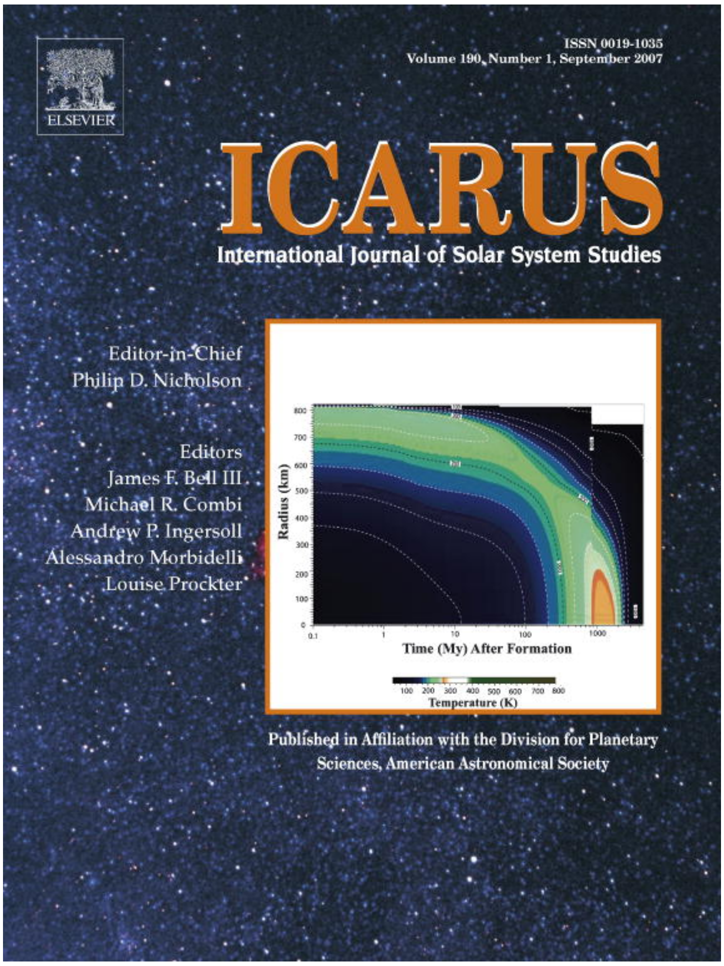
ISSN 0019-1035
Volume 190, Number 1, September 2007
ELSEVIER
ICARUS
International Journal of Solar System Studies
Editor-in-Chief
Philip D. Nicholson
Editors
James F. Bell III
Michael R. Combi
Andrew P. Ingersoll
Alessandro Morbidelli
Louise Prockter
Radius (km)
Time (My) After Formation
Temperature (K)
Published in Affiliation with the Division for Planetary Sciences, American Astronomical Society

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Icarus 190 (2007) 24–31
ICARUS
www.elsevier.com/locate/icarus

The cause for the north–south orientation of the crustal dichotomy and the equatorial location of Tharsis on Mars

James H. Roberts [a,*], Shijie Zhong [b]

[a] *Department of Astrophysical and Planetary Sciences, University of Colorado at Boulder, UCB 390, Boulder, CO 80309-0391, USA*
[b] *Department of Physics, University of Colorado at Boulder, UCB 390, Boulder, CO 80309-0390, USA*

Received 21 September 2006; revised 28 February 2007

Available online 20 March 2007

Abstract

The crustal dichotomy and the Tharsis rise are the most prominent topographic features on Mars. The dichotomy is largely an expression of different crustal thicknesses in the northern and southern hemispheres, while Tharsis is centered near the equator at the dichotomy boundary. However, the cause for the orientation of the dichotomy and the equatorial location of Tharsis remains poorly understood. Here we show that the crustal thickness variations associated with the dichotomy may have driven true polar wander, establishing the north–south orientation of the dichotomy very early in martian history. Such a reorientation that placed the dichotomy boundary near the equator would also have constrained the Tharsis region on the dichotomy boundary to have originated near the equator. We present a scenario for the early generation and subsequent reorientation of the hemispheric dichotomy, although the reorientation is independent of the formation mechanism. Our results also have implications for the sharply different remanent magnetizations between the two hemispheres.

Keywords: Mars; Geophysics; Rotational dynamics

1. Introduction

The crustal dichotomy is one of the oldest features on Mars (Smith et al., 1999b) and is thought to have formed during or before the Early Noachian (Frey et al., 2002; Nimmo and Tanaka, 2005; Solomon et al., 2005). The Tharsis rise developed significantly later, and was largely emplaced by the Late Noachian (Phillips et al., 2001). No explanation has been proposed for why the dichotomy boundary should be roughly along the planet's equator (Fig. 1a) rather than in some other orientation. However, the location of Tharsis near the equator and observations of a large positive geoid anomaly (Smith et al., 1999a) associated with the province have lead to a number of studies examining the possibility of an episode of true polar wander (TPW) driven by Tharsis (Melosh, 1980; Willemann, 1984; Zuber and Smith, 1997). Although it has never been explicitly stated, TPW due to the Tharsis rise seems to be an appealing mechanism for explaining the north–south orientation of the dichotomy. However, this mechanism has two difficulties.

First, previous studies suggest that potential TPW due to Tharsis is limited. Based on moment of inertia calculations, Melosh (1980) determined that Tharsis may have driven up to 25° of TPW. However, it was also recognized that there was little tectonic evidence for significant Tharsis-induced TPW (Melosh, 1980; Grimm and Solomon, 1986), although many other tectonic features including faulting, extensional grabens and contractional ridges associated with the formation of Tharsis have been identified (Anderson et al., 2001). If the stabilizing effect of a ⩾100 km thick elastic lithosphere at the time of Tharsis formation (Zuber et al., 2000; Phillips et al., 2001; McGovern et al., 2002) is considered, the potential for TPW is reduced even further (Willemann, 1984). Collectively, these studies (Melosh, 1980; Willemann, 1984; Grimm and Solomon, 1986; Zuber and Smith, 1997) really suggested that Tharsis formed near the equator originally. However, no explanation has been given for this apparent coincidence.

* Corresponding author. Now at: Department of Earth and Planetary Sciences, University of California at Santa Cruz, 1156 High Street, Santa Cruz, CA 95064-1077, USA. Fax: +1 (831) 459 3074.
E-mail address: jhr@ucsc.edu (J.H. Roberts).

0019-1035/$ – see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2007.03.002

Second, even if Tharsis were able to produce a large amount of TPW, it may not have necessarily resulted in the north–south dichotomy orientation. Assuming the dichotomy had some arbitrary orientation (e.g., east–west) prior to Tharsis, then Tharsis must have formed at the northernmost or southernmost extent of the dichotomy boundary to produce the north–south orientation. Formation of Tharsis at any other location along the dichotomy boundary (e.g., near the equator) would leave the dichotomy in some arbitrary orientation after the TPW. Fig. 2 illustrates this problem. We consider an extreme case in which the dichotomy forms east–west (Fig. 2a). 90° of TPW are required to bring the dichotomy into a north–south orientation. If this TPW is due to Tharsis, then Tharsis must form at one of the poles (black load at south pole in Fig. 2a). However, in this situation the TPW path is uncertain. Tharsis could migrate perpendicular to the dichotomy boundary (curved arrow), bringing the dichotomy into a north–south position (Fig. 2b), or it could migrate along the boundary (straight arrow), leaving the dichotomy orientation unchanged (Fig. 2c). Note also that if Tharsis starts at any point on the boundary other than the poles, a TPW less than 90° will occur, and that this will be along the dichotomy boundary. In a more general case, the dichotomy begins in an arbitrary orientation, and Tharsis forms at a random spot along this boundary (e.g., Fig. 2d). Tharsis moves to the equator (dashed curve), causing the planet to reorient about an axis (solid line) perpendicular to both the rotation axis in inertial space and a line (dotted) running from Tharsis through the center of the planet. If Tharsis does not start at the northernmost or southernmost point on the dichotomy boundary, the dichotomy will still be tilted after the TPW (Fig. 2e).

In order for Tharsis-driven TPW to be responsible for the orientation of Mars, a remarkable coincidence must occur. We therefore find this to be an unsatisfactory explanation, and propose an alternative. Here we suggest that the north–south orientation of the dichotomy is established directly after its formation, due to the effects of the associated crustal thickness variations on the planet's moment of inertia, and that the later formation of Tharsis may only have a secondary effect. Our proposed model explains not only the present-day orientation of the dichotomy but also the equatorial location of Tharsis in the absence of any substantial Tharsis-driven TPW.

2. Methods and models

The key to this study is to determine rotational pole positions through computing degree-2 geoid anomalies and the inertial tensor, for physically reasonable early martian crustal and mantle buoyancy structures. More specifically, we calculated the geoid due to the loads associated with crustal dichotomy and one-plume mantle buoyancy. Only the degree-2 components of the geoid are relevant for the calculation of the inertial tensor. The degree-1 geoid of a planet corresponds to an offset between the center-of-mass and the center-of-figure. In a center-of-mass coordinate system such as that used by Mars Global Surveyor and many other spacecraft, the degree-1 geoid is zero by definition. The degree-2 geoid is related to the inertial tensor by MacCullagh's formula (Michael and Blackshear, 1972; Lambeck, 1980) which is then diagonalized to determine the rotation axis (Melosh, 1980; Willemann, 1984; Steinberger and O'Connell, 1997).

This method ignores the effects of the elastic lithosphere, similar to the studies on long-term TPW of the Earth (Richards et al., 1997; Steinberger and O'Connell, 1997). This is justified, given that we consider the TPW at the time of formation of the crustal dichotomy, during or before the Early Noachian (Frey et al., 2002; Nimmo and Tanaka, 2005; Solomon et al., 2005) when the thickness, T_e of the elastic lithosphere was very small (<10 km) (Zuber et al., 2000; McGovern et al., 2002). This is different from Willemann (1984)'s study in which the thick ($\geqslant$100 km) and likely unbroken elastic lithosphere at the formation of Tharsis required consideration of the effects of lithosphere on the TPW (Matsuyama et al., 2006). T_e is estimated to be <10 km for Hellas (McGovern et al., 2002) at the time of the basin formation, and similarly small for the southern highlands in general (Zuber et al., 2000; McGovern et al., 2002), suggesting an even smaller T_e at the time of dichotomy formation. As stated by Willemann (1984), such a thin elastic plate is susceptible to fracture under the TPW (or other tectonic processes including mantle convection), and his formulation for thick, unbroken lithosphere does not apply under these conditions (Willemann, 1984). Although it may still support short-wavelength loads, a thin and broken lithosphere should be transparent to long-wavelength forces and can therefore be ignored in computing the TPW (Willemann, 1984; Steinberger and O'Connell, 1997; Richards et al., 1997).

To determine the effect of crustal dichotomy on the TPW, we constructed simple crustal models as a proxy for early Mars after the dichotomy was formed but before the formation of Tharsis and the heavy bombardment. The martian crust may have been significantly modified at large impact basins and at Tharsis after the formation of the dichotomy (Zuber et al., 2000; Wieczorek and Zuber, 2004). However, the modification of the dichotomy boundary was limited to that caused by erosion and faulting (Irwin et al., 2004; Smrekar et al., 2004; Nimmo, 2005), except in the Tharsis region where the dichotomy boundary was completely buried by the volcanic construction. Apart from Tharsis and Arabia Terra, the transition across the dichotomy boundary is sharp and well-defined.

We considered four crustal models. In the first three models, the crustal thickness is bimodal, with a uniform thickness on each side of the dichotomy boundary. The fourth model uses variable crustal thickness based on the most recent model, *marscrust2* (Neumann et al., 2004). For the first crustal model, the northern and southern hemispheres are separated by a dichotomy boundary that passes through the present-day dichotomy transition regions, except in the Tharsis region where we connected the two known endpoints of the dichotomy boundary on either side of Tharsis with a straight line (Fig. 1a, red line). The second crustal model is identical to the first except that the boundary passes north of the bulk of Tharsis (Fig. 1a, white line. Note that the red and white lines overlap except in the Tharsis region). In the third model, the dichotomy boundary is placed to exclude the western Tharsis region (Zuber et al., 2000) and along the south end of the dichotomy transition

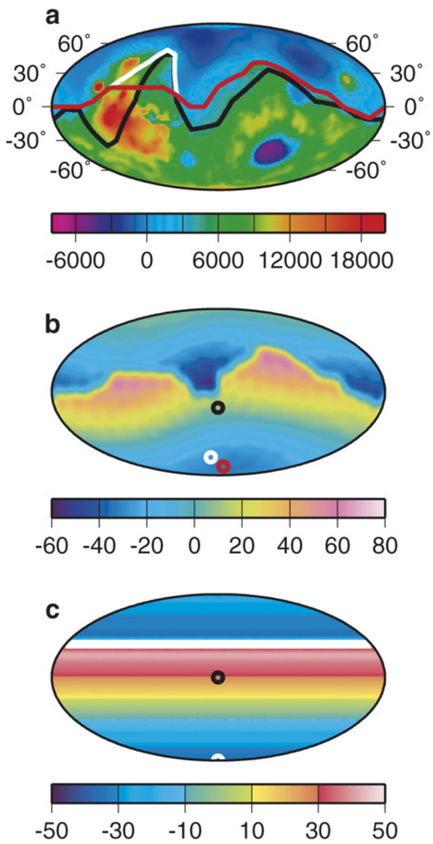

Fig. 1. Present day topography of Mars and three different dichotomy boundaries shown by red, white, and black lines (a), geoid from crustal dichotomy with red line as boundary and predicted pole position shown by red circle (b), and geoid from axisymmetric crustal load with thickened crust that is centered at the south pole and has a radius of 120° with the white line marking the edge of the thickened crust, and predicted pole position shown by white circle (c). In (a), the red and white boundaries are identical except at Tharsis. In (b), the predicted poles for dichotomy boundaries shown by white and black lines are also plotted as white and black circles, respectively. In (c), the predicted pole position for thickened crust with radius of 60° is shown by the black circle. All scales in meters. All maps in this paper use the Molleweide equal-area projection.

elsewhere (Fig. 1a, black line). For these three crustal models, the crustal thickness is assumed to be 32 km in the north and 58 km in the south (Neumann et al., 2004). The thickness increases linearly from the lower value at a position 5° north of the boundary to the upper value 5° south of the boundary.

We constructed the fourth crustal model by directly modifying the recent global crustal thickness model, *marscrust2* (Neumann et al., 2004) (Fig. 3a). Because the crustal dichotomy pre-dates Tharsis and the large impact basins (Hellas, Isidis, Argyre, Utopia), we have removed these features and replaced the crustal thickness in these regions with the background values (Fig. 3b). In the Tharsis region, we used the red line in Fig. 1a as the dichotomy boundary. For all four crustal models, we assumed that the crust is isostatically compensated at the Moho. This is justified given that the early martian lithosphere was very thin (Zuber et al., 2000; McGovern et al., 2002) and that only the longest wavelength (i.e., spherical harmonic degree $\ell = 2$) is of interest to us.

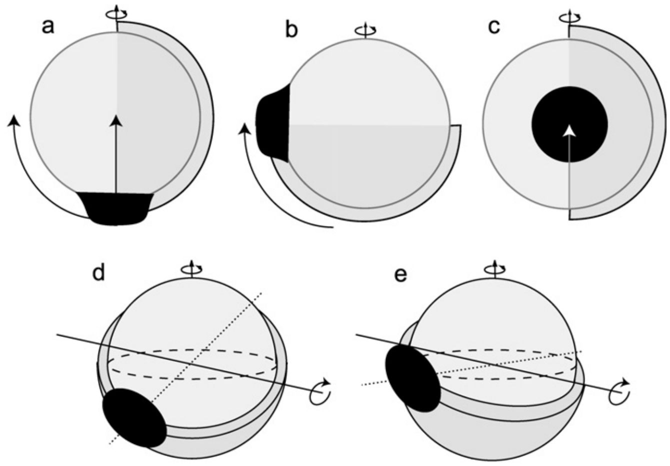

Fig. 2. Examples of TPW due to Tharsis. The upper panels describe an extreme case in which the dichotomy is initially east–west, and Tharsis (black region) forms at the pole (a), Migration of Tharsis to equator, bringing dichotomy north–south (b), migration of Tharsis to equator, leaving dichotomy east–west (c). The lower panels depict a more general case, in which the dichotomy starts in a random orientation, and Tharsis forms at a random spot on the boundary (d). Tharsis induces TPW rotating the planet about an axis (solid line) perpendicular to both the rotation axis and a line drawn from Tharsis through the center of the planet (dotted). Tharsis moves to the equator, but the dichotomy remains tilted (e).

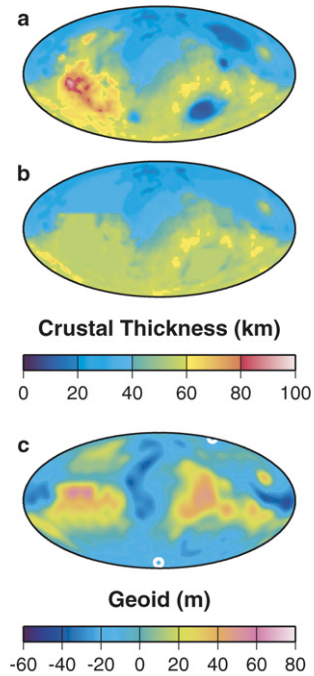

Fig. 3. The crustal thickness map of Mars from the *marscrust2* model (Neumann et al., 2004) (a). Crustal thickness map with Tharsis removed and Hellas, Argyre, Isidis, and Utopia basins filled in (b). Geoid determined from this crustal structure (c), with the predicted north and south pole positions marked by the white circles.

In addition to crustal loads, other physical processes including mantle convection may affect the planetary moment of inertia and pole position (Richards et al., 1997; Steinberger and O'Connell, 1997). Degree-1 mantle flow resulting from either one-plume thermal convection (Zhong and Zuber, 2001; Roberts and Zhong, 2006a) or overturn of magma ocean cu-

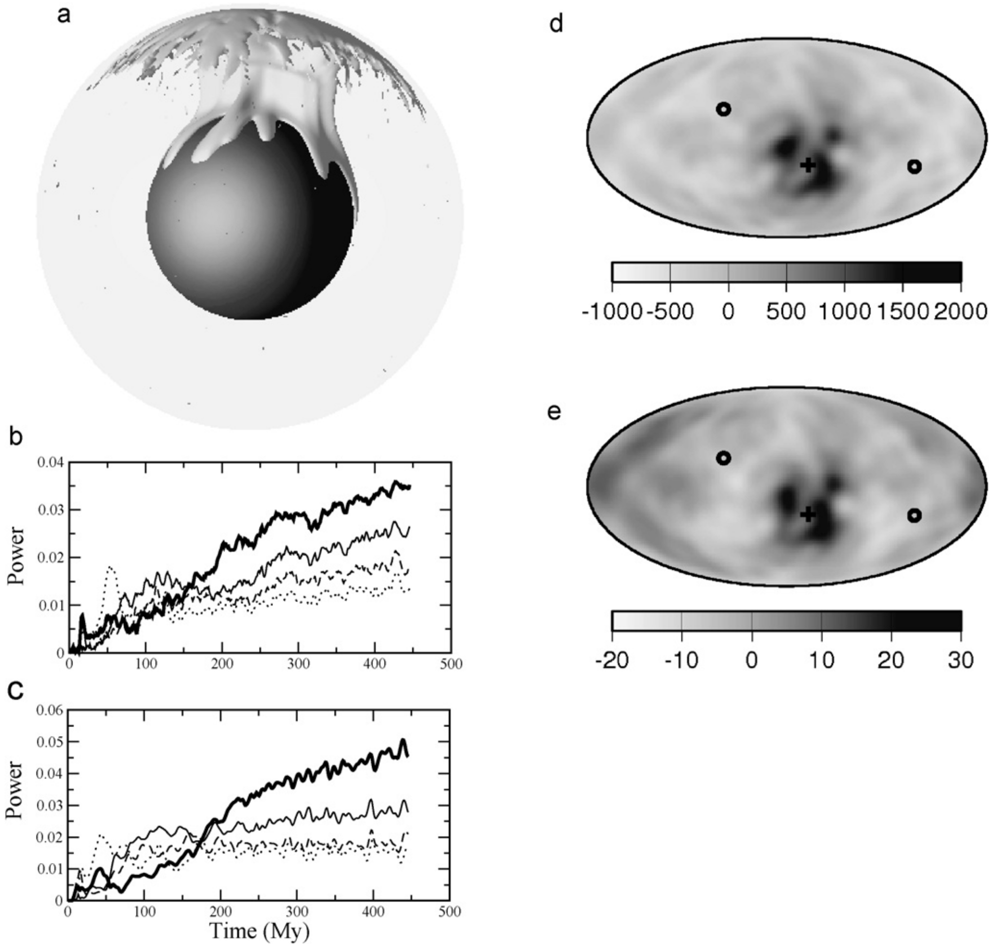

Fig. 4. Degree-1 convection from a 3D convection calculation (a). The upwelling is shown by the isosurface of residual temperature, representing a region in which the nondimensional temperature is at least 0.025 greater than the mean at that depth. The downwellings have been omitted for clarity. Time-dependent spectrum of temperature structures for the first four spherical harmonics at a depth of 110 (b) and 1670 km (c). Degrees 1–4 represented by the thick solid, thin solid, dashed, and dotted lines, respectively. Dynamic topography (d) and geoid (e) in meters produced by the plume. The crosses in (d) and (e) mark the plume centroid and the circles mark the predicted pole positions. Both poles are shown, unlike in Fig. 1.

mulates (Elkins-Tanton et al., 2005) has been suggested to be responsible for the crustal dichotomy. Degree-1 convection may lead to the formation of the dichotomy by preferentially thickening the crust in one hemisphere. Extensive melting in the plume head may generate a substantial amount of crust in the hemisphere containing the plume (Zhong and Zuber, 2001; Roberts and Zhong, 2006a). Given the aforementioned crustal thickness variation between the hemispheres, this plume-melting process may produce the secondary crust that may comprise $\sim 1/3$ of the present crustal volume and may be added on to 20–30 km of primordial crust (Norman, 1999; Wieczorek and Zuber, 2004).

Mantle convection models in a 3D spherical shell including temperature- and depth-dependent viscosity have been shown to produce a single upwelling plume (Fig. 4a) within the first couple hundred Ma (Roberts and Zhong, 2006a), rapidly enough to be associated with the origin of the dichotomy (Frey et al., 2002; Nimmo and Tanaka, 2005). These convection models were developed using a variant of the mantle convection code CitcomS (Zhong et al., 2000), using the extended Boussinesq approximation and including adiabatic and frictional heating. We only show one case (case V3 from Roberts and Zhong, 2006a) here, but the results for other cases are similar. This case has a basal Rayleigh number of 1.25×10^8, activation energy of 157 kJ/mol, activation volume of 2.7 cm^3/mol. Superimposed on the temperature- and pressure-dependent viscosity is a viscosity layering such that the upper mantle viscosity is 25 times lower than that in the lower mantle. The mantle is heated both basally and internally, with a radiogenic heating of 7.4×10^{-8} $W\,m^{-3}$. Although the one-plume structure is dominated by spherical harmonic degree $\ell = 1$, it contains significant power at $\ell = 2$ as well (Figs. 4b and 4c), thus affecting the inertial tensor.

3. Results

We first present TPW results from our crustal models. We assumed a crust with a density of 2900 $kg\,m^{-3}$ in isostasy atop a mantle with a density of 3500 $kg\,m^{-3}$. We computed the geoid from the surface and Moho topography, and found for the crust with the red dichotomy boundary (i.e., the first crustal model), a positive geoid anomaly of $\sim$60 m near the equator and that the predicted pole is 17° away from the present-day pole (Fig. 1b

Table 1
Degree-2 Stokes coefficients of the geoid (in meters)

Crust model	C20	C21	S21	C22	S22	Polar separation
1 (red)	−38.2	12.4	15.5	−33.3	17.6	17°
2 (white)	−40.9	19.1	−1.73	−44.6	8.37	28°
3 (black)	−2.50	9.88	−9.73	−35.8	−12.0	76°
4 (*marscrust2*)	−26.3	−3.26	−1.96	−32.1	24.8	22°

for the geoid and red circle for the pole position, and also Table 1). For the crust with the white dichotomy boundary (i.e., the second crustal model), the predicted pole is 28° away from the present-day pole (Fig. 1b, white circle, and Table 1). These results suggest that the formation of crustal dichotomy with its boundary as described above would orient the planet such that the dichotomy is approximately north–south. However, for the crust with the black dichotomy boundary (i.e., the third crustal model), the resulting geoid anomalies lead to poles that are 76° away from present-day poles (Fig. 1b, black circle, and Table 1). This model fails to reproduce the observed orientation, and suggests that a dichotomy boundary with this shape would be largely east–west. The difference in the predicted pole positions between these three models demonstrates that the orientation of the dichotomy is sensitive to the area extent of the thickened crust.

The reason for these different pole positions can be best understood by examining an idealized crustal model. We repeated the geoid and pole calculations for a series of axisymmetric crustal structures, in which the region of thickened crust is treated as a disk load. For a disk load (i.e., thickened crust) with radius exceeding 90°, the long-wavelength geoid signal is negative over and opposite the load, and the predicted pole overlaps with the center of the load (Fig. 1c, white circle). However, for a disk load with radius smaller than 90°, the geoid is positive over the load, and the poles are exactly 90° away from the center of the disk (Fig. 1c, black circle). For a disk load with radius of exactly 90°, the long-wavelength geoid vanishes and any pole position is equally likely. These results suggest that the different pole positions in Fig. 1b are largely controlled by the area extent of the thickened crust. For a region of thickened crust covering more than one hemisphere such as that with the red and white dichotomy boundaries (Fig. 1a), the pole should be close to the center of the thickened crust and to the present-day pole.

We note that the shape of the boundary may also be important. In crustal model 3 (black curve), the northward excursion of the dichotomy boundary into eastern Tharsis creates strong $(\ell, m) = (2, 2)$ components of the geoid, which dominate over the axisymmetric 2, 0 component (Table 1). Consequently, the predicted pole in this case is in the region of low geoid between Tharsis and Arabia Terra. The less oscillatory (and probably more geologically reasonable) dichotomy boundaries in crustal models 1 and 2 (red and white curves) have stronger $(2, 0)$ geoid components and thus the area extent of thickened crust is most important in controlling the pole positions in those cases.

For crustal model modified from *marscrust2* (i.e., the fourth crustal model, see Fig. 3a and Neumann et al., 2004), we found a pole position 22° away from the present-day pole (Fig. 3c for the geoid and poles, and Table 1), similar to those from the first and second models with uniform crustal thicknesses in two hemispheres (red and white circles in Fig. 1b).

We now consider the effects of a one-plume mantle structure (e.g., Fig. 4a) on the TPW. The lower-density plume material is a mass deficit and produces a negative geoid anomaly. In dynamic isostasy, the plume buoyancy is compensated at the surface in the form of dynamic topography (Fig. 4d) which produces a positive geoid. Because the mass deficit associated with the plume is further from the surface, the net geoid at the surface is dominated by the topography, and is positive over the plume and its antipode (Fig. 4e). The geoid has an amplitude of ∼20 m at long-wavelengths which is significantly less than that from the aforementioned crustal structure (Figs. 1b and 3c). We found that the predicted pole is offset from the center of the plume by nearly 90°, placing the plume and its associated positive geoid near the equator. The same results of ∼90° offset between the pole and the center of the plume and of significantly less geoid for the plume than the crust are also observed for all the convection models that we examined with rapid formation of the $\ell = 1$ pattern (Roberts and Zhong, 2006a).

4. Discussions and conclusions

While the TPW caused by crustal loads associated with the dichotomy (e.g., crustal models 1, 2, and 4) leads to poles close to present-day ones, a one-plume structure results in ∼90° offset between the poles and the center of the plume, placing the plume and the thickened crust near the equator if the thickened crust is caused by the plume melting. During the early stage of formation of the dichotomy, the area extent of the thickened crust may have been relatively small, and therefore most stable at the equator. The geoid contributions from the plume and crust reinforced each other, driving the plume and the thickened crust to the equator and leading to an early east–west dichotomy. As the region of thickened crust grew to its current distribution covering more than half the planet (e.g., the red or white curves in Fig. 1a, or as in Fig. 3b), the long-wavelength geoid above the thickened crust became negative. At this stage, the geoid contributions from the crust and plume opposed each other.

However, we think that the crustal distribution ultimately controls the pole position for two reasons. First, the plume geoid is always significantly less than crustal geoid, as mentioned earlier (Fig. 4e). Second, the dichotomy-producing plume must have diminished after the formation of the dichotomy, as suggested by the relatively uniform surface age for the southern highlands and the subsequent formation of the Tharsis by a plume (Harder and Christensen, 1996) at nearly 90° arc distance from the center of the thickened crust. As the dichotomy-producing plume faded away, the crust was left as the predominant contributor to the geoid before the formation of the Tharsis.

Based on these results, we propose the following scenario for the origin and evolution of the crustal dichotomy. Degree-1 mantle convection developed within the first couple hundred Ma (Roberts and Zhong, 2006a) (Fig. 5a). The net positive

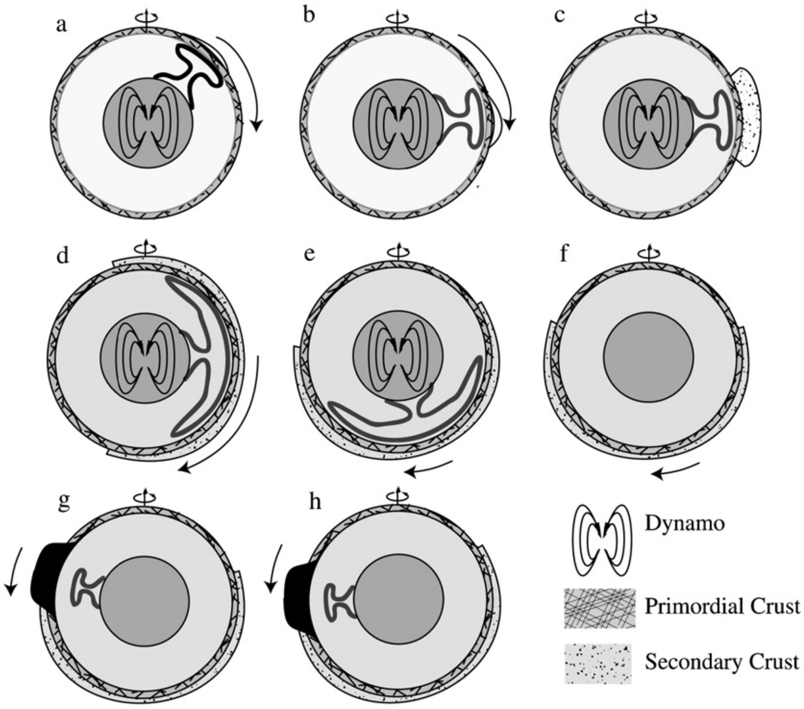

Fig. 5. Evolution of the crustal dichotomy for early Mars. A degree-1 plume develops at some arbitrary location within the first couple hundred Ma of martian history beneath a primordial crust (a). Dynamic topography associated with the plume produces a load that drives it to the equator. (b). Melt in the plume head begins to thicken the crust above it (c). This secondary crust cools in the ancient global magnetic field and takes on stronger remanent magnetization than the thin crust in the other hemisphere that is largely primordial. The extent of this region grows until it occupies more than one hemisphere (d) at which point the degree-2 crustal geoid becomes negative and causes additional TPW, placing the center of the crust near the pole (e). After the formation of the dichotomy, the plume dies away and the pole adjusts (f). The core is no longer being cooled as efficiently, and the dynamo shuts down. Tharsis grows at the dichotomy boundary by the Late Noachian (g), and migrates a short distance to the equator. Tharsis adjusts the dichotomy into its final position (h), but need not drive a great deal of TPW in order to do so.

dynamic geoid associated with the plume would have driven TPW placing the plume at the equator if it did not initially form there (Fig. 5b). Partial melt in the plume head was transported to the surface and a small region of thickened crust formed above the plume (Fig. 5c), increasing the positive geoid and reinforcing the plume's equatorial location. At this time the elastic lithosphere was quite thin, <10 km (McGovern et al., 2002), much thinner than even the lowland crust (Zuber et al., 2000). As plume materials spread out below the lithosphere, they caused extensive melting and crust production over a larger area. The lower crust may also have flowed laterally, and grew throughout the plume hemisphere, forming the crustal dichotomy in an east–west orientation. The thickened crust expanded to occupy more than one hemisphere (Fig. 5d), and the geoid over the thickened crust became negative. A second phase of TPW took place, moving the thickened crust to the pole and the dichotomy close to its present north–south orientation (Fig. 5e). The dichotomy-forming plume eventually dissipated, crustal production greatly diminished or ceased altogether, and the crustal dichotomy became the sole control on the planetary orientation (Fig. 5f).

These proposed TPW events occurred during or before the Early Noachian when the elastic lithosphere was very thin (<10 km). The readjustment of the rotational bulge due to the reorientation would have created large stresses in the lithosphere and is likely to have fractured it, as suggested by Melosh (1980) and Willemann (1984). However, the fractures should have been largely erased by subsequent surface tectonic and cratering activities including the heavy bombardment. This is consistent with the general absence of tectonic features (i.e., faulting) that predate the formation of Tharsis by the Late Noachian (Nimmo and Tanaka, 2005; Anderson et al., 2001). An early TPW before the Tharsis formation is the key to reconciling with the lack in TPW-related fractures (Grimm and Solomon, 1986). Our study provides a physical mechanism for this early TPW.

While still a very old feature, the Tharsis rise post-dates the crustal dichotomy and sits on the boundary. The precise reason that Tharsis formed on the dichotomy boundary is not well understood, but it may be related to edge-driven convection (King and Anderson, 1998) in which an abrupt change in the thickness of the conductive lid may drive instabilities in the convecting region beneath the transition. Tharsis is an elastically-supported volcanic construction (Phillips et al., 2001), and as such, produces a substantial degree-2 geoid load (100–1000 m). This signal overwhelms that due to the crustal thickness variations, encouraging equatorward migration of the Tharsis. In the scenario described above, however, the dichotomy boundary is already close to the equator prior to the Tharsis loading. The formation of Tharsis on the dichotomy boundary implies that it formed near the equator initially (Fig. 5g), and thus would only have driven a small additional amount of TPW (Fig. 5h). This is consistent with early studies of Tharsis-driven TPW (Melosh, 1980; Willemann, 1984), and suggests that Tharsis had only a secondary effect on the dichotomy's orientation. Although Matsuyama et al. (2006) has since shown that under certain circumstances, Tharsis could have driven larger TPW, that study does not suggest that this has occurred, and a small TPW is more consistent with the lack of observed tectonic features expected from a large reorientation (Melosh, 1980; Grimm and Solomon, 1986).

Simple calculations show that Tharsis should move the poles determined from the crust (e.g., the red circle in Fig. 1b) closer to the present-day poles. For example, if we choose a reference frame with the pole determined from the first crustal model (red circle in Fig. 1b) as south pole and the present-day south pole at 180° longitude, then the center of Tharsis will be at (129° W, 17° N) and the present-day south pole at (180°, 73° S), given that Tharsis is currently centered at (112° W, 6° N) (Zuber and Smith, 1997). As Tharsis-induced TPW moved Tharsis south to the equator, the pole moved closer to its present-day position. The result for the case with the second crustal model is similar.

Our proposed scenario may also explain why the magnetic anomalies are much stronger in the southern highlands than the northern plains (Connerney et al., 1999; Hood and Zakharian, 2001), a key observation that remains largely unexplained (Nimmo and Tanaka, 2005; Solomon et al., 2005). In our model, early core cooling drives a geodynamo (field lines in the core in Figs. 5a–5e). The newly formed crust (stippled regions in Figs. 5c–5h) in the southern highlands produced by the plume may have cooled in the presence of an ancient global magnetic field, thus taking on remanent magnetization. This secondary crust is added onto a primordial crust (which may also have been weakly magnetized by an earlier, weaker global field, (Fig. 5, cross-hatched regions)), resulting in the southern hemisphere becoming much more strongly magnetized than the northern hemisphere. Following the formation of the dichotomy and the dissipation of the plume, the core is no longer cooled efficiently, and the dynamo dies off (Figs. 5f–5h). Recent estimates of paleomagnetic pole positions northwest of Olympus Mons that suggest an episode of TPW since the rocks were magnetized (Arkani-Hamed and Boutin, 2004; Hood et al., 2005) are also consistent with an initially east–west dichotomy from our model. Our scenario suggests that the thickened crust (i.e., the present-day southern highlands) may be younger than the thinner crust, but probably not significantly because of the rapid formation of the dichotomy. This age is supported by recent MARSIS radar observations that indicate the buried crater population in the heavily resurfaced northern lowlands may have been significantly underestimated, and that the basement of the lowlands may be older than previously thought (Watters et al., 2006).

We also examined the effect of an intact elastic shell on the geoid from a degree-1 plume and its consequence on the TPW, as presented in Roberts and Zhong (2006b). Zhong (2002) and Roberts and Zhong (2004) demonstrated that an elastic lithosphere may significantly reduce the geoid from a plume and may even lead to a negative geoid over a plume. Roberts and Zhong (2006b) found that when T_e exceeds ~30 km, the net geoid over the plume becomes negative for models we examined, but the magnitude is still significantly smaller than the crust geoid. In the absence of any other effects, this would drive a TPW event, shifting the plume to the pole (Roberts and Zhong, 2006b). However, for early Mars with relatively thin elastic plate, the plate could fracture in response to TPW, which in turn may eliminate its filtering effect on the geoid. Clearly, whether an elastic plate could place a plume at the poles by reducing the plume geoid hinges on the extent to which a fractured plate could support long-wavelength loads, which should be an important question in future study (Zhong, 2001).

Finally, we want to point out that the scenario described above assumes a certain origin for the crustal dichotomy, that is formation by long-wavelength mantle convection (Zhong and Zuber, 2001; Roberts and Zhong, 2006a). Considerable controversy remains about this issue with other alternate formation mechanisms for the dichotomy (Solomon et al., 2005), such as giant impacts (e.g., Frey et al., 2002), and overturn of magma ocean residue (Elkins-Tanton et al., 2005). Solomon et al. (2005), on the basis of isotope ratios in martian meteorites, argued that the main bulk of martian crust is produced in the initial 50 Ma after Solar System formation as a result of primary planetary differentiation and that the dichotomy is formed on the same time scale. They further suggested that this early formation time for the dichotomy is inconsistent with mantle convection as formation mechanism for the dichotomy. However, we note that other similar geochemical mass balance calculations suggest production of significant amount of secondary crust (Norman, 1999). Also, the timescale for the formation of degree-1 convection is dependent upon the viscosity structure, and it is possible that degree-1 convection is generated on 50 Ma time-scale (Roberts and Zhong, 2006a). We emphasize, however, that the orientation of the dichotomy after its formation is independent of the formation mechanism. Although the first stage of TPW, moving the plume to the equator (Fig. 5b), is particular to the scenario described above, the subsequent north–south orientation of the dichotomy is controlled entirely by the crustal thickness variations associated with the dichotomy, regardless of its formation mechanism. Alternative origins for the magnetization of the highland crust may also be consistent with our scenario, provided that the magnetization occurs before the crust-induced TPW event as suggested by the magnetic paleopole studies (Arkani-Hamed and Boutin, 2004; Hood et al., 2005). Future work in this area may be helpful in providing constraints on the timing of the reorientation.

In conclusion, we suggest that the north–south orientation of crustal dichotomy and the equatorial location of Tharsis are not coincidences, but rather natural consequences of formation of crustal dichotomy. Our proposed TPW that turns an initially east–west dichotomy to its present-day north–south orientation also supports the recent proposed large TPW based on estimates of paleomagnetic pole positions (Arkani-Hamed and Boutin, 2004; Hood et al., 2005). Additionally, our results highlight the importance in understanding why Tharsis was formed near the dichotomy boundary, possibly as a result of lithospheric/crustal thickness variation or edge-driven convection (King and Anderson, 1998; Wenzel et al., 2004).

Acknowledgments

This research is supported by NASA Grant NNG05GM11G, the David and Lucille Packard Foundation and the Alfred P. Sloan Foundation. The authors thank Patrick McGovern and an anonymous reviewer for constructive reviews, and Archie Paulson and Maria Zuber for discussions.

References

Anderson, R.C., Dohm, J.M., Golombek, M.P., Haldemann, A.F.C., Franklin, B.J., Tanaka, K.L., Lias, J., Peer, B., 2001. Primary centers and secondary concentrations of tectonic activity through time in the western hemisphere of Mars. J. Geophys. Res. 106, 20563–20586.

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

Connerney, J.E.P., Acuna, M.H., Wasilewski, P.J., Ness, N.F., Reme, 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.

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, doi:10.1029/2005JE002480. E12S01.

Frey, H.V., Roark, J.H., Shockey, K.M., Frey, E.L., Sakimoto, S.E.H., 2002. Ancient lowlands on Mars. Geophys. Res. Lett. 29, doi:10.1029/2005JE002480. 1384.

Grimm, R.E., Solomon, S.C., 1986. Tectonic tests of proposed polar wander paths for Mars and the Moon. Icarus 65, 110–121.

Harder, H., Christensen, U.R., 1996. A one-plume model of martian mantle convection. Nature 380, 507–509.

Hood, L.L., Zakharian, A., 2001. Mapping and modeling of magnetic anomalies in the northern polar region of Mars. J. Geophys. Res. 106, 14601–14620.

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.

Irwin, R.P., Watters, T.R., Howard, A.D., Zimbelman, J.R., 2004. Sedimentary resurfacing and fretted terrain development along the crustal dichotomy boundary, Aeolis Mensae, Mars. J. Geophys. Res. 109, doi:10.1029/2004JE002248. E09011.

King, S.D., Anderson, D.L., 1998. Edge-driven convection. Earth Planet. Sci. Lett. 160, 289–296.

Lambeck, K., 1980. The Earth's Variable Rotation: Geophysical Causes and Consequences. Cambridge Univ. Press, Cambridge/New York. 458 pp.

Matsuyama, I., Mitrovica, J.X., Manga, M., Perron, J.T., Richards, M.A., 2006. Rotational stability of dynamic planets with elastic lithospheres. J. Geophys. Res. 111, doi:10.1029/2005JE002447. E02003.

McGovern, P.J., Solomon, S.C., Smith, D.E., Zuber, M.T., Simons, M., Wieczorek, M.A., Phillips, R.J., Neumann, G.A., Aharonson, O., Head, J.W., 2002. Localized gravity/topography admittance and correlation spectra on Mars: Implications for regional and global evolution. J. Geophys. Res. 107, doi:10.1029/2002JE001854. 5136.

Melosh, H.J., 1980. Tectonic patterns on a reoriented planet—Mars. Icarus 44, 745–751.

Michael Jr., W.H., Blackshear, W.T., 1972. Recent results on the mass, gravitational field, and moments of inertia of the Moon. Moon 3, 388–402.

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, doi:10.1029/2004JE002262. E08002.

Nimmo, F., 2005. Tectonic consequences of martian dichotomy modification by lower crustal flow and erosion. Geology 33, 533–536.

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

Norman, M.D., 1999. The composition and thickness of the crust of Mars estimated from REE and Nd isotopic compositions of martian meteorites. Meteor. Planet. Sci. 34, 439–449.

Phillips, R.J., Zuber, M.T., Solomon, S.C., Golombek, M.P., Jakosky, B.M., Banerdt, W.B., Smith, D.E., Williams, R.M.E., Hynek, B.M., Aharonson, O., Hauck, S.A., 2001. Ancient geodynamics and global-scale hydrology on Mars. Science 291, 2587–2591.

Richards, M.A., Ricard, Y., Lithgow-Bertelloni, C., Spada, G., Sabadini, R., 1997. An explanation for Earth's long-term rotational stability. Science 275, 372–375.

Roberts, J.H., Zhong, S., 2004. Plume-induced topography and geoid anomalies and their implications for the Tharsis rise on Mars. J. Geophys. Res. 109, doi:10.1029/2003JE002226. E03009.

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

Roberts, J.H., Zhong, S., 2006b. Polar wander of Mars driven by degree-1 mantle convection and its implications for the formation of the crustal dichotomy and the Tharsis rise. Lunar Planet. Sci. XXXVII. Abstract 1206.

Smith, D.E., Sjogren, W.L., Tyler, G.T., Lemoine, F.G., Konopliv, A.S., 1999a. The gravity field of Mars: Results from Mars Global Surveyor. Science 286, 94–97.

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.C., Hauck, S.A., Ivanov, A.B., McGovern, P.J., Zwally, H.J., Duxbury, T.C., 1999b. The global topography of Mars and implications for surface evolution. Science 284, 1495–1503.

Smrekar, S.E., McGill, G.E., Raymond, C.A., Dimitriou, A.M., 2004. Geologic evolution of the martian dichotomy in the Ismenius area of Mars and implications for plains magnetization. J. Geophys. Res. 109, doi:10.1029/2004JE002260. E11002.

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.

Steinberger, B., O'Connell, R.J., 1997. Changes of the Earth's rotation axis owing to advection of mantle density heterogeneities. Nature 387, 169–173.

Watters, T.R., Leuschen, C.J., Plaut, J.J., Picardi, G., Safaeinili, A., Clifford, S.M., Farrell, W.M., Ivanov, A.B., Phillips, R.J., Stofan, E.R., 2006. MARSIS radar sounder evidence of buried basins in the northern lowlands of Mars. Nature 444, 905–908.

Wenzel, M.J., Manga, M., Jellinek, A.M., 2004. Tharsis as a consequence of Mars' dichotomy and layered mantle. Geophys. Res. Lett. 31, doi:10.1029/2003GL019306. L04702.

Wieczorek, M.A., Zuber, M.T., 2004. Thickness of the martian crust: Improved constraints from geoid-to-topography ratios. J. Geophys. Res. 109, doi:10.1029/2003JE002153. E01009.

Willemann, R.J., 1984. Reorientation of planets with elastic lithospheres. Icarus 60, 701–709.

Zhong, S., 2001. Effects of interaction between the Earth's centrifugal potential and lithosphere on long-wavelength geoid anomalies. In: AGU Spring Meeting.

Zhong, S., 2002. Effects of lithosphere on the long-wavelength gravity anomalies and their implications for the formation of the Tharsis rise on Mars. J. Geophys. Res. 107, doi:10.1029/2001JE001589. 5054.

Zhong, S., Zuber, M.T., 2001. Degree-1 mantle convection and the crustal dichotomy on Mars. Earth Planet. Sci. Lett. 189, 75–84.

Zhong, S., Zuber, M.T., Moresi, L., Gurnis, M., 2000. Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection. J. Geophys. Res. 105, 11063–11082.

Zuber, M.T., Smith, D.E., 1997. Mars without Tharsis. J. Geophys. Res. 102, 28673–28686.

Zuber, M.T., Solomon, S.C., Phillips, R.J., Smith, D.E., Tyler, G.L., Aharonson, O., Balmino, G., Banerdt, W.B., Head, J.W., Johnson, C.L., Lemoine, F.G., McGovern, P.J., Neumann, G.A., Rowlands, D.D., Zhong, S., 2000. Internal structure and early thermal evolution of Mars from Mars Global Surveyor topography and gravity. Science 287, 1788–1793.