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Geophysical Limitations on the Erosion History within Arabia Terra, Mars—need reference for crustal thickness model

A. J. Evans, J.C. Andrews-Hanna*†, and M.T. Zuber

Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

Abstract. The Arabia Terra region, an area of $\sim1 \times 10^7 \text{ km}^2$ lying south of the hemispheric dichotomy boundary and centered at (25E, 5N), is a unique physiographic province with topography and crustal thickness intermediate between those of the southern highlands and northern lowlands. Previous workers have identified numerous morphological indicators suggestive of erosion. Using altimetry data returned by the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) along with gravity data from the Mars Reconnaissance Orbiter (MRO), we place geophysical constraints on the amount of erosion permitted within Arabia Terra. Admittance estimates using a multi-taper, spatiotemporal localization approach provide a best-fit to the observations through degree 50 at a lithospheric thickness of 15 km. The elevation difference between Arabia Terra and the highlands would require as much as 5 km of erosion in certain areas to yield the current topography, neglecting the effects of subsequent flexure. However, incorporating flexural rebound requires substantially more erosion, up to 25 km, in order to reproduce the elevation and crustal thickness deficit of Arabia Terra. Such a large amount of erosion would result in exterior flexural uplift exceeding 1 km and gravity anomalies exceeding observations by $\sim80$ mGal. Consequently, it is unlikely that Arabia Terra was formed from surface erosion alone. We determine that no more than $3 \times 10^7 \text{ km}^3$ of material could have been eroded within Arabia Terra, while $1.7 \times 10^8 \text{ km}^3$ of erosion is required to explain the observed crustal thickness.

1. Introduction

Arabia Terra, with an area of $1 \times 10^7 \text{ km}^2$ centered at (25E, 5N), is an anomalous region along the Martian dichotomy. Traditionally considered part of the southern highlands [e.g. Scott & Tanaka 1986 [†]; Greeley & Guest 1987 [‡]; McGill & Squyres 1991 [§]]; Frey et al. 1998 [¶]). Arabia Terra provides a more gradual transition from the southern highlands to the northern lowlands in both topography [Smith et al. 1999 [†]; Smith et al. 2001 [‡]] and crustal thickness [Zuber et al. 2000 [§]—Neumann et al. 2004 [¶]]. While the geological processes leading to the formation of the region have not been clearly identified [e.g. Kiefer 2005 [¶]], Arabia Terra contains morphological evidence indicative of surface erosion including isolated mesas [Hynek & Phillips 2001 [‡]; Malin & Edgett 2000 [¶]] and partially degraded craters [Craddock et al. 1997 [¶]]. Though surface modification has been suggested for the entirety of the highlands [e.g. Craddock & Maxwell 1993 [©]], the anomalous nature of Arabia Terra and its geomorphology may indicate preferential erosion of the region. The amount of erosion may have generated a significant volume of sediment, possibly contributing to the resurfacing of the northern lowlands. Though previous workers have attempted to constrain the amount of erosion for Arabia Terra and the southern highlands, in general, much of the analysis has been based on crater degradation with anywhere between 200 m to 2300 m of material being eroded, as put forth by Craddock & Maxwell 1993 [©]. Hynek & Phillips 2001 [©] approached the problem from an alternative geomorphic perspective: using the height of local elevation maxima (isolated mesas) in concert with the mapping of geological units. Their analysis indicates that a minimum of 1000 m of material was removed from the Arabia Terra region in the late Noachian. Recent analysis of data from the Mars Exploration Rover landing site at Meridiani Planum within Arabia Terra suggests smaller amounts of erosion have occurred since $\sim3.0$ Ga, though evidence for this erosion is found on sedimentary deposits that lie above the original surface and thus does not constitute net loss [Golombek et al. 2006 [©]]. It has generally been suggested that erosion during the Noachian and early-mid Hesperian may have been greater due to a warmer and wetter environment [Craddock & Maxwell 1993 [©]; Golombek et al. 2006 [©]]. However, widespread layered deposits across the region suggest an early period of deposition as well [Fassett & Head 2007 [©]; Moore 1990 [©]]. Prior analyses of erosion in Arabia Terra [Hynek & Phillips 2001 [©]] relied on the geomorphology of the terrain and craters. In this paper, we present our constraints for the erosion of Arabia Terra based on geodynamical modeling coupled with limitations established from topography and gravity data returned by the Mars Orbiter Laser Altimeter (MOLA) [Zuber et al. 1992 [©]; Smith et al. 1999 [©]] on the Mars Global Surveyor (MGS) [Albee et al. 2001 [©]] and the gravity field investigation on the Mars Reconnaissance Orbiter (MRO) [Zurek & Smrekar 2007 [©]], respectively. By comparing the expected flexural response and gravitational signature [Turcotte et al. 1981 [©]] of various erosional loads to the observational data, we establish an upper limit on the amount of material that could have been removed from within Arabia Terra. We employ a lithospheric flexure model [Turcotte et al. 1981 [©]] to attain the flexural rebound and gravitational signature associated with a given erosional load. Exploiting recent advances in spherical harmonic localization techniques [Simons, Dahlen, & Wieczorek 2006 [©]; Wieczorek & Simons 2005 [©]; Wieczorek 2006 [©]; *Now at Department of Geophysics, Colorado School of Mines, Golden, Colorado, USA.
†Also at Southwest Research Institute, Boulder, Colorado, USA.

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Any square-integrable function defined on a spherical surface can be expanded as a linear combination of spherical harmonics [Wieczorek 2007 [\textcopyright]].

\[ f(\Omega) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} f_{lm} Y_{lm}(\Omega), \]

(1)

and

\[ f_{lm} = \int_{\Omega} f(\Omega) Y_{lm}(\Omega) d\Omega, \]

(2)

where \( \Omega \) is the solid angle, and \( Y_{lm} \) is the spherical harmonic basis function of degree \( l \) and order \( m \).

We apply a method for spatio-spectral localization on a sphere, in which data is localized to an arbitrarily-shaped region of interest by applying a family of orthogonal spherical harmonic tapers [Simons 2006 [\textcopyright]; Simons, Dahlen, & Wieczorek 2006 [\textcopyright]]. Ultimately, we apply this localized spectral analysis within Arabia Terra to attain the regional elastic thickness at the time of formation. To spatially concentrate a bandlimited function, \( f(\Omega) \), within an arbitrarily-shaped region, \( R \), we maximize the energy concentration, \( \lambda \), according to

\[ \lambda = \frac{\int_{R} f(\Omega)^2 d\Omega}{\int_{\Omega} f(\Omega)^2 d\Omega} = \text{maximum}, \]

(3)

within the region, \( R \) where \( 0 \leq \lambda \leq 1 \). By use of Eq. (2), we can rewrite (3) as

\[ \lambda = \frac{\sum_{l=0}^{L_{\text{win}}} \sum_{m=-l}^{l} f_{lm} \sum_{l'=0}^{l'} \sum_{m'=-l'}^{l'} D_{lm,l'm'} f_{l'm'} + \sum_{l=0}^{L_{\text{win}}} \sum_{m=-l}^{l} f_{lm}^2}{\sum_{l=0}^{L_{\text{win}}} \sum_{m=-l}^{l} f_{lm}^2}, \]

(4)

where \( D_{lm,l'm'} = \int_{R} Y_{lm}(\Omega) Y_{l'm'}(\Omega) d\Omega \),

(5)

and \( L_{\text{win}} \) is the bandwidth of the localization (window). Each order, \( l \), receives contributions from across the range \( l - L_{\text{win}} \leq l' \leq l + L_{\text{win}} \). Hence, our choice for the window bandwidth restricts the resulting localization, such that the following inequality holds for all degrees, \( l_{\text{loc}} \), of the windowed field, \( L_{\text{win}} \leq l_{\text{loc}} \leq L_{\text{obs}} - L_{\text{win}} \), where \( L_{\text{obs}} \) is the maximum expansion degree of the data set being considered.

As shown by Simons, Dahlen, & Wieczorek 2006 [\textcopyright], Equation (4) reduces to a matrix eigenvalue equation where the eigenfunctions of a kernel given by \( D_{lm,l'm'} \) are spherical harmonic coefficients of the space concentrated tapers [e.g. Wieczorek & Simons 2005 [\textcopyright]]. The result of this reduction in full index notation is,

\[ \sum_{l'=0}^{l'} \sum_{m'=-l'}^{l'} D_{lm,l'm'} f_{l'm'} = \lambda f_{lm}. \]

(6)

The number of eigenfunctions optimally-concentrated within the region of interest can be obtained by calculating the Shannon number, \( N \),

\[ N = \sum_{n=1}^{(L_{\text{win}}+1)^2} \lambda_n = (L_{\text{win}} + 1)^2 \frac{A}{4\pi}. \]

(7)

We use the \( N \) optimally-concentrated eigenfunctions to localize the region, similarly to the method prescribed by Wieczorek & Simons 2005 [\textcopyright].

2.2. Loading Model

2.2.1. Thin Elastic Shell Adaptation

In order to represent the effects of erosion in Arabia Terra, we account for the resultant flexure and gravity signature of the erosional load. We establish limits on the extent of regional erosion by analyzing these resultant signatures and comparing to observational data. We employ an adapted version [Johnson et al. 2000 [\textcopyright]] of the thin elastic lithosphere (shell) model outlined by Turcotte et al. 1981 [\textcopyright]. Following Turcotte et al. 1981 [\textcopyright], we introduce the dimensionless parameters,

\[ \tau = \frac{E T_e}{R^2 g \Delta \rho}, \]

(8)

and

\[ \sigma = \frac{D}{R^2 g \Delta \rho}, \]

(9)

where \( E \) is Young’s modulus, \( T_e \) is the elastic lithosphere thickness at the time of loading, \( R \) is the mean radius of the shell, \( g \) is the Martian gravitational acceleration, and \( \Delta \rho \) is the density contrast between continua below and above the shell. The mean shell radius, \( R \), and flexural rigidity, \( D \), can be represented as \( R = R_p - T_e/2 \) and \( D = E T_e^3 / 12 (1 - \nu^2) \), where \( \nu \) is Poisson’s ratio and \( R_p \) is the equatorial planetary radius. The independent parameters that we use for the loading model are listed in Table 1.

We use spherical harmonic representations of the load thickness \( h \), the resulting deflection \( w \), the Martian geoid offset \( h \), and the equitopotentially-referenced, final topography \( \bar{h} \). Relating the load thickness and flexure in the spectral domain yields the relationship

\[ w_{lm} = -\frac{R}{\Delta \rho \alpha_l} h_{lm}, \]

(10)

where \( \rho_L \) is the load (crustal) density and the transfer function, \( \alpha_l \),

\[ \alpha_l = \left[ 1 - \frac{3 \rho_m}{(2l + 1) \bar{p}} \right] \left[ 1 - \frac{3 \rho_m}{(2l + 1) \bar{p}} \right]^{-1}, \]

(11)

with \( \bar{p} \) as the mean Martian density and

\[ \bar{p}_l = \frac{[l(l+1)+1]}{[l(l+1)]^{3/2}} \frac{[l(l+1)]^{3/2}}{[l(l+1)]^{3/2}} \frac{[l(l+1)]^{3/2}}{[l(l+1)]^{3/2}} \]

(12)

This formalism allows us to solve for a final topography where \( \bar{h} = \bar{h} + w \); additionally, by substituting \( \bar{h} \) for \( h \) in Equation 10
with the density contrast applied between the mantle and crust, we can solve for the associated erosional load via \( h = \hat{h} - w \).

2.2.2. Geoid Solution
We define a spherical harmonic representation of topography, \( H \), similarly to McGovern et al. 2002 [@] as

\[
H(\Omega) = \hat{S}(\Omega) - A(\Omega),
\]

where \( \hat{S} \) is the planetary shape and \( A \) is the Martian reference geoid. We choose the mean planetary radius, 3389.5 km [Smith et al. 2001 [@]] as the first term of a spherical harmonic expansion of the radius similar to McGovern et al. 2004 [@] and approximate the deviation of the geoid from the mean planetary radius as,

\[
A(\Omega) = 0.95\hat{S}_{2,0}.
\]

For our erosional model, a degree-1 term is included in Eq. (14) to account for the center-of-mass offset resulting from the erosional load. Referencing the topography with respect to the geopotential accounts for the self-gravitation of Turcotte et al. 1981 [@] [e.g. McGovern et al. 2002 [@]], allowing us to apply the gravity calculation demonstrated by Wieczorek & Phillips 1998 [@]. Throughout our computational analysis, we consider both the shape and the topography to ensure an accurate representation of the resulting flexure and gravity field.

2.2.3. Gravity Solution
We calculate the gravity anomalies resulting from the erosional load and flexural deformation using the finite amplitude formulation of Wieczorek & Phillips 1998 [@]. The gravity anomaly can be expressed as,

\[
\Delta g = \frac{GM}{r^2} \left( \frac{R_p}{r} \right)^l (C_{\text{surf}}^{lm} + C_{\text{moho}}^{lm}) Y_{lm},
\]

where \( C_{\text{surf}}^{lm} \) and \( C_{\text{moho}}^{lm} \) represent the topography along the surface and base of the crust, respectively. However, we slightly modify the solution, as described by McGovern et al. 2002 [@] for \( C_{\text{moho}}^{lm} \),

\[
C_{\text{moho}}^{lm} = \frac{4\pi \Delta \rho r^3}{M(2l+1)} \sum_{n=1}^{\infty} \frac{\hat{S}_{lm}^{n}}{r^{n+l}} \prod_{j=1}^{n} \frac{(l + 4 - j)}{(l + 3)}.
\]

3. Erosional Constraints within Arabia Terra
Using altimetry data returned by the Mars Orbiter Laser Altimeter (MOLA) [Zuber et al. 1992 [@]; Smith et al. 1999 [@]] on the Mars Global Surveyor (MGS) [Albee et al. 2001 [@]] along with gravity data from the Mars Reconnaissance Orbiter (MRO) [Zurek & Smrekar 2007 [@]], we place geophysical constraints on the maximum amount of erosion for Arabia Terra. We analyze the topography [Smith et al. 2001 [@]] and gravity [Konopliv et al. 2009, in preparation [@]] in a \( l = 75 \) resolution grid in the spatial domain. Unless otherwise noted, we expand our spherical harmonics fields to \( l = 75 \). We define and restrict our investigation of Arabia Terra to the region outlined by Figure 1. Here, we examine the unique structure of Arabia Terra and key evidence interpreted as erosional indicators.

3.1. Terrain and Crustal Thickness
The elevation [Smith et al. 1999 [@]; Smith et al. 2001 [@]] and crustal thickness [Zuber et al. 2000 [@]; Neumann et al. 2004 [@]] profiles within Arabia Terra decrease gradually to the north, in between more discrete transitions at the northern and southern boundaries of the province [Andrews-Hanna et al. 2008 [@]]. The topography decreases by ~5 km over a distance of 4000 km across Arabia Terra between the northern and southern boundaries (Figure 2), while the crustal thickness decreases by ~25 km. Unlike other areas along the Martian dichotomy, Arabia Terra is afforded a more gentle transition from the highlands to the northern lowlands in elevation and crustal thickness as shown in Figure 3 [Smith et al. 1999 [@]; Smith et al. 2001 [@]]. Though the region possesses topography and crustal thickness that are arguably more similar to the northern lowlands [Zuber et al. 2000 [@]], recent analysis by Andrews-Hanna et al. 2008 [@] reveals the northern edge of Arabia Terra is continuous with the crustal dichotomy boundary, suggesting that Arabia Terra is, in a physiographic sense, part of the highlands.

Arabia Terra contains many inliers (local elevation maxima) and isolated mesas (fretted terrain) that have been interpreted as evidence for a prior, more elevated surface [e.g. Hynek & Phillips 2001 [@]; Carr 2001 [@]]. In order to gauge the minimal amount of eroded material, Hynek & Phillips 2001 [@] use the local elevation maxima to establish a lower bound on regional erosion. Hynek & Phillips 2001 [@] restricted their investigation to western Arabia Terra and Margaritifer Sinus and estimated a minimum of 4.5 \( \times 10^6 \) km\(^3\) of eroded material. If distributed across Arabia Terra, this total amount of erosion is equivalent to a uniform erosional load of 450 m.

As a result of the prominence of partially degraded craters [Cradock & Maxwell 1993 [@]], infilled craters [Forsberg-Taylor et al. 2004 [@]] and ancient valley networks [Carr 1987 [@]], surface modification processes, namely erosion and deposition, have been proposed to have acted across the whole of the highlands [McGill 2000 [@]; Cradock & Maxwell 1993 [@]]. While partially degraded craters are inherent to Arabia Terra as part of the highlands, Arabia Terra lacks a widespread presence of the ancient valley networks characteristic of highlands terrain [Phillips et al. 2001 [@]]. The absence of the valley networks and an apparent deficit in the large surface crater population [McGill 2000 [@]; Cradock & Maxwell 1993 [@]], both of which are physiographic indicators of the southern highlands, have been interpreted as increased activity of erosion and deposition within Arabia Terra in early Martian history [Hynek & Phillips 2001 [@]]. The abundant geomorphologic evidence indicates a complex, yet ambiguous erosional history [Forsberg-Taylor et al. 2004 [@]; McGill 2000 [@]; Cradock & Maxwell 1993 [@]; Golombek et al. 2006 [@]]. Given that it is difficult to place firm constraints on the net volume of material eroded and removed from the region, we focus on the geodynamic response to evaluate the maximum volume of eroded material that is consistent with the gravity and topography.

3.2. Gravity
Notwithstanding the geomorphic evidence for surface erosion, the gravity anomalies expected within a region of massive denudation...
are not observed. However, the gravity anomalies over Arabia Terra are dominated by Tharsis' antipodal bulge [Phillips et al. 2001 [@]]. By virtue of its long-wavelength nature, we can approximate this Arabia bulge by incorporating a degree-1 offset into our gravity anomaly as shown in Figure 3. Though we acknowledge this approximation is insufficient to remove the entirety of the gravitational signature associated with the Tharsis rise and its flexural response, this correction more satisfactorily removes the Tharsis-induced gravity anomalies in Arabia Terra than does the application of high-pass filters.

With the Arabia bulge correction, we can evaluate the viability of different erosional scenarios by comparing the modeled and observed gravity anomalies. Unless explicitly stated, we assume Arabia Terra was initially devoid of any gravity anomaly differences across its boundaries beyond the isostatic signature associated with the Martian dichotomy. We expect the gravitational signature resulting from erosion interior to Arabia Terra to be observable as a change across the northern and southern provincial boundaries. We define this gravity anomaly difference between the exterior and interior of Arabia Terra as the relative gravity anomaly (RGA). Accordingly, we focus our comparison on analyzing the relative gravity anomaly across the boundaries. We use the standard error on the mean (noise measurement) and average gravity anomaly on either side of the boundary to establish a limit of 4 mGal for the relative gravity anomaly along the southern boundary of Arabia Terra. Exterior to northern Arabia Terra, we observe a strong negative gravity anomaly immediately north of the boundary. Relative to Arabia Terra, this highly localized signal provides for a negative relative gravity anomaly across the northern lowlands boundary, whereas an erosional load within Arabia Terra will generate a positive relative gravity anomaly. This anomaly could not have been generated by an erosional load interior to Arabia Terra and could conceivably be a result of crustal flow along the dichotomy Nimmo & Stevenson 2001 [@]. This negative gravity anomaly was interpreted by Andrews-Hanna et al. 2008 [@] as the signature of inwards lower crustal flow during the formation of Arabia Terra as a multi-ring structure around the Borealis impact basin. As a result, we contrast the interior gravity anomaly with its exterior counterpart beyond this highly localized signature to attain a 16 ± 2 mGal relative gravity anomaly along the northern boundary.

We use the values of 6 mGal and 20 mGal for the maximum relative gravity anomalies for the southern highlands and northern lowlands, respectively.

3.3. Estimating Regional Elastic Thickness

3.3.1. Admittance & Coherence

In order to model the geophysical response to erosion within Arabia Terra, we must first constrain the elastic thickness at the time of the erosion. The free-air admittance relation is used to place limits on the effective elastic thickness for a given region [Crosby 2007 [@]]. Over geologic timescales, the effective response of the Martian lithosphere to a surface load can be well approximated by an elastic plate with a specified thickness, $T_e$. For thin elastic shell loading, Equations (8-15) provide a linear mapping between the applied load and the gravity anomaly [Johnson et al. 2000 [@]], neglecting finite amplitude effects. The transfer function relating the final topography to the gravity anomaly is primarily sensitive to the elastic thickness and not the magnitude of the load. In order to estimate the elastic thickness at the time Arabia Terra formed, we compute the localized admittance spectrum over the region and compare with similarly localized admittance spectra from the thin elastic shell model. The admittance spectrum [Wieczorek & Simons 2005 [@]], $Z$, is defined as

$$Z(l) = \frac{S_{\text{gt}}(l)}{S_{\text{gt}}(l)}$$

where $S_{\text{gt}}$ is the cross-power spectrum of the free-air gravity and topography and $S_{\text{gt}}$ is the power spectrum of the topography. The observed topography, relative to a mean highlands’ elevation of 2.1 km, is used to determine the associated gravity anomaly by Eq. (15) for an elastic thickness estimate; admittance spectra are calculated for a range of elastic thicknesses. The associated coherence represents the correlation between the surface topography and the gravity field. The associated coherence function, $\gamma$, is given by

$$\gamma(l) = \frac{S_{\text{gt}}(l)}{\sqrt{S_{\text{tt}}(l)S_{\text{gg}}(l)}}$$

where $S_{\text{gt}}$ is the power spectrum of the gravity field. A mismatch between the modeled and observed coherence may be indicative of loads that have not been represented. Modification processes such as un-modeled surface and subsurface loading may be primary factors in reducing the correlation between the gravity field and the surface topography [McKenzie 2003 [@]]. A satisfactory elastic thickness estimate, requires an admittance fit over a significant portion of wavelengths as well as a strong coherence.

For our analysis, all power spectra have been localized to the region of interest prior to admittance and coherence computation. Invoking this formalism assumes that surface and subsurface loading are statistically independent processes [Forsyth 1985 [@]]. The localization of the model and observational data averts the upward bias (inflated admittance values) as described by Crosby 2007 [@].

3.3.2. Results

Since elastic thickness in Eqs. (8) and (9) is a sensitive parameter with respect to the permissible erosional load and is poorly constrained for Arabia Terra, we utilize the free-air gravity admittance to attain a better estimate for $T_e$. We identify the best-fit lithosphere thickness of $T_e=15$ km by minimizing the misfit (Figure 4) between modeled and observed admittances. As we choose $L_{\text{win}}=15$, the localized admittance can only be computed for degrees 15-60, limited by the finite bandwidth of our spatio-spectral localization. As shown in Figure 4, this provides a reasonable fit between degrees 20 and 50, though the observed admittance takes a downturn beyond degree 50. The local maximum at degree 18 is a distortion by the long-wavelength effects of the rotational flattening and Tharsis, since degree 18 in the localized data includes contributions from as low as degree 3 in the global data fields. Notwithstanding this aberration in the admittance, an elastic thickness of 15 km provides a best fit between degrees 20 and 50.

For any region with accurately modeled loads, we expect a coherence near unity for all degrees [McKenzie 2003 [@]]. In the presence of noise, un-modeled surface loads, or sub-surface loading, the coherence may decrease. Though we restrict our investigation to only surface loading, the lesser values in the observed coherence also suggest that other processes – subsurface erosion or generation of crustal density anomalies – may have acted within Arabia Terra. Even so, the coherence (Figure 4) remains relatively high for the localized region which indicates that if subsurface erosion did occur, it is not a significant influence on the regional gravitational anomalies.

4. Erosional Scenarios

We focus on four main erosional scenarios for the province of Arabia Terra:

1. Highlands’ Elevation Load – an erosional load of the spatially-varying elevation difference between the mean southern highlands’ elevation and the Arabia Terra elevation.

2. Highlands’ Flexural Fit – an erosional load yielding the current surface elevation of Arabia Terra after flexural adjustment.

3. Uniform Erosion – a uniformly thick layer of erosion applied to the whole of Arabia Terra.
4. Bounded Erosion – a linearly-interpolated load with erosional constraints at the northern and southern provincial boundaries.

We employ a forward modeling approach to thoroughly examine each of the aforementioned loading scenarios for Arabia Terra. For each scenario, the erosion is represented as a removal of a surface load with a uniform density of 2900 kg m$^{-3}$ [Zuber et al. 2000 [@]]; McGovern et al. 2002 [@]]. Though we acknowledge that other cases which partially erode a sub-region of Arabia Terra may be equally valid, for simplicity, we constrain our study to scenarios which erode the whole of Arabia Terra. The material eroded in these scenarios is assumed to have been removed entirely from the region.

4.1. Highlands' Elevation Load

The Highlands' Elevation Load represents the elevation difference of Arabia Terra from the mean highlands' elevation of 2100 m as shown in Figure 5. In this scenario, we investigate the viability of forming Arabia Terra from highlands-like terrain and crustal thickness by removing a load representative of the elevation difference. The erosional load ranges from 0 to 5100 m in thickness. We contrast this scenario with the Highlands' Flexural Fit to quantify the importance of flexure. Along with the assumption of an initial 2100-m elevation for Arabia Terra, we assume that the basic physical properties of the highlands are the same as those within Arabia Terra.

Applying the Highlands’ Elevation Load to the thin elastic shell model results in a topography that does not match the current Arabia Terra, as shown in Figure 5. We disregard the sharp transition at the northern and southern edges as a result of spherical harmonic ringing inherent in such a model.

The flexural rebound (deflection) generates significant uplift, yielding a region with an elevation that decreases by 700 m from the southern to the northern edge of Arabia Terra. This produces a final topography with an elevation trend shallower than the current Arabia Terra and deviates from the observed elevation at the northern boundary by over 4 km. As illustrated in Figure 5, the flexural rebound also generates 500 m of uplift exterior to the northern boundary. This 500-m uplift exterior to northern Arabia Terra lies outside of one standard deviation of the regional elevation profile (Figure 2). Additionally, the amount of erosion does not achieve the deficit required to match the observed crustal thickness (Figure 3). Thus, the crustal thickness and the topography, interior and exterior to Arabia Terra, fail to match the observations. Although the relative gravity anomaly along the southern boundary is small at 8 mGal, it still exceeds the 6-mGal limit imposed by the observations. Larger amounts of erosion at the northern boundary results in a greater relative gravity anomaly of 20 mGal, consistent with the maximum allowable RGA identified for northern Arabia Terra.

While this erosional scenario is nearly consistent with the observed gravity anomalies, it cannot reproduce the present-day topography or crustal thickness of the region. The inability of this scenario to yield an elevation consistent with the current state of Arabia Terra demonstrates the importance of flexure. The topography of Arabia Terra cannot be reproduced without significantly more erosion than calculated by the elevation difference alone. Hence, this erosional load cannot be singularly responsible for the formation of Arabia Terra.

4.2. Highlands' Flexural Fit

Incorporating flexure into the reconstruction of the original surface requires erosion of a significantly greater amount than the prior scenario. We employ the Turcotte et al. 1981 [@] model as described by Section 2.2 with $\Delta \rho = \rho_m - \rho_L$. This adaptation effectively permits an implicit calculation of the amount of additional erosion required to produce the observed topography. The supposition of erosion as the primary mechanism responsible for the current physiographic state of Arabia Terra requires the initial (pre-erosion) elevation to be coincident with the southern highlands elevation of 2100 m.

The erosional load required to form the topography of Arabia Terra from an initial state similar to the southern highlands is shown in Figure 6. The amount of erosion is equivalent to a 750-m layer of sediment spread across the whole of the northern lowlands. With a 15-km elastic thickness, this scenario erodes up to 22 km at the northern extremity yielding a total eroded volume of $1.7 \times 10^8$ km$^3$. This erosional load more closely reproduces the crustal thickness deficit of Arabia Terra relative to the southern highlands.

As a consequence of erosional amounts in excess of the elastic (lithosphere) thickness, we invoke the caveat that the erosion must transpire on a timescale sufficiently long to allow for thermal diffusion to maintain a minimal elastic thickness of 15 km. Using the thermal diffusion timescale, the erosion must occur on a timescale of greater than 2.4 My or at a rate less than 9.2 mm/yr. This rate is orders of magnitude greater than the average erosion rates estimated for Mars Craddock & Maxwell 1993 [@], justifying the assumption of a minimal elastic thickness during the erosional event.

Though the erosional load is designed to reproduce the topographic expression of Arabia Terra, the scenario fails to reproduce the elevation exterior to Arabia Terra and an allowable relative gravity anomaly. In eroding nearly 22 km at the northern extremity, the resultant flexural rebound produces uplift of over 1 km immediately exterior to Arabia Terra. This substantial elevation rise is contradictory to the observations and is too large to be masked by measurement noise. While this 1-km exterior uplift alone is sufficient to deem this scenario implausible, the resultant gravitational anomaly further diminishes the viability of this scenario. The gravity anomaly map in Figure 6 contains an 80-mGal relative gravity anomaly across the northern boundary, substantially greater than allowable for northern Arabia Terra. Furthermore, this scenario establishes a strong gradient in the gravity anomaly interior to Arabia Terra, contradictory to observations of a nearly uniform gravity anomaly. The relative gravity anomaly on the southern boundary of 40 mGal also exceeds the allowable RGA.

Though the relative gravity anomalies are too large to be accommodated by the observations, the resulting crustal thickness trend more closely resembles crustal thickness models than the prior scenario. While the discrepancy in crustal thickness in the erosional model is small, the overcompensated, excess crustal thickness is insufficient to produce large negative gravity anomalies over Arabia Terra, in conflict with the observations.

This scenario is designed to reproduce the topography of Arabia Terra via erosion from an initial state similar to the southern highlands. Using this scenario, we produce an overcompensated Arabia Terra crustal thickness estimate with a gravity anomaly trend interior to Arabia Terra and relative gravity anomalies on the northern and southern boundaries that exceed the observations. These results demonstrate that erosion cannot be solely responsible for the formation of the current Arabia Terra from the southern highlands.

4.3. Uniform Erosion

This scenario diverges from the notion of a pre-erosional Arabia Terra commensurate with the southern highlands and instead erodes a uniformly thick layer from Arabia Terra. In order to provide a final elevation and crustal thickness consistent with the current state of Arabia Terra, the pre-erosional state includes isotropic crustal thickness variations specific to the applied erosional load. As the gravity anomalies arising from isostatically-compensated topography are small relative to those arising from flexurally-supported loads, the uniform erosion scenario will produce a similar relative gravity anomaly across all boundaries. We first consider an amount of erosion consistent with Hynek & Phillips 2001 [@], a uniform erosional load of 450 m. This erosional load produces a 3-mGal relative gravity anomaly on the northern and southern boundaries. The amount of flexural rebound immediately exterior...
to Arabia Terra is minimal. Accordingly, this amount of erosion is allowable based on the observations. Using an iterative, forward-modeling approach to minimize the misfit between the modeled and observed relative gravity anomalies, we can determine the maximum amount of uniform erosion consistent with the observations. The 6-mGal relative gravity anomaly on the southern boundary is the primary constraint, allowing for a uniform maximum erosional load of approximately 1300 m. Neglecting contributions to the southern relative gravity anomaly from noise/error, Table 3, a best-fit uniform erosional load can also be determined: 750 m.

4.4. Bounded Erosion

The difference in the observed northern and southern RGA upper limit suggests that a relatively larger amount of erosion is allowable on the northern boundary. In this scenario, we consider a load with assigned erosional amounts on each boundary; between the boundaries, the erosion is linearly interpolated to attain the erosional load. Through an iterative forward-modeling scheme similar to the prior scenario, we determine the maximum bounded erosional load — erosion linearly increases from 300 m in the south and culminates at 5000 m in the north. As shown in Figure 7, this maximum erosional load attains the 6-mGal and 20-mgal relative gravity anomaly upper limit along the northern and southern boundaries, respectively. Thus, this bounded erosional load is able to reproduce the difference between the respective relative gravity anomalies on the boundaries. This maximum erosional load amounts to $3.1 \times 10^7$ km$^3$ of material that could have conceivably been removed from Arabia Terra. Additionally, we calculate a best-fit bounded erosional load (Figure 8) designed to match the observed northern and southern RGA without error. The best-fit bounded erosional load increases from no erosion in the south to 4000 m in the north.

5. Discussion

The thin elastic shell loading model applied here provides constraints on the maximum volume of erosion which can reproduce the observed gravity anomalies (Table 3). In addressing erosion from the vantage of geophysics, we eliminate uncertainty in the interpretation of geological units and employ a model independent of specific fluvial or aeolian processes. Any significant alteration of Arabia Terra would have likely occurred prior to the onset of the Hesperian epoch in order to maintain current estimates for the terrain age [Craddock et al. 1997 [?]] and to be consistent with the thin elastic thickness. It is likely that if erosion did occur within Arabia Terra, it may have occurred over a period of time [Golombek et al. 2006 [?]; Hynek & Phillips 2001 [?]; Craddock & Maxwell 1993 [?]] rather than in a singular event. As our admittance analysis indicates Arabia Terra was formed in the presence of a 15-km thick elastic lithosphere, any subsequent surface modification would have occurred at a greater elastic thickness. Since the lithosphere becomes more rigid over time, a given erosional load will result in a relatively larger gravity anomaly. By modeling erosion with a 15-km elastic lithosphere, the erosional load calculated is an upper limit for erosion within Arabia Terra.

As illustrated by the highlands’ elevation load, the Arabia Terra topography cannot be reproduced by the removal of a load representative of the elevation difference as a result of subsequent flexural rebound. Although we can reproduce the topography of Arabia Terra via the highlands’ flexural fit scenario, the erosion required produces large gravity anomalies and uplift exterior to the region in conflict with the observations. Although the current physiographic expression of Arabia Terra cannot be explained by erosion, lesser amounts of erosion are allowable within the region from the geodynamical constraints. Employing a fit to the relative gravity anomaly of Arabia Terra, uniform erosion of material, no greater than 1300 m could have occurred; beyond 1300 m, the relative gravity anomaly along the southern boundary of the province is exceeded. However, the larger, relative gravity anomaly in northern Arabia Terra allows for a greater amount of material to have been removed. Accordingly, our bounded erosional load can reproduce the difference between the observed relative gravity anomalies. The erosional load linearly increases with distance from the southern boundary of Arabia Terra with 300 m of erosion in the south and up to 5000 m in the north. The load represents the maximum amount of erosion that can be removed from Arabia Terra: $3 \times 10^7$ km$^3$ of material. Given the constraint on the surface age from crater statistics, a majority of the erosion from the Highlands Flexural Fit scenario would have had to occur no later than $\sim 3.8$ Ga. Though lateral crustal flow may have diminished the resultant gravity anomalies observed on present-day Mars, the persistence of the north-south crustal dichotomy through the early Noachian provides a constraint on crustal relaxation [?, Zhong and Zuber, 2000; Nimmo & Stevenson 2001 [?]; ?]. On the basis of thermal models that include consideration of crustal heat production and the role of hydrothermal circulation in the crust, relaxation rates $10^{-17}$ s$^{-1}$ are required to maintain crustal thickness variations [Parmentier and Zuber, 2007]. This constraint is easily met for plausible thermal structures in the Noachian, and limits vertical perturbation of the crust-mantle boundary to be on the order of 1 km within Arabia Terra. Thus, while crustal flow within Arabia Terra would affect our estimate on the maximum amount of erosion, erosion with crustal flow still cannot explain the formation of Arabia Terra from the southern highlands. Additionally, it is likely crustal-thinning resulting from erosion would increase the effective viscosity allowing for greater preservation of the Arabia Terra crustal profile [Nimmo & Stevenson 2001 [?]; ?]. Ultimately, given the assumption of a pre-erosional Arabia Terra similar to the highlands, the preservation of the large-scale Noachian crustal thickness variations on Mars (i.e. crustal dichotomy, Hellas) [see Nimmo & Stevenson 2001 [?]] suggests that lower crustal flow would not have been substantial within Arabia Terra.

6. Conclusions

In order for erosion to be a viable candidate for the formation of Arabia Terra from the southern highlands, an erosional model must reproduce the topography and gravity anomaly both within and exterior to the region. Appropriately reproducing the topography entails the consideration of flexure; without the consideration of flexure the load itself cannot properly be determined or evaluated.

Our admittance analysis demonstrates that the present-day topography of Arabia Terra was established in the presence of a 15-km thick elastic lithosphere. This lithosphere thickness determines the flexural response of Arabia Terra to any large-scale loading event. In order to generate the observed topography of Arabia Terra via erosion from the highlands alone, $1.7 \times 10^3$ km$^3$ of material must be eroded from the region. However, this erosion would result in a substantial flexural uplift of the lithosphere immediately exterior to Arabia Terra and resultant gravity anomalies that exceed observations.

This work demonstrates the maximum amount of erosion that could have occurred in Arabia Terra is $3 \times 10^7$ km$^3$, consistent with the geological minimum established by Hynek & Phillips 2001 [?]. Further, we conclude erosion cannot explain the observed topography and crustal thickness deficit of Arabia Terra. If the unique physiography of this region is a result of erosion, it must have been accompanied significant viscous relaxation [Nimmo & Stevenson 2001 [?]] or alternatively must have possessed large isostatic crustal thickness variations prior to an erosional event.

References


Greeley, R. & Guest, J.E., 1987, Geologic Map of the Eastern Equatorial Region of Mars, Scale 1:15,000,000, U.S. Geol. Survey Map I-1802-B.


Konopliv et al. (in preparation).


A. J. Evans, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Ave., 54-825, Cambridge, MA, 02139, USA. (xan@mit.edu)
Figure 1. Mars Topography in kilometers. (a) Solid line outlines the region of Arabia Terra. The dashed box represents (b) in the global topography. (b) Shaded relief elevation map of the Arabia Terra region. Over a 4000-km span, the topography of Arabia decreases by 5-km. The dashed box represents (c) in the regional topography. (c) A view of the isolated mesas within Arabia Terra.
Figure 2. Mean surface elevation across Arabia Terra. The black line represents the average elevation and the grey lines represent one standard deviation about the mean. From Andrews-Hanna et al. 2008 [@].
Figure 3. Mars Crustal Thickness and Gravity. (a) Global Crustal Thickness (km). Within the region of Arabia Terra, the crustal thickness decreases from 53-km to 28-km near the northern border, yielding a total crustal thickness reduction of 25-km. The region enclosed by the solid line is Arabia Terra. (b) Martian Gravity in mGal. Solid line outlines the region of Arabia Terra. The Arabia Terra region is dominated by the antipodal signature associated with Tharsis. (c) A regional gravity anomaly map with a center-of-mass offset incorporated to remove the antipodal signature associated with Tharsis.
Figure 4. (a) Model and Observation Admittance. The model admittance is shown above for an elastic lithosphere thickness of 5, 15, 25, 40, 50 kilometers. The dark solid line represents the actual free-air admittance for Arabia Terra. The peak in admittance near degree 18 is likely due to Tharsis. (b) Admittance Minimum Misfit. The admittance for Arabia Terra is best fit by a model with an elastic thickness of 15-km, denoted in the misfit by the asterisk. The misfit is applied between degrees 20 through 50. The minimum misfit is at a 15-km elastic lithosphere. (c) Coherence. The thick solid line represents the coherence for Arabia Terra and the thin solid line represents the coherence for an elastic lithosphere of 15-km.
Figure 5. Highlands’ Elevation Load. (a) Load applied to Arabia Terra region. The erosional load is the spatially-varying elevation difference between the mean southern highlands’ elevation and the Arabia Terra elevation. (b) Resultant flexure from erosional load. (c) The final elevation of terrain after the erosional load is applied. Final elevation is a summation of the erosional load (a) and the resultant flexure (b). (d) The resultant gravity anomaly includes the finite amplitude effect resulting from topography on the surface and along the crust-mantle boundary.
Figure 6. Highlands’ Flexural Fit Scenario. (a) Load applied to Arabia Terra region. The erosional load is designed to match the observed elevation of Arabia Terra. (b) Resultant flexure from erosional load. (c) The final elevation of terrain after the erosional load is applied. Final elevation is a summation of the erosional load (a) and the resultant flexure (b). (d) The resultant gravity anomaly includes the finite amplitude effect resulting from topography on the surface and along the crust-mantle boundary.
Figure 7. Maximum, Bounded Load Scenario. (a) Load applied to Arabia Terra region. The erosional load is formed from a linear interpolation between erosional amounts assigned to the northern and southern provincial boundaries, respectively. The erosional load is designed to match the maximum allowable RGA. (b) Resultant flexure from erosional load. (c) The final elevation of terrain after the erosional load is applied. Final elevation is a summation of the erosional load (a) and the resultant flexure (b). (d) The resultant gravity anomaly includes the finite amplitude effect resulting from topography on the surface and along the crust-mantle boundary.
Figure 8. Best-Fit, Bounded Load Scenario. (a) Load applied to Arabia Terra region. The erosional load is formed from a linear interpolation between erosional amounts assigned to the northern and southern provincial boundaries, respectively. The erosional load is designed to best-fit the RGA. (b) Resultant flexure from erosional load. (c) The final elevation of terrain after the erosional load is applied. Final elevation is a summation of the erosional load (a) and the resultant flexure (b). (d) The resultant gravity anomaly includes the finite amplitude effect resulting from topography on the surface and along the crust-mantle boundary.
**Table 1.** Parameter Values for the Thin Elastic Shell Loading Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Crustal Density, $\rho_c$</td>
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<tr>
<td>Load Density, $\rho_L$</td>
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<td>Mantle Density, $\rho_m$</td>
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<td>Young’s Modulus, $E$</td>
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**Table 2.** Parameter Values for the Density Interfaces

<table>
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<th>Parameter</th>
<th>Surface Interface</th>
<th>Mantle Interface</th>
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<td>$\rho_m - \rho_c$</td>
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<td>Shape, $S_{lm}$</td>
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<td>$w_{lm} + A_{lm}$</td>
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### Table 3. Erosion Scenario Summary

<table>
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<th>Scenario</th>
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<th>Erosional Load (m)</th>
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<td>North</td>
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<td>Highlands’ Flexural Fit</td>
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<td>6</td>
</tr>
<tr>
<td>Uniform Erosion: Best-fit*</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Bounded Erosion: Maximum</td>
<td>20</td>
<td>6</td>
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<tr>
<td>Bounded Erosion: Best-fit</td>
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