Anomalies of Density, Stresses, and the Gravitational Field in the Interior of Mars

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Abstract

We determined the possible compensation depths for relief harmonics of different degrees and orders. The relief is shown to be completely compensated within the depth range of 0 to 1400 km. The lateral distributions of compensation masses are determined at these depths and the maps are constructed. The possible nonisostatic vertical stresses in the crust and mantle of Mars are estimated to be 64 MPa in compression and 20 MPa in tension. The relief anomalies of the Tharsis volcanic plateau and symmetric feature in the eastern hemisphere could have arisen and been maintained dynamically due to two plumes in the mantle substance that are enriched with fluids. The plumes that originate at the core of Mars can arise and be maintained by the anomalies of the inner gravitational field achieving +800 mGal in the region of plume formation, – 1200 mGal above the lower mantle–core transition layer, and –1400 mGal at the crust.

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Introduction

Since seismic studies have not been carried out on Mars, preliminary information about its internal composition can be obtained using the observational data on its gravitational field and relief, as well as some theoretical conclusions verified when studying the density structure of the Earth. Earlier, we developed the technique for determining (in quadratic approximation) the contribution of anomalous masses distributed over ellipsoidal surfaces to a planet’s gravitational field \[1\]–\[3\] and applied this technique when studying the structure of the envelopes of Earth and Mars \[4, 5\]. In this paper, we estimate the possible distributions of relief compensation depths and anomalies of density and stresses more accurately, as well as anomalous gravitational field in the crust, mantle, and core of Mars. In their similar studies, other authors considered the compensation of relief masses only at one level, namely, at the Mohorovičić surface \[6\]–\[9\]. Our results that were obtained for the Earth show that several compensation levels can exist in the interior of a planet, which agrees with the analysis of the Earth’s free oscillations and seismological data \[4\]. The compensation depths for different relief harmonics depend strongly on the degree and order of the harmonics. So, our first task was to determine the possible compensation depths for the harmonics of different degrees and orders of the expansion of the Martian topographic heights with respect to the hydrostatic ellipsoid.

We solved this problem for the crust and mantle of Mars without allowing for possible stresses in the lithosphere \[5\]. However, our further studies, along with the studies of other researchers \[8\]–\[11\], showed that the lithospheric layer of Mars is able to endure appreciable nonhydrostatic loads. Stresses arise that are isostatically unbalanced; ignoring these stresses can yield unreasonably great depths of isostatic compensation for small (in length) relief inhomogeneities characterized by the high degree harmonics. Since every relief inhomogeneity is characterized by a specific set of harmonics, the maximum concentration the compensates this set within a specified range of depths can indicate the most probable compensation depths for the relief inhomogeneity of interest. The compensation depths determined this way will allow us to find the depth distribution of compensation masses and to determine possible anomalies of the internal gravitational field.

Mars belongs to the group of terrestrial planets that have some features in common concerning their formation and composition \[8\]. The technique we developed for the Earth can be reliably applied to Mars because the results obtained for Earth agree well with the seismological data and the analysis of free oscillations \[4\]. We must bear in mind, however, that this is a mere simulation that can be helpful in future studies on the surface of Mars.
1 Compensation depths for relief masses

The solution to the problem must satisfy a system of two equations; one equation reflects the correspondence between the observations and the contribution of the relief masses and compensation masses to the gravitational field, while the other is the condition of the pressures below the compensation depth, which is equal to the hydrostatic pressure. The compensation depth \(d_{nm}\) for an arbitrary relief harmonic \(a_{nm}\) is obtained from the relationship

\[
d_{nm} = R_0 - R_M \left( \frac{a_{nm}^{M1}}{b_{nm}^{M2}} \right)^{1/n},
\]

where \(R_0 = 3389.5\) km is the mean radius of Mars; and \(a_{nm}^{M1}, a_{nm}^{M2}\) are the coefficients in the spherical function expansion of the altitudes of compensation surfaces \(M1\) (obtained using the gravitational field after deduction of the contribution of relief masses in the quadratic approximation) and \(M2\) (obtained using the hypothesis of isostatic compensation for the relief masses) with respect to the corresponding hydrostatic ellipsoid, with the compensation radius \(R_M\) being fixed (a similar relationship is valid for \(b_{nm}\) when \(b_{nm}\) is substituted for \(a_{nm}\)).

As can be seen, solution (1) is possible, i.e. \(d_{nm} \geq 0\), if \(0 \leq a_{nm}^{M1}/b_{nm}^{M2} \leq (R_0/R_M)^n\). Studying solution (1) for both Earth and Mars shows that it is possible to compensate the relief masses at one level only for a certain set of harmonics. To make the compensation for the remaining harmonics, when the solution does not correspond to the obtained condition for \(d_{nm} < R_0\), the following two versions were chosen to ensure the minimum deviations between the internal composition of Mars and the equilibrium state:

(1) Compensation is made at two levels. The upper crust is taken as the first level. The possible depths of the second level are determined from the analysis of the results that were obtained for the harmonics for which solution (1) exists. The final choice is made with allowance for the weight function, which is inversely proportional to the deviations of the internal composition of Mars from the hydrostatic equilibrium.

(2) The uncompensated relief harmonics yield the stresses in the lithosphere of Mars provided that the stresses do not exceed the strength limit of the lithosphere.

We used the harmonic expansion of degree \(n \leq 18\) as the initial presentation for the gravitational field of Mars [12] and for the relief [13] after taking the hydrostatic values into account [14]. Figure 1a shows the distribution of the mean compensation depths for the relief harmonics as function of degree \(n\) of the harmonic. The mean depth was calculated separately when considering the compensation in the upper crust (\(d \leq 25\) km). We did not analyze the harmonics whose amplitudes were smaller than the mean amplitude for the considered degree and the deviation of the compensation depth from the mean value exceeded 3\(\sigma\). These harmonics are likely to contribute to the stresses in the lithosphere of Mars. Figure 1 shows that the relief harmonics of low degrees \(n = 2\) \((a_{20}, a_{22}, b_{22})\), \(n = 3\) \((a_{33})\) and \(n = 4\) \((b_{44})\) are
compensated at depths of $d = 1000–1350$ km. The large scatter in compensation depths for the harmonics of degrees $n = 3, 4$ is due to the harmonics $b_{32}, a_{40}$ ($d = 320$ km), $b_{33}$ ($d = 450$ km), $a_{32}, b_{42}$ ($d = 760$ km), $a_{33}$ ($d = 1250$ km), and $b_{44}$ ($d = 1050$ km). The harmonics of degrees $n = 5–18$ are compensated mostly at depths of $34–240$ km; the scatter relative to the mean values is small, with the exception of $a_{55}$ ($d = 400$ km) and $a_{53}$ ($d = 270$ km).

As for the harmonics that do not satisfy condition (1), only two harmonics ($a_{30}, b_{31}$) can be isostatically compensated according to the first version as follows from the analysis of harmonic amplitudes of the simple layer corresponding to the relief and upper crust; the other harmonics lead to stresses in the lithosphere of Mars. Figure 1b shows that the relative contribution of stresses achieves the maximum for the harmonics of degrees $n \geq 11$ for which the load pressure of the relief and anomalous masses of the crust is compensated mostly due to stresses (according to [15], the contribution of these harmonics is greatest for the Olympus Mons). For the same harmonics, the correlation coefficient is greatest between the load pressure and stresses ($k = 0.72–0.99$), which implies that Olympus creates mainly compressive stresses (Fig. 2b). The correlation coefficient is lowest for the harmonics of low degrees ($n \leq 7$), namely, $k < .05$ for $n = 1–3$ and $k < .3$ for $n = 4–7$; this indicates that large relief inhomogeneities spanning more than $25^\circ$ (Tharsis, Hellas, Argyre) are mostly isostatically compensated or partly overcompensated (the correlation between the stresses and relief is negative for the harmonics of degrees $n = 1–4, 6, 7$).

The histograms in Figs. 1c, d show the distributions of compensation depths for the relief harmonics after excluding the harmonics responsible for the stresses. The histograms and mean depths were calculated with account of the weights corresponding to the contribution of the harmonics to the gravitational field. The analysis of the histograms allows us to conclude that the relief is completely compensated in the depth range $d = 0–1400$ km, with more than 17% of compensation occur in the upper crust ($d = 0–25$ km, $\bar{d} = 5.0 \pm 3.6$ km). Further, several major compensation layers can be singled out: a crust–mantle transition layer ($d = 30–210$ km, $\bar{d} = 100 \pm 43$ km); a lithospheric boundary layer ($d = 230–330$ km, $\bar{d} = 280 \pm 41$ km); an upper–middle mantle transition layer ($d = 390–460$ km, $\bar{d} = 450 \pm 11$ km); an anomalous layer in the middle mantle ($d = 750–770$ km, $\bar{d} = 760 \pm 5$ km); and a mantle–core transition layer ($d = 1000–1350$ km, $\bar{d} = 1180 \pm 138$ km). When applied to the Earth, this technique shows that the most probable compensation depths agree well with the depths based on the seismic data and spectral analysis of the normal modes of Earth’s free oscillations. Applying this technique to Mars will most likely yield reliable results.
2 Stresses and density anomalies in the crust and mantle of Mars

Figure 2a shows the smoothed relief of Mars presented in the form of an altitude expansion with respect to the hydrostatic ellipsoid for \( n \leq 18 \). Here, the major relief features on Mars that are greater than 10° are reflected. The distribution of possible stresses in the lithosphere of Mars is mapped in Fig. 2b. It can be seen that the major vertical compressive stresses (positive values) correspond to the volcanic craters (Olympus, Arsia, Pavonis, and Elysium Montes), Alba Patera, Utopia and Isidis Planitie, and the eastern part of Vastitas Borealis. They are encircled with the vertical tensile stresses (negative values). The tensile stresses also correspond to the Valles Marineris, Echus Chasma, and the western part of Vastitas Borealis. All the stresses do not exceed the compressive strength (266 MPa) and tensile strength (22 MPa) of basicrocks [11]. Since the strengths of acid intrusive rocks (granites) are twice as low, the large patterns of faults surrounding Tharsis and flanks at the Vallis Marineris are likely to indicate the more acidic composition of rocks in the regions of faults. They correspond as well to negative anomalies of crust density (Fig. 2c). The Argyre Planitia and Hellas Planitia, as well as Planum Boreum and Planum Australe, seem to be mostly compensated and do not create large stresses.

Figures 2c, d and 3a, b, c, d present the maps of density distributions of compensation masses recalculated relative to the density of the simple layer at middle depths of 0, 100, 280, 450, 760, and 1180 km, which correspond to the set of harmonics for the layers with above middle depths. The comparison of these density distributions allows us to draw the following conclusions:

(1) The dichotomy of the relief on Mars caused by the harmonics of the first degree is mostly compensated due to lava filling of the crust in the plains of the northern hemisphere (Fig. 2c). The impact features (Hellas, Isidis, Utopia, Argyre), which are possibly similar to the lunar mascons of enhanced density, have roots stretching down to depths of 280 ± 41 km and are surrounded by circular features of reduced density(Figs. 2c, d; 3a).

(2) There is no clear correlation between the possible depths \( M \) that were obtained using Fig. 2d by taking the density jump at \( M \) into account as well as the relief features (with limited exceptions for Hellas and its surroundings, as well as Utopia, Elysium, Argyre, Arsia, and Alba, due to local compensation at \( M \)). The boundary at \( M \) could have been raised due to flows ascending from the mantle below Vastitas Borealis, Utopia, and Arabia Terra (Fig. 3a). The regions of negative anomalies (including circumpolar ones) are likely to indicate fluid supplies (perhaps water) that did not have enough time to reach the Martian surface through the solidified crust.

(3) The relief anomalies of the Tharsis volcanic plateau and symmetric feature in the
eastern hemisphere, which are mostly caused by the harmonics of the second degree, seem to have appeared and been maintained dynamically due to two plumes in the mantle substance enriched with fluids. They originate in the lower mantle (Fig. 3d) and divide into several branches in the upper mantle (Figs. 3a, 2d).

(4) Figure 3b shows that the ascending flow of a light substance in the mantle, which is stronger below Tharsis and pushes the descending heavier masses aside, while the stronger descending flow in the symmetric equatorial region pushes the light ascending masses aside. The sloping features in Fig. 3c are also of interest. They may arise due to the lateral gradient of gravitational potential (Fig. 5c) and the Coriolis force. The heavier components of the mantle substance that descend from a depth of 450 km shift to the South (toward the maximum potential) and then, affected by the Coriolis force, to the West, as well as North, and then East. The lighter components ascending from a depth of 1180 km shift toward the minimum potential, namely, to the North and then East.

3 The sources of plumes and the forces that maintain their existence

Obtained by us the density anomalous in the crust and mantle of Mars force the internal gravitational field to deviate appreciably from the hydrostatic equilibrium in the core, although they satisfy the condition, thus suggesting that the pressure is hydrostatic below 1350 km; this may cause convective motions to appear. The fact that Mars does not have an intrinsic magnetic field can indicate either the hydrostatic equilibrium of the core or possible convective motions that are symmetrical relative to the polar axis (which does not satisfy the operating condition of a hydromagnetic dynamo). To verify these conditions, we considered two three-layer models that do not distort the external gravitational field of Mars and satisfy the condition of hydrostatic equilibrium below the lower layer. The first model suggests that the core as a whole is in hydrostatic equilibrium. To meet this model condition, the lower layer must correspond to the boundary of the external core. With the density jump at the core boundary being \(3 \times 10^3 \text{ kg/m}^3\), the anomalies in density can correspond to variations (–6, 13) km for the accepted core boundary \(R = 1700 \text{ km}\); a part of these variations, namely, (–6, 3) km can be accounted for by the fact that the core compression exceeds the hydrostatic compression (0.0053) by 0.0027. Such excess in the core compression over the hydrostatic compression is unlikely to correspond to the modern liquid core. Thus, we considered another model, whose lower layer corresponds to the accepted boundary of the solid inner core \(R = 1000 \pm 100 \text{ km}\) while the two upper layers correspond to the external core boundary \(R = 1700 \pm 300 \text{ km}\) and the transition layer between the lower mantle and core \(d = 1000—1350 \text{ km}\). The distributions
of anomalous masses obtained in this core model are presented in Figs. 3e, f.

We mapped the relative anomalies of internal gravity (relative to $g_0 = 3.73 \text{ m/s}^2$) using the obtained distributions of anomalous masses (Fig. 4). The maps outline the regions where the differentiation of the light and heavy components of the Martian material occurs with greater rates in the areas of positive anomalies. Thus, Fig. 4a shows that the ascending plumes of light substance originate from the equatorial regions of the core where the maximum rate corresponds to the core regions below Tharsis and the diametrically opposed region. The pattern of anomalies presented in Fig. 4a holds within the region between the boundaries of the inner core and up to the transition mantle–core layer. The pattern of anomalies changes above this layer (Fig. 4b). The differentiation rate achieves a minimum at the plume area, which leads to the trapping of light matter at the plume area spanning up to the lithosphere boundary (Fig. 4d). The differentiation rate changes in the lithosphere (Fig. 4e, f) according to the plume fragmentation into separate branches. Figures 4e, f show that the minimum differentiation rate corresponds to the highest and isostatically uncompensated relief features (Olympus, Arsia, Pavonis, and Elysium Montes) while the regions of positive anomalies correspond to lowlands compensated in the lithosphere and upper mantle (Hellas Planitia, Vastitas Borealis, and Acidalia Planitia).

4 Convective motions in the mantle and core of Mars

Convective motions can appear if forces exist that cause lateral motions of matter. In the gaseous and liquid envelopes of the planets (and Sun), the Coriolis forces that arise due to radial motions in the spherical envelopes can act in the lateral direction. In the solid envelopes, the lateral gradients of gravitational potential can be such forces; as a result, the heavy components not only move down (which is energetically expedient) but also shift laterally toward the maximum potential, while the light plume components move toward the minimum potential.

The lateral distributions of the anomalies of inner potential caused by anomalous masses (Figs. 2, 3) at various depths with respect to $V_0 = g_0 R_0$ are mapped in Fig. 5. The maps are presented upward from the outer core boundaries because the distribution pattern inside the core is similar and the anomalies rapidly decrease to zero at the inner core boundary. Figures 5a, b, c show that the lateral gradients of potential achieve the maximum in the mantle–core transition layer and that the behavior of their distribution scarcely changes until the upper–middle mantle transition layer. It is interesting to note that the distribution of potential at depths of 450, 760, and 1180 km correlates with the distribution of anomalous masses at these depths (Figs. 3b, c, d). This signifies that the distribution of anomalous masses at these depths is stable against the gravitational effect of anomalous masses at other levels.
and is defined by the potential of these masses. The situation is entirely different at depths of 280, 100, and 30 km, where the distribution of potential is due to the masses of the relief and upper crust. Thus, the anomalous features at these depths (Figs. 2d, 3a) are unstable and depend on processes that change the structure of relief and upper crust.

As for the convective motions due to variations of potential, these motions can cover the entire mantle between the core and lithosphere boundaries (where the lateral motions are directed opposite to the motions near the core boundaries) (Figs. 2–5). The flows of electrically conductive material that arise in the meridional planes can create toroidal magnetic fields; since the magnetic fields in the northern and southern hemispheres have opposite directions and are nearly symmetrical, the total field approaches zero. Similarly, the weaker flows in the planes parallel to the equatorial plane are almost symmetric relative to the rotational axis and cannot create a global poloidal magnetic field, according to the Cowling theorem.

**Conclusions**

The crust and mantle of Mars are characterized by nonuniform distributions of density and stresses down to a depth of 1450 km. The relief anomalies of the Tharsis volcanic plateau and symmetric feature in the eastern hemisphere are likely to have arisen and been maintained dynamically due to two plumes of the mantle substance, which originate at the core boundary and are enriched with fluids. The plumes can arise and be maintained due to anomalies in the inner attractive forces. The volcanic craters of enhanced density and large relief depressions are maintained mostly due to the elastic properties of the lithosphere and create stresses that do not exceed the strength of the lithosphere.

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Figure 1: Fig. 1. (a) Distribution of the compensation depths of relief masses as a function of degree $n$ of the expansion; (b) distributions of the loading pressure of homogeneous relief (2), relief and anomalous masses of upper crust (1), and stresses (3) as functions of degree $n$ of the expansion; (c) distribution histogram of the compensation depths for the relief harmonics with a step of 30 km for the entire depth range between 0 and 1400 km, (d) step of 10 km for the depth range between 0 and 340 km.
Figure 2: Anomalous structures of the Martian crust for the expansion up to the 18th degree: (a) – relief heights relative to the hydrostatic ellipsoid, the cross section of isolines is 1 km; (b) – anomalies of the vertical stresses in the crust, the cross section of isolines is 5 MPa; (c) – anomalous masses of the upper crust (at a depth of 0–25 km), the cross section of isolines is $2 \cdot 10^6$ kg/m$^2$; (d) – anomalous masses of the crust–mantle transition layer (at a depth of 30–210 km), the cross section of isolines is $2 \cdot 10^6$ kg/m$^2$. 
Figure 3: Anomalous masses of the mantle and core of Mars for the expansion up to the 18th degree, the cross section of isolines is $2 \cdot 10^6$ kg/m$^2$: (a)— at a depth of 230–330 km; (b) — at a depth of 390–460 km; (c)— at a depth of 750–770 km; (d) — at a depth of 1000–1350 km; (e)— at the outer core boundary; (f)— at the inner core boundary.
Figure 4: Relative anomalies of the attractive force in the core, mantle, and crust of Mars; the cross section of isolines is $2 \cdot 10^{-4} \, g_0$: (a) — above the inner core boundary (for $R = 1100 \, \text{km}$); (b) — above the mantle–core transition layer (for $R = 2400 \, \text{km}$); (c) — above the layer at a depth of 760 km (for $R = 2700 \, \text{km}$); (d) — above the upper–middle mantle transition layer (for $R = 3000 \, \text{km}$); (e) — above the lithosphere boundary layer (for $R = 3170 \, \text{km}$); (f) — above the crust–mantle transition layer (for $R = 3360 \, \text{km}$)
Figure 5: Relative anomalies of the attractive potential in the core, mantle, and crust of Mars; the cross section of isolines is $2 \cdot 10^{-5} V_0$: (a)— at the outer core boundary; (b)— at a depth of 1180 km; (c)— at a depth of 760 km; (d)— at a depth of 450 km; (e)— at a depth of 280 km; (f)— at a depth of 100 km.