2D and 3D Density Block Models Creation Based on Isostasy Usage

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Abstract. Usual method of tectonic maps construction is the gravity field analysis. However, this method is significantly limited because the gravity field includes integral information about density features in lithosphere. This makes impossible to split selected tectonic blocks by depth. We suggest a new technique, which is based on 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 can help 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: Lithostatic pressure anomaly, isostatic compensation, local isostasy, density model

1 Introduction

The Earth crust and upper mantle are often predicted to have block structure. However, a common way to select these blocks is the analysis of the gravity field or its derivative. But the gravity field contains integral information about all lithosphere features in the whole depths interval from 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 calculation of 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 Jimnez-Munt et al. in [1].

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 modeling (i.e., to minimize difference between the observed gravity field and one of the model). Isostatic compensation is the hypothesis that, starting from some depth level, there are no more lateral changes in pressure. For out study region (Ural mountains in Russia and neighboring areas), there is a theory of compensation on level of 80 km [2]. We performed our modeling 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 Two-dimensional case

We used gradient velocity cuts of the Timan-Pechora region as the input data. Velocities were converted to density values using empirical formula for Timan-Pechora area [3]

$$\sigma(V) = \begin{cases} 0.113V + 2.034; \quad 2.35 \le V < 5, \\ 0.2V + 1.6; \quad 5 \le V < 7.75, \\ 0.25V + 1.3; \quad 7.75 \le V < 8.5. \end{cases} \tag{1}$$

Then we performed averaging filtration of density values and, thus, the initial model was obtained. Figure 1 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 isostatic compensation on this level.

Since the model is obtained as the result of seismic data interpretation, its calculated gravity field (Fig. 1a, red curve) has significant discrepancy comparing with the observed one (Fig. 1a, purple curve). Usage of isostasy hypothesis helps to reduce this difference.

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

$$P(x,z) = g_a \int_h^0 \sigma(x,z)dz, \tag{2}$$

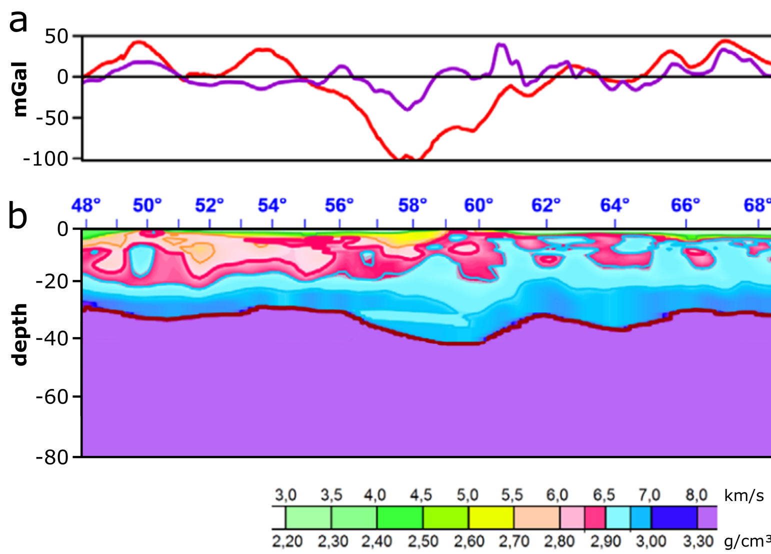

Fig. 1. Density model with homogeneous mantle along the "Quartz" profile obtained from seismic data (b) and its gravity field (a, red curve) compared with the observed gravity field (a, purple curve).

$$\overline{P}(h) = \frac{1}{L}\int_0^L P(x,z)dx = \frac{g_a}{L}\int_h^0\int_0^L \sigma(x,z)dxdz = g_a\int_h^0 \overline{\sigma}(z)dz, \tag{3}$$

$$\Delta P(x,h) = P(x,h) - \overline{P}(h) = g_a\int_h^0 \Delta\sigma(x,z)dz. \tag{4}$$

Here, $g_a = 9.80665$ 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, $\overline{\sigma}(z)$ is the mean value of density on a depth z

$$\overline{\sigma}(h) = \frac{1}{L}\int_0^L \sigma(x,h)dx. \tag{5}$$

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

$$\Delta P(x,h_i) \equiv 0. \tag{6}$$

In our case, h_i=–80 km.

The lithostatic model for our density cut is presented in Fig. 2. As it can be clearly seen, there is no constant value on h_i=–80 km.

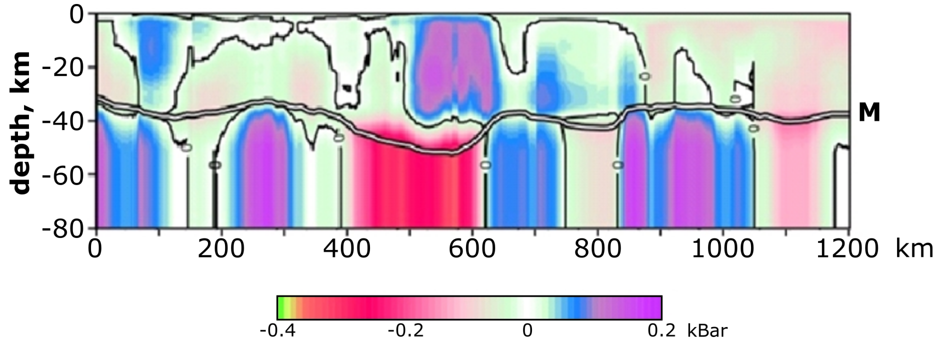

Fig. 2. Lithostatic model for the "Quartz" density cut; the Mohorovicic discontinuity M is shown with the double line.

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 (6) 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

$$\Delta P(x, h_i) = \Delta P_{\mathrm{hom}}(x, h_i) - g_a[h_{\mathrm{M}}(x) - h_i]\rho(x) \tag{7}$$

Here $z = h_{\mathrm{M}}(x)$ is Mohorovicic discontinuity position.

From condition (6), we have

$$\rho(x) = \frac{\Delta P_{\mathrm{hom}}(x, h_i)}{g_a[h_{\mathrm{M}}(x) - h_i]} = \frac{1}{h_{\mathrm{M}}(x) - h_i} \int\limits_{h_i}^{0} \Delta\sigma_{\mathrm{hom}}(x, z)dz. \tag{8}$$

The compensator function for study cut is presented in Fig. 3. 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 (Fig. 4).

As it can be seen from Fig. 4a, the model field (red curve) now have a good match with the observed one (purple curve). Figure 5 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 (Fig. 2). Thus, for the case of relatively flat Mohorovicic discontinuity (when denominator of Eq. 6 is close to constant)

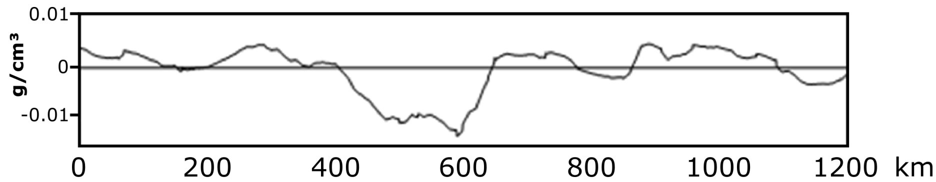

Fig. 3. Compensating function for the "Quartz" density cut.

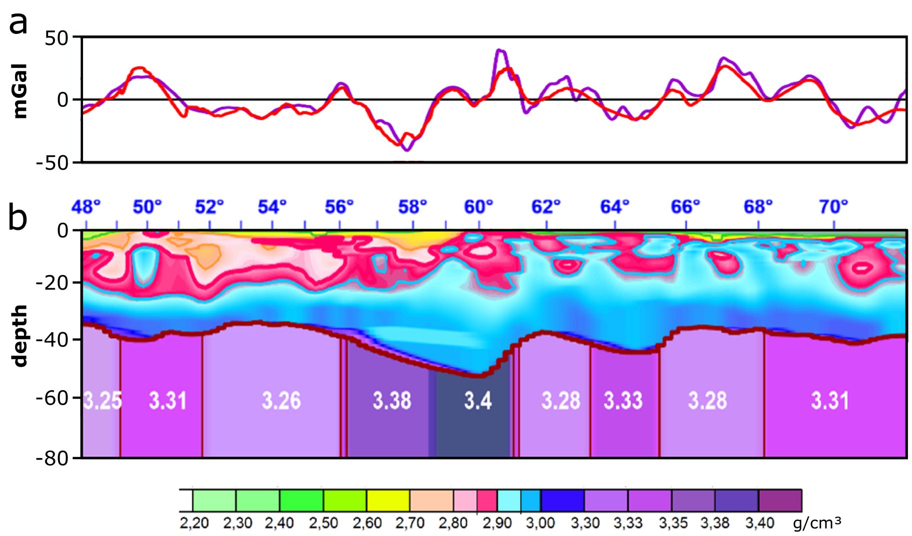

Fig. 4. Resulting block density model for the "Quartz" density cut.

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.

3 Three-dimensional case

Input data for the three-dimensional case are a tectonic structures map of the study region (Fig. 6) and a set of two-dimensional profiles (constructed as described in Section 2. The tectonic map composed of different previously published maps of tectonic structures [4]. Profiles were included in a united 3D model (Fig. 7a). Then we interpolated this sparse model to fill density gaps between the profiles. Preferred interpolation methods are triangulation with linear interpolation method or natural neighbor method [7]. As a result, the initial model was obtained in a form of the density prism (Fig. 7b).

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

$$\Delta P(x,y,h) = P(x,y,h) - \overline{P}(h) = g_a \int\limits_h^0 \Delta\sigma(x,y,z)dz. \qquad (9)$$

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. We omit description of this procedure. It was presented in [5] and [6]. Resulting model has the gravity field equal to the observed one with error $\epsilon < 0.001$ mGal. The horizontal cut of the resulting model is presented in Fig. 8a.

Then we calculated anomaly lithostatic pressure distribution for the resulting density model. Its horizontal cut is presented in Fig. 8b. 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 map of tectonic structures with horizontal cuts of the lithostatic model (Fig. 8b). This operation was performed for four depths: 10 km, 20 km, 40 km, and 60 km. Result is presented in Fig. 9.

4 Results and conclusion

The main problem in lithosphere blocks selection is impossibility to separate blocks by depth. Maps of tectonic structure are usually created by gravity field, which contains only integral information about all features on all depths. In this paper, we suggested a new technique, which is based on lithostatic pressure calculation. Although the method is rather simple, it produces interesting results.

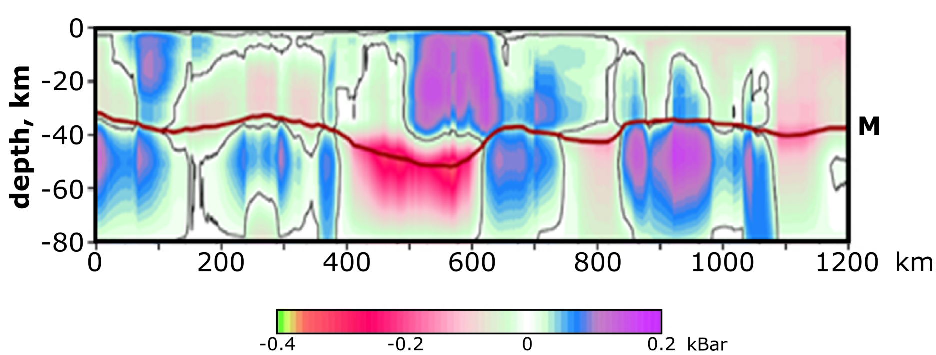

Fig. 5. Compensated lithostatic model for the "Quartz" density cut.

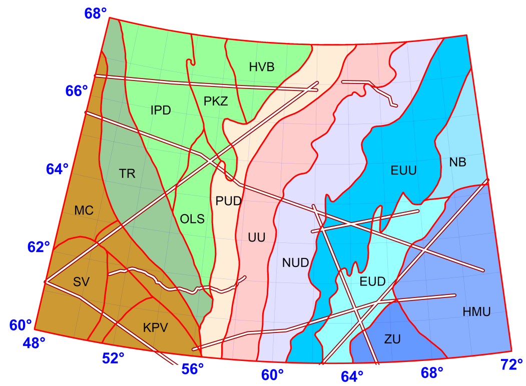

Fig. 6. Tectonic structures map of the Ural region and position of profiles; abbreviations: Sysolsk vault (SV), Mezensk syneclise (MC), Komi-Perm vault (KPV), Timan ridge (TR), Izhma-Pechora depression (IPD), Omra-Luza saddle (OLS), Pechora-Kolvinsk zone (PKZ), Horeyversk basin (HVB), Pre-Urals deflection (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).

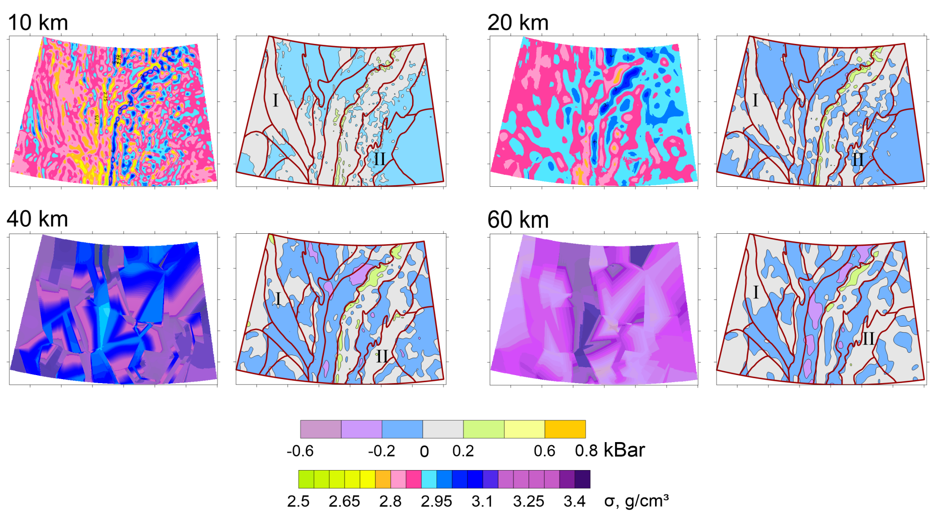

Fig. 9. Horizontal cuts of density model (left image in each pair) mapped to horizontal cut of the lithostatic model (right image in pair).

In Figure 9 four cuts of density and lithostatic models are presented. It can be seen that different structures are traced on different depths of lithostatic pressure cuts. For example, structure I (which is the Timan ridge) can be identified on 10 km and 20 km cuts, but disappears deeper. On the other hand, structure II

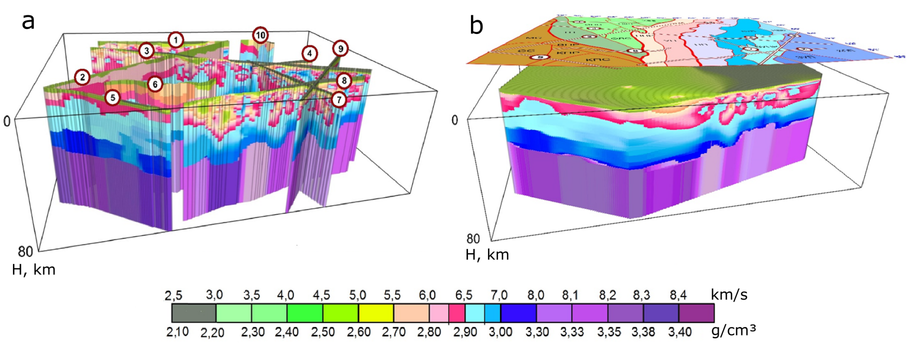

Fig. 7. Three-dimensional model of the Urals region; (a) density cuts position, (b) interpolated density prism with the map of tectonic structures.

(which is the East Urals Deflection) cannot be traced in upper half of lithosphere, but is clearly seen on 40 km and deeper. And these structures are not visible on density cuts on corresponding depths.

For the two-dimensional case we suggested the technique of mantle splitting into blocks, which can be used to improve the model. Gravity field of the updated model has noticeably lower discrepancy relative to the observed field than that of the initial model. Homogeneous mantle with constant density 3.36 g/cm^3 (Fig. 1) was split into 9 blocks with densities in range [3.25-3.4] g/cm^3. This was performed under the hypothesis of isostatic compensation. But it was shown that blocks can be selected by the lithostatic model itself without need to equalize lithostatic pressure on some depth. However, hypothesis of local isostasy gives a simple method for calculation of resulting densities of selected blocks.

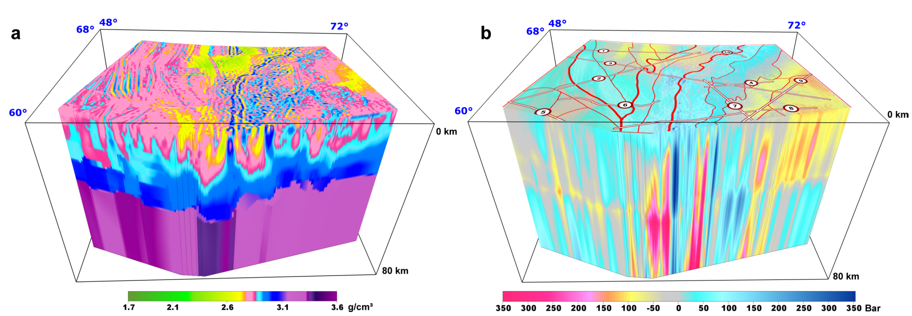

Fig. 8. Horizontal cut of density model; (a) mapped to horizontal cut of the lithostatic model (b); depth of cut is 10 km.

Section 3 research was supported by the Russian Science Foundation (project 14-27-00059).

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