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Relation of thermal, velocity and gravity models of Kamchatka mantle

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Abstract. Deep-seated processes in the tectonosphere of geosynclines are analyzed in terms of the advection-polymorphism hypothesis. It has been shown that the said hypothesis makes it possible to explain, without resorting to numerical tailoring, major events in geological history (formation of the sedimentary veneer, magmatism, temperatures prevailing at large depths), as well as anomalies of the heat flow, seismic wave velocities, gravity field, and electrical conductivity.

1. Introduction

The available data point to a great similarity in the evolution of Kamchatka and the Carpathians. Two zones have also been identified in Kamchatka: The Alpine geosynclinal process started somewhat earlier in the western than in the eastern zone. It is precisely for the latter that we have constructed a very detailed three-dimensional velocity model of the crust and upper mantle (down to 200 km; the model is one-dimensional for larger depths). In the same area, deep geoelectrical surveys have been carried out, and numerous petrological data are available. In addition to Eastern Kamchatka, the velocity model also covers the deep-sea trench and the northwestern plate margin of the Pacific Ocean. These particular circumstances have prompted the choice of the region for studies described below.

The schematic pattern of deep-seated processes and the evolution of the thermal model at the margin of the Pacific Ocean northwestern plate (east of bearing picket 240 on the profile) matches the pattern described by Gordienko [9], and will not be dealt with in this paper. The resulting deep-seated T values are incorporated in the general model (**figure 1**). Processes in the western Kamchatka geosyncline (west of bearing picket 0) have also been simulated and their effect has been taken into account in the thermal model on the profile.

The construction of the pattern of deep-seated processes in Kamchatka resembles a similar procedure performed for the Carpathians. It has been assumed that the widths of the zones of western and eastern Kamchatka are almost the same: about 240-250 km (i.e., n-tuple size of a QTA; four quanta of tectonic action are located nearby). In the west, the process started 140 million years ago and ended 60 million years ago. In the east, the estimates are 120 and 20 million years ago, respectively [13, 14, 12 and others]. At the eastern end of the profile the development of the process is markedly affected by events beneath the oceanic plate, while at the western end – by events within Early Alpides. Migrations of the material occurred from depth intervals where QTAs might have formed (in other words, a partial melting layer had been in place by the time of QTA formation) into depth intervals above the asthenosphere, as is standard for the geosynclinal process: 1) 120 million years



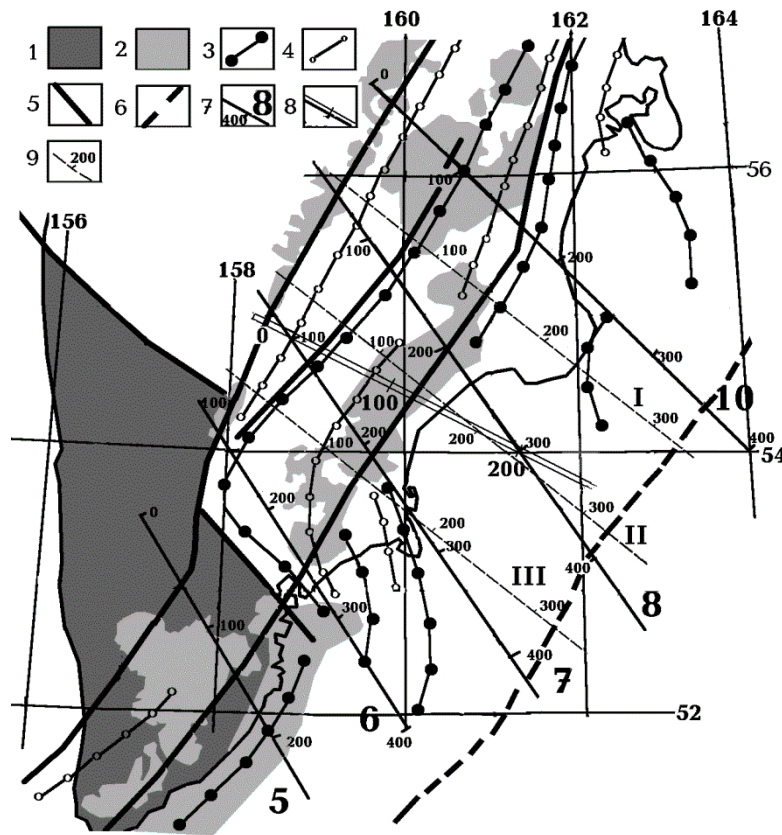


Figure 1. Eastern Kamchatka: Elements of geological structure and layout of mantle velocity profiles. 1 – Activated portion of the Sea of Okhotsk plate; 2 – young effusive rocks; 3 – anticline axis; 4 – synclinal axis; 5 – major faults; 6 – trench axis; 7—profiles along which velocity models were built with bearing pickets on them (see below); 8 – composite interpretation profile; 9 – profiles along which density models were constructed.

ago at bearing pickets 0-100 from the depths of 330-480 km and at pickets 100-200 from the depths of 260-460 km to the depths of 160-220 km; 2) 80 million years ago at pickets 380-480 km and at pickets 100-170 km – from the depths of 180-260 km to the depths of 100-160 km; 3) 20 million years ago at pickets 0-80 from the depths of 120-190 km, at pickets 80-120 – from the interval of 120-180 km, at pickets 120-160 – from the depths of 140-180 km, and at pickets 180-240 – from the depths of 440-480 km to the depths of 40-100 km. The times of QTAs' ascent have been estimated approximately, and a more detailed analysis of the geosyncline's geological history may help further specify those age intervals. At all stretches of the profile (except for the easternmost length, where the crust is thin), the final stage of the process is further complemented by intrusions into the crust to depths of about 20-40 km. Over recent millions of years, the territory of Kamchatka has been involved in contemporary active processes. In the model, the activation was represented by transport into the crust of the melt from the residual asthenosphere at bearing pickets 20-0 and 40-80, something that happened 5 and 0.5 million years ago [14 and others]. Each displacement of the material resulted in the formation of anomalous temperature zones of dissimilar signs at different depths. They were analyzed as nonstationary three-dimensional heat sources whose effect was calculated for the entire interval of time from their emergence to present time. Anomalous temperatures were summed up with the background temperature that had existed prior to the active process. Kamchatka's pre-geosynclinal history has not been properly studied, and for that reason a thermal model constructed for other Alpides was used to represent the background.

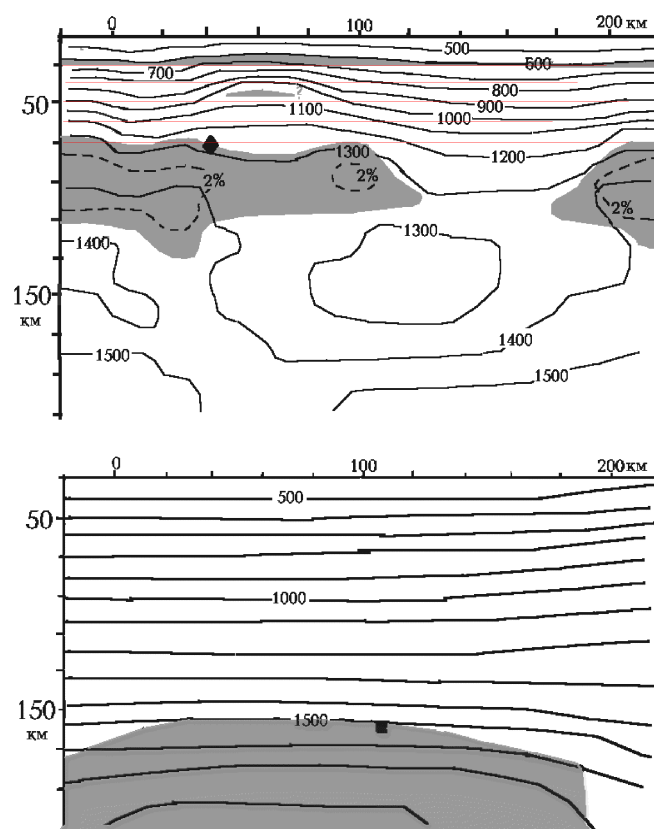


Figure 2. Thermal model (isotherms in °C) along the profile. The diagram at the top is a recent model, and the diagram at the bottom reflects the situation that prevailed 100 million years ago. Partial-melting layers are shown in gray color. The dashed line marks the boundary of the area with melt concentration higher than 2%. The black rhomb and square denote foci of magmatism based on petrological evidence (see below).

The resulting thermal model along the interpretation profile is depicted in **figure 2**. Geological information suitable for numerical verification of the pattern of the deep-seated processes that was used is but scarce. Of particular interest in this context is verification with the help of velocity and density models. The extent of detail in the velocity model [3, 4, 5 and 15] is sufficient for spotting differences in the structure of the crust and upper (to 200 km) mantle in parts of the region. The pattern of the deep-seated process (and the thermal model) only represent a two-dimensional construction. The geological information used is adjusted to “fit” such a model structure.

It was assumed that recent volcanism is represented by two zones that stretch across the entire region (see above).

2. Heat and velocity models

For comparison with such an averaged construction, we selected data for three profiles (representing a three-dimensional tomographic model) on which there should be no visible effect from areas encircling the Kamchatka geosyncline from north to south: profiles 7, 8, and 10 which are shown in **figure 1**. Comparison was performed both with the mantle velocity model averaged for three profiles and with those constructed along each of those profiles (see below).

It is obvious that the thermal model incorporates the mantle asthenosphere (where temperatures exceed T_{solidus}) at depths of about 70-120 km and a thin layer of partial melting in the crust at depths of about 20-30 km. In the latter case, partial melting was believed to start at temperatures higher than 600°C [10]. It is likely that both partial-melting layers are absent at pickets 130-170. It also seems

likely that a small partial-melting layer exists at the bottom of the hottest portion in the thickest crust at temperatures higher than 1,050°C.

The crustal part of the thermal model that was not taken into account in the construction of the velocity model has been calculated in very general outlines, without much detail that might reflect rather complicated processes within the crust, processes typical of post-geosynclinal activation. Information on temperatures and pressures (depths) at which crustal rocks presently lying at the surface formed [1, 14 and 12] makes it possible to verify the crustal part of the thermal model (**figure 3**).

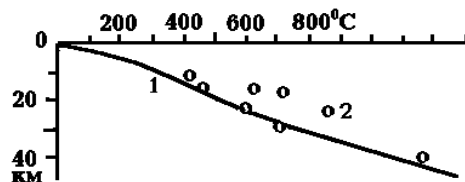


Fig. 3. Comparison between estimated (1) and experimentally derived (2) temperatures in the Earth's crust of Kamchatka.

On the whole, a fairly good match has been achieved. Experimentally derived temperatures that turned out to be higher than estimated in some areas are confined to a range of depths above a partially-melting layer within the crust. High temperatures there indicate that crustal rocks around magma intrusions into the upper crust absorbed the heat. This twist of the process was not taken into account in the model. Its analysis provides explanation for such temperature anomalies (see above).

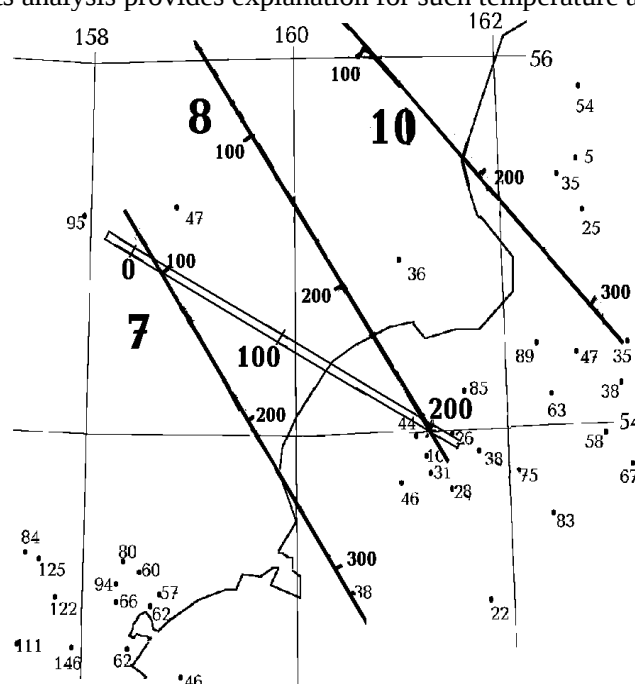


Figure 4. Distribution of heat flow (in mW/m²) in the area under study (Smirnov et al., 1991).

According to petrological data (Frolova et al., 1989), depths of pockets of young magmatism in Kamchatka's mantle may be located at depths ranging from 70±10 km to 140±20 km. This result agrees fairly well with the contemporary thermal model (**figure 2**). Using larger amounts of data, Gordienko [9] analyzed depths of magma chambers and temperatures in them and provided a relevant bibliography. Depths and temperatures were determined for the foci of initial magmatism: 215 km and 1,750°C and 155 km and 1,550°C. In the median stage of the cycle: 90 km and 1,300°C; and for the final stage and contemporary activation: 55 km and 1,200°C. These data are in agreement with thermal models representing respective ages.

Consequently, petrological control of the thermal model appears to be a success. It may be continued further with the use of information on the composition of igneous rocks of mantle origin but of different age collected from other areas of Kamchatka.

Distribution of heat flow values in the region might seem like a logical verification of the thermal model. In fact, however, it is hardly workable at all in the case of Kamchatka because of the region's insufficient coverage by geothermal studies (**figure 1**).

On the basis of the thermal model (in terms of differences between temperatures at different depths and background temperatures beneath the Precambrian platform) and the data on the distribution of velocities in the mantle of the Precambrian platform (in line with the hypothesis and lherzolite composition of mantle rocks), V_p values in the region were calculated and correlated with those derived experimentally. The data on V_p variation with temperature at various depths have been analyzed fairly well. They are listed, for example, in a study by Sobolev et al. [17]. In calculations, the $V_p=f(T)$ was simplified to linear which does not cause errors larger than 0.01 km/sec. It was assumed that 100°C temperature differences from the background temperature (beneath the platform) cause V_p to change by 0.06 km/sec. With the emergence of melt (solidus temperature of mantle rocks is exceeded: $T_s=1.013+3.914H - 0.003H^2$, where H designates depth in km), V_p values further decrease by 0.07 km/sec per each percent of its concentration. The amount of melt was assumed to be increasing from 1% at the point of solidus by 1% with the temperature increase by 50°C [10 and others]. An estimated velocity model along the interpretation profile is shown in **figure 5** where it is compared to experimental results.

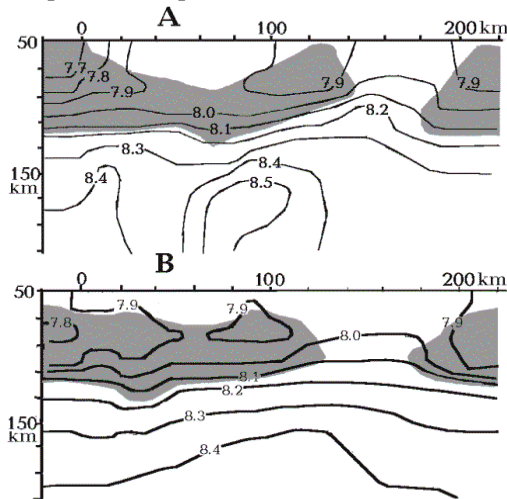


Figure 5. Experimental (A) and estimated (B) velocity models along the profile. The asthenosphere is marked by gray color.

Elements matching the experimental model and those differing from it can be clearly seen. In a generalized form, they can be represented through comparison between V_p values pertaining to each depth (**figure 6**). Estimated velocities (with the exception of those at the topmost part of the profile) turn out to be slightly lower than experimental.

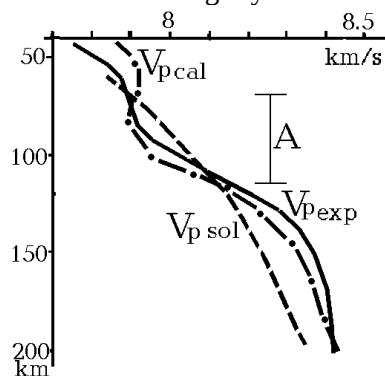


Figure 6. Comparison between mean estimated and experimentally derived velocities along the profile. A is the asthenosphere according to seismological and geothermal data.

A more detailed analysis of the balance between estimated and experimental velocity models was performed in the following way [3]. Areas of the models were divided into elementary cells 20x20 km in size; for each of them the mean value of V_p was calculated. A histogram showing distribution of

differences between them is shown in **figure 7**. The distribution of differences deviates somewhat from normal, but the assessment of the modal value (0.075 km/sec) is quite reliable. Apparently, this can be accounted for by errors in both values being correlated (the calculation error is clearly 0.05 km/sec or larger). Therefore, the agreement can be viewed as acceptable.

The mean deviation, according to results of comparison with individual sections on three profiles is 0.12 km/sec. In view of the conditions making the comparison difficult to perform, such a divergence may be accepted as satisfactory. To put it differently, considering the adopted composition and mineralogy of mantle rocks, as well as temperature distribution, the experimentally derived velocity values can be accounted for.

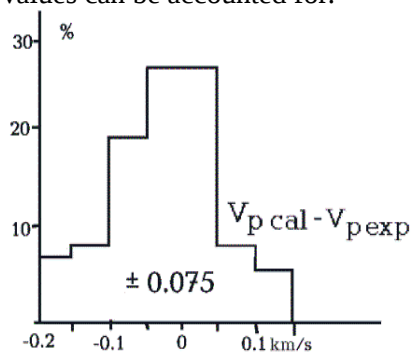


Figure 7. Histogram showing differences between estimated and experimentally derived V_p along the profile.

A velocity model for Kamchatka's entire upper mantle was constructed on the basis of a thermal model by authors – see **figure 8**.

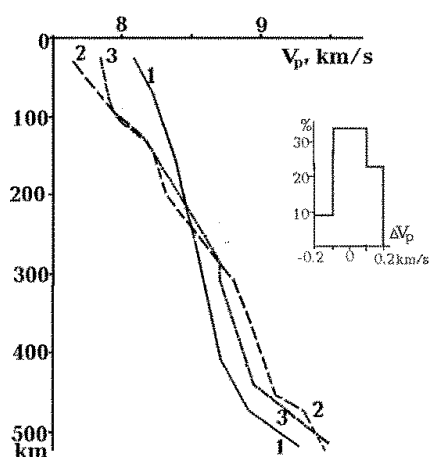


Figure 8. Comparison between the upper mantle velocity model for island arcs and those constructed in terms of the advection-polymorphism hypothesis (APH).

1. Velocity distribution in the upper mantle of the Precambrian platform; 2. Velocity distribution constructed by authors; 3. Predicted velocity model for the Alpine geosyncline upper mantle based on the APH theory.

The divergence between the velocity models averages about 0.1 km/sec, which is readily accounted for by errors in the determination of experimental data. Differences between the above models and the platform model point to an advective nature of the heat and mass transfer.

The thermal model reflecting deep-seated processes in the region must also, to a certain extent, reflect seismicity, which is an important parameter at the contemporary stage of events. To analyze it, it is necessary to consider numerous parameters of the medium and earthquake characteristics. It will therefore be reported in a special paper largely based on a study by Gordienko [8].

3. Density model of the tectonosphere

The aforementioned three-dimensional velocity model incorporates the Earth's crust. It turned out to be sufficiently detailed and reliable for constructing (in combination with other data – [12] and others) diagrammatic models of density distribution along the three profiles running across Eastern Kamchatka (**figure 1**). The crustal model represented the distribution of depths for the M. discontinuity, 6.5 and 7 km/sec velocity levels, and the basement. The velocity of a layer between the 7 and 6.5 km/sec isolines was assumed to be 6.7 km/sec. The V_p value of 6.0 ± 0.5 km/sec was adopted

for the basement surface, and 6.5 km/sec was considered as an average between the basement and the 6.5 km/sec isoline. Thus, the velocity profile used is overschematized, yet, given the available factual data, it is impossible to construct a more detailed profile: The details would be inaccurate.

The abundance of basic and ultrabasic rocks in the Earth's crust of Kamchatka has prompted us to use, alongside conventional formulas, also conversion formulas from V_p to σ applicable to the layer of crust-mantle mixture (CM): $\sigma = 2.69 + 0.26 (V_p - 6)$ and $\sigma = 3.02 + 0.28 (V_p - 7)$, where σ is density in g/cm^3 . It certainly largely applies to the lower layer of a consolidated crust: without the effect of high temperature, velocity values there would have been like in the CM layer. Small corrections ($0.005\text{--}0.01 \text{ g/cm}^3$) made up for the anomalous heating of the crust. The thickness and density (2.55 g/cm^3) of the sedimentary-igneous veneer on dry land was adopted according to a study published by Gordienko et al. [12] and others. These data do not contradict the rather scanty information on seismic wave velocities in Kamchatka's veneer (2.4 - 4.6 km/sec). The thickness of sediments beneath the seabed was believed to be decreasing in the direction from the shore to the trench from 4-5 to 1-0.5 km in accordance with typical distributions of the parameter in other areas of southern Kamchatka, as well as the Kuriles and Hokkaido. It was assumed that the density there is somewhat lower than on dry land: 2.45 g/cm^3 . There is no material to specify the parameter, and the influence of its variation on crustal effect is hardly significant at all.

Provided that density distribution in the upper mantle is normal, the estimated gravitational effect of the crust resembles in shape the distribution in the observed field, but as far as its level is concerned, it has nothing in common with the latter: It is higher by approximately 200 mGal (170-190 mGal) on dry land and by over 200 mGal at sea. The magnitude of the mantle anomaly generally resembles that common for the Alpine geosyncline undergoing contemporary activation, as well as for young oceanic basins. It testifies to a very intensive heating of the upper mantle's top portion, something that (in terms of the APH) is inevitably associated with the cooling of the mantle's lower portion and polymorphic transformations of mantle rocks.

A thermal model for the upper portion of the mantle (to approximately 200 km) was already presented earlier in this paper. A certain adjustment was introduced for the mantle beneath the basin. The major problem in the construction of a model for the basin encompassing the entire thickness of the upper mantle boils down to the lack of reliable geological information on the events that have taken place over recent dozens of millions of years. The problem is further aggravated by the fact that the process beneath the Obruchev Hills may differ from the processes in the basin proper. Even if temperatures in the top portion of the upper mantle are similar for different versions of the process, they may differ considerably in the mantle's lower portion and cause changes in density (which may turn out to be quite appreciable once conditions become ripe for polymorphic transformation of rocks), so that the resulting densities would differ from those used in the calculations. These considerations have prompted us to restrict the area of calculations and not to go beyond the trough axis. Further southeast the reliability of the results may sharply decrease.

The distribution of temperatures was used to determine anomalous densities. The following factors σ relative to normal distribution (T_n) under the effect of an anomalous temperature, i.e. its deviations from the background temperature. At the point of solidus (T_s) the amount of fluid was assumed to equal 1%, so that for its increase by 1% (to the level of segregation – presumably amounting to 3-5%), a heating by 50°C was assumed to be required. One percent of basaltic fluid (at depths indicated in the model) reduced the density by 0.0033 g/cm^3 . This correlation cannot be applied to larger depths: For melt composition corresponding to the composition of the rock, the melt is more compact than the solid mantle at depths larger than 200-250 km.

2. High temperatures caused mantle rocks at depths of about M.-30 and 30-100 km to transform to plagioclase and spinel facies, respectively. This resulted in the reduction of their densities by 0.125 and 0.08 g/cm^3 [10 and others]. A concept regarding preservation of relics of the reworked continental crust beneath a thin oceanic crust (down to 33 km) in the northwestern basin [2] suggests the same densities.

The anomalous density values for upper mantle rocks of the region are presented in **figure 9**.

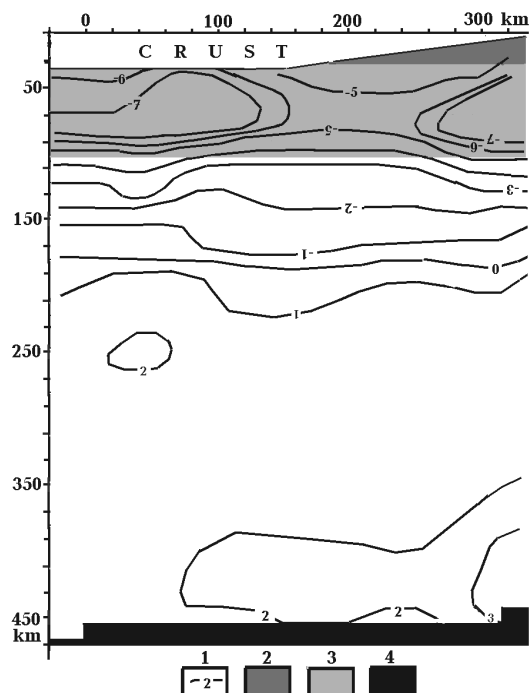


Figure 9. Anomalous densities in the upper mantle beneath the profiles.

1 – isolines of anomalous densities (in 0.01 g/cm³) associated with anomalous temperatures and partial melting; 2 – plagioclase lherzolite zone; 3 – spinel lherzolite zone; 4 – zone (above 470 km) of anomalous compaction in connection with polymorphic transformation at the bottom of the upper mantle.

Attempts to precisely determine the error in calculations of the effect of the mantle's anomalous densities have so far failed. Real errors in the calculation of temperatures [10 and others] enable us to assess errors in drawing boundaries of polymorphic transformation zones at just a few kilometers. Associated with them in each case may be errors in the calculation of the field equaling 10-15 mGal.

3. During the process of cooling of the upper mantle's lower portion as a result of the overlying deep-seated material sinking there, conditions arise that promote a temperature at which olivine transforms into a mineral with the structure of spinel, and thus the rock undergoes compaction by approximately 0.21 g/cm³ [10 and others]. At a normal temperature distribution, the transformation occurs at the depth of about 470 km.

With an account for all the errors in the determination of estimated and observed fields listed above as $(\Sigma(\Delta g)^2)^{0.5}$, we get an assessment of the divergence that they caused between the Δg values being compared amounting to about 40 mGal. The estimated gravitational effect of anomalous densities in the upper mantle beneath the profiles makes it possible to approximately equalize the estimated and observed fields (**figure 10**). Significant divergences have largely been detected in marine portions of the profiles where errors in the determination of both values being compared may increase. It cannot be ruled out that after the used a priori information is refined, the estimated and observed fields may turn out to be closer in magnitude. On the whole, correlation between the fields may be viewed as satisfactory, with an allowance for the lack of accuracy and, occasionally, the hypothetical character of the data used and colossal swings in the values of gravitational fields along the profiles.

Maximum divergences between the estimated and observed fields at some sites reach 89-100 mGal, which is a lot, yet they do not contradict the assessment made above. Maximum divergences are confined to the trough and to the area east of it. The overall results of the comparison between the fields are shown in **figure 11**. It follows from them that the average difference between the fields along all the three profiles does not exceed the forecast value and amounts to 30-40 mGal. A histogram of the distribution of the divergences is more or less symmetrical and points to its relative similarity to normal distribution.

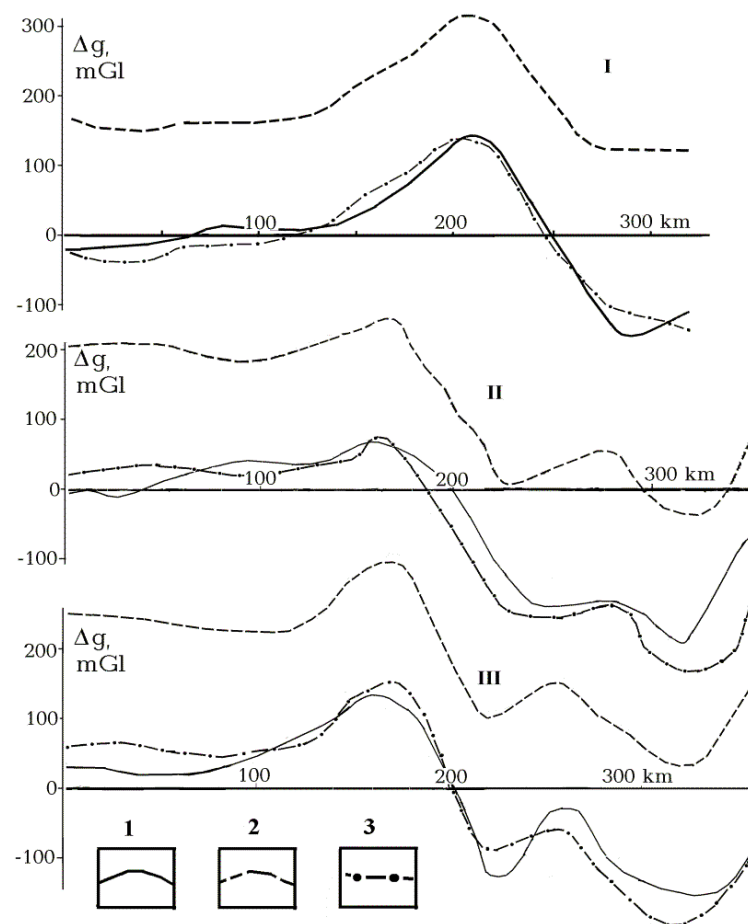


Figure 10. Comparison between estimated and observed gravitational fields along profiles I, II, and III.

1-3 are gravitational fields: 1 – observed, 2 and 3 estimated (2 – is the effect of the crust and normal mantle, 3 – taking into account the mantle's anomalous density).

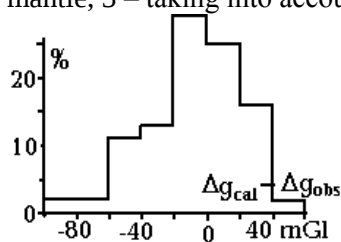


Figure 11. Histogram illustrating divergences between calculated and observed fields along profiles I, II, and III.

We can generally claim that in the case of Kamchatka, a fairly good match between prognostic and experimentally derived parameters can be achieved without the need to adjust them, and the level of deviations is in line with errors in both sets of parameters.

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