trending anomalies found in several models of crustal sources (Fig. 2a), commonly referred to as lineations, that are 100–200 km wide and can be as long as 2000 km (Connerney et al., 1999, 2001, 2005; Purucker et al., 2000; Arkani-Hamed, 2002; Cain et al., 2003; Langlais et al., 2004; Hood et al., 2005; Lillis et al., 2008). The lineations are found to alternate in polarity (e.g., Connerney et al., 2005), although this notion is disputed recently by other interpretations of the magnetic field data (Lillis et al., 2008). Assuming that the alternating polarity is valid, several theories have been suggested to explain the presence and polarity of the lineations: plate tectonics (Connerney et al., 1999, 2001, 2005; Sprenke and Baker, 2000; Whaler and Purucker, 2005), accretion of terrains (Fairén et al., 2002; Baker et al., 2002; Dohm et al., 2002), chemical remnant magnetization (Connerney et al., 1999), dike intrusion with a moving locus (Nimmo, 2000), and plume tracks from lithospheric drift (Kobayashi and Sprenke, 2010). Particularly, because patterns of alternating magnetic lineations are created on the earth's seafloor together with the production of oceanic crust in the plate tectonic process (Pitman and Heirtzle, 1966; Vine and Matthews, 1963), it has been suggested that the lineations observed on Mars may be related to similar processes of plate tectonics and crustal production (Connerney et al., 2005).

Mars likely had an active dynamo sometime before the Late Heavy Bombardment (Stanley et al., 2008; Nimmo and Tanaka, 2005), evidenced by the absence of crustal magnetic signatures in large impact basins such as Hellas and Argyre (Acuña et al., 1999). This is congruent with models of the Martian dynamo, in which multiple impacts would have caused a cessation of activity shortly after the Utopia impact (~4.1 Ga) (Roberts et al., 2009). The Martian dynamo was likely active during the formation of the crustal dichotomy, which may have occurred sometime between 100's Myr after Mars formation and the late heavy bombardment (Frey, 2006a,b). Such timing is supported by buried impact basins in the lowlands, which could have formed as early as 500 Myr after the formation of Mars (Frey, 2006b), and based on an age of the Utopia basin of ~4.08 Ga (Watters et al., 2007; Frey, 2006a). Clearly, both the crustal dichotomy and magnetic features represent global processes active early in Martian history. Determining the effects of various theories of dichotomy formation on the observed patterns of crustal magnetism could aid in understanding the early history of Mars.

The relation between the origin of the crustal dichotomy and the magnetic signatures revolves around two key questions. For exogenic theories, it is critical to understand if a giant impact will

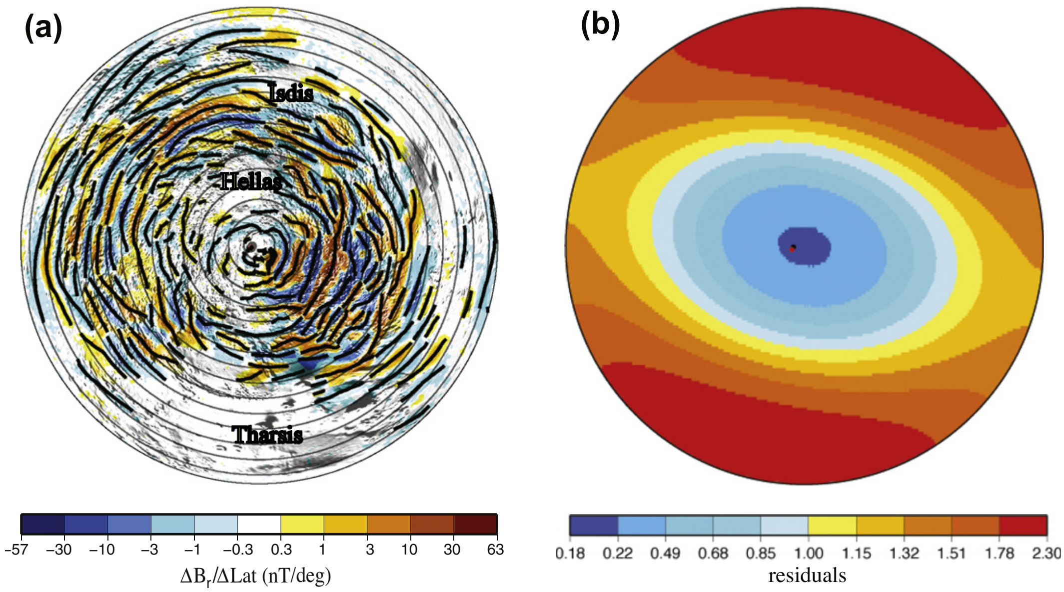

Fig. 2. (a) Polar projection of the magnetic field of Mars from the Mars Global Surveyor (Connerney et al., 2005), centered on 76.5° E, 84.5° S and extending to a horizon of 140 degrees. Concentric circles with a spacing of 1000 km are shown from the plot center. Highland centroids are plotted as red and black circles, as in Fig. 1. Lineations from Kobayashi and Sprenke (2010) are plotted as black lines. (b) Polar projection of the residuals of the lineation pole fits, centered on 76.5° E, 84.5° S and extending to a horizon of 90 degrees. Residuals are the sum of the squares of distance from each point to the best-fit plane for the lineations, for each point on the surface, normalized to the average residual sum across the surface.

weaken or eliminate crustal magnetization in one hemisphere, or over the whole planet via ejecta demagnetization. For endogenic theories, it is important to explore if mantle convection that creates the thickened crust in the southern hemisphere over a 100 Ma or longer time scale could explain the magnetic lineations simultaneously. In this paper, we explore processes relating to both exogenic and endogenic mechanisms of dichotomy formation and their relation to the emplacement or destruction of crustal magnetic signatures. Calculations are done to determine the extent that impact demagnetization could have eliminated magnetic signatures in the southern hemisphere following an impact in the Borealis basin. This is accomplished by calculating crustal geotherms following ejecta emplacement. We also examine if an endogenic mechanism could simultaneously explain magnetic lineations and crustal production in the highlands. We determine where crustal sources would originate during degree-1 mantle convection and compare the location of crustal generation with the distribution of the magnetic lineations. Our results suggest that observations of the crustal magnetic sources can be used to constrain the proposed formation mechanisms of the crustal dichotomy.

2. The crustal dichotomy and crustal magnetization

The two most prominent theories for the formation of the crustal dichotomy are a giant impact and degree-1 mantle convection. A giant oblique impact into the northern hemisphere of Mars would explain the sharpness of the dichotomy edge and the thinning of the northern crust (Andrews-Hanna et al., 2008). Numerical simulations confirm that a giant impact can produce an impact basin and crustal structure similar to present observations (Marinova et al., 2008; Nimmo et al., 2008). Alternatively, degree-1 mantle convection caused by radially stratified viscosity could cause a single upwelling in the southern hemisphere, causing substantial melting and thickening of the southern crust over time (Zhong and Zuber, 2001; Keller and Tackley, 2009; Šrámek and Zhong, 2012). During this process, the creation of a highly viscous melt residue layer beneath the thickened crust in the southern hemisphere could lead to subsequent lithospheric rotation, resulting in the migration of volcanism centers towards the dichotomy boundary and emplacement of Tharsis there (Zhong, 2009; Šrámek and Zhong, 2010, 2012), which is consistent with surface geological and crater density observations (Hynek et al., 2011). Each of these processes may have different implications for crustal magnetic signatures that need to be examined.

From an exogenic perspective, it is generally argued that a giant impact would have de-magnetized preexisting crustal magnetic signatures in the Borealis basin (Solomon et al., 2005; Arkani-Hamed and Boutin, 2004; Nimmo and Tanaka, 2005; Nimmo et al., 2008; Watters et al., 2007), explaining the relative strength of the signature sources between the southern and northern hemispheres. However, it is possible that the southern crust also experienced widespread demagnetization due to the giant impact event because of the large amount of re-accreting material there. The burial of an originally magnetized crust under a new layer of crust can heat the original crust above the Curie temperature (e.g., Connerney et al., 2005). If the layer of ejecta is hot, additional heat transfer can cause demagnetization in a layer of the original crust with thickness that is 0.5–1 times that of the layer of ejecta (Connerney et al., 2005). A giant impact can also demagnetize the crust in the antipodal region to the impact, because of shock wave focusing effects (e.g., Nimmo et al., 2008). Additionally, the shock waves caused by the ejecta impacts can demagnetize the upper few km of original crust, provided that craters over 20 km in diameter are produced globally from the ejecta (Arkani-Hamed and Boutin, 2012). The effects associated with ejecta emplacement allow a significant possibility that a giant impact in the northern hemisphere could have demagnetized both the northern and southern hemispheres of Mars. However, the extent to which the southern hemisphere is demagnetized during and after a giant impact has not yet been examined in detail.

From an endogenic perspective, the strength of crustal magnetic signatures in the southern hemisphere results from the production of crust from a single upwelling in the presence of a magnetic field. In degree-1 mantle convection scenarios, a single hot upwelling would cause widespread melting and crustal production in the southern hemisphere (Keller and Tackley, 2009; Šrámek and Zhong, 2012). New crustal sources would retain magnetic signatures after cooling. Crustal production in this scenario could also explain the lineations of alternating polarity observed in the crustal magnetic signatures. A single upwelling may produce new crustal sources radially outward from the center of the plume, in a series of concentric circles (Fig. 3a). In the presence of an alternating magnetic field, a pattern of concentric circles of alternating polarity would be expected to form, spreading radially away from the plume upwelling (Fig. 3b and c). In this scenario, the center of the concentric circles or magnetic lineations would be expected to coincide with the center of the thickened crust. The possibility that the lineations are a product of crustal production spreading from a single mantle plume can be examined by comparing the centroid of the thickened crust to the best-fit pole about which the lineations form concentric circles (Fig. 2).

3. Ejecta demagnetization of the crust in the southern hemisphere

The amount of original crust that reaches demagnetization temperatures (i.e., the Curie temperatures) due to thermal blanketing effects of ejecta is largely dependent on the thickness of the ejecta blanket. The thickness of the ejecta layer can be estimated from numerical simulations of giant impacts, the current crustal distribution, and mass balance arguments. Numerical simulations show that the crust in the impact basin or the northern hemisphere is almost completely removed during the proposed impact event (Nimmo et al., 2008; Marinova et al., 2008, 2011). The redistribution of this ejecta material depends on the impact parameters. For impacts of energies $>10^{29}$ J and $\theta \leqslant 45$ degrees, the ejecta is distributed globally, but can lead to large variations in ejecta thickness, yielding post-impact crustal thicknesses in the highlands from doubling the original thickness to unchanged (Marinova et al., 2008, 2011). Impacts with angles >60 degrees produce short-wavelength features, such as an annulus of thicker crust around the impact basin (Marinova et al., 2008, 2011; Nimmo et al., 2008). However, a global distribution of ejecta is supported by numerical studies, which suggest that the features related to the Borealis basin best match impacts of energies $3–6 \times 10^{29}$ J and $\theta = 45$ degrees (Marinova et al., 2008).

The present-day highland crustal thickness is relatively uniform and lacks crustal thickening near the edge of the Borealis basin, except for impact basins and the Tharsis region where the thicker crust is related to Tharsis volcanism (e.g., Zuber, 2001). This suggests that if the dichotomy was caused by the proposed giant impact, either crustal relaxation smoothed an initially diverse distribution of ejecta, or the initial ejecta distribution was relatively global and uniform. Unfortunately, how ejecta and its underlying crust evolve dynamically after a giant impact is poorly understood. It may be a challenge to have crustal relaxation to homogenize the highland crustal thickness variations, while keeping the dichotomy boundaries nearly unchanged, given that the topographic gradient at the dichotomy boundary is largest, although for smaller basins such as Hellas, the thin crust may prohibit crustal flow, thus maintaining the basin shape (Mohit and Phillips, 2006). Assuming a relatively uniform ejecta distribution, the amount of deposited ejecta can be estimated using a simple mass balance argument. According to dichotomy boundaries, the lowlands encompass about 42% of the surface area of Mars (Roberts and Zhong, 2007; Andrews-Hanna et al., 2008). If the impact excavated the entire crust of the northern hemisphere, as the impact models indicated (e.g., Nimmo et al., 2008; Marinova et al., 2008), and if the ejecta was uniformly distributed on the southern hemisphere to give rise to the present-day 58 km thick crust there, then we estimate that the averaged ejecta thickness on the southern highlands is 25 km and the pre-impact crust thickness is 33 km.

Here, we use a simple one-dimensional steady state heat conduction model to determine the conditions under which the temperature increase caused by ejecta burial in the highlands is sufficient to demagnetize the original crust. Because the thickness

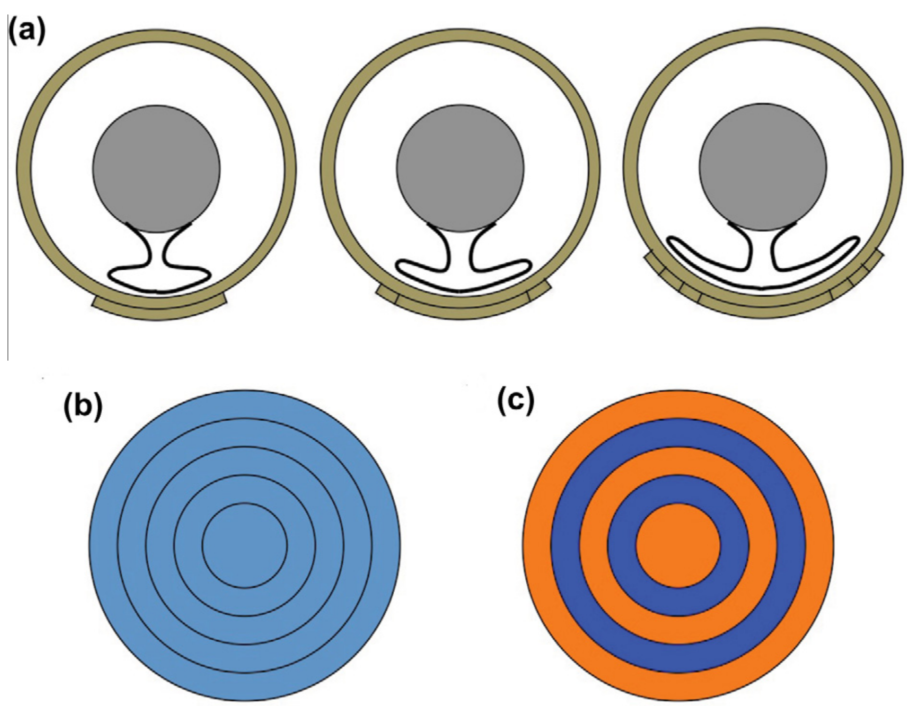

Fig. 3. Cartoons showing that new crust produced during degree-1 mantle convection is emplaced in concentric circles spreading radially from a single upwelling (a). If the crust is produced without a magnetic field, or in the presence of a magnetic field that does not undergo polarity reversals, then a polar projection centered on the upwelling would show concentric circles of crust with the same polarity (b). If crustal production occurs in the presence of a magnetic field that undergoes periodic reversals in polarity, then concentric circles of crust of alternating polarity would be expected (c).

of ejecta is ~20 km as discussed earlier, the time for the crustal temperature to reach a steady state is relatively short and is likely less than 100 Ma. This steady state temperature following the impact is the relevant temperature for demagnetization of the original crust covered by ejecta. Our model consists of a layer of original crust with thickness of L, covered by a layer of ejecta with thickness of h. We assume that the mantle heat flux for the crust (i.e., at the crust-mantle boundary) is fixed at q_b. The temperature profile of the original crust and ejecta blanket is determined by the geotherm,

$$T(z) = T_s + \frac{q_b z}{k} + \frac{Hz}{2k}[2(L+h) - z], \quad (1)$$

where z is the depth and is zero at the surface of the ejecta, k is the thermal conductivity, T_s is the surface temperature, and H is the heat generation in the crust.

Covering the original crust, the ejecta can cause the temperature of the original crust to increase to exceed the Curie temperature, thus demagnetizing the crust. For complete demagnetization to occur, approximately the upper 30 km of the original crust must be demagnetized (Nimmo and Watters, 2004). Instantaneous demagnetization occurs at the Curie temperature, which is 700–950 K for haematite, 500–860 K for titano-magnetite, and 600–675 K for pyrrhotite (Nimmo and Tanaka, 2005). However, temperatures in excess of 570 K are sufficient to demagnetize most forms of magnetite if sustained for millions of years, while haematite and pyrrhotite can be viscously demagnetized at temperatures 670–820 K (Shahnas and Arkani-Hamed, 2007; Dunlop and Ozdemir, 1997). Because burial of the original crust will increase temperatures for sustained periods, viscous demagnetization temperatures are reasonable limits for erasing magnetic signatures in the original crust. We compute demagnetization for both 570 and 820 K, although haematite and pyrrhotite are more likely to produce TRM than magnetite (Clark, 1983). While the initial magnetized layer could be between 35–60 km (Nimmo, 2000), it will undergo demagnetization from surface effects and viscous demagnetization from below. Viscous demagnetization could initially leave magnetized only the upper 35, 42, and 20 km for magnetite, haematite, and pyrrhotite, respectively (Shahnas and Arkani-Hamed, 2007; Arkani-Hamed ,2005).

Using estimates of ejecta thickness and demagnetization temperature, Eq. (1) is evaluated to determine the extent of demagnetization in the upper 30 km of the original crust ($z = h$ to $z = h + 30$), with various values of ejecta thickness h and crustal internal heating H (Fig. 4). Because ejecta thickness h may be varied, we compute from $h = 0$ km to a maximum of $h = 33$ km, although the most likely thickness is between 20 and 25 km. A nominal H value of 0.59 μW m^{-3} is given by Nimmo and Tanaka (2005) for a 50 km crust at 4.1 Ga containing 45% of the planet's net heat generation. Heat production in the crust can vary depending on the crustal composition, crustal thickness, and the percent of total heat generation in the crust. Using crustal thicknesses between 25 and 50 km, percent of radiogenic heat production in the crust between 35% and 75% (McLennan, 2001), and bulk heat production between ~0.1 and 0.5 μW m^{-3} (Hauck and Phillips, 2002), we find the heat production in the crust could range from ~0.5 to 2 μW m^{-3}. We use a constant mantle heat flux of q_b = 50 mW m^{-2} (Hauck and Phillips, 2002) and 30 mW m^{-2}, T_s = 200 K, and k = 3 W m^{-1} K^{-1} (Nimmo and Tanaka, 2005).

Fig. 4 shows that for ejecta thickness between 20 and 25 km, the original crust achieves temperatures >570 K at all depths for both q_b = 50 mW m^{-2} and 30 mW m^{-2}. This suggests that viscous demagnetization of magnetite would occur in the original crust for ejecta thickness greater than 20 km. However, viscous demagnetization of haematite and pyrrhotite (T > 820 K) does not occur at shallow depths of the original crust when ejecta thickness is ~20 km, depending on the crustal heat production rate H (Fig. 4b and d). For q_b = 50 mW m^{-2} and h = 20 km, the upper 0 to 5 km of original crust does not reach temperatures greater than 820 K when H is less than 0.9 μW m^{-3} (Fig. 4b). For q_b = 30 mW m^{-2} a more significant fraction of the original crust does not reach 820 K, as much as 15–20 km for H < 0.6 μW m^{-3} and h = 20 km, but <10 km for H > 0.6 μW m^{-3} and h = 25 km (Fig. 4d).

Because the most likely ejecta thickness as suggested by the impact models is ~25 km, our calculations here demonstrate that the ejecta burial of uniform thickness should viscously demagnetize the original crust for q_b = 50 mW m^{-2}; for q_b = 30 mW m^{-2}, the upper 5–10 km of original crust does not reach viscous demagnetization temperatures for haematite and pyrrhotite when H is less than 0.8–1.0 μW m^{-3}. It should be pointed out that our model gives a conservative estimate of demagnetization, because other processes that we ignored also contribute to demagnetization. Saturating the Mars surface with impacts that form craters at least 20 km in diameter can demagnetize the upper 10–15 km of crust as a result of the shock pressure, excavation, and gardening (Arkani-Hamed and Boutin, 2012). Additionally, if the emplaced ejecta are hot, it could demagnetize a crustal layer at least half the thickness of the ejecta layer (Connerney et al., 2005). Shock heating and heat transfer during the ejecta emplacement could contribute to demagnetization of the upper 5–10 km of original crust. Therefore, we conclude that for a uniform and global ejecta distribution on the highlands, the thermal blanketing effect of the ejecta is likely to demagnetize the original crust in the highlands, making it difficult to explain the observed crustal magnetization.

4. Formation of magnetic lineations

We examine the connection between degree-1 mantle convection and magnetic signatures by determining if the lineations form a pattern of concentric circles that originate near the centroid of the highlands. The set of lineations are taken from Kobayashi and Sprenke (2010), which are derived from the maxima and minima of the ΔB_r map from Connerney et al. (2005) (Fig. 2a). We begin by fitting the lineations to a set of poles spaced across the Martian surface. For a given pole, each lineation is fit to a small circle about the pole using the least-squares method. The fit optimizes a best-fit small circle through the lineation points, ensuring the small circle is about the chosen pole. For each pole, a goodness of fit is estimated by computing the sum of the residuals between each lineation and the respective best-fit small circle. The residuals for each lineation are simply the sum of the squares of the difference between each evenly spaced lineation point and the best-fit small circle, yielding a naturally higher weighting for longer lineations that contain more points. This process is repeated for poles with 0.5 degree spacing on the Mars surface, determining which pole has the minimum sum of residuals. We find the best-fit pole intersects the Martian surface at 76.5° E, 84.5° S (Fig. 2b).

We also examined the effect of weighting our analysis using the strength of the magnetic field in order to minimize the effect of regions with weak crustal fields. The process described above was repeated using a linear weight for each lineation based on the mean strength of magnetic field over the length of the lineation. We find that the weighted best-fit pole intersects the Martian surface at 66.5° E, 81.5° S which differs from the non-weighted pole by ~3° in arc distance, suggesting that the weak field bias is small. Kobayashi and Sprenke (2010) also determined such poles for the lineations using a different scheme. They divided the lineations into two sets and determined two different poles, one for each set. The pole locations from our analyses differ by <4° in arc distance from one of the poles from Kobayashi and Sprenke (2010).

The center of the thickened crust is determined by calculating the centroid of the crust in the southern highlands according to

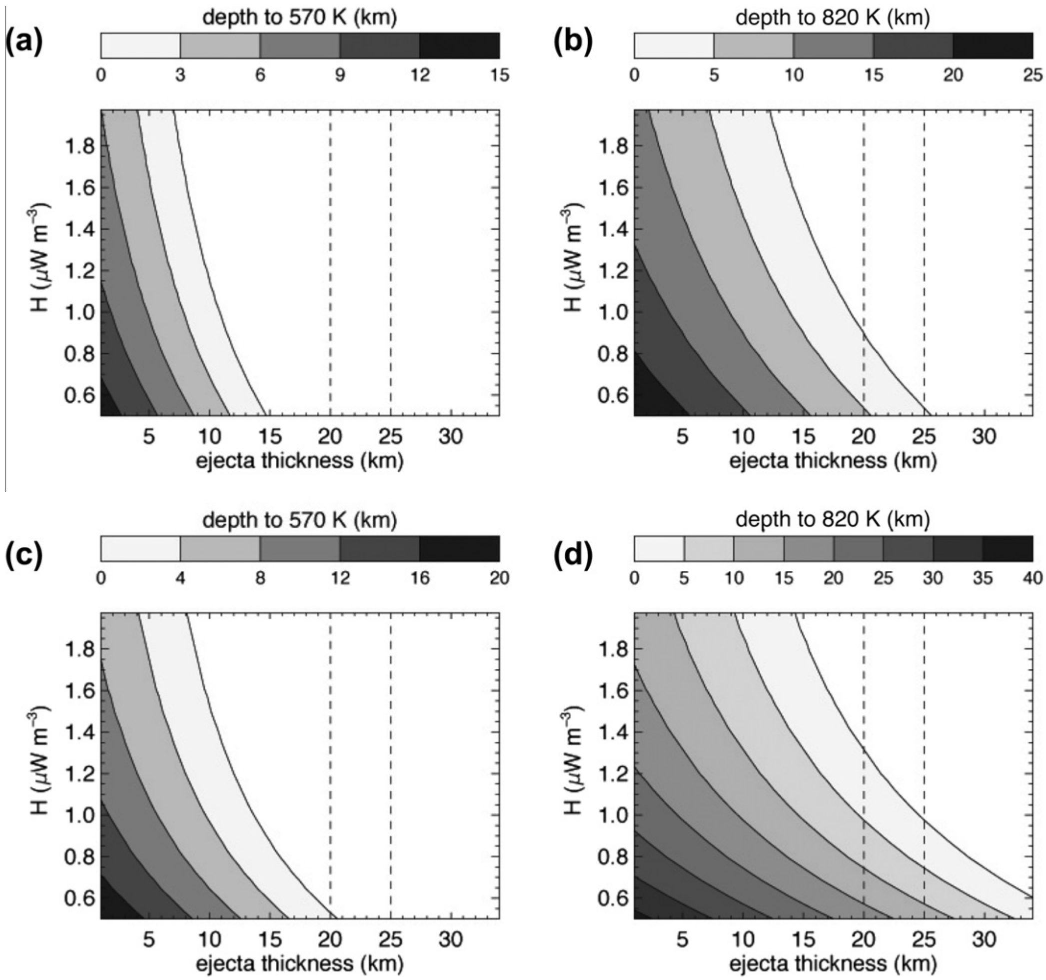

Fig. 4. The depth in the original crust to the isotherm of viscous demagnetization for 570 K (magnetite) and 820 K (pyrrhotite and haematite) for q_b = 50 mW m^{-2} (a and b) and q_b = 30 mW m^{-2} (c and d), plotted as a function of ejecta thickness *h*, and heat production in the crust *H*. The depth to the viscous demagnetization temperature is the same as kilometers (in depth) of original crust that does not achieve sufficient temperature increase from ejecta burial to cause viscous demagnetization. Dashed vertical lines bound the most likely range of ejecta thickness.

Table 1
Comparison of various points by distance to the best-fit pole for the magnetic lineations. Black and Red centroids represent centers of mass computed from the black or red dichotomy boundary in Fig. 1. Antipodes are also listed from proposed centers of a dichotomy-forming giant impact (Marinova et al., 2008; Andrews-Hanna et al., 2008; Nimmo et al., 2008).

Pole	Long (0–360 deg)	Lat (deg)	Dist. to center (km)	Arcdist. to center (deg)
Black centroid	37.29	−83.49	245	4.1
Red centroid	27.18	−83.78	291	4.9
Marinova et al. (2008)	26	−66	1237	20.9
Andrews-Hanna et al. (2008)	28	−67	1169	19.8
Nimmo et al. (2008)	350	−50	2365	40.0

the crustal dichotomy boundaries given by Roberts and Zhong (2007), as shown in Fig. 1. The red boundary uses the middle of the dichotomy transition and connects the two boundary points on either side of Tharsis with a straight line (Roberts and Zhong, 2007). The black boundary uses the south edge of the dichotomy transition and excludes the western region of Tharsis (Roberts and Zhong, 2007; Zuber, 2001). The centers of the thickened crust are found to compare reasonably well with the center of the best-fit poles for the magnetic lineations (Table 1). The black crustal model has a center of mass that is only 4.1° (245 km) from the non-weighted best-fit pole for magnetic lineations (Fig. 2) and 4.2° (251 km) from the weighted pole. The centers of mass for the two crustal models differ from the antipodes of the proposed giant impact sites by 20–40° in arc distance (∼1200–2400 km) (Table 1) (Marinova et al., 2008; Andrews-Hanna et al., 2008). However, it should be noted that the center of the impact from Nimmo et al. (2008), based on surface observations of Wilhelms and Squyres, (1984), is ∼63° in arc distance (>4000 km) from that proposed by Andrews-Hanna et al. (2008). In general, the centroids of the highlands appear to be distant from the proposed impact antipodes but near the best-fit center for a radial spreading of magnetic lineation emplacement.

5. Conclusions and discussion

In this study, we examined the implications of crustal magnetization for two prominent theories of the formation of the Martian crustal dichotomy: a giant impact and degree-1 mantle convection. Using a simple steady state heat conduction model, we determined the conditions (i.e., ejecta thickness and crustal radiogenic heating) under which the ejecta emplaced on the southern highlands from a giant impact may cause sufficient temperature increase in the original crust to lead to demagnetization. We estimated that the average ejecta thickness in the southern highlands is most likely ~25 km to explain the crustal dichotomy and the crustal structure, if we consider the recent giant impact models that all predict complete crustal removal of the northern plains by the impact (e.g., Marinova et al., 2008). We found that for a commonly accepted amount of crustal radiogenic heating H, 25 km thick ejecta may raise the temperature of the original crust enough to cause viscous demagnetization of magnetite. For haematite and pyrrhotite, at lower values of H or mantle heat flux q_b, the upper 5–15 km of the original crust may not reach the viscous demagnetization temperature. However, ejecta cratering and heat transfer from the emplacement of a hot ejecta layer may be sufficient to remove pre-existing magnetic signatures in the upper 5–15 km of original crust. Therefore, our results suggest that if a giant impact formed the Martian crustal dichotomy, significant demagnetization of the southern highlands would occur, thus presenting a difficulty for the giant impact model in explaining the observed strong crustal magnetization in the southern highlands. The fundamental difficulty in reconciling the giant impact model with the magnetic signatures is that while the ejecta is used to produce the thickened crust in the southern hemisphere, the impact may not explain neither the crustal magnetization nor their lineations observed in the highlands.

Considering that the magnetic lineations display concentric features, we determined the center of the concentric lineations to be at 76.5° E, 84.5° S. This result was compared to the center of the southern highland crust, which was determined by considering two different possible dichotomy boundaries at Tharsis. We found that the center of magnetic lineations is nearly identical to that of the southern highland crust. This leads us to propose the following formation mechanism that explains simultaneously the thickened crust in the southern highlands (i.e., the crustal dichotomy), the strong crustal magnetization, and the magnetic lineations there. This mechanism is based on degree-1 convection in which a one-plume convection leads to significant melting and crustal production in the southern hemisphere, forming the Martian crustal dichotomy. The emplacement locus of new crustal sources spreads radially away from the upwelling plume over time, forming a series of concentric rings of crust about the plume center (Fig. 3). The newly emplaced crust retained magnetic signatures as it cooled via thermoremnant magnetism. If this occurs in the presence of a dynamo that undergoes polarity reversals, then the rings of crust emplaced subsequently would retain magnetic signatures that alternate in polarity. The proposed sequence of events would occur before Tharsis formation. In a recent proposed model for Tharsis formation, the one-plume structure, after producing the thickened crust in the highlands and sufficiently thick melt residue below (i.e., the keels), would rotate away from the highlands to the dichotomy boundary, causing additional melting and forming Tharsis (Zhong, 2009; Šrámek and Zhong, 2012). The melting associated with migration of the plume and the Tharsis formation occurs after the termination of the Martian dynamo, and weakens or remove the crustal magnetic field in the Tharsis region and along the plume path, supported by the observation (Hynek et al., 2011).

An important caveat in our study is the uniform distribution of ejecta in the southern highlands from the proposed giant impact. If the ejecta thickness is non-uniform, some regions may have little or no increase in crustal thickness while other regions may double in thickness (Marinova et al. 2008; Nimmo et al., 2008). This would cause variable demagnetization due to thermal blanketing across the southern highlands. However, current observations do not show significant variations in crustal thickness in the highlands (apart from impact basins and Tharsis), suggesting that either the ejecta thickness was initially uniform, or crustal relaxation homogenized any significant variations. A number of studies examined crustal relaxation associated with dichotomy boundary (e.g., Zuber et al., 2000; Nimmo and Stevenson, 2001), but crustal relaxation following a giant impact is not well studied. However, if we accept that the current dichotomy boundaries demark the original impact basin (Andrews-Hanna et al., 2008), we have to conclude that crustal relaxation is rather limited, because the relaxation effect would be the strongest at the dichotomy boundaries where the topographic gradient is largest. Additionally, the distribution of magnetic signatures in the southern highlands also shows no significant variations that might indicate a non-uniform ejecta distribution. Demagnetization in the highlands is limited to the Tharsis region and the Argyre and Hellas impact basins, and is explained by those post-dichotomy events (e.g., Mohit and Arkani-Hamed, 2004; Jellinek et al., 2008).

Another possible scenario proposed in the framework of a giant impact origin for the crustal dichotomy is to create the crustal magnetization after the giant impact. For example, a giant impact may induce a dynamo only operating in the opposite hemisphere, thus explaining the strong magnetization of the southern crust (Stanley et al., 2008; Lin et al., 2011). However, it is unclear in this model how the crustal materials in the southern hemisphere that are magnetized after the impact are created and acquire magnetic lineations. A giant impact in the southern hemisphere may create a hemispherical magma ocean there that cools and solidifies to form the thickened crust (i.e., crustal dichotomy) that acquires crustal magnetization (Reese et al., 2011). However, it is unclear how this mechanism explains the magnetic lineations, given that the cooling and solidification of the magma ocean should happen on a short time-scale and progress uniformly in the vertical direction across the entire magma ocean.

Further studies of ejecta emplacement during a Borealis-scale impact could determine the magnitude and distribution of ejecta demagnetization of crustal sources in the southern hemisphere. Additionally, studies of crustal magnetization during crustal thickening could also explore the feasibility of producing the magnetic lineations during degree-1 mantle convection. Degree-1 mantle convection models with crustal production (e.g., Šrámek and Zhong, 2012) need improved melting calculations and treatment of time evolution. Further analysis of how the formation and destruction of magnetic signatures relate to the formation of the crustal dichotomy is critical to determining what processes were prevalent during the early history of Mars. Current exogenic theories of crustal dichotomy origin present several inconsistencies with the observations of crustal magnetism, while endogenic theories may explain the simultaneous thickening of the southern crust and emplacement of magnetic signatures.

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References

Acuña, M.H., Connerney, J.E.P., Ness, N.F., Lin, R.P., Mitchell, D., Carlson, C.W., McFadden, J., Anderson, K.A., Rème, H., Mazelle, C., Vignes, D., Wasilewski, P., Cloutier, P., 1999. Global distribution of crustal magnetization discovered by the mars global surveyor MAG/ER experiment. Science 284, 790–793. http://dx.doi.org/10.1126/science.284.5415.790.

Andrews-Hanna, J.C., Zuber, M.T., Banerdt, W.B., 2008. The Borealis basin and the origin of the Martian crustal dichotomy. Nature 453, 1212–1215. http://dx.doi.org/10.1038/nature07011.

Arkani-Hamed, J., 2002. Magnetization of the Martian crust. J. Geophys. Res. 107, 5032. http://dx.doi.org/10.1029/2001JE001496.

Arkani-Hamed, J., 2005. Magnetic crust of Mars. J. Geophys. Res. 110, E08005. http://dx.doi.org/10.1029/2004JE002397.

Arkani-Hamed, J., Boutin, D., 2004. Paleomagnetic poles of Mars: revisited. J. Geophys. Res. 109, E03011. http://dx.doi.org/10.1029/2003JE002229.

Arkani-Hamed, J., Boutin, D., 2012. Low-magnetic crust underlying South Province of Mars. Icarus 217, 209–230. http://dx.doi.org/10.1016/j.icarus.2011.10.023.

Baker, V.R., Maruyama, S., Dohm, J.M., 2002. A Theory for the Geological Evolution of Mars and Related Synthesis (GEOMARS). Lunar and Planetary Science Conference XXXIII, Abstract 1586.

Cain, J.C., Ferguson, B.B., Mozzoni, D., 2003. An $n = 90$ internal potential function of the Martian crustal magnetic field. J. Geophys. Res. 108, 5008. http://dx.doi.org/10.1029/2000JE001487.

Clark, D., 1983. Comments on magnetic petrophysics. Explor. Geophys. 14, 49–62. http://dx.doi.org/10.1071/EG983049.

Connerney, J.E.P., Acuña, M.H., Wasilewski, P.J., Ness, N.F., Rème, H., Mazelle, C., Vignes, D., Lin, R.P., Mitchell, D.L., Cloutier, P.A., 1999. Magnetic lineations in the ancient crust of Mars. Science 284, 794–798. http://dx.doi.org/10.1126/science.284.5415.794.

Connerney, J.E.P., Acuña, M.H., Wasilewski, P.J., Kletetschka, G., Ness, N.F., Rème, H., Lin, R.P., Mitchell, D.L., 2001. The global magnetic field of Mars and implications for crustal evolution. Geophys. Res. Lett. 28, 4015–4018. http://dx.doi.org/10.1029/2001GL013619.

Connerney, J.E.P., Acuña, M.H., Ness, N.F., Kletetschka, G., Mitchell, D.L., Lin, R.P., Reme, H., 2005. Tectonic implications of Mars crustal magnetism. Proc. Natl. Acad. Sci. 102, 14970–14975. http://dx.doi.org/10.1073/pnas.0507469102.

Dohm, J.M., Maruyama, S., Baker, V.R., Anderson, R.C., Ferris, J.C., Hare, T.M., 2002. Plate Tectonism on Early Mars: Diverse Geological and Geophysical Evidence. Lunar and Planetary Science XXXIII, Abstract 1639.

Dunlop, D., Ozdemir, O., 1997. Rock Magnetism: Fundamentals and Frontiers. Cambridge Univ. Press, New York, p. 573.

Elkins-Tanton, L.T., Hess, P.C., Parmentier, E.M., 2005. Possible formation of ancient crust on Mars through magma ocean processes. J. Geophys. Res. 110, E12S01. http://dx.doi.org/10.1029/2005JE002480.

Fairén, A.G., Ruiz, J., Anguita, F., 2002. An origin for the linear magnetic anomalies on Mars through accretion of terranes: implications for dynamo timing. Icarus 160, 220–223. http://dx.doi.org/10.1006/icar.2002.6942.

Frey, H.V., 2006a. Impact constraints on, and a chronology for, major events in early Mars history. J. Geophys. Res. 111, E08S91. http://dx.doi.org/10.1029/2005JE002449.

Frey, H.V., 2006b. Impact constraints on the age and origin of the lowlands of Mars. Geophys. Res. Lett. 33, L08S02. http://dx.doi.org/10.1029/2005GL024484.

Frey, H., Schultz, R.A., 1988. Large impact basins and the mega-impact origin for the crustal dichotomy on Mars. Geophys. Res. Lett. 15, 229–232. http://dx.doi.org/10.1029/GL015i003p00229.

Hauck, S.A., Phillips, R.J., 2002. Thermal and crustal evolution of Mars. J. Geophys. Res. 107, 5052. http://dx.doi.org/10.1029/2001JE001801.

Hood, L.L., Young, C.N., Richmond, N.C., Harrison, K.P., 2005. Modeling of major Martian magnetic anomalies: further evidence for polar reorientations during the Noachian. Icarus 177, 144–173. http://dx.doi.org/10.1016/j.icarus.2005.02.008.

Hynek, B.M., Robbins, S.J., Šrámek, O., Zhong, S.J., 2011. Geological evidence for a migrating Tharsis plume on early Mars. Earth Planet. Sci. Lett. 310, 327–333. http://dx.doi.org/10.1016/j.epsl.2011.08.020.

Jellinek, A.M., Johnson, C.L., Schubert, G., 2008. Constraints on the elastic thickness, heat flow, and melt production at early Tharsis from topography and magnetic field observations. J. Geophys. Res. 113, E09004. http://dx.doi.org/10.1029/2007JE003005.

Ke, Y., Solomatov, V.S., 2006. Early transient superplumes and the origin of the Martian crustal dichotomy. J. Geophys. Res. 111, E10001. http://dx.doi.org/10.1029/2005JE002631.

Keller, T., Tackley, P.J., 2009. Towards self-consistent modeling of the Martian dichotomy: the influence of one-ridge convection on crustal thickness distribution. Icarus 202, 429–443. http://dx.doi.org/10.1016/j.icarus.2009.03.029.

Kobayashi, D., Sprenke, K.F., 2010. Lithospheric drift on early Mars: evidence in the magnetic field. Icarus 210, 37–42. http://dx.doi.org/10.1016/j.icarus.2010.06.015.

Langlais, B., Purucker, M.E., Mandea, M., 2004. Crustal magnetic field of Mars. J. Geophys. Res. 109, E02008. http://dx.doi.org/10.1029/2003JE002048.

Lillis, R.J., Frey, H.V., Manga, M., Mitchell, D.L., Lin, R.P., Acuña, M.H., Bougher, S.W., 2008. An improved crustal magnetic field map of Mars from electron reflectometry: highland volcano magmatic history and the end of the Martian dynamo. Icarus 194, 575–596. http://dx.doi.org/10.1016/j.icarus.2007.09.032.

Lin, J.-R., Gerya, T.V., Tackley, P.J., Yuen, D.A., Golabek, G.J., 2011. Protocore destabilization in planetary embryos formed by cold accretion: feedbacks from non- Newtonian rheology and energy dissipation. Icarus 213, 24–42. http://dx.doi.org/10.1016/j.icarus.2011.02.021.

Marinova, M.M., Aharonson, O., Asphaug, E., 2008. Mega-impact formation of the Mars hemispheric dichotomy. Nature 453, 1216–1219. http://dx.doi.org/10.1038/nature07070.

Marinova, M.M., Aharonson, O., Asphaug, E., 2011. Geophysical consequences of planetary-scale impacts into a Mars-like planet. Icarus 211, 960–985. http://dx.doi.org/10.1016/j.icarus.2010.10.032.

McLennan, S.M., 2001. Crustal heat production and the thermal evolution of Mars. Geophys. Res. Lett. 28, 4019–4022. http://dx.doi.org/10.1029/2001GL013743.

Mohit, P.S., Arkani-Hamed, J., 2004. Impact demagnetization of the Martian crust. Icarus 168, 305–317.

Mohit, P.S., Phillips, R.J., 2006. Viscoelastic evolution of lunar multiring basins. J. Geophys. Res. 111, E12001. http://dx.doi.org/10.1029/2005JE002654.

Neumann, G.A., Zuber, M.T., Wieczorek, M.A., McGovern, P.J., Lemoine, F.G., Smith, D.E., 2004. Crustal structure of Mars from gravity and topography. J. Geophys. Res. 109, E08002. http://dx.doi.org/10.1029/2004JE002262.

Nimmo, F., 2000. Dike intrusion as a possible cause of linear Martian magnetic anomalies. Geology 28, 391–394.

Nimmo, F., Stevenson, D.J., 2001. Estimates of Martian crustal thickness from viscous relaxation of topography. J. Geophys. Res. 106, 5085–5098. http://dx.doi.org/10.1029/2000JE001331.

Nimmo, F., Tanaka, K., 2005. Early crustal evolution of Mars. Annu. Rev. Earth Planet. Sci. 33, 133–161.

Nimmo, F., Watters, T.R., 2004. Depth of faulting on mercury: implications for heat flux and crustal and effective elastic thickness. Geophys. Res. Lett. 31, L02701. http://dx.doi.org/10.1029/2003GL018847.

Nimmo, F., Hart, S.D., Korycansky, D.G., Agnor, C.B., 2008. Implications of an impact origin for the Martian hemispheric dichotomy. Nature 453, 1220–1223. http://dx.doi.org/10.1038/nature07025.

Pitman, W., Heirtzle, J., 1966. Magnetic anomalies over Pacific-Antarctic ridge. Science 154, 1164–1166. http://dx.doi.org/10.1126/science.154.3753.1164.

Purucker, M., Ravat, D., Frey, H., Voorhies, C., Sabaka, T., Acuña, M., 2000. An altitude-normalized magnetic map of Mars and its interpretation. Geophys. Res. Lett. 27, 2449–2452. http://dx.doi.org/10.1029/2000GL000072.

Reese, C.C., Orth, C.P., Solomatov, V.S., 2011. Impact megadomes and the origin of the Martian crustal dichotomy. Icarus 213, 433–442. http://dx.doi.org/10.1016/j.icarus.2011.03.028.

Roberts, J.H., Zhong, S.J., 2006. Degree-1 convection in the Martian mantle and the origin of the hemispheric dichotomy. J. Geophys. Res. 111, E06013. http://dx.doi.org/10.1029/2005JE002668.

Roberts, J.H., Zhong, S.J., 2007. The cause for the north-south orientation of the crustal dichotomy and the equatorial location of Tharsis on Mars. Icarus 190, 24–31. http://dx.doi.org/10.1016/j.icarus.2007.03.002.

Roberts, J., Lillis, R., Manga, M., 2009. Giant impacts on early Mars and the cessation of the Martian dynamo. J. Geophys. Res. 114, E04009. http://dx.doi.org/10.1029/2008JE003287.

Shahnas, H., Arkani-Hamed, J., 2007. Viscous and impact demagnetization of Martian crust. J. Geophys. Res. 112, E02009. http://dx.doi.org/10.1029/2005JE002424.

Sleep, N.H., 1994. Martian plate tectonics. J. Geophys. Res. 99, 5639–5655. http://dx.doi.org/10.1029/94JE00216.

Smith, D.E., Zuber, M.T., Solomon, S.C., Phillips, R.J., Head, J.W., Garvin, J.B., Banerdt, W.B., Muhleman, D.O., Pettengill, G.H., Neumann, G.A., Lemoine, F.G., Abshire, J.B., Aharonson, O., Brown, D., Hauck, S.A., Ivanov, A.B., Mcgovern, P.J., Zwally, H.J., Duxbury, T.C., 1999. The global topography of Mars and implications for surface evolution. Science 284, 1495–1503. http://dx.doi.org/10.1126/science.284.5419.1495.

Solomon, S.C., Aharonson, O., Aurnou, J.M., Banerdt, W.B., Carr, M.H., Dombard, A.J., Frey, H.V., Golombek, M.P., Hauck, S.A., Head, J.W., Jakosky, B.M., Johnson, C.L., Mcgovern, P.J., Neumann, G.A., Phillips, R.J., Smith, D.E., Zuber, M.T., 2005. New perspectives on ancient Mars. Science 307, 1214–1220. http://dx.doi.org/10.1126/science.1101812.

Sprenke, K.F., Baker, L.L., 2000. Magnetization, paleomagnetic poles, and polar wander on Mars. Icarus 147, 26–34. http://dx.doi.org/10.1006/icar.2000.6439.

Šrámek, O., Zhong, S.J., 2010. Long-wavelength stagnant-lid convection with hemispheric variation in lithospheric thickness: link between Martian crustal dichotomy and Tharsis? J. Geophys. Res. 115, E09010. http://dx.doi.org/10.1029/2010JE003597.

Šrámek, O., Zhong, S.J., 2012. Martian crustal dichotomy and Tharsis formation by partial melting coupled to early plume migration. J. Geophys. Res. 117, E01005. http://dx.doi.org/10.1029/2011JE003867.

Stanley, S., Elkins-Tanton, L., Zuber, M.T., Parmentier, E.M., 2008. Mars' paleomagnetic field as the result of a single-hemisphere dynamo. Science 321, 1822–1825. http://dx.doi.org/10.1126/science.1161119.

Vine, F., Matthews, D., 1963. Magnetic anomalies over oceanic ridges. Nature 199, 947–949. http://dx.doi.org/10.1038/199947a0.

Watters, T.R., Mcgovern, P.J., Irwin, R.P., 2007. Hemispheres apart: the crustal dichotomy on Mars. Annu. Rev. Earth Planet. Sci. 35, 621–652. http://dx.doi.org/10.1146/annurev.earth.35.031306.140220.

Whaler, K.A., Purucker, M.E., 2005. A spatially continuous magnetization model for Mars. J. Geophys. Res. 110, E09001. http://dx.doi.org/10.1029/2004JE002393.

Wilhelms, D.E., Squyres, S.W., 1984. The Martian hemispheric dichotomy may be due to a giant impact. Nature 309, 138–141. http://dx.doi.org/10.1038/309138a0.

Zhong, S.J., 2009. Migration of Tharsis volcanism on Mars caused by differential rotation of the lithosphere. Nat. Geosci. 2, 19–23. http://dx.doi.org/10.1038/NGEO392.

Zhong, S.J., Zuber, M.T., 2001. Degree-1 mantle convection and the crustal dichotomy on Mars. Earth Planet. Sci. Lett. 189, 75–84.
Zuber, M.T., 2001. The crust and mantle of Mars. Nature 412, 220–227. http://dx.doi.org/10.1038/35084163.
Zuber, M.T., Solomon, S.C., Phillips, R.J., Smith, D.E., Tyler, G.L., et al., 2000. Internal structure and early thermal evolution of Mars from Mars Global Surveyor topography and gravity. Science 287, 1788–1793.