УДК.550.838

КОМПЬЮТЕРНАЯ ТЕХНОЛОГИЯ ВЫДЕЛЕНИЯ МАГНИТНЫХ АНОМАЛИЙ ОТ СЛОЕВ ЗЕМНОЙ КОРЫ И РЕЗУЛЬТАТЫ ЕЕ ПРИМЕНЕНИЯ ДЛЯ СЕВЕРНОЙ ЧАСТИ ЕВРАЗИИ

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Аннотация. Для северной части Евразии в пределах сектора, заключенного между 48°–72° в.д. и 60°–68° с.ш., для построения карт региональных и локальных магнитных аномалий применена компьютерная технология. В этой работе описывается математический аппарат и алгоритмы параллельных вычислений, которые применены при разработке компьютерной технологии. Методика трансформации полей с помощью пересчетов в верхнее полупространство и затем аналитического продолжения в нижнее полупространство использована для разделения аномального магнитного поля на составляющие. Процедура продолжения вниз является некорректной задачей, для ее решения применялась регуляризация. Для выбора параметра регуляризации мы использовали результаты интерпретации магнитных аномалий вдоль профилей ГСЗ. Карты локальных магнитных аномалий от верхней части литосферы основаны на вычислениях для высот 5 и 20 км. Карта региональной компоненты была получена продолжением магнитного поля вверх на высоту до 40 км, и его последующего пересчета вниз, а затем к нулевому уровню.

Магнитное поле, параллельные алгоритмы, параметр регуляризации, пересчет вверх и вниз.

THE COMPUTER TECHNOLOGY FOR HIGHLIGHTING THE MAGNETIC ANOMALIES OF THE EARTH CRUST LAYERS, AND RESULTS OF ITS USAGE FOR THE SECTOR OF NORTHERN EURASIA

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Abstract. The computer technology is used for constructing the maps of the regional and local anomalies the magnetic fields for the Northern Eurasia sector of within an area confined between 48°–72° E and 60°–68° N. In this work, we describe the mathematical apparatus and algorithms of parallel computations that are used for designing the computer technology. The algorithm for separating the anomalies in the different intervals of the wavelengths is based on subsequent upward and downward magnetic data continuation. The downward continuation procedure is an ill-posed problem, the regularization is applied. For selecting the regularization parameter, we used the results of the interpretation of the magnetic anomalies along DSS profiles. We used the computed data on the magnetic field at heights 5 and 20 km for constructing the maps of local anomalies in the upper lithosphere. The map of the regional component was obtained by the upward continuation of the field to a height of 40 km and its subsequent recalculation back to the zero level.

Magnetic field, Parallel algorithms, Regularization parameter, Upward and downward continuation.

Introduction

Ural fold belt is a boundary structure between Europe and Asia. As part of the project of the Russian Science Foundation «3D models of Urals region Nether-Polar zone deep structure construction based on new geophysical fields complex interpretation methods and modern computer grid modeling technologies» we studied the magnetic field of northern Eurasia between 48°–72° E and 60°–68° N. For this current project, we conducted the studies of the structural features of the magnetic anomalies over a part of Northern Eurasia.

From a tectonic view, this area comprises the northeastern part of the East European Platform, the Timan–Pechora Plate, a large part of West-Siberian Plate and the segment of the Ural folded system, which includes Northern, Nether-Polar and Polar Urals

(Fig. 1, color tab).

Study and analysis of the anomalous magnetic field structure have practical values for geological mapping, geological survey, and in the sense of revealing the peculiarities of tectonic structure of the lithosphere and building geomagnetic models of the Earth's crust, also prospecting for mineral resources.

On the Earth's surface formations of the upper layer of crystalline crust create intense anomalies which greatly contribute to the lithosphere's magnetic field. The task of finding the magnetic field anomalies of the deeper layers of Earth's crust is rather difficult. It is known that the intensity of the magnetic induction F of the magnetized source decreases rapidly when distance increases, and at a distance r, exceeding the size of the source, it decreases proportionally to the value of $1/r^3$. Therefore the long-wave or regional anomalies of the magnetic field are associated with the deeper layers of the Earth's crust.

To divide the long and shortwave components of the amplitude spectrum of anomalies, geophysicists utilize numerical methods of field simulation at various altitudes (Magnetic Exploration, 1990). In Northeastern Eurasia the amplitudes of magnetic induction module ΔF_a for the anomalies of the lithosphere do not exceed 3000 nT, therefore, the methods for harmonic functions can be applied (Magnetic Exploration, 1990).

Martyshko and Prutkin (Martyshko and Prutkin, 2003) and Martyshko et al. (Martyshko et al., 2010a) suggested the following procedure of field transformation for separating the sources of gravity along the height. The initial stage involves solving the problem of separating the effects of the sources located between the surface and a certain depth H. The field is continued upwards to level H, due to which the effects of the local near surface sources (up to a depth H) are significantly suppressed if not eliminated altogether.

In order to get rid of the influence of the local sources located in the horizontal layer between the surface and depth H, the field, which was calculated to the height level above the initial surface, is then continued downwards to the depth H. At the final step of the procedure, the field is continued upwards again to the initial surface. The resulting field can be treated as the field of the sources that are located below the H level. Subtraction of this field from the observed one gives the field that is generated by the layer. By repeating this procedure for different heights and depths, we can separate the fields generated by the layers within the corresponding boundaries.

This technique of separating the gravity field was used for constructing the density model of the Earth's crust for the northern and middle segments of Ural region (Martyshko et al., 2010b; 2011) as well as for other regions of the Earth (Prutkin and Saleh, 2009; Prutkin et al., 2011). We used this method of upward and downward data continuation for the magnetic field and for highlighting the anomalies of different layers of the Earth's crust. The downward continuation procedure is an ill-posed problem, the regularization is applied. To select the regularization parameter, we used the results of the interpretation of the magnetic anomalies along the DSS profiles.

The studies of vast territories require handling extensive data, which makes the required calculations on the single-processor machines highly time-consuming. By applying the parallel algorithms for multiprocessor computing systems, the time of the calculations can be significantly reduced (Martyshko et al., 2012; 2014).

In this work we describe the mathematical apparatus and algorithms of parallel computations that were used for to design the computer technology, and present the results of applying this technology for the studies of the structural features in the magnetic field of the lithosphere in the northern sector of Eurasia.

Identification of anomalous magnetic field

In our calculations, we used the numerical models of the magnetic field that are based on the cartographical data (Ovcharenko, 1996). The information basis for the maps was the data of areal aero-geophysical and land based magnetic surveys of large, medium, and small scales performed from 1955 to 1980.

Investigation of large areas using magnetic surveys has that peculiarity the surveying period lasts several decades and the terrestrial magnetic field, obviously, changes during this time. Modern surveys imply measuring the modulus of the induction vector F. In order to distinguish the anomalous magnetic field ΔF_a produced by the sources within the lithosphere, we must exclude the planetary magnetic field, F_N (the so called main or normal field), and the effects from sources in the magnetosphere. The models of normal fields built on the basis of surface survey data contain significant errors of up to ±100 nT; this takes place due to the mentioned non-simultaneous survey over the whole area, due to the presence of many high-intensity anomalies caused by magnetized sources in the upper crust, and due to ignoring secular variations in the magnetic field. Magnetic surveys using satellites have allowed the pattern of the magnetic field distribution to be acquired and the centennial variations of the field to be specified over the whole globe, without «white spots». At present, knowledge about the spatial–temporal peculiarities of the terrestrial magnetic field has been significantly broadened, and the methods of spherical harmonic analysis have been well developed. This has allowed scientists to elaborate the international models of the main magnetic fields (International Geomagnetic Reference Field or briefly IGRF) for every 5 year interval using the unified technique (IAGA Division … , 1995).

In the framework of the Federal Program «Development of prognostic geophysical maps for the principal minerogenic zones of Russia», the territory of the Russian Federation has been being mapped with digital maps in the past decade. The information basis for the maps was the aerial, aero-geophysical and land based magnetic surveys data of large, medium, and small scales made from 1955 to 2004.

The geophysical data were processed using modern computer methods. In order to unify the survey data and unite it, observations on the reference airborne magnetic profiles were made and a Uralian mapping network was organized. The correction values of centennial variations in the geomagnetic field were calculated based on the IGRF. The data on the anomalous magnetic field for the whole territory are set with a spacing of 250 m. Resulting from these works, a digital model of the new map for the anomalous geomagnetic field ΔF in the Middle Uralian Region and its vicinity (East European Plain and West Siberia) was created in the segment bounded by 52°–64° N and 54°–66° E. Six sheets of 1:1 000 000 were produced as the result (P-40, P-41, O-40, O-41, N-40, N-41) with the corrections made based on the errors found on the normal level (Chursin et al., 2008) 54°-66° E 52°-64° N.

This newly obtained data were used to study of the anomalous magnetic field structure in the Middle Ural region. Maps of magnetic anomalies for different ranges of wave lengths, showing the distribution of magnetization in the layers of the Earth's crust of Southern, Middle and part of Northern Urals, were built (Martyshko et al., 2012).

We did not have the opportunity to conduct a modern aeromagnetic survey for the studied area of northern Eurasia to make corrections to the data and bring the level of the maps to the normal field model IGRF. While constructing fields of relativity during the aeromagnetic survey, the property of the circularity of the magnetic field induction lines is applied, therefore the following condition for given area S must be satisfied:

$$\oint \Delta F_a \partial s = 0.$$

Despite the large area of research (~900x1330 km), this condition is not satisfied, the average value of ΔF_a = 88 nT.

Two sheets (N-40, N-41) of the Northern Ural magnetic maps, are included in the data sets for the segment of northern Eurasia, as well as for the new map of the Middle Ural region. The comparison of data sets has showed that the differences are little in the range of 20–40 nT for sheet N-40, but significantly increased to 100–150 nT for sheet N-41. This is why we calculated a new relativity field and made amendments to the dataset of northern Eurasia.

The procedure of constructing such a relativity field has been described by Fedorova and Shapiro (Fedorova and Shapiro, 1998). In brief, it involved constructing a relativity field for region based on a 4th-order polynomial surface fitted to all the airborne survey data. After subtraction of this relativity field, an anomalous field is left which contains only those wavelengths less than about 800–1000 km.

Mathematical apparatus of the transformations

We introduce the rectangular Cartesian coordinates with axis Z pointing downwards and plane XOY coinciding with the surface of the observations. The upward continuation of the field measured on area

$$D = \{(x, y)\ \hat{\mathrm{I}}\ R^2 : a \le x \le b,\ c \le y \le d\}$$

of the Earth's surface $U(x,y,z)|_{z=0}$ to level $z = -H$ is calculated by Poisson formula:

$$U(x,y,-H) = \\ = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{-H}{\left[(x-x')^2+(y-y')^2+H^2\right]^{3/2}}\times \\ \times U(x',y',0)dx'dy'. \quad (1)$$

For recalculating the field downwards to depth $z = H$ and finding the values $U(x, y, -H)$, we solve Fredholm equation of the first kind:

$$Ku \equiv \frac{1}{2\pi}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\frac{2H}{\left[(x-x')^2+(y-y')^2+4H^2\right]^{3/2}}\times \\ \times U(x',y',H)dx'dy' = U(x,y,-H). \quad (2)$$

Solving the integral equation of the first kind (2) is an ill-posed problem, which requires application of the regularization methods. The operator of Eq. (2) is positive definite and self-adjoint; therefore we can apply the scheme of M.M. Lavrent'ev (Lavrent'ev, 1962).

After the grid discretization of equation (2) and approximation of the integral operator by the quadrature formulas, the problem is reduced to solving the system of linear algebraic equations (SLAEs) with the symmetric matrix K. In the regularized form, the system is

$$(K = \alpha I)u = U, \quad (3)$$

where I – is the identity matrix and α is the regularization parameter.

For solving the SLAEs we can apply the gradient type iterative methods, which include the following methods (Vasin and Eremin, 2005):

(1) the iteratively regularized simple iteration method

$$u^{k+1} = u^k - \frac{1}{\lambda_{\max}}\left[(K+\alpha I)u^k - \overline{U}\right], \quad (4)$$

where $\lambda_{\max}$ is the maximal eigenvalue of matrix $K + \alpha I$ (symmetric case);

(2) the minimal residual method

$$u^{k+1} = u^k - \frac{\left(K\left(Ku^k-\overline{U}\right), Ku^k-\overline{U}\right)}{\left\|K\left(Ku^k-\overline{U}\right)\right\|^2}\left(Ku^k-\overline{U}\right); \quad (5)$$

(3) the method of minimal error

$$u^{k+1} = u^k - \frac{\left\|Ku^k-\overline{U}\right\|^2}{\left\|K^T\left(Ku^k-\overline{U}\right)\right\|^2}K^T\left(Ku^k-\overline{U}\right); \quad (6)$$

(4) the method of steepest descent

$$u^{k+1} = u^k - \frac{\left\|K^T\left(Ku^k-\overline{U}\right)\right\|^2}{\left\|KK^T\left(Ku^k-\overline{U}\right)\right\|^2}K^T\left(Ku^k-\overline{U}\right). \quad (7)$$

We note that for methods (5)–(7) in the regularized form, matrix K is replaced by $K = \alpha I$.

The stopping criterion in the iterative processes (4)–(7) is the fulfillment of the condition

$$\frac{\left\|Ku^k-\overline{U}\right\|}{\left\|\overline{U}\right\|} < \varepsilon$$

with a sufficiently small ε.

For solving the SLAEs these methods are successfully applied on the multiprocessor computing systems of different types for the inversions of the gravity and magnetic field data, which reconstruct the boundaries between the layers and the density in the layer (Martyshko et al., 2010a).

Parallel algorithms

The parallel algorithms of the height transforms based on the gradient type iterative

methods have been designed and numerically implemented on Uran supercomputer at the Institute of Mathematics and Mechanics of the Ural Branch of the Russian Academy of Sciences.

The Uran supercomputer is a cluster of multiprocessor systems, each computing unit of which is based on two 4-core Intel Quad-Core Xeon processors with a speed of 3 GHz and a 16/32 Gb cache. Overall, 1664 computing cores and 3584 Gb cache memory are available to the user.

Parallelization of the gradient type iterative methods (4)–(7) (the stage of the downward continuation of the field) is based on the partition of matrix K by horizontal or vertical banding into m blocks and partition of the solution vector u and the vector of the right hand side of the SLAEs, into m parts so that $n = m \times L$, where n is the dimension of the system of equations, m is the number of the processors, and L is the number of the rows or columns in the block.

On the current iteration, each of the m processors computes its part of the solution vector. In the case of multiplication of matrix K on vector u, each of the m processors multiplies its part of the rows of matrix K on vector u. The host (leading) processor is responsible for transferring the data; it also computes its part of the solution vector.

At the stage of the upward continuation of the field, the parallel algorithm of matrix multiplication by a vector is applied for computing integral operator (1).

The codes that implement the parallel algorithms of multi-height transformations on the «Uran» super-computer are written in Fortran using the MVAPICH2 (MPI) library.

We note that for solving the problem by the double-precision iterative methods on the Uran supercomputer, significant memory is required for storing matrix K. For the 300x300 grid, the number of the elements of matrix K takes 60.3 Gb, while the code-run system on the Uran cluster normally allocates at most 2 Gb for each separate process of the MPI program.

Therefore, matrix K is preliminarily divided by the vertical bands into blocks and is stored in the memory of each processor by parts. Thus, considering the memory constraints, at least 50 Uran processors are required to solve our problem.

The computational experiments show that for large data volumes, paralleling the algorithms significantly reduces the time of the computations (Martyshko et al., 2014).

Selecting the regularization parameter

The downward continuation procedure is an ill-posed problem so the regularization is applied. For selecting the regularization parameter α, we used the results of the interpretation of the magnetic anomalies by the two-dimensional method (Tsirul'skii et al., 1980). The deep structure of the Ural region was studied along the geotraverses and DSS (deep seismic sounding) profiles (Fedorova, 2001; Martyshko et al., 2010b; Shapiro et al., 1997), part of which fall in the considered territory (Fedorova and Kolmogorova, 2013).

Fig. 2 (color tab) shows the construction of geophysical models based on the fragment of the geotraverse Rubin-1. A model of the magnetization distribution in the Earth's crust was build based on the results of the interpretation of the magnetic field (Fig. 2b, color tab). The velocity distribution of longitudinal waves (Fig. 2c, color tab) was constructed based on the seismic sounding data (Fedorova and Kolmogorova, 2013).

As a result of the approximation of the magnetic fields, we obtained the distribution of the anomalous sources in the crustal layers (Fig. 2b, see color tab). Local anomalies sources are located in the upper crust layer with the depth up to 20 km. Depth of the local anomalies sources exceed 5 km.

Seismic studies results were taken into account during modeling of sources which create long continuous anomalies. On the seismic section it can be seen that in the Eastern part of profile the high-velocity layer (with longitudinal waves velocities above 6.5–6.6 km/s) is located on the depth of 12–15 km, but the same layer is located deeper (20–25 km) in the Western part of profile (Fig. 2c, color tab).

Petro-magnetic research has shown that the formations of upper mantle have low mag-

netic features and lower boundary of magnetized lithosphere rocks can match with the Mohorovicic discontinuity between crust and mantle (Petromagnetic, 1994). On the seismic section of Rubin-1 profile the Mohorovicic discontinuity has a flat relief and is located on the depth of 38–42 km. It seems that the Mohorovicic discontinuity relief does not introduce significant affect into magnetic field. Therefore for the regional magnetic sources the inverse problem was solved for the magnetic layer contact surface boundary in the lower crust. Boundary of this layer was calculated with following parameters: average depth of 20 km, magnetization of 3 A/m (Fig. 2b, see color tab). The bottom of the layer is limited with horizontal plane at 40 km (Fedorova and Kolmogorova, 2013).

This result allowed us to compare the anomalies from the model sources with the computed transformations of the magnetic fields for the set of the values of the regularization parameter and select the value of α for the further computations by the criterion of the best fit of the graphs of the fields.

Due to the depths of the model sources located deeper that 5 km on the section (Fig. 2b, see color tab), such value of height was chosen for the test calculations. According to the proposed field transformation technique for local sources for separation by depth of occurrence, the magnetic field was recalculated upward to the height of 5 km, and then was analytically continued downward to depth of 5 km, and then recalculated up to the Earth surface again.

Graphs of obtained values for the transformed field for parameters $\alpha = 0.01$ and $\alpha = 0.1$ are presented on Fig. 3a (color tab). Graphs for $\alpha = 0.01$ are shown with solid line, and for $\alpha = 0.1$ with dash line. Results show that graphs of anomaly and calculated fields have good match with $\alpha = 0.01$, but have significant differences when $\alpha = 0.1$.

The same calculations were performed for $H = 10$, 20, 30, 40 and 50 km. For the bigger values of $H = 40$ and 50 km graphs have only non-significant differences when $\alpha = 0.01$ and $\alpha = 0.1$. For the height $H = 40$ km calculation results are shown on Fig. 3a (see color tab). Based on the above, we selected regularization parameter $\alpha = 0.01$ for further calculations.

In the bottom part of Fig. 3b (color tab) results are shown for the magnetic field being analytically continued downward to the depth of 50 km. Isolines of the magnetic anomalies are drawn with 50 nT step and values of local maximums are shown with dots. Positions of these maximum values coincide with upper edges of some of the model sources (Fig. 2b, see color tab).

It should be noticed that, generally, analytical continuation downward from the Earth surface level (without additional upward recalculations) can be done only until topmost singular point of the field.

The results of the computations for the sector of Northern Eurasia

The anomalous magnetic field within the northern segment of Eurasia is shown in Fig. 4 (color tab).

This map is superimposed on the tectonic scheme of the region. With the use of the computer technology developed, the maps of the regional and local anomalies of the magnetic field are constructed for this region.

We used the computed data on the magnetic field at $H = 5$ km and $H = 20$ km for constructing the maps of local anomalies in the upper lithosphere. The highest frequency part of the anomalous magnetic field is illustrated in Fig. 5 (color tab). The sources of these anomalies are located in the upper layer of the Earth's crust up to a depth of 5 km. The map (Fig. 6, color tab) shows the magnetic anomalies whose sources are located in the upper layer of the Earth's crust with the depths of 5 to 20 km. These maps are constructed by calculating the difference between the initial anomalous field $\Delta F(0)$ and the transforms $\Delta F(5)$, obtained by the continuation of the field $\Delta F(0)$ to the depths $H = 5$ km and the difference between $\Delta F(5)$ and $\Delta F(20)$, respectively.

In the geophysical practice, the local magnetic anomalies within the unexposed territories are efficiently used for determining the depths of the crystalline basement. By analyzing the distributions of local anomalies

one can reveal the faults in the crust, identify the magmatic intrusions, etc.

Results of a modeling along the DSS profiles show that long-wavelength magnetic anomalies can be created by the lower crust layer terrain changes, the magnetization of which significantly exceeds the magnetization of upper layers (Fedorova and Kolmogorova, 2013).

With recalculation in the upward direction to a given height (of 50–100 km), the intensity of magnetic anomalies from the sources with large horizontal sizes (more than 30 km) decreases significantly slower than from the local sources with small dimensions. Therefore in order to choose the recalculation parameter for the selection of regional anomalies of the lower crust, a comparison was performed for such anomalies obtained during field transformations for different heights, selected with approximation modeling technique along the DSS profiles. In result a height of 40 km was selected.

For the part of Rubin-1geotraverse a profile graph of long-wavelength anomaly created by lower magnetized layer of Earth crust is presented on Fig. 2a (see color tab) and the graph of upward and downward continuation with H = 40 km is shown on Fig. 3a (see color tab).

The Fig. 7 (color tab) presents the map of the regional component obtained by the upward continuation of the field to a height of 40 km and its subsequent recalculation back to the zero level.

Discussion and conclusions

Parallel algorithms are developed for solving the problems of the height transformation of the magnetic field to different levels, which makes it possible to separate the anomalies in the different intervals of the wavelengths. The maps of the regional and local anomalies of the magnetic field are constructed for the northeastern segment of Eurasia.

It can be seen that the maps of local anomalies (Figs. 5, 6, see color tab) most distinctly reflect the belts of ultrabasic and basic intrusions and other signs of magmatic and tectonic activity in the region.

These maps clearly show that upper crust rocks of TPP as well as Western UFB have low magnetic properties, especially in the upper layer till the depth of 5 km.

For the map of the layer located from depth 5 to 20 km in the EEP territory, magnetic anomalies chains extend along the TPP boundary. Some of the anomalies cross the boundary and a part of them is located inside neighboring TPP. This shows that at the depths more than 5 km the EEP boundary moves to the North-East relative to the border shown on the surface formations tectonic map. On the Eastern TPP edge (Fig. 6, see color tab) anomalies continue fairly far to the East from UFB boundary and few of them reach the middle of the Ural Fold. This undoubtedly shows a thrust fault from the Eastern Uralides onto TPP structures. The same conclusions can be drawn based on regional magnetic anomalies distribution. In future these maps will allow refining of the tectonic schemes of region lithosphere at different depths.

Intensity of the regional magnetic anomalies varies from -250 to +250 nT (Fig. 7, see color tab). The most noticeable feature on the regional field map is the big negative anomaly. Transverse dimension of this anomaly reaches 350 km with intensity reach of -250 nT. This anomaly captures almost half of the TPP territory.

In the Southern part of the region, negative Timan-Pechora anomaly merges with the chain of negative anomalies spread across the Urals. Regardless of the fact that within the boundaries of Ural Mountains the crystalline rocks located near Earth surface create intensive positive local anomalies, the low-periodic part of magnetic field consists of negative anomalies.

Urals mountains extend over more than 2300 km and are divided into South, Middle, North, Nether-Polar and Polar sectors. Previously negative regional anomalies were found in the areas of South, Middle and North Urals (Martyshko et al., 2012). In this work regional negative anomalies of the magnetic field of the lithosphere were found in the Nether-Polar and Polar Ural Mountains region.

Positive regional anomalies are observed in the Eastern part of TPP, besides that the most intensive anomaly continues from North to South and partially covers the Western edge of Nether-Polar Urals. Chains of positive anomalies are observed along the edge of EEP and on the territory of WSP.

For the Timan-Pechora regional negative magnetic anomaly an interpretation was made and initial 3D model of lower layer of the Earth crust was constructed for the case of vertical direction of magnetization vector (Fedorova et al., 2013).

In the future, the results of field separation can be used for constructing the volumetric models of the Earth's crust for the northern part of Eurasia.

Acknowledgments

The work was supported by the Russian Scientific Foundation. Study and analysis of the anomalous magnetic field structure of the northern segment of Eurasia were are carried out under project no. 14-27-00059 «3D models of Urals region Nether-Polar zone deep structure construction based on new geophysical fields complex interpretation methods and modern computer grid modeling technologies».

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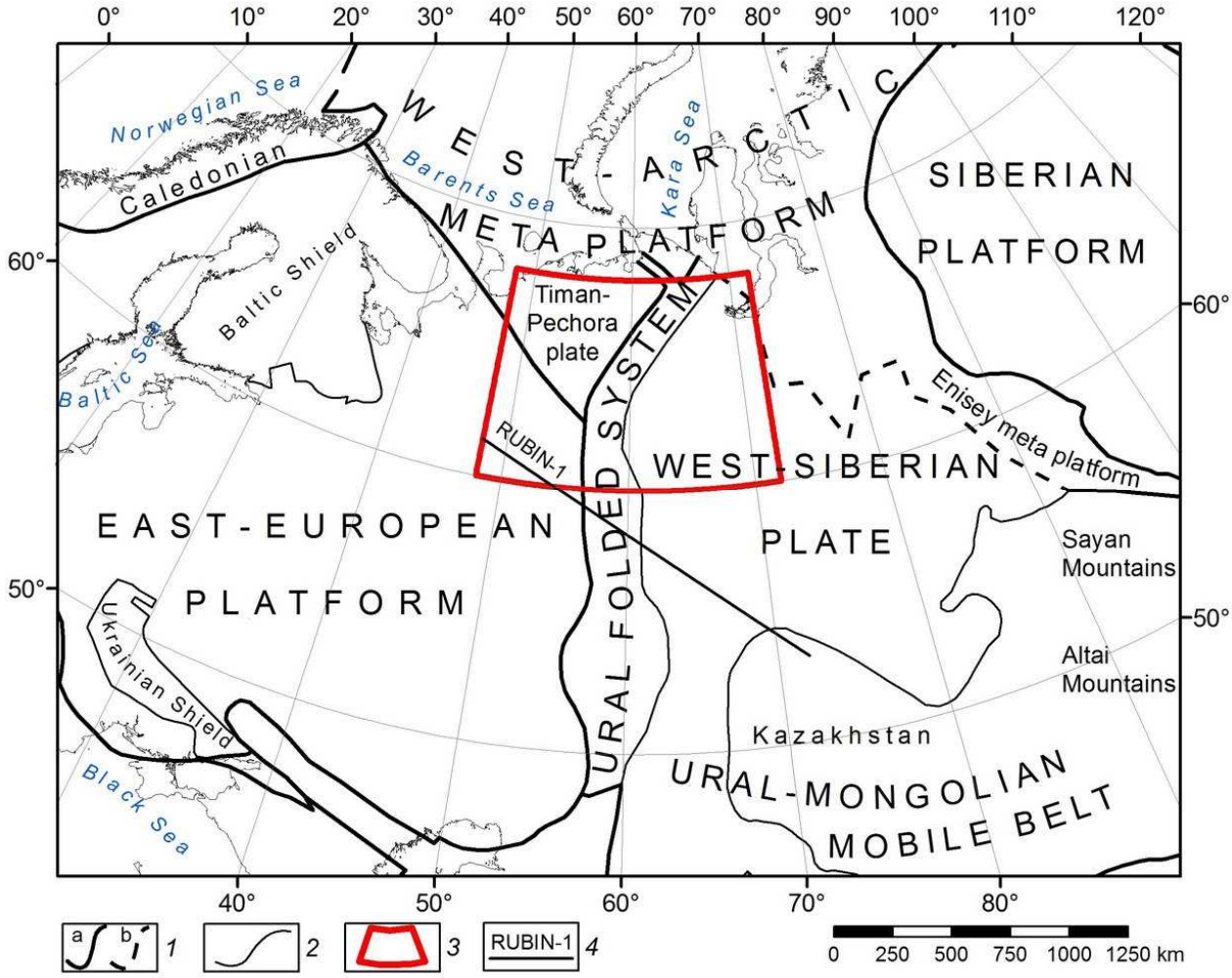

Fig. 1. The tectonic map northern Eurasia (Milanovsky, 2006):
1 – borders of ancient platforms, meta platforms and mobile belts (a), the same less reliable under a cover (b); 2 – borders of tectonic structures in there limits; 3 – contour of the territory of researches; 4 – DDS profile Rubin-1

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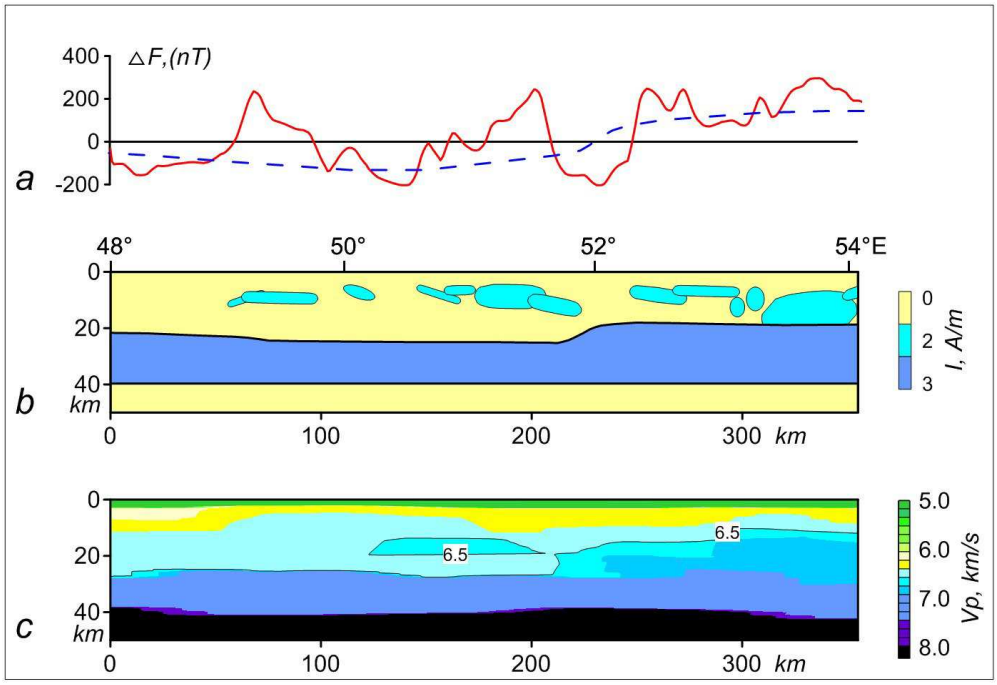

Fig. 2. Rubin-1 profile fragment:
a) graphs of magnetic field (solid line) and model field of lower layer (dashed line); b) magnetic model of magnetization distribution; c) seismic model of longitudinal waves velocities

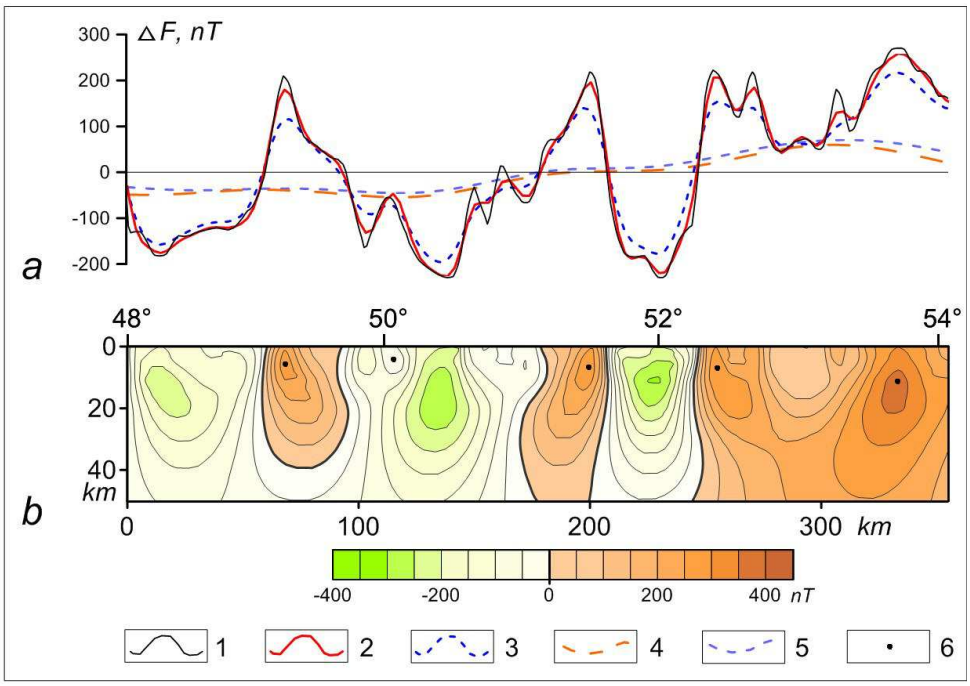

Fig. 3. Result of magnetic field upward and downward continuation along the Rubin-1 profile:
a) Magnetic anomalies graphs; b) field, continued downwards to 50 km (isolines step is 50 nT).
1 – observed field; 2–4 calculated on the Earth level magnetic anomalies for transformation parameters:
2 – H = 5 km и α = 0.01, 3 – H = 5 km и α = 0.1, 4 – H = 40 km и α = 0.01; 5 – H = 40 km и α = 0.1;
6 – local maximums of continued downward field

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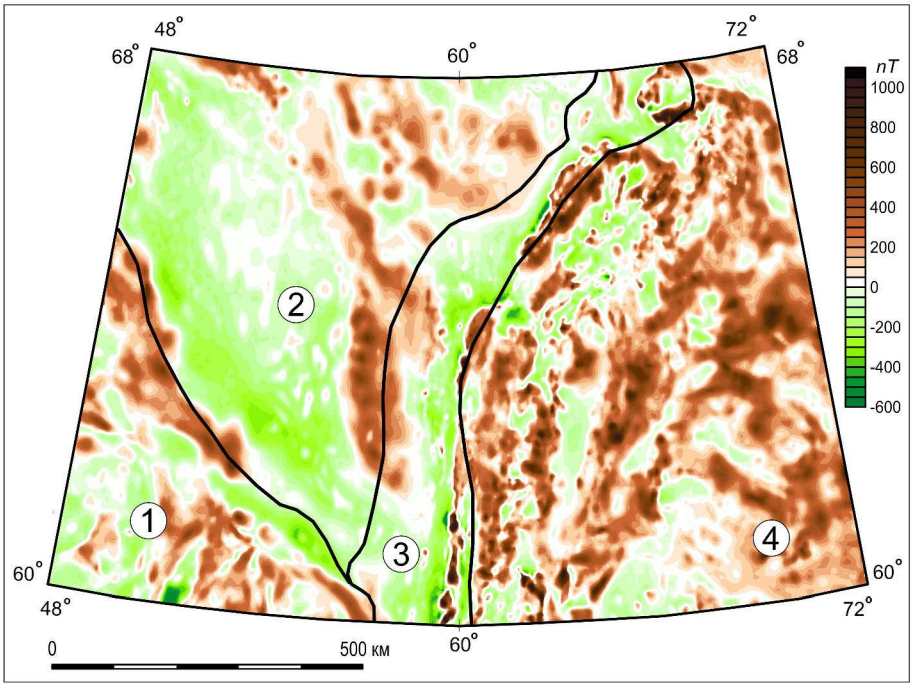

Fig. 4. The map of the magnetic field over the northern sector of Eurasia. The lines depict the boundaries of the main tectonic structures of the region:
1 – East European Platform; 2 – Timan–Pechora Plate; 3 – Ural folded system; 4 – West-Siberian Plate

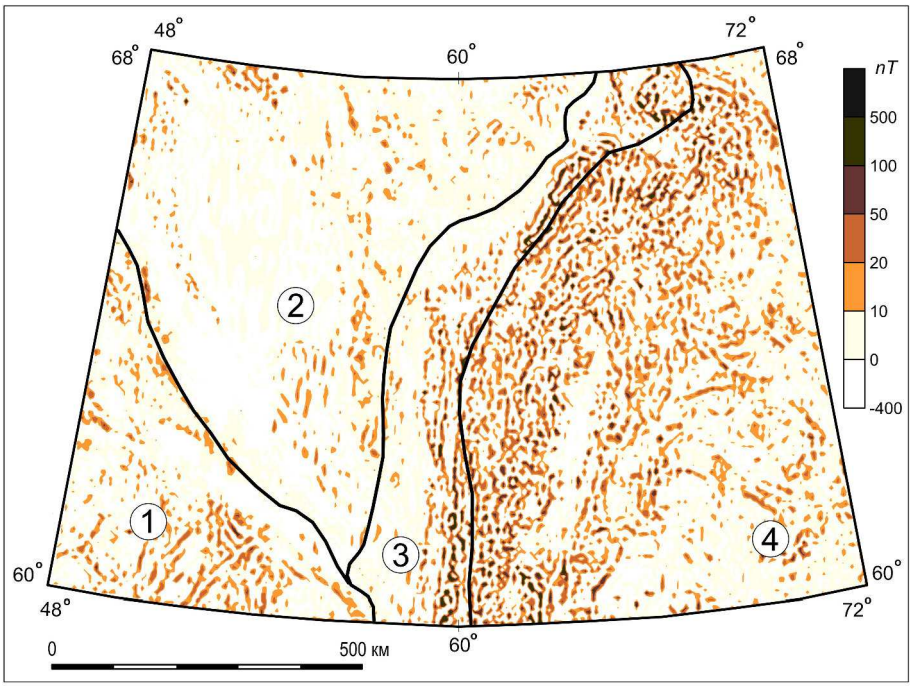

Fig. 5. The map of the local anomalies whose sources are located in the upper layer of the Earth's crust up to a depth 5 km: 1–4 see Fig. 4

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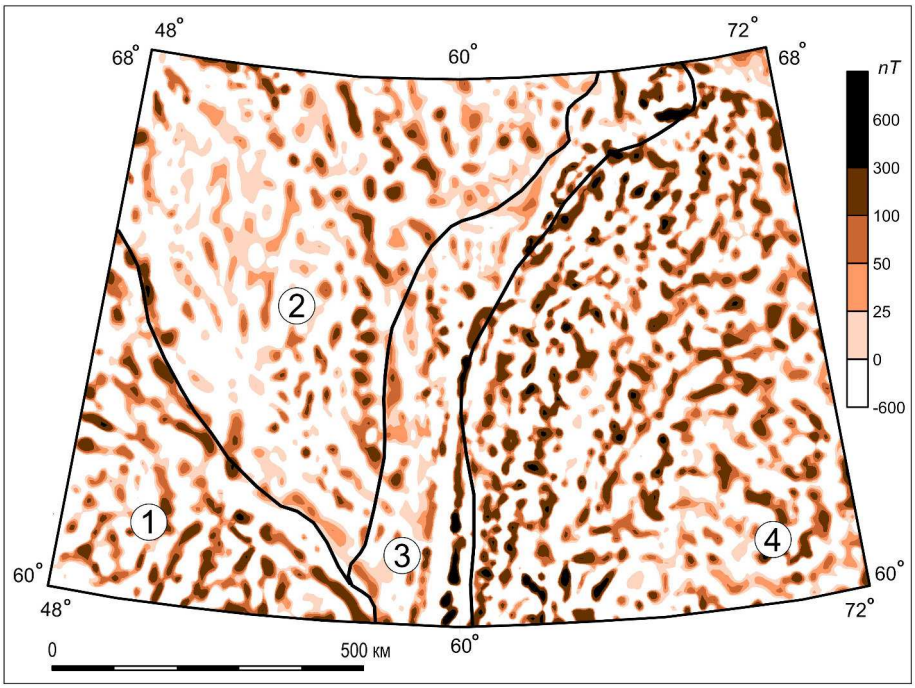

Fig. 6. The map of the local anomalies and whose sources are located in the upper layer of the Earth's crust up to a depth from 5 to 20 km: 1–4 see Fig. 4

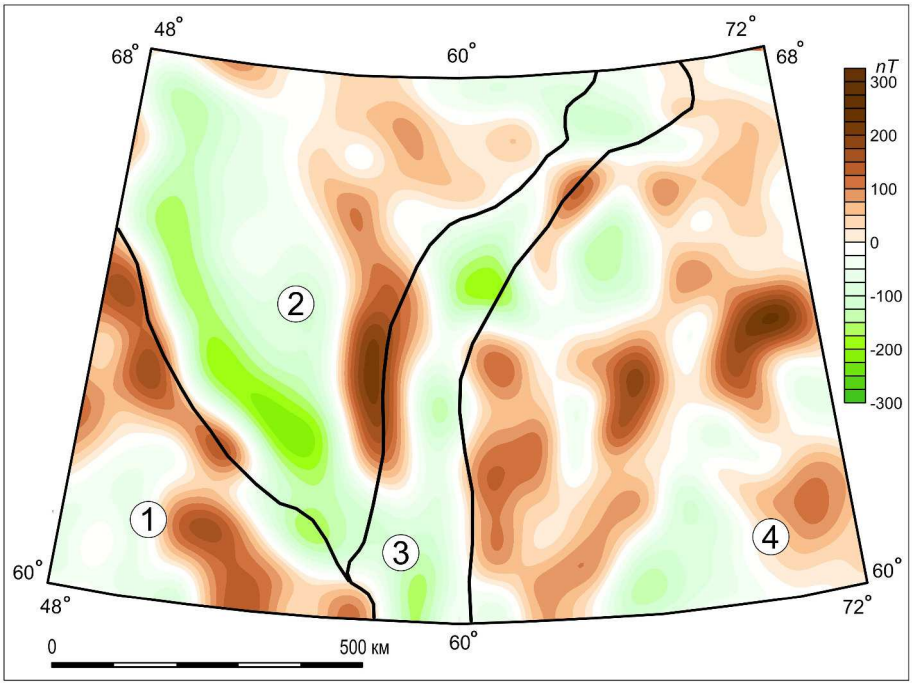

Fig. 7. The map of the regional magnetic anomalies over the northern sector of Eurasia: 1–4 see Fig. 4