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Structural Tectonic Scheme Creation Based on Seismic-Gravity Models and Isostasy Usage: Ural Case

P. S. Martyshko*,[1], I. V. Ladovskii[1], D. D. Byzov*,[1], A. G. Tsidaev[1]

[1] Bulashevich Institute of Geophysics, Ekaterinburg, Russia
* **Correspondence to:** Petr Martyshko, pmart3@mail.ru

Abstract: Process of Earth's density models creation leads to the solution of direct and inverse gravimetry problems. The inverse problem of gravimetry is a classic example of an ill-posed problem: in the common statement, its solution is not unique and unstably depends on input data. Therefore, it is necessary to determine solutions belonging substantial sets of correctness, choosing reasonable models of an initial approximation. In this paper the application of complex interpretation methods of seismic and gravitational data for the creation of three-dimensional models of crust and the upper mantle are presented. Original algorithms and programs were developed for implementation of these methods. They contain solution of non-linear (structural) inverse problem and the solution of the linear three-dimensional inverse problem taking note of the side sources. Coefficients of the "density-velocity" correlation formulas for a number of geo-traverses were defined. Also, we suggest a technique of tectonic maps construction, which is based on the lithostatic pressure calculation. Its idea can be applied to both two- and three-dimensional cases. In the 2D case we show the way to split the mantle to blocks with vertical boundaries. If lithostatic compensation hypothesis is adopted, the method also allows one to calculate density value for each block. Such separation of the mantle helps to diminish discrepancy between model and observed fields. In 3D case we suggest a method, which can be used to construct tectonic structure maps with information about approximate depth and height of each tectonic block.

Keywords: density crust models, geophysical data interpretation, inverse gravity problems.

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1. Introduction

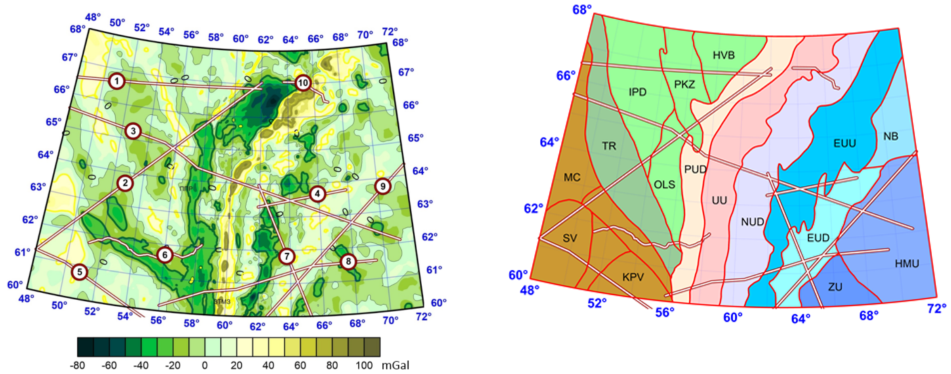
The results of complex interpretation of geophysical data are geological and geophysical models of structure of Earth's upper lithosphere (crust and upper mantle). One of main indicators of model correctness is a density [*Strakhov and Romanyuk*, 1984]. This is because density reflects petrophysical features of inhomogeneous structure and lithological consistency more than any of other physical parameters.

It is known that the most visible income to anomaly gravity field is generated by inhomogeneities that are located in upper part of geological cut (depth down to 10–15 km). However, seismic survey shows that seismic waves velocity is inhomogeneous not only in the crust, but also in the upper mantle. Therefore, we can build a compensated model where gravity anomaly from different inhomogeneous layers are partially (or fully) compensated. Such a model is a possible density analogue for the velocity model of the deep structures. The idea of the gravity and seismic methods combination is transparent. Seismic data allows one to build models of the lithosphere structure down to some specified depth. Gravity data can be used to connect model density with the observed gravity anomalies. This joint interpretation is performed under empirical constraints. Correlation between longitudinal waves velocities in inhomogeneous media and densities of different rocks defines desired result. Our goal is to select morphologically similar structures in anomaly fields of different nature. But the gravity field contains integral information about all the lithosphere features in the whole depths interval from the surface to the mantle. Thus, blocks selected by the gravity field could not be split by depth. Moreover, these blocks are usually invisible in horizontal maps of density distribution. So, even having the gravity field inverted, an attempt to separate lithosphere blocks by depth will most likely be unsuccessful. We propose a different approach. Assume that we have a density model, which can be obtained as a result of the gravity inversion or seismic velocity model conversion. Such a model is the input data for the calculation of the lithostatic pressure distribution. We calculate lithostatic pressure in a point by a mass of vertical rock column, which top is on the Earth surface and the lower end contains the point of calculation. Then, the mass is converted to the weight. But the lithostatic pressure itself is not representative parameter because pressure deviations inducted by density variations have much smaller value than pressure associated with absolute density values. Instead, we analyze lithostatic pressure anomaly, which is calculated as difference between the actual pressure value at the point and the mean pressure (hydrostatic) on this depth level. Similar approach was used by [*Jiménez-Munt et al.*, 2010]. Also the idea of usage of isostasy as an additional constrain in gravity inversion was studies in [*Geng et al.*, 2022; *Li and Yang*, 2020; *Satyakumar et al.*, 2023].

In this paper, we describe our method for both two- and three-dimensional cases. In the two-dimensional case, we also show how adoption of an idea of isostatic compensation helps one to reduce the error of density modelling (i.e., to minimize difference between the observed gravity field and one of the model). Isostatic compensation is the hypothesis that there are no more lateral changes in pressure starting from some depth level. For out study region (Ural Mountains in Russia and neighbouring areas), there is a theory of compensation on level of 80 km [*Druzhinin et al.*, 1990]. We performed our modelling under assumption that this theory is correct. However, we noticed that block structure can be traced even without actual performing of isostatic equalization of the model. In a three-dimensional case, we show that the block boundaries are visible just in the lithostatic model. Coordinate systems of lithostatic model and density model are equal, so, the block positions determined in the lithostatic model remain the same in the density model.

2. Data and Methods

Initial data is presented as gravity map of the region and deep seismic survey data along profiles. Figure 1 shows a fragment of the complete-Bouguer gravity anomaly map derived from the combined global gravity field model XGM2019e_2159_GA [*Zingerle et al.*, 2020] and converted to the Gauss-Krueger map projection coordinates. The positions of the regional seismic profiles are tied to the gravity map fragment; the structural schemes of tectonic zoning are used to verify the results of quantitative interpretation of gravity data. Study area is located inside trapezia 60°–68°N, 48°–72°E (Figure 1a). For territories in the boundaries of several 6-degree Gauss-Kruger zones it is permissible to use gravity model of flat layer. This is Near-Arctic zone of important Russian geological provinces junction: northeastern part of East-European platform, Timan-Pechora plate, northern part of Ural Folding System and northwestern sector of Western Siberia. Input data for initial 3D density model contains 3 parts: a) profile hodographs, time fields and appropriate 2d velocity models, b) empiric correlation between density and velocity and c) gravity field anomalies digital maps in Bougier reduction. The main stages of proposed methods are [*Martyshko et al.*, 2010, 2013, 2016] construction of velocity sections of the Earth's crust, refinement of the coefficients of the regression "velocity-density" dependence from the results of 2D gravitational modeling for the given region, construction of 3D model of the initial approximation, calculation of difference between observed and modelling field, extracting field from layers, density values calculating by method of local corrections with adaptive regularization in each layer. It is known that correlation between density and longitudinal wave velocity for Earth crust rocks can be represented as piece-wise linear regression dependence. Although the dependence coefficients are different for different regions, the trend is that density increases monotonically with increasing elastic waves speed. Density as well as velocity reflects petrochemical structure and physical mechanical state of rocks only partially. Linear regression does not regulate bijection “velocity-density”, there can be fluctuation for both of values within the confidence interval. Any change is equiprobable. Modern views on Ural genesis and its platform structure were taken into account [*Druzhinin et al.*, 1990; *Sobolev et al.*, 1983] and form map of tectonic structures (Figure 1b). 2D velocity and corresponding density values along 10 seismic profiles form 3D carcass of initial model. Model itself is obtained after interpolation. We used gradient velocity cuts of region as the input data. Velocities were converted to density values using empirical formula *Martyshko et al.* [2017]. The following correlation between density and velocity was used for values recalculation. We had obtained this correlation as a result of inverse linear problem solution for 2D profiles [*Ladovskii et al.*, 2017]:



(a) **(b)**

Figure 1. a): gravity field and seismic profiles: 1) Agat-2; 2) Globus; 3) Quartz; 4) V. Nildino – Kazym; 5) Rubin-; 6) Syktyvkarsk; 7) N. Sosva – Yalutorovsk; 8) Krasnolelinsk; 9) Granit – Rubin-2; 10) Polar-Urals transsect. b): Tectonic scheme: Sysolsk vault (SV), Mezensk syneclise (MC), Komi-Perm vault (KPV), Timan ridge (TR), Izhma-Pechora depression (IPD), Omra-Luza saddle (OLS), PechoraKolvinsk zone (PKZ), Horeyversk basin (HVB), Pre-Urals deflection (PUD), Urals uplift (UU), Near-Urals deflection (NUD), East-Urals uplift (EUU), East-Urals deflection (EUD), Nadym block (NB), Zauralsk uplift (ZU), Hantymansiysk middle uplift (HMU).

$$\sigma(V) = \begin{cases} 0.113V + 2.034; 2.35 \le V < 5, \\ 0.2V + 1.6; 5 \le V < 7.75, \\ 0.25V + 1.3; 7.75 \le V < 8.5. \end{cases}$$

Then we performed averaging filtration of density values and, thus, the initial model was obtained. Figure 2 presents one of the model cuts. All the models are constructed down to 80 km only, and we accepted the hypothesis of the existence of the isostatic compensation on this level.

Since the model is obtained as the result of seismic data interpretation, its calculated gravity field (Figure 2a, red curve) has significant discrepancy comparing with the observed one (Figure 2a, purple curve). Usage of isostasy hypothesis helps to reduce this difference [*Martyshko et al.*, 2017].

The lithostatic anomaly $\Delta P(x,z)$ is defined as difference between the lithostatic pressure $P(x,z)$ on a given level h and hydrostatic pressure calculated as mean pressure along the profile on the same depth

$$P(x,h) = g_a \int_h^0 \sigma(x,z)dz,$$
$$\overline{P}(h) = \frac{1}{L}\int_0^L P(x,h)dx = \frac{g_a}{L}\int_h^0 \int_0^L \sigma(x,z)dxdz = g_a \int_h^0 \overline{\sigma}(z)dz,$$
$$\Delta P(x,h) = P(x,h) - \overline{P}(h) = g_a \int_h^0 \Delta\sigma(x,z)dz.$$

Here, $g_a = 9.80665\ \mathrm{m/s^2}$ is the average value of gravity acceleration, $\sigma(x,z)$ is the density value at the point (x,z) of the cut, $\sigma(z)$ is the mean value of density on a depth z

$$\overline{\sigma}(z) = \frac{1}{L}\int_0^L \sigma(x,z)dx, \Delta\sigma(x,z) = \sigma(x,z) - \overline{\sigma}(z).$$

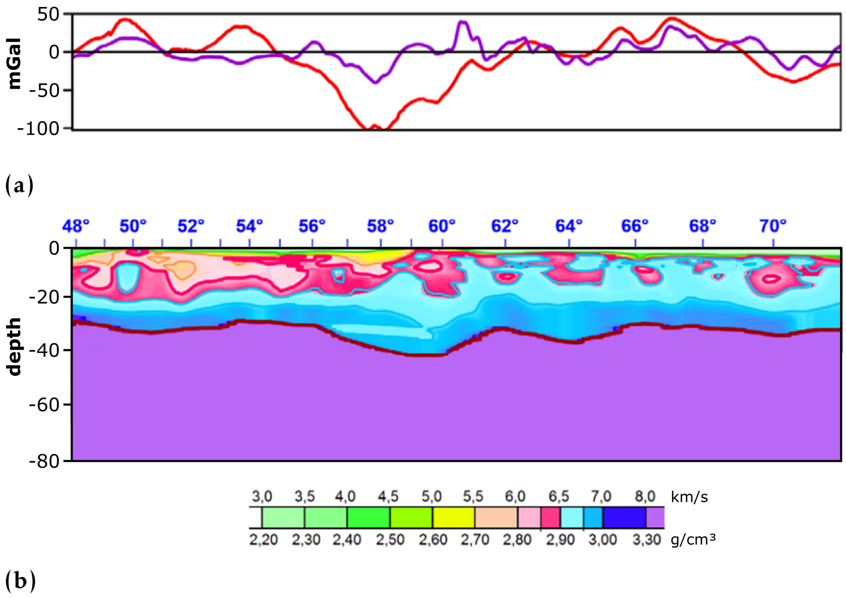


Figure 2. Density model with homogeneous mantle along the "Quartz" profile obtained from seismic data (b) and its gravity field (a, red curve) compared with the observed gravity field (a, purple curve).

Isostatically compensated model with the compensation level h_i should have no lateral pressure variations

$$\Delta P(x,h_i) = 0. \tag{1}$$

In our case, $h_i = -80$ km.

The lithostatic model for our density cut is presented in Figure 3. As it can be clearly seen, there is no constant value on $h_i = -80$ km.

To construct such a compensated model, we introduced compensation function $\rho(x)$. This compensator shows what density value should be subtracted from the mantle (in our case, this is the layer between the Mohorovicic discontinuity and the h_i level) to make condition (1) satisfied.

Let ΔP_{hom} and $\Delta\sigma_{\mathrm{hom}}$ be the deviations of pressure and density from their mean values on given depth for the model with the homogeneous mantle. Lithostatic anomaly after addition of $\rho(x)$ is

$$\Delta P(x,h_i) = \Delta P_{\mathrm{hom}}(x,h_i) - g_a(h_m(x) - h_i)\rho(x).$$

Here $z = h_M(x)$ is Mohorovicic discontinuity position.

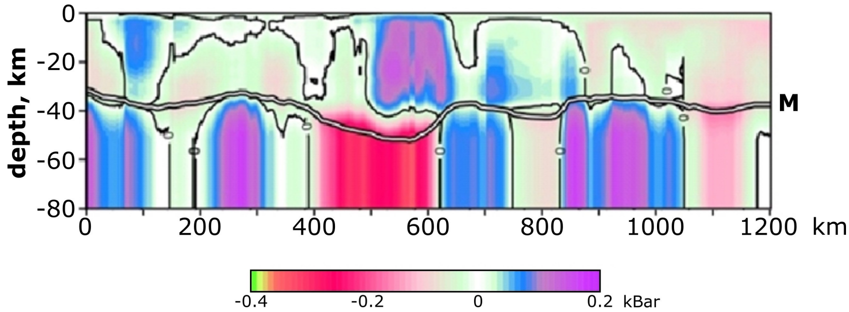


Figure 3. Lithostatic model for the "Quartz" density cut; the Mohorovicic discontinuity M is shown with the double line.

From condition (1), we have

$$\rho(x) = \frac{\Delta P_{\text{hom}}(x, h_i)}{g_a(h_m(x) - h_i)} = \frac{1}{h_m(x) - h_i} \int_{h_i}^{0} \Delta\sigma_{\text{hom}}(x, y) dy. \quad (2)$$

The compensator function for study cut is presented in Figure 4. As it could be easily predicted, it qualitatively repeats form of the Mohorovicic discontinuity. Zeros of compensator function were taken as boundaries of the mantle blocks. After, we distributed these excess densities in the upper mantle and performed density averaging inside blocks, and by this we obtained resulting density model (Figure 5).

As it can be seen from Figure 5a, the model field (red curve) now have a good match with the observed one (purple curve). Figure 6 presents the lithostatic model of resulting density distribution. There is isostatic compensation on $h_i = -80$ km now and the lithostatic anomaly on h_i is zero for almost all profile length. It is interesting to note that the same block boundaries could be selected without performing model compensation at all. Positions of blocks are clearly seen on the initial lithostatic model (Figure 3). Thus, for the case of relatively flat Mohorovicic discontinuity (when denominator of (2) is close to constant) blocks selection can be performed even for isostatically non-compensated model. We will use this approach in the three-dimensional case in the next section.

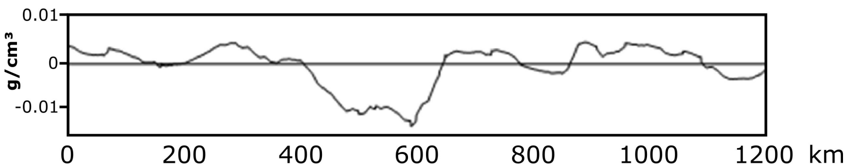
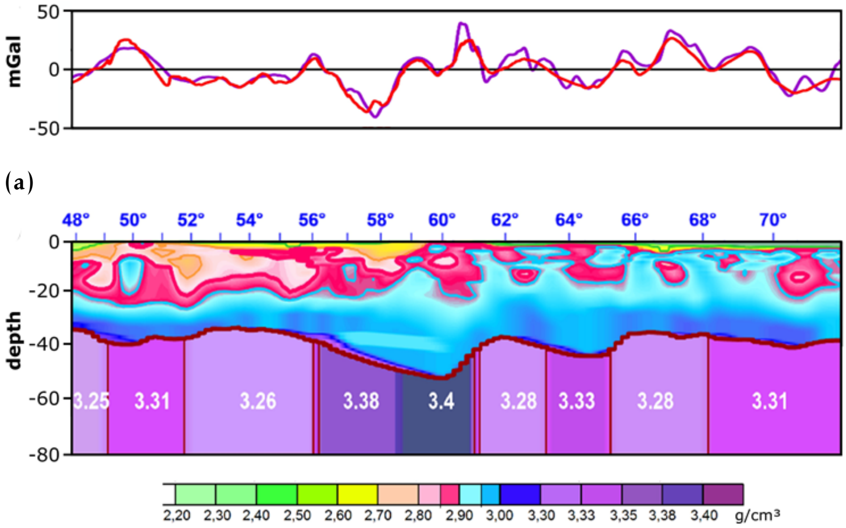


Figure 4. Compensating function for the "Quartz" density cut.

2D velocity cuts are digitized within the gravity field map limits and then are combined into 3D seismic carcass (Figure 7). This considers the mutual position of the seismic profiles (with curvature taken into account). Now we go to the 3D array of volume density model. The missing velocity data are filled with interpolated values. Interpolation was done in by slicing the model into 800 flat horizontal layers and performing triangulation and linear interpolation method for all of them. As the result the digital parallelepiped of 3D model is constructed [*Ladovskii et al.*, 2017].

2D-density models usage for 3D construction do not need high accuracy gravity field alignment along the profiles. It is enough to get qualitative agreement between model field and observed field projected to profile. There are 2 more important problems: correction for 3D density distribution near 2D profiles and removal of 3D model field edge attenuation outside the area under study.

Resulting 3D model contains 1336×969×800 discrete elements. Its anomaly gravity field is calculated using the background density, which is taken as a function of depth only. Such a density can be called "hydrostatical". It is used to calculate excessive density of anomaly masses on any depth.



(a)

(b)

Figure 5. Resulting block density model for the "Quartz" density cut.

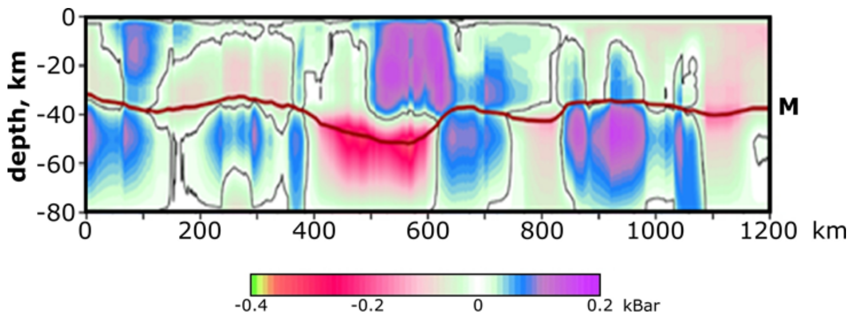
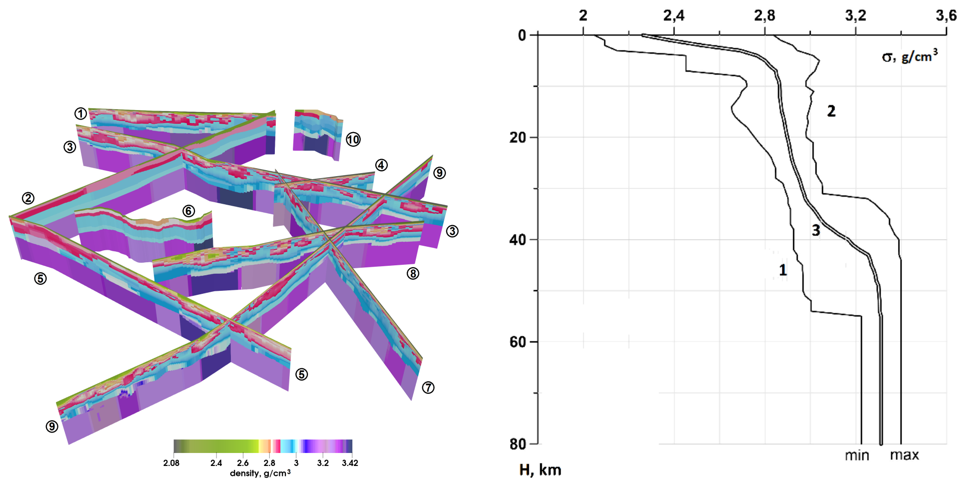


Figure 6. Compensated lithostatic model for the "Quartz" density cut.

The process of density models construction can be reduced to gravity inversion. One should search solution for the inverse gravity problem on practically meaningful sets of correctness by selecting reasonable initial models. Layered velocity distribution in a form of grid arrays fits initial model ideally. This provides stability of inverse gravity problem in a class of weak-unique solutions for models with inhomogeneous layers [*Martyshko et al.*, 2013]. The stable algorithm of layer-by-layer inversion use 2D corrective additions with zero average value [*Martyshko et al.*, 2016]. Iterative scheme of corrective additions calculations in horizontal layers provides uniqueness of inverse problem solution. In addition, it keeps the geological meaning of initial model (constructed by seismic data) in the resulting model (Figure 8).

3D models of upper lithosphere, which were constructed as a result of interpretation of geophysical fields complex, allows one to select a set of curvilinear layers. Boundaries of these layers are selected for specified interval of density values. Gravity anomalies on Earth's surface level reflect information about density inhomogeneities from all sources below. Elements of tectonic schemes are not visible in layers of density models. We offer to calculate masses of columns with unit square from the Earth's surface level down to some specified depth. These integral density parameter forms a block model of crystallic crust on different depth slices. The same is visible in maps of the lithostatic pressure anomalies. The lithostatic pressure values are proportional to the excess density. So, the 3D density model can be easily recalculated into a 3D model of the lithostatic pressure anomalies by summing values from density grids for all layers down to specified depth. The distribution of the lithostatic pressure on the horizontal slices have a good match with the tectonic scheme [*Ladovskii et al.*, 2017].



(a) **(b)**

Figure 7. Density model of initial approximation. Left: spatial position of velocity sections within the study area (for profile designations, see Figure 1). Right: graph of changes in depth of one-dimensional density $\sigma_0(z)$ of the normal model (curve 3). Here are graphs of the minimum (curve 1) and maximum (curve 2) density values.

As a next step of the crust study, we select boundaries that are located inside the crust layer. These boundaries separate layers with constant densities. Such an approximation of a complex 3D model with a set of 2D boundaries is a possible way to lower number calculations and calculation time [*Martyshko et al.*, 2010].

Gravity field Δg of a boundary $z(x,y)$ with flat asymptota plane $z = h$ is calculated using formula

$$\Delta g\left(x',y',0\right) = \Delta\sigma\ f \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(\frac{1}{\sqrt{\left(x-x'\right)^2+\left(y-y'\right)^2+z^2(x,y)}} - \frac{1}{\sqrt{\left(x-x'\right)^2+\left(y-y'\right)^2+h^2}}\right)dxdy.$$

Here $\Delta\sigma$ is density jump on the boundary (density value below boundary minus upper density value), f – gravity constant.

Using technique of boundary selection in density interval, we selected three boundaries. They correspond to density values of 2.8 g/cm^3, 2.88 g/cm^3 and 2.95 g/cm^3 (Figure 9).

3. Isostasy three-dimensional case

Input data for the three-dimensional case are a tectonic structures map of the study region (Figure 1) and a set of two-dimensional profiles (constructed as described above). Profiles were included in a united 3D model (Figure 7). Then we interpolated this sparse model to fill density gaps between the profiles. Preferred interpolation methods are triangulation with linear interpolation method. As a result, the initial model was obtained in a form of the density prism.

The lithostatic anomaly in the three-dimensional case is defined similarly to 2D

$$\Delta P(x,y,h) = P(x,y,h) - \overline{P}(h) = g_a \int_h^0 \Delta\sigma(x,y,z)dz.$$

But for the blocks selection we used a different technique than for the 2D case. Firstly, we equalized the model field with the observed one. This was done by density inversion using local corrections method. The description of this procedure was presented in [*Martyshko et al.*, 2010, 2013], we omit it here. Resulting model has the gravity field equal to the observed one with error $E < 0.001$ mGal.

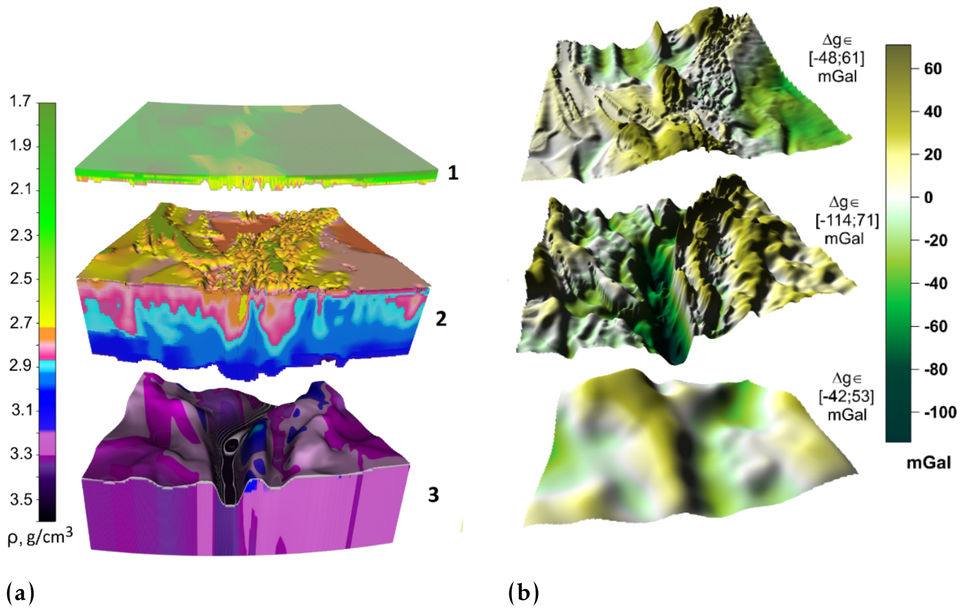


Figure 8. Three-dimensional density model of the region (a), divided along the surface of the roof of the crystalline basement and the roof of the upper mantle: sedimentary cover (1); crystalline crust (2); upper mantle (3). On the right (b) are separated field anomalies calculated from densities that are excess of the normal model's one-dimensional "hydrostatic" density distribution.

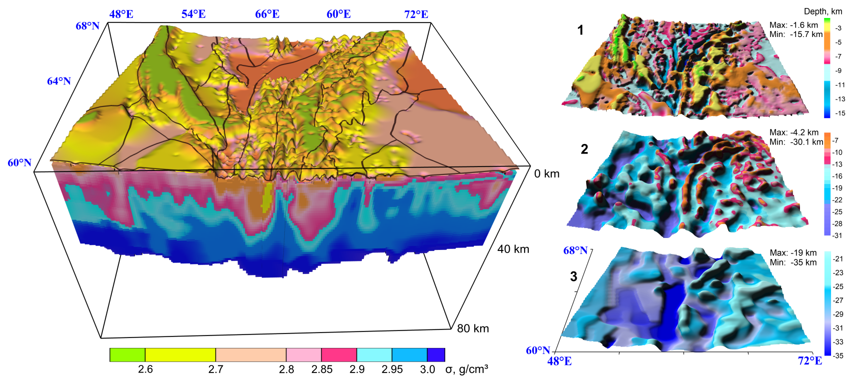


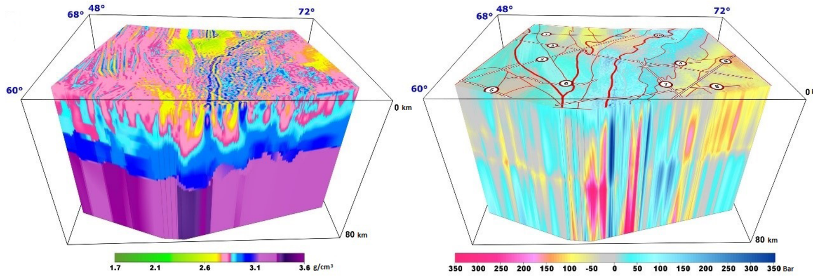
Figure 9. Resulting crust model: 3D layer (left); upper (1), middle (2) and lower (3) inner crust boundaries.

Then we calculated anomaly lithostatic pressure distribution for the resulting density model. Its horizontal cut is presented in Figure 10. Although we used isostatically compensated cuts, neither the initial nor the resulting models are isostatically compensated. This is related to the interpolation. Since we have no information of 3D positions of blocks, which were selected earlier on 2D cuts, we cannot perform correct continuation.

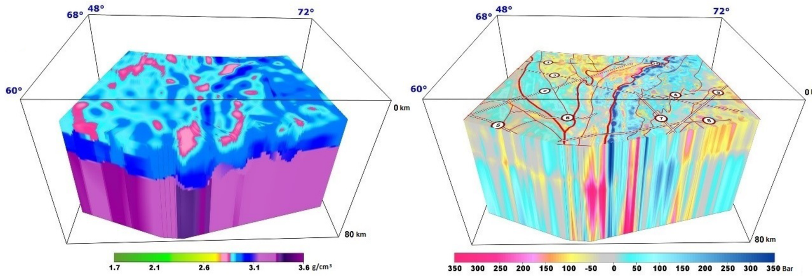
However, we are not obligated to compensate the model to detect blocks. As it was seen from the two-dimensional case, positions of block boundaries could be selected using the initial lithostatic model. We can perform matching of the map of the tectonic structures with the horizontal cuts of the lithostatic model (Figure 11).

4. Discussion

The sections were used to create new structural maps of the main boundaries of the upper lithosphere: between the sedimentary layer and the basement, as well as the Moho boundary – between the earth's crust and the upper mantle. The boundaries are identified by extreme values of the vertical gradient of longitudinal wave velocity. The basement map is in good agreement with previously constructed maps based on both seismic materials and drilling data (VSEGEI, GEON, etc.). A sharp subsidence of the foundation up to 6–8 km



(a)



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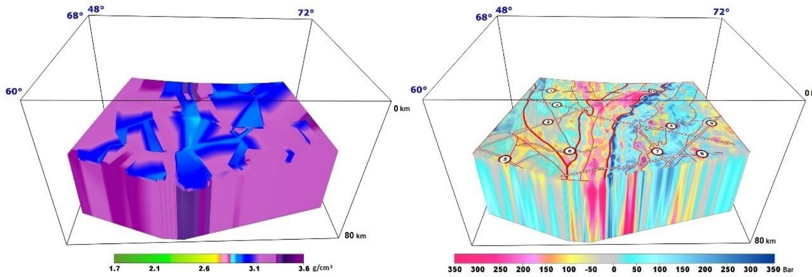

(c)

Figure 10. Horizontal section at a depth of 10 km (a), 20 km (b) and 40 km (c) of density model (left) and lithostatic model (right).

has been confirmed in the Pre-Ural foredeep and in the depressions of Western Siberia. The map of the Moho surface shows previously known features of the deep structure of the territory, published in the atlases of VNIIGeophysics, VSEGEI, GEON, CRUST1.0 and other works. However, the new map significantly clarifies and details the structure of this surface within the specified territory. The subsidence of the Moho boundary and an increase in crustal thickness to 50 km under the Urals have been confirmed, but the area of this subsidence is significantly reduced compared to all previous data. A sharp rise (from 48–50 to 36–38 km) of the Moho surface was revealed within the Tagil trough, in the immediate vicinity of the Main Ural Fault. A map of the surface of the basalt layer was constructed. When constructing, data for longitudinal wave speeds of 6.4–6.5 km/s were used. The average depth to the border is 18–20 km. Under the Ural Mountains and the Timan uplift, the surface of this layer has significant deflections, reaching 26–30 km.

5. Conclusion

We applied new methods for density models construction based on joint interpretation of seismic and gravity data for the structural tectonic schemes creation. These methods for interpretation of the potential geophysical fields are based on a stable algorithm for the solution of the inverse problem. Usage of the initial approximation density model and original fast algorithms for solution of the gravity problems on large grids make it possible to calculate large-scale geophysical models on a real-time basis.

The methods were tested by a practical example: Ural case study. On the first stage, seismic velocity data are recalculated into density values using known correlation between velocity and density. Then the interpolation is performed to fill space between profiles and initial 3D model is obtained. Now, analysing density distribution in the model, it is possible to select boundaries that correspond to known seismic-geological levels. Crust roof and the Mohorovicic discontinuity boundaries were selected using this method. These boundaries slice our model to sediments, crust and mantle. Finally, using the calculated lithostatic pressure distribution we created structural tectonic schemes of the region.

1: Basement $\sigma \in [2.7; 2.9]$ g/cm^3:
($V_p \in [5.6; 6.6]$ km/s)

Relief amplitude:
$\Delta z = -(1.2; 6.4)$ km

2: Basement $\sigma = 2.8$ g/cm^3:
($V_p > 6$ km/s)

Relief amplitude:
$\Delta z = -(1.6; 15.7)$ km

3: Basement $\sigma = 2.88$ g/cm^3:
($V_p > 6.4$ km/s)

Relief amplitude:
$\Delta z = -(4.2; 30.8)$ km

4: Basement $\sigma = 2.95]$ g/cm^3:
($V_p > 6.75$ km/s)

Relief amplitude:
$\Delta z = -(19; 35)$ km

5: Basement $\sigma \in [3.24; 3.42]$ g/cm^3:
($V_p \in [7.7; 8.4]$ km/s)

Relief amplitude:
$\Delta z = -(32.5; 52.2)$ km

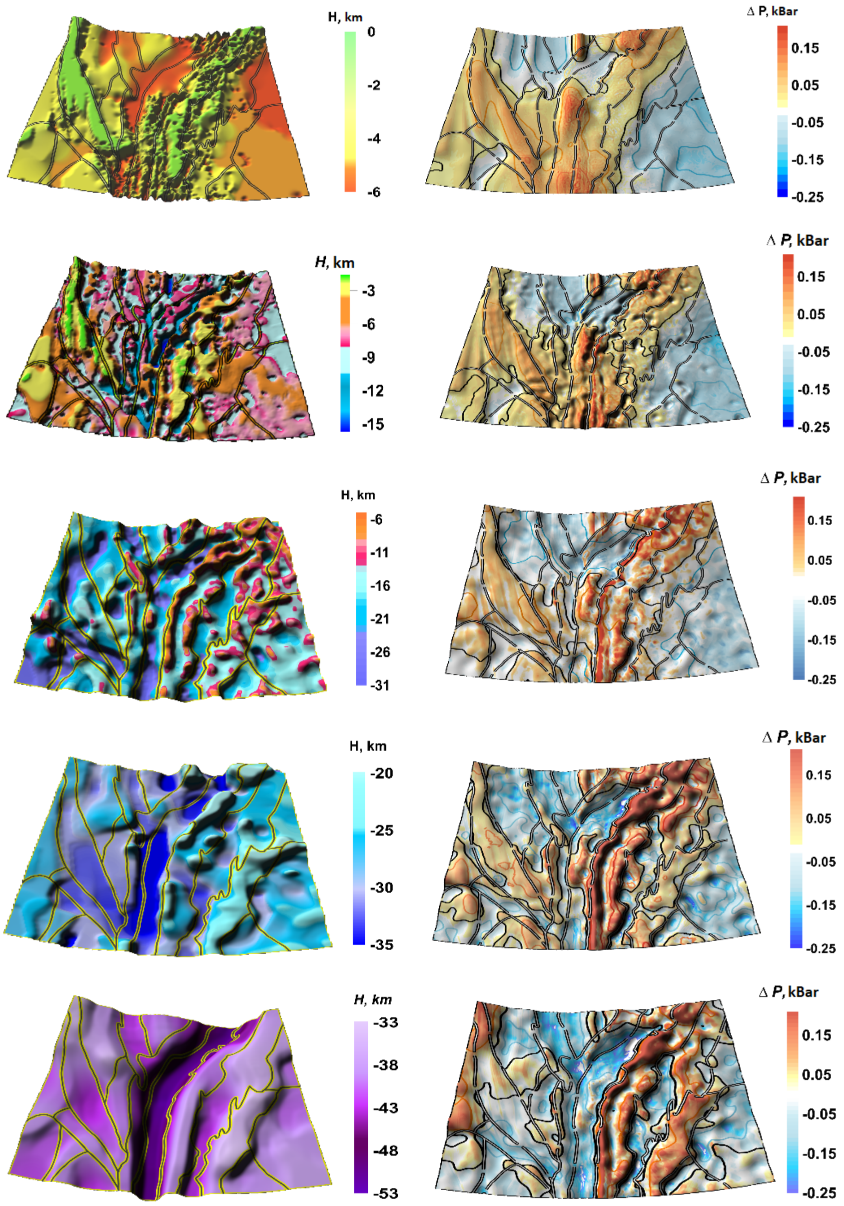

Figure 11. Boundaries of the main structural horizons, constructed using a density model (left) and lithostatic pressure anomalies on them. The contours of tectonic structures are also plotted (see Figure 1).

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