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Lateral Density Inhomogeneities of the Continental and Oceanic Lithosphere and Their Relationship with the Earth's Crust Formation

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Abstract—This paper presents the results of the study of the free mantle surface (FMS) depth beneath continents and oceans. The reasons for the observed dependence of the FMS depth on the crustal thickness in the continental lithosphere are discussed. The influence of radial variations in the mantle's density is evaluated. The calculations performed have indicated that the observed dependence of the FMS depth on the crustal thickness is caused mostly by lateral inhomogeneities in the lithospheric mantle, and the size of these inhomogeneities is proportional to the thickness of the crust. The origin of such inhomogeneities can be related to the process of continental crust formation.

Keywords: isostasy, free mantle surface, Earth's crust, lithosphere, density inhomogeneities.

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INTRODUCTION

The ability of the Earth's lithosphere to compensate for all the density inhomogeneities appearing within its body or on its surface, which is called isostasy, was known as early as in the middle of the 19th century. The modern knowledge of the Earth's crust structure allows researchers to determine the density inhomogeneities in the mantle part of the lithosphere based on its nearly common isostatic compensation.

The present work deals with the results of studying the lithospheric density inhomogeneities of continents and oceans on the basis of free mantle surface anomalies. The aim of this work is to explain the observed correlation of the free mantle's surface depth with the Earth's crustal thickness; this dependence was discovered by Soviet scientists in the 1970s [1], but its causes still remain unclear.

The results of our studies indicated an explicit relationship between the free mantle's surface depth and the mechanisms of the Earth's crust formation, which supports the assumptions of some researchers that the crustal growth mechanism in the Archean differed from that at the post-Archean stages of the Earth's evolution.

THE FREE MANTLE'S SURFACE: ITS DETERMINATION AND RELATIONSHIP WITH THE CRUSTAL THICKNESS

The free mantle surface (FMS) is one of the characteristics of the Earth's surface isostatic state. This parameter shows the uplift or lowering of the Earth's crust relative to the normal position required for the isostatic leveling of the lithosphere with the density-homogeneous mantle. Correspondingly, it provides information about the density inhomogeneities located above the level of the isostatic compensation in isostatically compensated ~~for~~ regions; in the isostatically uncompensated ~~for~~ regions, the FMS anomalies can be used to determine uncompensated ~~for~~ density inhomogeneities in the mantle.

The calculation of the FMS depth performed by M.E. Artemiev [1] revealed the principal tendencies of the FMS depth distribution between the continents and oceans. It was found that the FMS depth in the continental lithosphere increases with the growth in the crustal thickness. However, the rate of the FMS depth's increase cannot be explained by the incorrect choice of the mantle's density value used in the calculations, because, according to [1], this dependence can be completely obliterated only by the decrease of the ρ_m value to 3.0 g/cm^3, which seems to be unacceptable for the mantle.

On the basis of the obtained data, it was concluded that the continental lithosphere contains lateral density inhomogeneities with their magnitude (thickness or density) depending on the crustal thickness. However, it is still unknown which processes were responsible for their appearance.

To shed light on this problem, the FMS depths of the continental and oceanic crusts were studied using the modern models of the earth's crust (namely, the CRUST 2.0 [15] and AsCrust [2]) with allowance for the influence of the radial variation of the mantle's density on the FMS depth. The results of this study are given below.

CALCULATION OF THE FMS DEPTH IN CONTINENTS AND OCEANS

The geophysical data obtained worldwide during the past half century of intense research of the Earth's structure allowed a global model of the earth's crust to be made. The first model of this kind was called CRUST 5.1 and was made by American geophysicists more than 10 years ago [21]. This model represents the crustal structure as 5 × 5 degree cells based on seismic data and contains information on the P- and S-wave velocities, on the density of all the crustal and subcrustal layers, and on the depths of the boundaries (including the Moho discontinuity) dividing the crust into layers. The more detailed CRUST 2.0 model based on 2 × 2 degree cells was compiled later [15]. Both models are available on the web-site http://mahi.ucsd.edu/Gabi/rem.html.

Figure 1 demonstrates the scheme of the global FMS depth distribution calculated on the basis of the CRUST 2.0 model. The FMS depth was calculated using the formula from [1]:

$$H_{FMS} = H_m - \frac{1}{\rho_m}\sum_{1}^{n} m_i \rho_i, \qquad (1)$$

where H_{FMS} is the calculated FMS depth; H_m is the depth of the Earth's crust base; ρ_m is the mantle's density; and m_i and ρ_i are, respectively, the thickness and the density of the Earth's crust layers, sediments, water, and ice.

According to our model, the Earth's crust contains seven layers: the water layer where it is, three sedimentray layers from the model [19], and three crustal layers. All the data for these layers were taken from the digital models with resolution of 1 × 1 degree for the sediments, 2 × 2 degrees for the crust, and 0.1 × 0.1 degree for the water layer (bathymetry).

The FMS depth depends on the temperature mode of the lithosphere, on the presence of lithospheric density inhomogeneities, and on the degree of its isostatic equilibrium. Isostatic disequilibrium in the models of the Earth's crust with 1-degree resolution and lower is poorly manifested, which is related to the averaged character of the data used [1]. Only in active convergent zones, island arcs, and deep trenches have notable anomalies related to the isostatic disequilibrium of these structures been noted. Therefore, all the data beyond these structures will be further considered as isostatically compensated ~~for~~. Correspondingly, all the FMS depth anomalies in the considered structures denote density inhomogeneities in the lithospheric mantle.

Continents generally have an older and colder lithosphere than the oceans [14]; therefore, greater FMS depths (Fig. 1). Additionally, the FMS depth in the continents shows a clear dependence on the crustal thickness. In particular, it is 5–5.5 km in cratonic continental regions, increases up to 6–6.5 km in mountains, and reaches 8 km in the modern collision zones such as Tibet and the Andes.

In the oceans, the mid-ocean ridges are distinct for the uplifting of the FMS depth to 3–2.5 km, whereas mature oceanic basins have FMS depths of 4.5–5 km, which are close to those of the continental platforms.

Thus, the FMS depth in stable continental and oceanic tectonic structures is within 4.5–5.5 km. Continental and oceanic rift zones are characterized by a shallower FMS depth owing to the elevated heat flow.

The subduction zones of the Pacific continental framing are manifested in a pair of adjacent anomalies of shallower and deeper FMS positions in volcanic belts and deep trenches, respectively, which is related to the isostatic disequilibrium of these structures, as mentioned above.

The oceanic lithosphere originates in mid-ocean ridges and becomes cooler with the distance away from them, which results in the increase of its density and, correspondingly, depth [22].

Figure 2 demonstrates the variations in the FMS depth versus the crustal thickness based on the data of the CRUST 2.0 model. The linear dependence is expressed by the formula

$H_{FMS} = 3.8 + 0.02M_C$, where M_C is the crustal thickness excluding the water layer.

As is indicated by Fig. 2, the degree of the FMS's depth increase with the crustal thickness is different at different parts of the graph. For instance, the continental crust 33–50 km thick shows the highest increase in the FMS depth (about 0.05 km per kilometer of increase in the crustal thickness), whereas the continental crust more than 50 km thick demonstrates an opposite tendency: a decrease in the FMS with the increasing crustal thickness. The crust of such thickness is typical of Tibet and the Andes, being formed by the thrusting of one continental block over another [7, 16, 20, 24].

The AsCrust-08 model of the Earth's crust [2] includes the regions of Central and Southern Asia

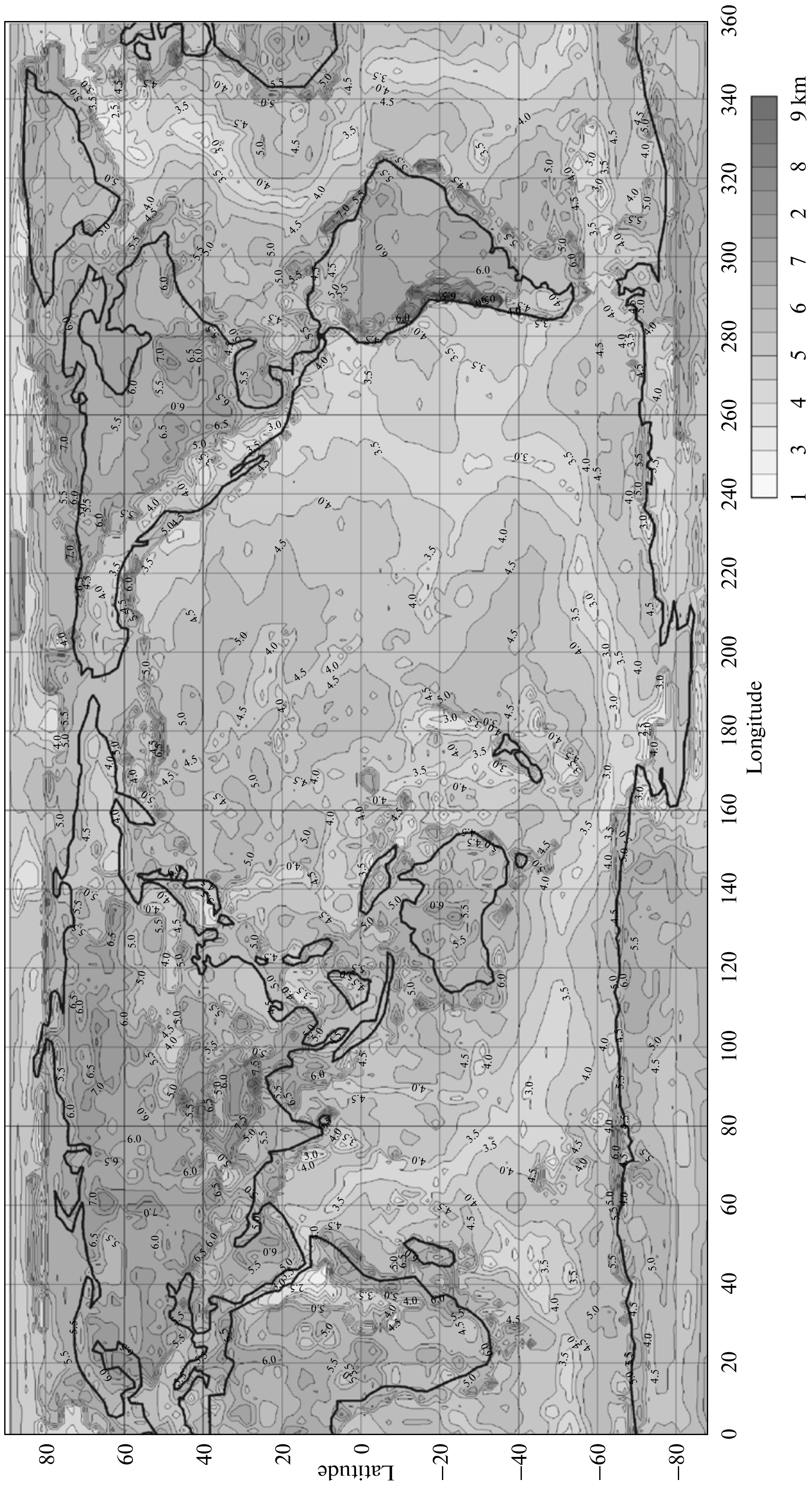

Fig. 1. The depth of the mantle's free surface calculated on the basis of the CRUST 2.0 model.

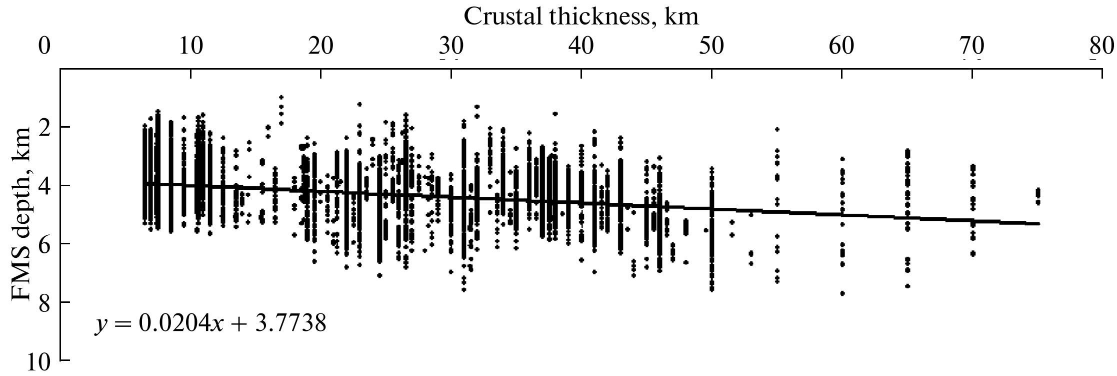

Fig. 2. The graph demonstrating the linear dependence of the FMS depth on the thickness of the solid crust as calculated from the CRUST 2.0 model.

between the coordinates of 25° and 55° N and 20° and 145° E.

The new seismic data obtained in recent years provide grounds for a substantially more detailed model of the Earth's crust, which includes the distribution of the density and seismic velocities in its individual layers and can be used for gravity modeling and other applications. Particular attention in the AsCrust model was paid to the regions of Arabia, China, India, and Indochina. The consistency of the numerous heterogeneous data was verified, and the most reliable of them were used to develop a unified model of the entire region.

The specified digital model of the Earth's crust includes the depth of the Moho discontinuity, the thicknesses of the individual crustal layers, and the distribution of the P- and S-wave velocities in these layers. During the building of this model, we analyzed a great body of new data on the reflected, refracted, and surface waves from earthquakes and explosions and integrated them into a common model with 1 × 1 degree cells. The results were presented in the form of 10 digital maps determining the following parameters: the depth of the Moho discontinuity; the thicknesses of the upper, middle, and lower parts of the consolidated crust; and the values of the density and P-wave velocities in these layers.

The distribution of the FMS depth in the Asian Region as calculated from the AsCrust and CRUST 2.0 (beyond the AsCrust coverage) models is shown in Fig. 3. The FMS depth was calculated by Eq. (1).

According to our calculations, the FMS depth in Central and Southern Asia (Fig. 3) varies within a wide range of 2–7 km, which is explained by the modern tectonic activity in the Alpine-Himalayan Fold Belt and by the rifting in the northeast framing of Africa. The shallowest level of the FMS depth is observed in the Red Sea, in the Gulf of Aden, and in the adjacent northern part of the East African Rift valley. The shallowest FMS depth is noted in the eastern Tien Shan. The Himalayas are distinguished as the narrow zone of a shallower (4–5.5 km) level of the FMS depth; the parallel zone located south of the previous one has a deeper (up to 6 km) FMS level and presumably corresponds to the boundary thrust zone between Asia and the Indian Plate [23]. The Tibetan Plateau is mainly characterized by the FMS depths from 4.5 to 5.5 km, which is substantially higher than the values described from the CRUST 2.0 model, and a narrow zone with the FMS depth up to 3 km is observed only at the boundary with the Tarim Basin. In the east of the plateau, the FMS depth subsides to 6.5 km, while the Tarim Basin has a normal FMS depth within the range of 4.5–5 km.

A slightly shallower (4 km and less) FMS level is observed in the Indonesian Region. This is probably related to the elevated heat flow, which is typical of the backarc regions above subduction zones spanning this region from the east and west [9].

Figure 4 demonstrates the AsCrust model-based dependence of the FMS depth on the crustal thickness in the Central and Southern Asian regions. As is seen, the observed dependence is generally nonlinear, which could be caused by the modern tectonic activity of the region manifested in the portions with extremely low and high thicknesses of the crust (i.e., at the ends of the graph). The middle part of the graph, which corresponds to the mature and tectonically stable crust 30–50 km thick, indicates a clear increase in the FMS depth approximately by 0.3 km per kilometer of increase in the crustal thickness.

RADIAL VARIATIONS IN THE DENSITY: THE CALCULATION OF LINEAR MODELS

While calculating with the use of Eq. (1), we assumed a priori that the mantle's density does not change with the depth. However, the involvement of possible variations in the mantle's density with depth in the calculations, as will be shown below, would inevitably produce the dependence of the calculated FMS depth on the crustal thickness.

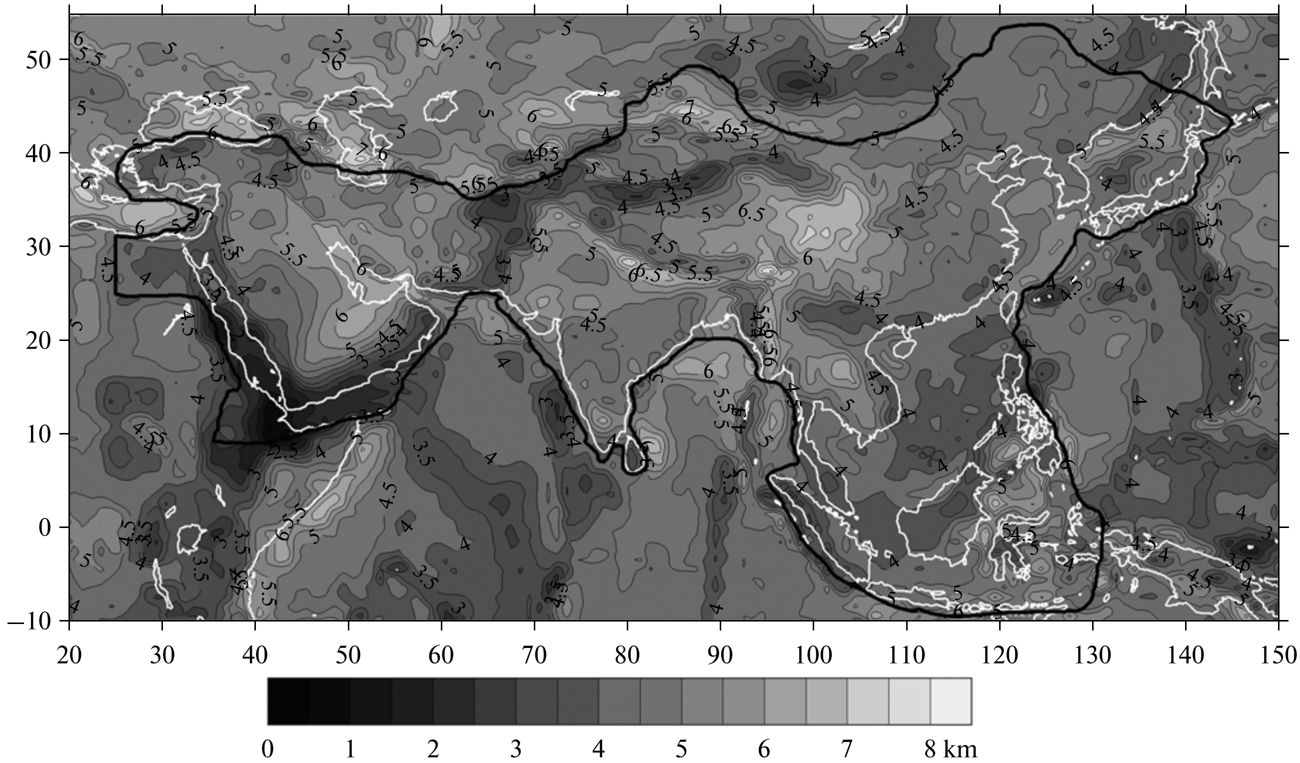

Fig. 3. Depth of the mantle free surface in Central and Southern Asia.
The solid line shows the boundary of the crustal regions modeled by the AsCrust [2] and CRUST 2.0 [15] models, while the white line, the contours of the land.

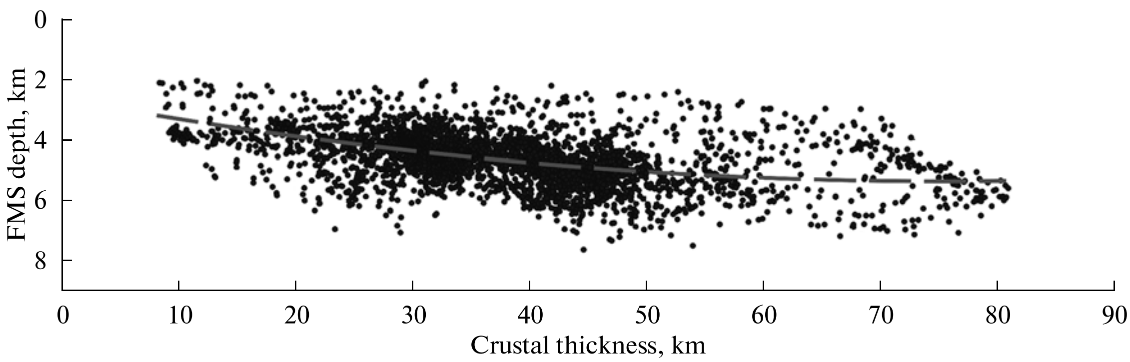

Fig. 4. Dependence of the FMS depth on the crustal thickness in Central and Southern Asia on the basis of the AsCrust model.

Taking into account the radial variations in the mantle's density, below we will differentiate between the "calculated" and "radial" FMS depths in the applied models. The "calculated" depth is referred to as the FMS depth calculated by Eq. (1) at a constant mantle density of 3.3 g/cm^3; the "radial" FMS depth denotes the depth given in the model of the radial change in density in accordance with Eq. (2), which will be given below. At the same time, the "radial" FMS depth in any given model is always constant, whereas the "calculated" depth varies depending on the radial distribution of the density and crustal thickness.

To assess the contribution made by radial variations of the mantle's density to the "calculated" dependence of the FMS depth on the crustal thickness, we simulated the deep position of the crust of various thicknesses in such a mantle.

Let us assume that the crustal density is unchangeable and that the change in the mantle's density is controlled by the law

$$\rho_m(h) = \rho_0 + \alpha h, \tag{2}$$

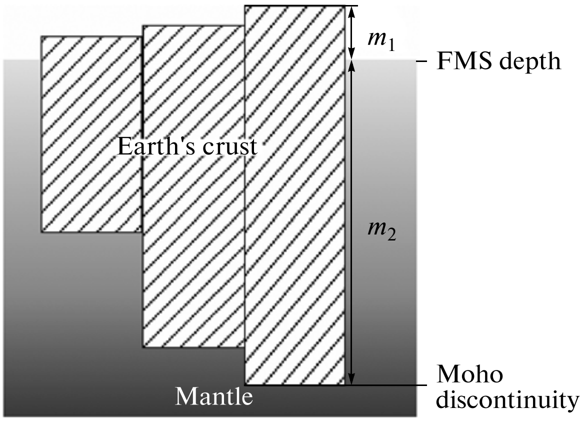

Fig. 5. Illustration of the formula for calculating the FMS depth in the mantle with the gradient density.

where ρ_0 is the mantle's density at the FMS depth, h is the FMS depth, and α is the coefficient of variation of the mantle's density with depth. Then, the equilibrium between the load and the compensation masses separated by the FMS level in the mantle with the depth-dependent density (Fig. 5) can be represented as follows:

$$m_1\rho_k = m_2\left(\rho_0 + \alpha\frac{m_2}{2} - \rho_k\right), \tag{3}$$

where m_1 is the thickness of the load layer (the upper part of the crust up to the FMS level), m_2 is the thickness of the compensation layer (the lower part of the crust below the FMS level; see Fig. 5), ρ_0 is the mantle's density at the FMS, and ρ_k is the mean density of the crust. Taking into account that the total thickness of the crust is $M_k = m_1 + m_2$, equation (3) can be modified into the following form:

$$M_k\rho_k = m_2\left(\rho_0 + \alpha\frac{m_2}{2}\right). \tag{4}$$

The "radial" FMS depth denoted as H'_{FMS} is constant in the model of the radial density distribution and can be calculated by subtracting the thickness of the compensation layer (m_2) from the Moho discontinuity's depth:

$$\begin{aligned} H'_{FMS} &= H_m(M_k) - m_2 \\ &= H_m(M_k) - \frac{1}{\alpha}(\rho_0 - \sqrt{\rho_0^2 + 2\alpha\rho_k M_k}. \end{aligned} \tag{5}$$

The last equation offers an opportunity to determine the variations of the FMS depth in a gradient medium. For this purpose, it is required to set all the parameters of the gradient medium, including the H'_{FMS}, and to determine the depth of the Moho discontinuity.

In the oceanic lithosphere, an additional load is produced by the water layer, the thickness of which depends on the thickness of the solid crust and is determined by the condition of the isostatic equilibrium. This transforms equation (5) into a more complicated form:

$$\begin{aligned} H'_{FMS} &= H_m(M_k) - \frac{1}{\alpha}(\rho_0 - \rho_@) \\ &- \sqrt{(\rho_0 - \rho_@)^2 + 2\alpha(M_k\rho_k + \rho_@(H'_{FMS} - M_k))}. \end{aligned} \tag{6}$$

Figure 6 demonstrates the curves for the theoretical dependences of the FMS depth on the crustal thickness. These curves were derived using Eqs. (1), (5), and (6) at $H'_{FMS} = 4$ km; various values of α; and the initial density at the FMS level.

In the models with the initial mantle density $\rho_0 = 3.3$ g/cm^3 (Fig. 6a), the positive and negative values of α correspond to the increase and decrease in the density with depth, respectively. As is seen, the degree of change in the FMS depth in this case appears to be nonlinear. Additionally, the curve shapes differ from the experimental dependence obtained by us for the Asian region.

Assuming that the mantle's density at the FMS level is 3.2 g/cm^3 and linearly increases with depth (Fig. 6B), the shape of the curves becomes similar to the experimental dependence.

Figure 6c shows the results of fitting the mantle's density distribution to obtain the experimental dependence of the FMS depth on the crustal thickness. It is seen that a good fit was obtained only in the range of the continental crust with density from 3.23 g/cm^3 at the 30 km depth to 3.28 g/cm^3 at the 80 km depth. For the <30-km crust (mainly the oceanic crust), the corresponding curve can be fit only by increasing the "radial" FMS depth to 3.2 km. This will provide an increase in the mantle's density from 3.2 g/cm^3 at the FMS depth to 3.3 g/cm^3 at 30-km depth. The difference in the "radial" levels between the oceanic and continental lithospheres indicates that the upper mantle beneath the oceans is generally less dense than beneath the continents, which is seen in the thicker asthenosphere layer.

Thus, the results of fitting the linear variations of the mantle's density yield significantly lower densities than was supposed in the currently accepted pyrolitic model of the mantle [6]. This discrepancy argues for the existence of lateral density inhomogeneities, which depend on the crustal thickness.

Below, we demonstrate the density distribution produced by calculating the nonlinear model.

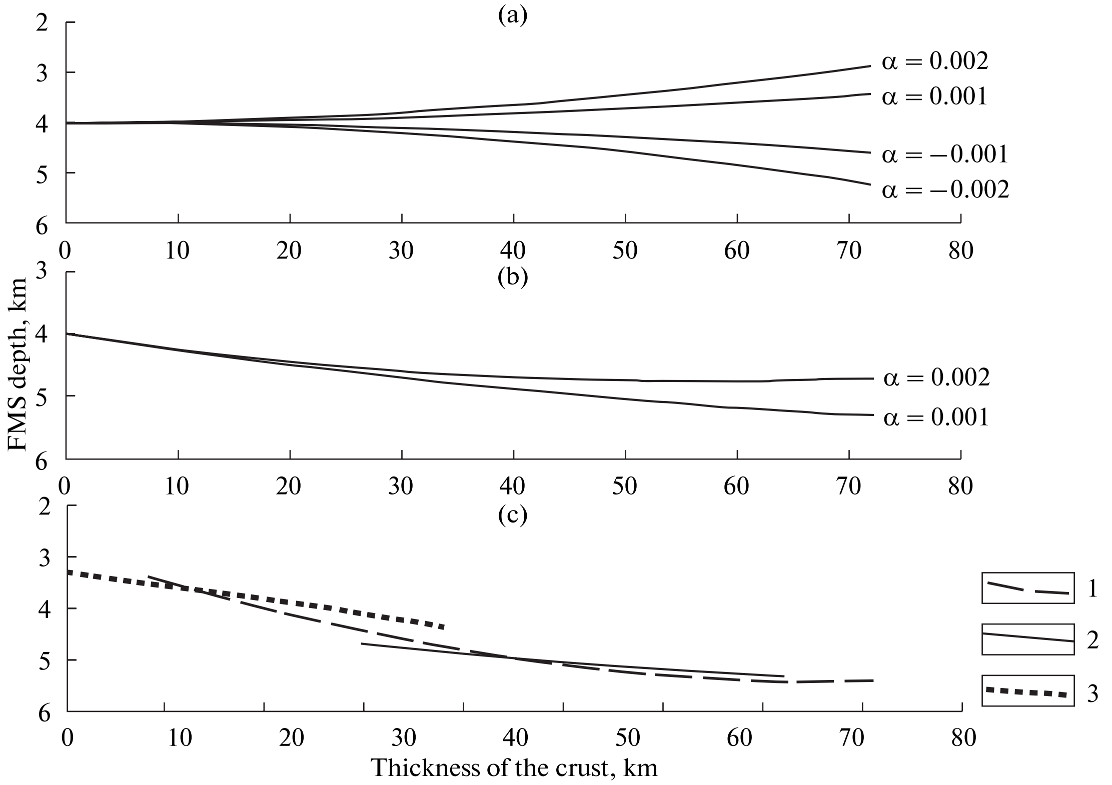

Fig. 6. Variations in the FMS depth in the model of the radial variations of the density with the various coefficient of increase ($\alpha > 0$) and decrease ($\alpha < 0$). (a) curves showing the increase and decrease in density with the depth relative to the initial value of 3.3 g/cm^3 at the FMS level. (b) curves showing an increase in the density with the depth relative to the initial value of 3.2 g/cm^3 at the FMS level (see the text for details). (c) result of fitting the model of the radial change in density on the basis of the experimental curve illustrating the dependence of the FMS depth on the crustal thickness based on the AsCrust model data (see the text for details).

(1) the polynomial trend determining the dependence of the FMS depth on the crustal thickness based on the experimental data (transposed from Fig. 1); (2) the curve of the FMS depth fitted by the linear increase of the density in the continental mantle; (3) the same as in 2 for the oceanic mantle (see the text for details).

RADIAL VARIATIONS IN THE DENSITY: DIRECT CALCULATION BASED ON THE EXPERIMENTAL DEPENDENCE

The presented above assessments of the density distribution with depth are based on revealing a general tendency in the linear variations of the density with depth. At the same time, our data make it possible to estimate the nonlinear density distribution with depth based on two assumptions:

(1) the entire studied area is isostatically compensated ~~for~~;

(2) the mantle's density varies only with depth while remaining unchangeable in the lateral direction.

If these conditions are met, the true ("radial") FMS depth would be expected to be similar everywhere, while the observed variations in the FMS values with depth calculated by formula (1) would demonstrate the change in average density in the interval from the true FMS depth to the depth of the Moho discontinuity. To eliminate the scatter of the FMS depths at the points with similar or close values of the crustal thickness, the calculated FMS values were averaged over the depth in the range of 1 km.

To assess the radial FMS depth, let us calculate its value for the 33-km crust. Different models indicate that the crust with such thickness is intermediate between the continental and oceanic, with its upper boundary at about 0 km. Assume that the crustal density is 2.85 g/cm^3 and the mantle's density is 3.3 g/cm^3. Then, Eq. (5) yields a radial FMS depth of 4.5 km.

Let us denote the weight of the density column at any set point k in Eq. (1) as $V_k = \sum_{i=1}^{N} m_i \rho_i$. Then, the formula for the FMS calculation can be rewritten in the following form:

$H'_{FMS} = H_m - V_k/\rho_m$, from which we derive

$$\rho_m(H_m) = \frac{V_k}{H_m - H'_{FMS}}. \tag{7}$$

The last expression allows the *mean mantle density* to be calculated in the depth range from the FMS level (i.e., from 4.5 km) to the Moho discontinuity at any

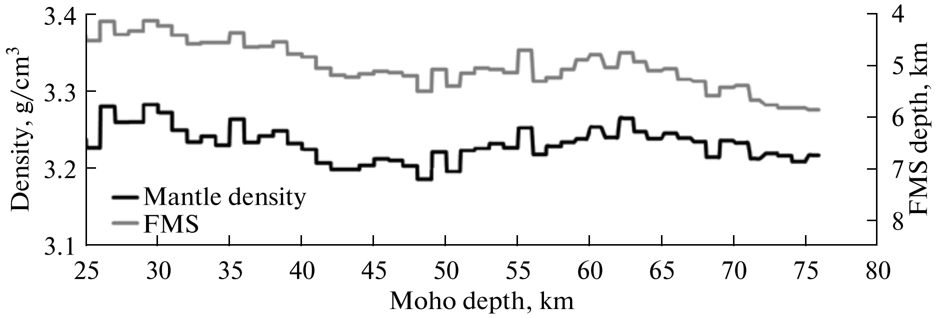

Fig. 7. Variations in the mean density of the subcrustal mantle and in the FMS level in the continental lithosphere depending on the depth of the Moho discontinuity based on the AsCrust model data.

point of the model. The V_i values are calculated on the basis of the AsCrust model data, and the H_m values are also given in this model. The calculated data on the depth distribution of the mean density of the continental mantle and the FMS level in the range from 25 to 75 km are shown in Fig. 7.

It is seen in Fig. 7 that the mean density of the mantle beneath the continents varies in the range of 3.18–3.28 g/cm^3, averaging 3.24 g/cm^3. Such low values of the density can only reasonably be explained by the existence of lateral density inhomogeneities beneath the crust in certain depth ranges.

Thus, all the calculations performed indicate that the lithospheric mantle contains lateral density inhomogeneities varying with the crustal thickness.

LATERAL DENSITY INHOMOGENEITIES: PROBABLE CAUSES OF THEIR ORIGIN

Lateral density anomalies in the lithosphere undoubtedly exist. This directly follows from the seismic tomography data and the significant spatial variations of the FMS depth in the isostatically compensated for regions. However, it is difficult to explain the presence and origin of such anomalies varying with the crustal thickness.

These anomalies can form either during the formation (or growth) of the Earth's crust or in the course of its subsequent evolution related, for example, with the cooling of the lithosphere or the metasomatic reworking caused by deep fluids. The answer to this question can be found by the examination of the FMS depth variations depending on the crustal thickness in the lithosphere of different ages.

Figure 8 presents a series of graphs demonstrating the dependence of the FMS depth on the crustal thickness in the continental lithosphere of different ages in the range from 24 to 56 km. As was indicated in [17], this range of thickness spans the overwhelming part of the continental crust. The data on the lithosphere's age used in the plots were taken from [14]. It is seen in these graphs that the coefficients showing an increase in the FMS depth with the thickening of the crust are nearly the same for the lithosphere of all the ages, except for the Archean; i.e., the relationship between the FMS depth and the crustal thickness in the lithosphere has remained almost constant since the Proterozoic.

On the basis of the derived data presented in Fig. 8, we may conclude that the observed dependence of the FMS depth on the crustal thickness presumably appeared at the stage of the Earth's crust formation. The explicit difference in the calculated dependence of the FMS on the crustal thickness between the Archean and the following periods of the Earth's evolution is explained by the differences in the mechanisms of the crustal formation in various periods [4, 10–12, et al.]. For instance, at the early stages of the evolution, the formation of the Earth's crust was probably driven by plume activity; beginning from the Late Archean or Proterozoic, the plume tectonics gave way to plate tectonics with the crust growing in island arcs under the influence of the subduction of the oceanic lithosphere. Therefore there are all grounds to suggest that the found dependence of the calculated FMS depth on the crustal thickness is related to the formation of the continental crust in the subduction zones.

To verify that the observed relationship between the FMS depth and the crustal thickness of the continental lithosphere is determined by the mechanism of crustal growth, we attempted to find it for the oceanic crust. As is known, the ocean contains mountain ridges and rises, and the crustal thickness beneath them is comparable to that of the continental crust. These ridges and rises are most probably of magmatic origin, which is analogous to that of the ancient continental crust in the Archean. It is, for instance, though that oceanic rises are formed in triple junctions (the Ontong-Java Plateau [18], the Shatsky Rise [5, 13, et al.]), whereas submarine ridges are results of "hot spot" activity on moving oceanic plates (see, for example, [3]).

This is seen on the map demonstrating the distribution of the FMS depth, which was calculated from the CRUST 2.0 model data (Fig. 1), that most of the oceanic rises and mountain ridges are characterized by

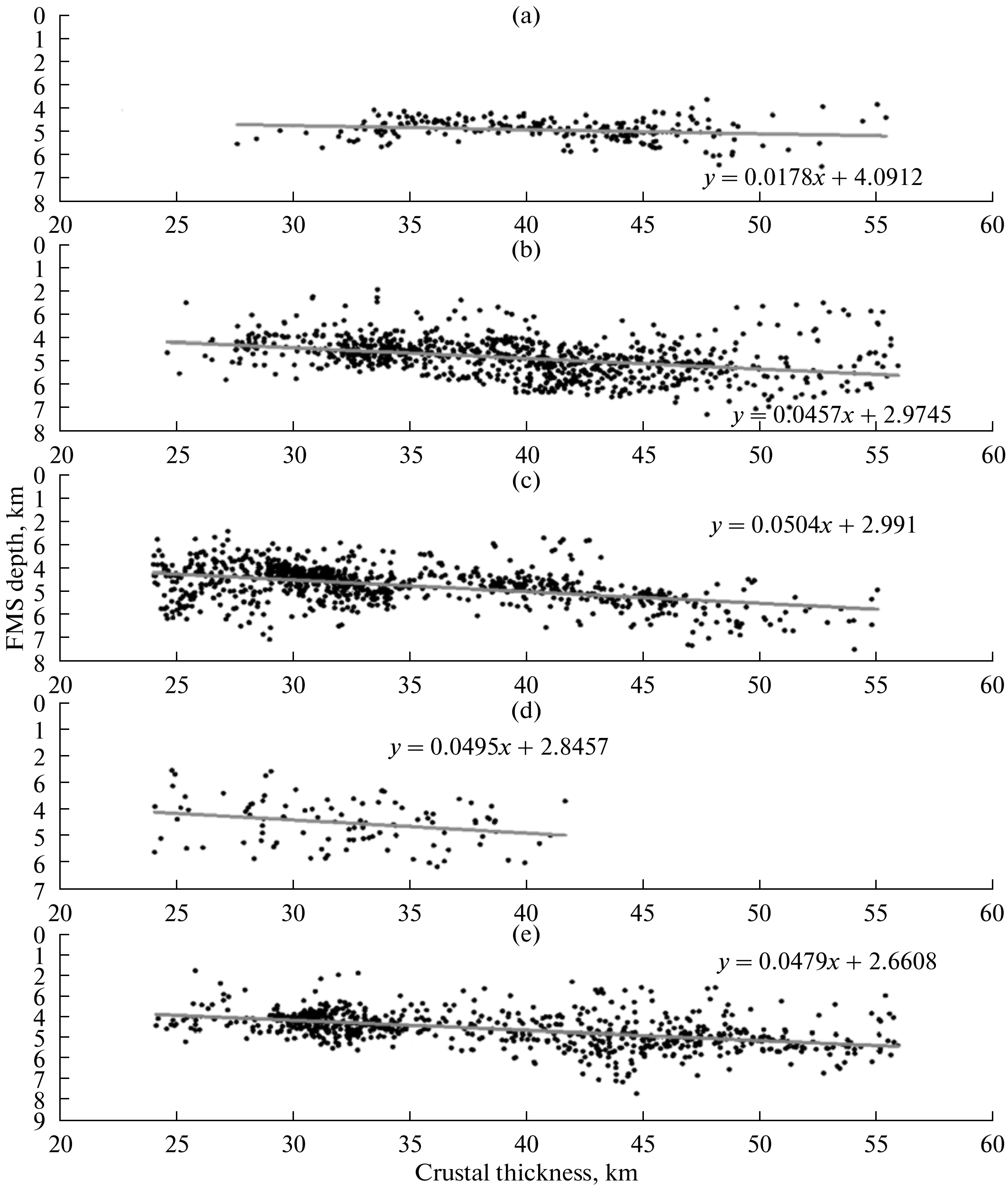

Fig. 8. Dependence of the FMS depth on the crustal thickness and age in the stable crust 24–56 km thick: (a) Archean (>2500 Myr); (b) Proterozoic (2500–570 Myr); (c) Paleozoic (570–245 Myr); (d) Mesozoic (245–66.4 Myr); (e) Cenozoic (66.4–0 Myr).

slightly elevated or nearly normal FMS levels (see, for example, the Hess and Shatsky rises; the Chatham, Emperor, and Hawaii ridges in the Pacific Ocean; the Ninetyeast Ridge in the Indian Ocean, etc.). This implies that the oceanic lithosphere shows no clear dependence of the FMS depth on the crustal thickness.

Figure 9 shows the dependence of the FMS depth on the crustal thickness for the oceanic lithosphere. The first graph (Fig. 9a) was plotted without allowance for the lithosphere's age at the model points. It shows the linear growth of the FMS depth with the crustal thickness. The coefficient of the FMS depth increase with the crustal thickness is 0.024 km/km, which is two times less than the analogous values for the continental crust. However, if the age dependence is excluded from the calculated FMS in the way that the FMS depth of the mature oceanic crust corresponded to the anomalous depth of 0 km, then the dependence of the FMS anomalies on the crustal thickness demonstrates a poor decrease in the FMS depth with the thickening of the crust with a coefficient of –0.004 km/km (Fig. 9b). The negative coefficient derived for

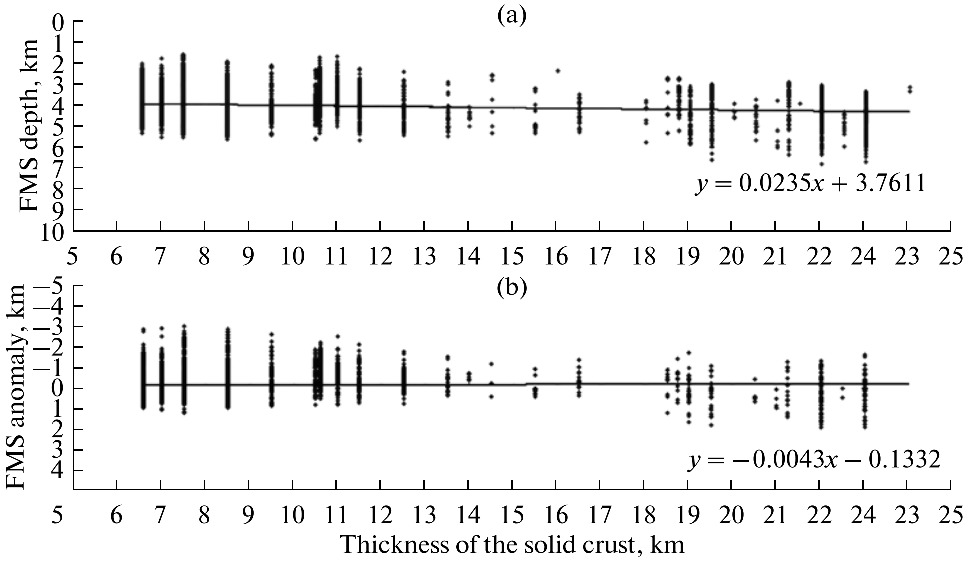

Fig. 9. Dependence of the FMS anomalous depth on the thickness of the solid crust in the range of 5–24 km within the oceanic lithosphere: (a) without correction for the lithosphere's age; (b) excluding the age dependence.

the FMS depth's dependence on the crustal thickness can be explained by the radial growth of the density in the oceanic lithospheric mantle of mature age.

DISCUSSION AND RESULTS

The results of our study have indicated that the influence of the radial density variations in the subcrustal mantle was insufficiently strong to explain the observed dependence of the FMS depth on the crustal thickness [8]. This indicates that the continental lithosphere contains lateral density inhomogeneities, which depend on the crustal thickness. The magnitude of these inhomogeneities practically does not depend on the age of the continental crust. This gives strong reasons to suppose that they appeared simultaneously with the formation of the continental crust and were preserved during its further evolution. The conservation of these inhomogeneities in the continental lithosphere for billions years indicates that their composition differed from that of the normal continental lithospheric mantle.

The nature of these high-density inhomogeneities is unknown. They may be formed from the upper part of the basaltic layer in the subsiding oceanic lithosphere, accumulated in the island arc lithosphere, and then subjected to complete or partial eclogitization.

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REFERENCES

1. M. E. Artemjev, *Isostasy in the USSR Territory* (Nauka, Moscow, 1975) [in Russian].
2. A. A. Baranov, "New Model of the Crust of Central and Southern Asia," Fiz. Zemli, No. 1, 37–50 (2010).
3. K. C. Burke and J. T. Wilson, "Hots Spots on the Earth's Surface," [Sci. Am. **235**, 46–57 (1976); Usp. Fiz. Nauk **123** (3), 615–632 (1977)].
4. O. A. Bogatikov and A. K. Simon, "Magmatism and Geodynamics of the Main Age Stages of the Earth's Evolution," Vestn. OGGGGN RAN, No. 2 (1997).
5. E. V. Verzhbitskii, L. I. Lobkovskii, M. V. Kononov, and V. D. Kotelkin, "Genesis of Shatsky and Hess Oceanic Rises in the Pacific Ocean As Deduced from Geologic–Geophysical Data and Numerical Modeling," Geotectonics **40**, 236–245 (2006).
6. A. E. Ringwood, *Composition and Petrology of the Earth's Mantle* (McGraw-Hill, New York, 1975; Nedra, Moscow, 1981).
7. T. V. Romanyuk, "The Late Cenozoic Geodynamic Evolution of the Central Segment of the Andean Subduction Zone," Geotectonics **43**, 305–323 (2009).
8. V. N. Senachin, "Free Mantle Surface as Indicator of Geodynamic Processes," Vestn. Dal'nevost. Otd. Ross. Akad. Nauk, No. 1, 18–25 (2006).
9. V. Senachin and A. Baranov, "Estimation of the Deep Density Distribution in the Lithosphere of Central and Southern Asia Using Data on Free Mantle Surface Depth," Izv. Phys. Solid Earth **46**, 966–973 (2010).
10. E. V. Sharkov, "Where does the Continental Lithosphere Disappears? (Volcanic Arc–Back-Arc Basin Sys-

tem)," Vestn. OGGGGN RAN **1** (2) (2000). http://www.scgis.ru/russian/cp1251/h_dggggms/2-3000/sharkov.htm#begin.

11. E. V. Sharkov and O. A. Bogatikov, "Evolution of the Tectonomagmagic Processes in the Earth's Evolution," in *Volcanology and Geodynamics. 6th All-Russian Symposium on Volcanology and Paleovolcanology, Petropavlovsk-Kamchatskii, Russia, 2009* (Petropavlovsk-Kamchatskii, 2009), Vol. 1, pp. 38–41 [in Russian].
12. V. E. Khain and M. G. Lomize, *Geotectonics with Fundamentals of Geodynamics* (Mosk. Gos. Univ., Moscow, 1995) [in Russian].
13. V. E. Khain, "Modern Geodynamics: Achievements and Problems," Priroda (Moscow, Russ. Fed.), No. 1, 51–59 (2002).
14. I. M. Artemieva, "Global 1.**1** Thermal Model TC1 for the Continental Lithosphere: Implications for Lithosphere Secular Evolution," Tectonophysics **416**, 245–277 (2006).
15. C. Bassin, G. Laske, and G. Masters, "The Current Limits of Resolution for Surface Wave Tomography in North America," EOS Trans. AGU, **81** (48), 81 (2000), Fall Meet. Suppl., Anstr. F897. (http:/mahi.ucsd.edu/Gabi/rem.html.
16. P. A. Cawood, A. Kroner, W. J. Collins, et al., "Accretionary Orogens through Earth History," Geol. Soc. London, Spec. Publ. **301**, 1–36 (2009).
17. N. I. Christensen and W. D. Mooney, "Seismic Velocity Structure and Composition of the Continental Crust: a Global View," J. Geophys. Res. **100** (B7), 9760–9788 (1995).
18. *Origin and Evolution of the Ontong Java Plateau*, Ed. by J. G. Fitton, J. J. Mahoney, P. J. Wallace, and A. D. Saunders, Geol. Soc. London. Spec. Publ. **229**, (2004).
19. G. Laske and G. Masters, "A Global Digital Map of Sediment Thickness, EOS Trans," AGU **78**, F483 (1997).
20. Ch. Li, R. D. Hilst, A. S. Meltzer, and E. R. Engdayl, "Subduction of the Indian Lithosphere beneath the Tibetian Plateau and Burma," Earth Planet. Sci. Lett. **274**, 157–168 (2008).
21. W. D. Mooney, G. Laske, and T. G. Masters, "Crust 5.1: A Global Model at 5°–5°," J. Geophys. Res. **103**, 727–747 (1998).
22. R. D. Muller, W. R. Roest, and R. D. Royer, "Digital Isochrones of the World's Ocean Floor," J. Geophys. Res. **102** (B2), 3211–3214 (1997).
23. R. S. Rajesh and D. C. Mishra, "Admittance Analysis and Modelling of Satellite Gravity Over Himalayas–Tibet and Its Seismogenic Correlation," Current Science **84** (2), 224–230 (2003).
24. Y. Yang and M. Liu, "Crustal Thickening and Lateral Extrusion During the Indo-Asian Collision: a 3D Viscous Flow Model," Tectonophysics **465** (1-4), 128–135 (2009).

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