The use of «native» wavelet transform for determining lateral density variation of the Volgo-Uralian subcraton

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THE USE OF «NATIVE» WAVELET TRANSFORM FOR DETERMINING LATERAL DENSITY VARIATION OF THE VOLGO-URALIAN SUBCRATON

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Abstract

In the last two decades in conjunction with the development of satellite gravimetry, the techniques of regional-scale inverse and forward gravity modeling started to be more actively incorporated in the construction of crustal and lithospheric scale models. Such regional models are usually built as a set of layers and bodies with constant densities. This approach often leads to a certain difference between the initially used measured gravity field and a gravity field that is produced by the model. One of the examples of this kind of models is a recent lithospheric model of the Volgo-Uralian subcraton. In the current study, we are applying the method of «native» wavelet transform to the residual gravity anomaly for defining the possible lateral density variations within the lithospheric layers of Volgo-Uralia.

Keywords:
Wavelet transform;
Gravity field inversion;
Forward gravity modeling;
Volgo-Uralian subcraton;
Satellite gravimetry.

1. Introduction

Volgo-Uralian subcraton is located on the eastern part of the Russian platform. The crystalline basement of Volgo-Uralia is comprised by the rocks of Early-Archean to Paleoproterozoic ages and represents an amalgamation of Archean blocks dissected by Paleoproterozoic rifts [1]. Volgo-Uralia has a relatively thick and dense crust and rather uniform sedimentary layer which completely covers the basement with few exceptions [1, 2]. The sedimentary cover of Volgo-Uralia is known for its large petroleum deposits attributed to the Volga-Ural hydrocarbon-bearing province [3]. The main features of the Volgo-Uralian crustal structure are described in numerous works (e.g., [1, 4-6]).

A recent study by Ognev et al. [7] provides a full 3D lithospheric model of the Volgo-Uralian subcraton. This model was created throughout the inverse gravity modeling with laterally variable density contrasts [8] and subsequent forward gravity modeling with seismic constraints in IGMAS+ software [9, 10]. The lithospheric scale models such as in [7] are valuable for the oil industry since they may be used for reconstructing the present-day thermal state of the studied region's crust which is necessary for basin and petroleum system modeling [11-13].

The present work is based on the model of Ognev et al. [7] and is aimed at investigating the possible trends of lateral density variations in the Volgo-Uralian region. Such an enhancement is done by the use of the «native» wavelet transformation of the residual gravity anomaly [14, 15].

2. Data and method

2.1. Lithospheric model of the Volgo-Uralian subcraton

The utilized model of the Volgo-Uralian subcraton is a three-dimensional multi-layered model which consists of 6 layers of the Earth's crust and the lithosphere with different densities. The densities of the layers are given in table.

Table
Density model of the Volgo-Uralian subcraton [7]

No	Layer	Density, kg/m^3
1	Sedimentary cover	$2430 \times z^{0.045}$*
2	Upper crust	2750
3	Lower crust	2900
4	Underplate	3100
5	Upper mantle	3234
6	Asthenosphere	3224

* *z is ½ of the depth of sediments in km*

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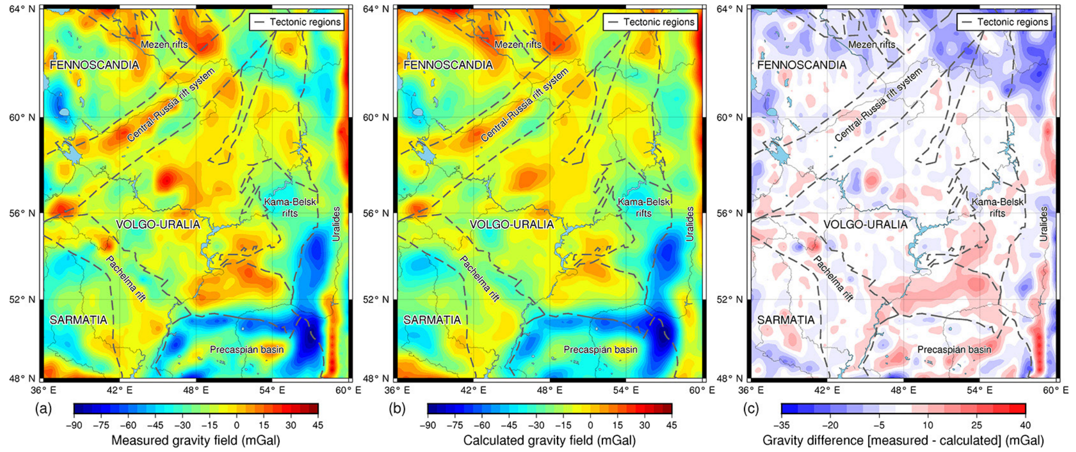

Fig.1. Comparison between measured and calculated gravity fields of Volgo-Uralian subcraton: (a) Measured Bouguer gravity anomaly from XGM2019e global gravity model [16]; (b) Calculated Bouguer gravity anomaly produced by the 3D lithospheric model; (c) The difference between measured and calculated gravity fields [7]

The discussed model is built is IGMAS+ software in the process of fitting the forward calculated gravity field to the measured gravity anomaly alongside respecting the given seismic constraints on the crustal structure. Moreover, satellite gravity gradient was also used to fit the model. Here we utilize the residual gravity anomaly between measured and calculated Bouguer gravity fields on the Earth's surface height for determining lateral variations of densities in the crustal and lithospheric layers (fig.1). The densities of sedimentary strata are considered changing only vertically.

2.2. «Native» wavelet-transform of the residual gravity field

A recent technique that was developed to analyze the potential fields is a continuous wavelet transform [14, 17, 18]. It allows recovering the causative sources of a given potential field with the estimations of their horizontal location, depth, and other parameters [18]. A class of so-called natural or «native» wavelets can be used to construct the density models of the geological media based on the given gravity anomaly [14]. The main outcome of the «native» wavelet transform is a set of causative point mass sources with their spatial coordinates and mass imbalances which explains the obtained wavelet spectrum. We are using the data processing technique that is based on the use of the «native» wavelet transform of gravity anomalies. A distinctive feature of the technique is its close relationship to both direct and inverse problems of gravimetry [14].

Depth of the causative sources is determined with a certain error due to the curvature of the Earth's surface. The magnitude of such error can be estimated by the following formula:

$$h_s = -Rln\left(1-\frac{h}{R}\right) \qquad (1)$$

where R – is the Earth's radius; h – is the depth of a causative source in the case of the «flat» surface model. The lower boundary of the used 3D model is set at the depth of 300 km, which gives an error magnitude of no more than 8 km (2.7%). It is a rather small value that practically allows determining the depths of the causative sources applied for the «flat» Earth model.

In the case of an isolated causative source with unit mass and coordinates $\{x_0, y_0, h_0\}$, its «native» wavelet spectrum is estimated as:

$$W\left[l^{(n)},V^{(1)}\right](h,x,y)= \\ =\frac{2^{n-1}}{(n-2)!\,f}h^{n-1}V^{(n)}\left(h+h_0,x-x_0,y-y_0\right) \qquad (2)$$

where f – is gravity constant; $V^{(n)}(h, x, y)$ – is an n-th vertical derivative of gravity potential point source. The central maximum of the spectrum is a point with coordinates:

$$x^* = x_0, y^* = y_0,\ h^* = \frac{(n-2)}{3}h_0 \qquad (3)$$

when $n = 5$ we have $h^* = h_0$. In this case, the mass of the source is

$$m = \frac{1}{5}W\left[l^{(n)},V^{(1)}\right]\left(h^*,x^*,y^*\right)fh^3 \qquad (4)$$

It means that the location and magnitude of the spectrum maximum exactly determine the coordinates and mass of the causative source.

In the case when fields of several sources interfere with each other, it is impossible to use formula (3) for their identification, since the extrema of the wavelet spectrum no longer indicate the exact position of the causative sources. For such cases, a special iterative algorithm has been developed (fig.2) [19].

We used the aforementioned algorithm to find the lateral density variations of the Volgo-Uralian subcraton's crustal and lithospheric layers. This algorithm finds the minimum possible number of causative sources which are represented by the extrema of wavelet spectrum with amplitudes above the predetermined threshold value in order to exclude the noise part of the signal. Then the

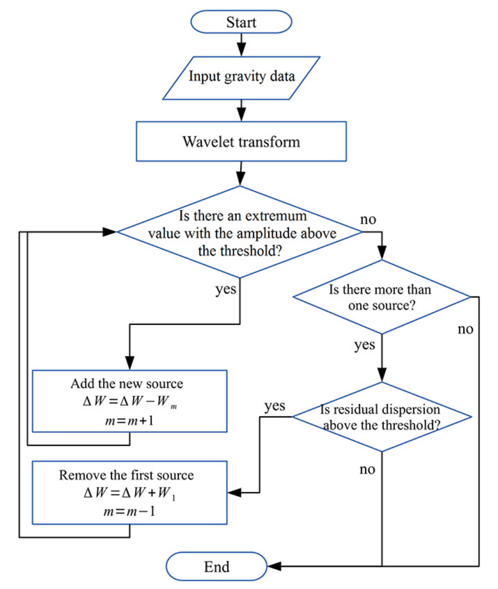

Fig.2. Block diagram of the algorithm for seeking causative sources [19]

obtained causative sources are attributed to certain layers of the lithospheric model depending on their depth. The masses of the sources are recalculated into the density surpluses and deficits which are consequently extrapolated on the whole area of study

3. Results and discussion

As a result, the maps of the lateral density variations for crustal and lithospheric layers of the Volgo-Uralian subcraton were obtained (fig.3, 4). The point sources causing these density variations are shown in figure 5.

As it can be seen from figures 3 and 4, the «native» wavelet transform suggests considerable lateral density variations in the different layers of the crust and the lithosphere of Volgo-Uralia. The underplated layer's density variations are not shown here because of their relatively low magnitude which can be neglected. There is a general increase of the lateral densities variations' degree with depth with the highest lateral variability observed in the upper-mantle layer.

Moreover, there are several worth-mentioning features that are visible on the density maps. The first one is a consistent density increase in the area of the southern Uralides which is observed both in crustal (fig.3a-b) and upper mantle layers (fig.4a). This anomaly is located below the URSES-95 seismic profile [7]. It shows a density rise up to 2800-2850 and 2950-3100 kg/m^3 in the upper and the lower crust respectively which corresponds to a density surplus of 50-200 kg/m^3 relative to the values used for the crustal layers in the 3D model (tabl.). A significant density surplus of 200-500 kg/m^3 is retrieved for the upper mantle layer as well. According to the gravity 2D-subsurface density model of URSEIS-95 profile which is based on correlating seismic velocity and density structure shown in [20], the crust under the South Ural mountains should indeed have slightly higher densities than the ones used in [7] and closer

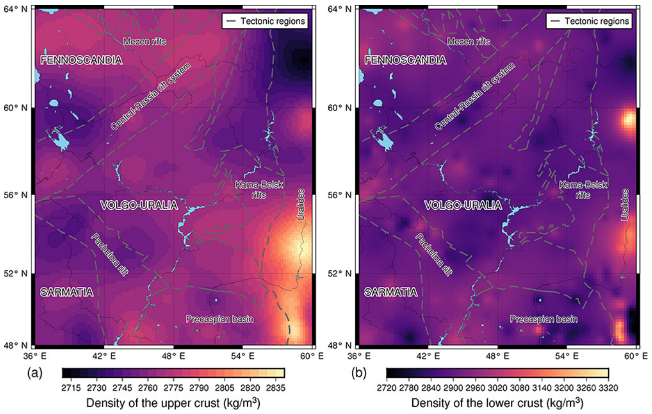

Fig.3. Lateral density variation of the Volgo-Uralian subcraton's crustal layers according to «native» wavelet transform:
(a) Density variation in the upper crust;
(b) Density variation in the lower crust

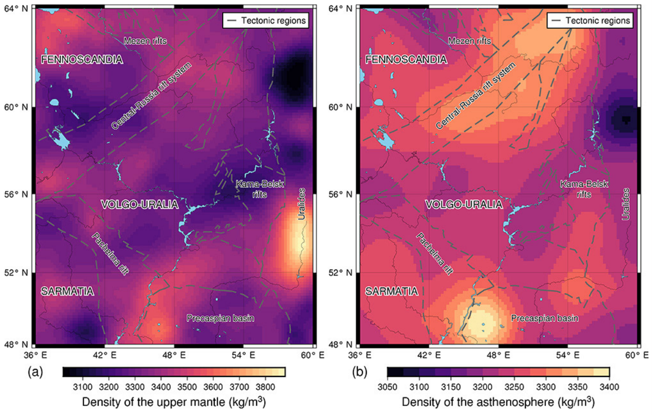

Fig.4. Lateral density variation of the Volgo-Uralian subcraton's lithospheric layers according to «native» wavelet transform:
(a) Density variation in the upper mantle;
(b) Density variation in the asthenosphere

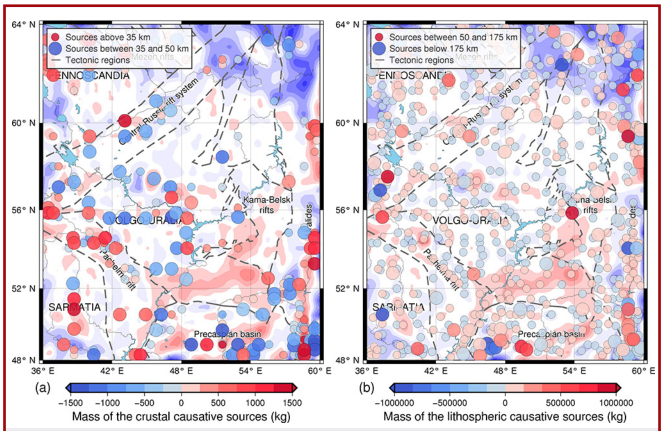

Fig.5. Point causative sources' distribution according to the «native» wavelet transform. The crustal (a) and the lithospheric (b) causative sources are distinguished arbitrarily depending on their depth: the sources above 50 km are attributed to the crust and the ones below 50km – to the deeper lithosphere. The residual gravity field from figure 1c is shown on the background

to the values shown in figure 3. The upper mantle in its turn is also expected to have densities in the range of 3340-3420 kg/m^3 [20], but this does not fully explain the inferred upper mantle density surplus for the region by the «native» wavelet transform. This could potentially be compensated by moderately increasing the thickness of the upper mantle in this area.

The second feature is consistent throughout the entire lithospheric column and is represented by a negative density anomaly in the northern Uralides closer to the Timan-Pechora basin. This anomaly may occur both due to the lower crustal densities in this region and due to the thicker crust. This feature is much less easy to interpret and should be treated with caution due to the lack of seismic constraints in this area [7].

Overall, we can summarize that the performed «native» wavelet transform suggests a slightly denser crust and lithosphere for the Volgo-Uralian subcraton compared to the model of [7]. The causative sources of the discussed anomalies with their depths and mass imbalances are outlined in figure 5. One can see that the masses of the crustal causative sources (fig.5a) are several orders of magnitude smaller than those of the lithospheric sources (fig.5b). It happens due to the nature of the transformation which is related to the spatial resolution decrease with depth leading the sources to merge. This results in fewer causative sources with bigger masses at greater depths. Nonetheless, even though the number of causative sources tends to decrease with depth, in the case of the analyzed model it is peaked at the depths of 50-100 km (fig.6). Such a result demonstrates that the heterogeneities in the lower crust, the crust-mantle interface, and the uppermost mantle are most likely responsible for a substantial fraction of the residual gravity anomaly (fig.1c). The sources of the upper mantle are not only the most numerous, but also have the highest mass imbalance as compared to other depths. It is reflected in the range of obtained lateral density variation for the upper mantle of Volgo-Uralia (fig.4a). This outcome implies that the upper mantle of the Volgo-Uralia may in fact have a considerable lateral density heterogeneity which can be linked to the variations of its geochemical composition.

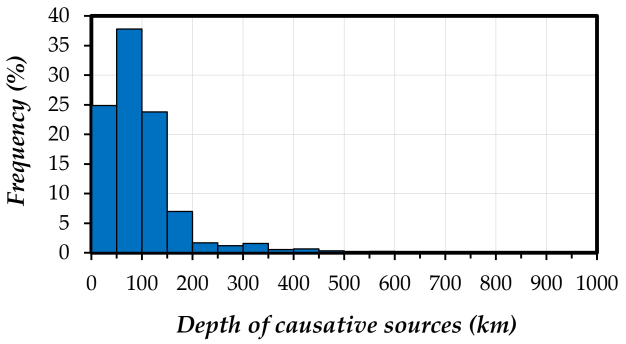

Fig.6. Causative sources' depth distribution

Conclusions

Native wavelet transform allows defining the parameters of the causative sources based on the residual gravity field between measured and forward calculated gravity signals. The set of causative sources with corresponding mass surpluses and deficits can be converted into densities surpluses and deficits of the crustal and lithospheric layers. Thus, the «native» wavelet transform can be used for improving the existing regional-scale layered crustal models with initially constant densities by introducing lateral density variation.

The case of the Volgo-Uralian subcraton was examined with a full 3D lithospheric model of Ognev et al. [7]. The «native» wavelet transform suggested considerable lateral density variations in the upper crustal, lower crustal, upper mantle, and asthenospheric layers with overall slightly higher densities than in [7]. The most prominent features of the obtained density variations are high crustal and upper mantle densities in the South Ural region and low-density anomaly in the North Urals close to Timanide orogeny relative to the model [7]. Nevertheless, each density anomaly obtained through the «native» wavelet transform should be treated individually as it may be explained not necessarily only by the lateral density variations within the existing layers. Other solutions like changing the layers' geometry or introducing additional layers of different densities should be considered as well when trying to explain the residual gravity field.

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Использование «естественного» вейвлет-преобразования для определения латерального изменения плотности Волго-Уральского субкратона

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Реферат

В последние два десятилетия, в связи с развитием спутниковой гравиметрии, стали активно применяться методы решения прямых и обратных задач гравиразведки для создания моделей земной коры. Создание региональных гравитационных моделей такого рода зачастую связано с заданием слоев или тел земной коры с постоянными плотностями. Такой подход нередко влечёт за собой определённое расхождение измеренного гравитационного поля и поля, рассчитанного на основании построенной модели. Одним из примеров таких моделей может являться недавняя литосферная модель Волго-Уральского субкратона. В настоящем исследовании авторы применяют метод «естественного» вейвлет-преобразования к разности измеренного и рассчитанного гравитационных полей для определения возможных латеральных изменений плотности в пределах слоёв литосферы Волго-Уральского субкратона.

Ключевые слова: вейвлет-преобразование; инверсия гравитационного поля; решение прямой задачи гравиразведки; Волго-Уральский субкратон; спутниковая гравиметрия.

Volqa-Ural subkratonunun sıxlığında lateral dəyişikliyin müəyyən edilməsi üçün «təbii» veyvlet-çevrilməsinin istifadəsi

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Xülasə

Son iki onillikdə peyk qravimetriyasının inkişafı ilə əlaqədar olaraq yer qabığı modellərinin yaradılmasında qravitasiya kəşfiyyatının düz və tərs məsələlərinin həlli üsulları fəal şəkildə istifadə olunmağa başlanmışdır. Bu cür regional qravitasiya modellərinin yaradılması çox vaxt yer qabığının sabit sıxlığa malik təbəqələrinin və ya cisimlərinin verilməsi ilə bağlı olur. Bu yanaşmada çox vaxt ölçülmüş qravitasiya sahəsi ilə qurulmuş model əsasında hesablanmış sahə arasında müəyyən fərqlənmələr yaranır. Belə modellərə misal olaraq Volqa-Ural subkratonunun son litosfer modeli göstərilir. Bu tədqiqat işində müəlliflər Volqa-Ural subkraton litosferinin təbəqələri daxilində sıxlığın mümkün lateral dəyişikliklərinin müəyyən edilməsi üçün ölçülmüş və hesablanmış qravitasiya sahələri arasındakı fərqə «təbii» veyvlet-çevrilmə metodunu tətbiq edirlər.

Açar sözlər: veyvlet-çevrilmə; qravitasiya sahəsinin inversiyası; qravitasiya kəşfiyyatının düz məsələsinin həlli; Volqa-Ural subkratonu; peyk qravimetriyası.