GEOPHYSICS

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ANISOTROPIC TRANSFORMATIONS OF REGIONAL GRAVI-MAGNETIC FIELDS OF THE UKRAINIAN SOUTHEAST CARPATHIANS

The aim of the research presented in this article is to analyze the properties and geological informative value of the anisotropic transformations of gravitational and magnetic fields, which use averaging procedures, including analysis of Andreev–Klushin's method. Anisotropic transformations of potential fields are designed to detect and track elongated anomalies or their chains, caused by deep linear dislocations in the geological section. The study of the anisotropic transformations properties is based on the analysis of their depth characteristics, as well as theoretical and practical experiments. The study applies the analysis method of fault tectonics reflection features in anisotropic anomalies of gravimagnetic fields, in particular, on the example of the South-East of the Ukrainian Carpathians. It is based on the search of morphological signs of manifestation of deep faults and other long structural-tectonic dislocations in gravitational and magnetic anisotropic anomalies. The method also suggests tracing these elements, relying on the comparison of morphology, intensity, size and direction of anisotropic anomalies with published regional tectonic and geological maps. Results. The paper presents definitions and algorithms of such anisotropic transformations as Andreev–Klushin's methods of anticlinal and terrace types, anisotropic averaging and anisotropic difference averaging. The research allowed us to perform study of the geological informative value of anisotropic transformations of potential fields on theoretical and practical examples. It is shown that in the morphology of anisotropic gravitational and magnetic anomalous fields in the south-east of the Ukrainian Carpathians long local anomalies are traced. They are caused by fault tectonics, in particular deep longitudinal and transverse faults, as well as linear complications into sedimentary cover. The analysis of anisotropic anomalous fields reveals a number of characteristic features of large tectonic zones reflecting regional behavior of the foundation surface and deep faults; on its basis fault tectonics schemes of the South-Eastern region of the Ukrainian Carpathians can be constructed. The study traced a significant extension of the foundation of the Eastern European platform from the Maidan's ledge and the Pokutsko-Bukovynian Carpathians under the Folded Carpathians. The definition of a number of anisotropic transformations is given and their properties are considered. The work substantiated geological informative value of the anisotropic transformations morphology of potential fields in the study of the Ukrainian Carpathians and adjacent depressions fault tectonics. The use of anisotropic transformations of potential fields will increase the reliability and detail of tracing deep faults, as well as other linear dislocations both in the foundation and in the sedimentary cover. The study of fault tectonics is an important factor in the successful solution of problems in the search and exploration of areas which are promising for oil and gas deposits.

Key words: Precarpathian Depression; fault tectonics; linear dislocations; transformation of gravity and magnetic fields; anisotropic averaging; deep characteristics of transformations; anisotropic anomalies.

Introduction

Qualitative interpretation of gravimagnetic anomalous fields is based on visual analysis of morphology, intensity, extension direction of groups of anomalies (anomalous zones), selected from the observed potential fields on certain grounds. The separation of certain parameters from the observed field of anomalies is performed by transformations. Types of transformations depend on geological problems. Interpretation is aimed at determining the geological and tectonic nature of individual anomalies or anomalous zones that differ in morphological features. Also, interpretations are performed to estimate the integral parameters of their geological and tectonic sources. Some positive results in the use of transformations of gravity-magnetic fields have been achieved in studies of oil and gas regions [Demidova, & Kalamkarov, 1978], basement fault systems and in the creation of a rotational hypothesis of structure formation

[Tiapkin, et al, 2000]. Examples of effective geological interpretation of gravimagnetic fields of the Ukrainian part of the Carpathian region are presented in [Mayevskiy, et al, 2012; Monchak, & Anikeyev, 2017; Anikeyev, et al, 2019]. Highly relevant tasks include clarification, detection and tracing of deep faults, systems of longitudinal and transverse faults, and other subordinate linear dislocations of different nature. They are connected with the experience of studying the regional tectonic structure and assessing the prospects of some areas for oil and gas deposits.

Differences in the nature of the display of the regional deep geological and tectonic structure in magnetic and gravitational anomalous fields are due to the specifics of their sources. Anomalous magnetic field significantly depends on the content of ferromagnetic minerals, which is much higher in the rocks of the crystalline basement. Therefore, the magnetic field is more sensitive (compared to the gravitational field) to the nature of the basement surface than to the structural construction of the sedimentary cover. Therefore, the magnetic field is more sensitive (compared to the gravitational field) to the nature of the foundation surface than to the structural construction of the sedimentary cover. However, the same morphological feature of the manifestation of deep linear dislocations in gravitational and magnetic fields are significantly elongated (linear) anomalies or anomalous zones. Anisotropic transformations are a tool in the study of fault tectonics. According to the B. A. Andreev and I. G. Klushin's definition, they are designed to identify and trace linearly elongated in a certain direction anomalous disturbances in gravimagnetic fields [Andreev, & Klushin, 1962]. For example, on the basis of the analysis of anisotropic transformations within the Caspian basin narrow long bands of the gravity field were traced and a lineament scheme was drawn up [Matusevych, 2013].

The purpose

The purpose of the work is to develop methods for the transformation of gravitational and magnetic fields based on anisotropic averaging procedures, the result of which depends on the chosen direction. The work is also devoted to evaluating the informative value of the experimental application of anisotropic transformations on the materials of the south-east of the Ukrainian Carpathians.

In his articles, V. M. Strakhov emphasized the need for active use and further development of the theory and practice of linear transformations [Strakhov, 1995].

Source materials

The initial theoretical materials of the work are the ideas of anisotropic transformation of potential fields, presented by B. A. Andreev, I. G. Klushin in [Andreev, & Klushin, 1962]. They are based on averaging procedures, theoretically substantiated by A. N. Tikhonov and Yu. D. Boulanger [Tikhonov, & Boulanger, 1945].

The tectonic map [Tektonicheskaya karta ..., 1986] (Fig. 1), gravitational and magnetic fields [Scheme ..., 2002, Karta ..., 2002] (Figs. 2, 3) have been used as the initial geological and geophysical materials. Observation matrices of gravitational and magnetic fields are presented with a step of 500 m (scale 1:50.000) with an accuracy of plotting maps of 0.25 mgl and 2 nT. This allows detailed study of the complex morphology of regional anomalous gravitational and magnetic fields.

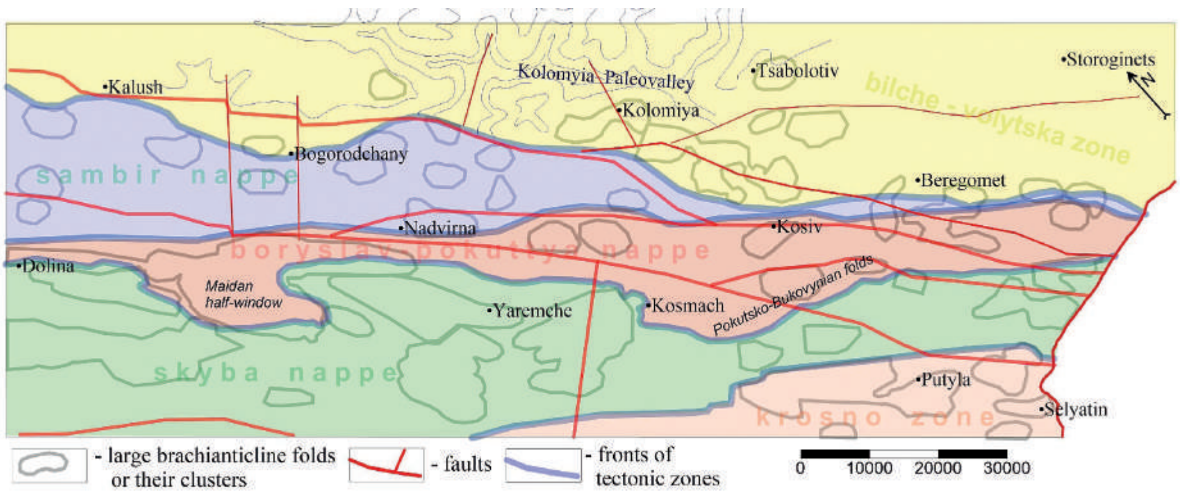

Fig. 1. Tectonics of the south-east of the Ukrainian Carpathians
(fragment of the map of V. V. Glushko, S. S. Kruglov et al. [Tectonic map…, 1986])

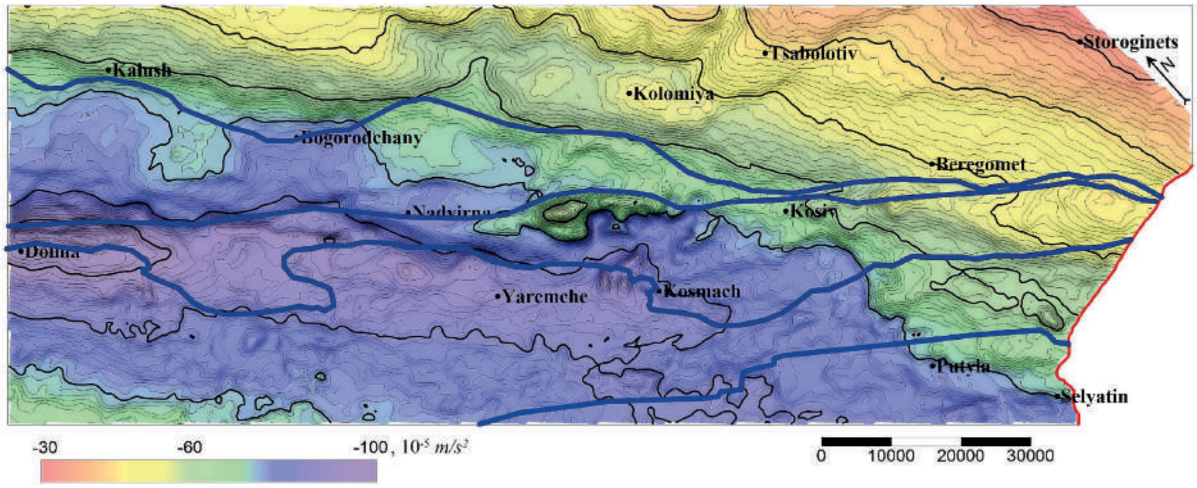

Fig. 2. The Bouguer gravity anomalies with elements of tectonics of the South-east of the Ukrainian Carpathians

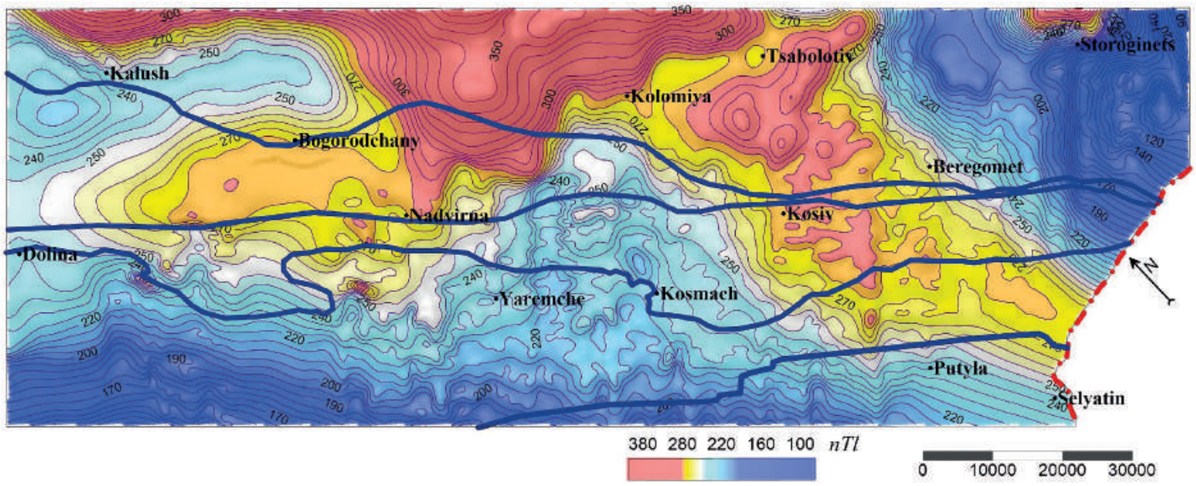

Fig. 3. The magnetic field anomalies with elements of tectonics of the South-east of the Ukrainian Carpathians

Briefly about the method of applying transformations

The method of qualitative interpretation of gravitational and magnetic fields is based on comparing the features of the distribution of their anomalous components with geological and tectonic materials.

Qualitative interpretation is an important part of geological interpretation. It is aimed at studying the nature of anomalies of fields or their groups, united by location or certain morphological features, and at building schemes of the regional tectonic structure. Methods of transformation are the tools of qualitative interpretation.

Confidence level of solving geological problems depends on the possibility of analyzing anomalies of the expected nature. Geological problems are defined in the application of transformations. According to formal positions, these are tasks of highlighting or enhancing certain local features of the field. That is why one should give preference to transformations with known features. The content and parameters of transformations can be estimated by their depth characteristic, which provides a qualitative relationship between the degree of attenuation (or enhancement) of anomalies and the relative depth of their sources ([Andreev, & Klushin, 1962], etc.). So, in the practice of applying gravity field averaging transformations, the radius of the transformation window R should be greater than or approximately equal to the depth of research:

$$R > h. \qquad (1)$$

A decrease in the intensity of local anomalies by 60 % (not less) that is achieved at $\varepsilon \le 0.6$ (Fig. 4) is considered to be a sufficient attenuation. The averaged field is taken as a regional background (regional component), which means low-frequency anomalies, whose sources are located deeper than the selected depth h. The difference between the observed and the averaged field is the field of local anomalies. They are caused by sources located mainly at depths $h < R$.

The closer the shape of geological objects (sources of anomalies) to isometric is, the more reliable the condition (1) is.

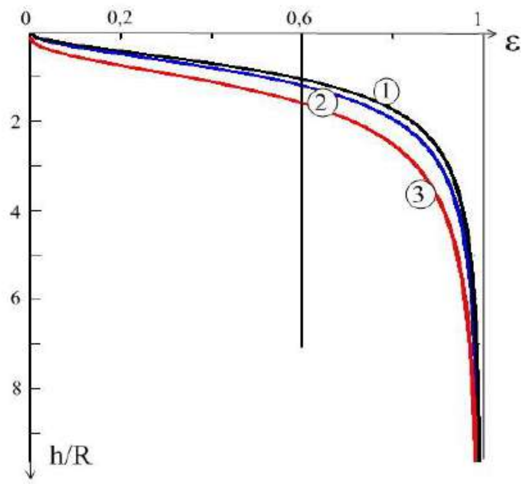

Fig. 4. The relative depth characteristics of the transformation of the averaging of the gravitational field Δg (1), the modulus of the total vector ΔT (2) and the vertical component ΔZ (3) of the magnetic field [Anikeyev, Maksymchuk, 2019]

Symbols: R – radius of the transformation window; h – the depth of anomalies sources; ε – the degree of attenuation of the intensity of the local anomalies

Comparison of the depth characteristics makes it possible to estimate the dependence of the depth intervals of the probable occurrence of the sources of localized anomalies on the parameters of the transformation windows. From a comparison of the transformations depth characteristics of the gravitational and magnetic fields averaging (Fig. 4) it follows that the condition is different for a sufficient attenuation of the magnetic field anomalies ΔT, ΔZ:

$$h \leq (1.2 \div 1.5) \cdot R. \quad (2)$$

Comparison (1) and (2) makes it possible to estimate the depth ratio of sources of gravitational and magnetic anomalies, which have the same size and are selected with averaging transformations of identical parameters in the observed fields. According to these data, the sources of magnetic anomalies are located at depths (1.2÷1.4)·h, where h is the depth of the sources of gravitational anomalies.

Obviously, the difference between two local fields, defined by different radii of the averaging window $R2$ i $R1$ ($R2>R1$), is a group of difference local anomalies caused by sources, mainly located in the depth band $R1 \div R2$. To obtain the field of difference anomalies, it is easier to take the difference: averaging from $R1$ minus averaging from $R2$. Transformation of difference averaging is intended for localization of a group of anomalies, caused mainly by a certain band of depths of a geological section [Anikeyev, 2009]. It is a combined Saxov – Nygaard type transformation (but nonnormalized), i.e. it is a bandpass filter (Figs. 1B, 2B). The depth characteristics of the difference averaging are given below.

[Mayevsky, et al., 2012; Anikeev, Maksimchuk, 2019] give the list of morphological signs of the display of structural forms and linear dislocations of the geological section in the fields of isotropic local anomalies, presented in the form of the distribution of isolines or in the relief-shadow image.

Anisotropic transformations

The use of transformations in which the window of transformation of potential fields is a circle (or square) is common in practice. The result of such transformations is independent of direction. In addition to “isotropic” transformations, “anisotropic” transformations can also be of practical importance. “Anisotropic” transformations are sensitive to anomalous forms that correlate in a certain direction. Their difference is an elongated window: a rectangle or an ellipse. The variegated morphology of the geophysical field is due to the complex structure of the geological section. Against this background, “anisotropic” transformations are capable to distinguish striped, elongated anomalies or chains of anomalies caused by linear dislocations [Klushin, & Tolstikhin, 1961] (tectonic disturbances, thrusts, faults), which are often associated with mineral deposits. Characteristic features of linear dislocations in gravimagnetic fields are [Andreev, & Klushin, 1962]:

1) significant length of anomalies which significantly exceeds their transverse dimensions;

2) more or less constant extension within the study area;

3) the correlation of linear anomalies, which are caused by long dislocations, is a sharply anisotropic value.

The background part of the field, which prevents the visual tracking of anomalies of linear dislocations, contains components with different correlations. These can be sharp anomalies that form a complex “mosaic” pattern, and smooth changes in the field, characterized by different extensions. The anisotropic transformation should be averaged or converted to height for attenuating “mosaic” anomalies. And the transformation should be differentiated to emphasize changes in the field in areas of linear dislocations.

Synchronized implementation of such actions is provided by a combined window (Fig. 5).

The window (“palette”) consists of densely spaced highly elongated five ellipses (in the original version of B. A. Andreev and I. G. Klushin – four rectangles). Fig. 5 shows a window of five ellipses with an angle of inclination (between the x – axis and the direction of the short axes of the ellipses) $\gamma = 0^0$. The main axis of the palette is perpendicular to the line of short axes of ellipses (the dashed line shows the options for its direction – the window rotation is provided, for example, every 45°).

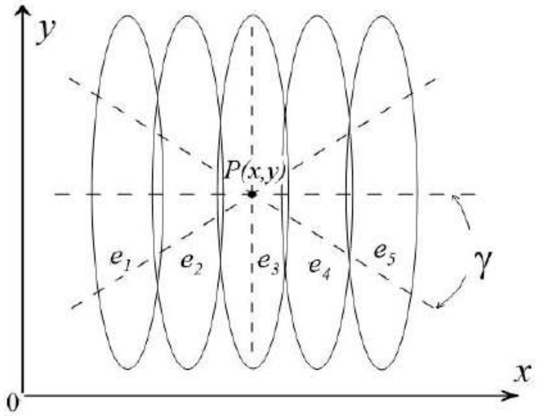

Fig. 5. General view of the anisotropic transformation window of Andreev – Klushin in the variant of ellipses combination

The algorithm for applying the window is standard: on the geophysical field map, the center of the palette is aligned with the picket P (x, y), to which the result of calculations will be assigned. The average value of the anomalous field is determined within each of the ellipses. These averages are used to calculate the following differences:

$$\Delta_1(x,y) = \frac{2}{3}(\overline{U_2} + \overline{U_3} + \overline{U_4}) - \overline{U_1} - \overline{U_5} \quad (3)$$

$$\Delta_2(x,y) = \overline{U_1} + \overline{U_2} - \overline{U_4} - \overline{U_5} \quad (4)$$

In the direction of the main axis there will be the greatest sensitivity both to long anomalies, and to changes of their extension. Conversely, anomalies that are perpendicular to the main axis will be weakened as much as possible.

The maximum values of the transformed field according to formula (3) will be where there are linear dislocations. Their cross section has the form of a relatively symmetrical maximum (minimum), such as the anticlinal fold arch. If the calculations give negative minimum values, we have the case of a relatively symmetric minimum of the syncline type. In the transformed field according to formula (4), the maximum values will indicate the presence of asymmetric linear dislocations – faults, thrusts, etc., which in the original field are reflected by anomalies such as "steps".

Small variations that are smaller than the length of the main axis of the palette will be reduced by averaging. Smooth field changes, which are larger than the size of the palette, characterize the general regional background and after calculating the differences, will give small or zero values. The same result will be obtained in the case when the main axis of the window is directed approximately perpendicular to the main strike of the linear dislocations.

B. A. Andreev and I. G. Klushin proposed to sequentially change the direction of the palette axis at each of the calculated points and, depending on the size of the differences Δ_1 and Δ_2 (3, 4), establish the extension of the required linear dislocations.

It is possible to restrict oneself to certain positions of the window, if the extension is known from independent data. This greatly speeds up the realization of transformations. Note that under the conditions of the Ukrainian Carpathians, in general, the extension of longitudinal and transverse dislocations is already known. Therefore, in a practical example, which will be given below, we have chosen only two directions of the main axis of anisotropic transformations: northwest and northeast.

Consider the properties of anisotropic transformations in the version of their simplest implementations: anisotropic averaging and difference averaging, the windows of which are shown in Fig. 6.

Anisotropic averaging is performed using a window consisting of a single ellipse (Fig. 6, a). There will be significant averaging along the major axis of the ellipse, so long anomalies or chains of anomalies along the axis will be emphasized, and regional (larger than the major axis of the ellipse) anomalies will remain virtually unchanged. If we determine the difference between the observed field and anisotropic averaging, these anomalies will be removed (or suppressed) from the field. The differences between the observed field and anisotropic transformations or between anisotropic transformations are called anisotropic anomalies.

Transformations of difference anisotropic averaging, which result in difference anisotropic anomalies, are constructed in two versions:

1) the difference between the two averages: averaging with a small ellipse minus averaging with a large ellipse (Fig. 6, b);

2) the difference of two averages with the same ellipse windows, but in different directions:

$$\Delta \overline{g}_{WE} = \overline{g}_W - \overline{g}_E\,; \quad (5)$$

their major axes have a northwestern and northeastern direction; the angle between them is 90^0 (Fig. 6, c).

By the difference anisotropic transformation of the first type we will have a result similar to the difference between the observed field and the anisotropic averaging, just with the smoothing action effect of the upper part of the section. The next section provides considerations for estimating the conditional depth of the division of the section into upper and lower parts (or the maximum possible depth of the isolated anomalies sources).

Difference anisotropic transformation of the second type weakens regional and elongated anomalies. Their direction differs from the one of the ellipses' major axis. It also significantly suppresses small anomalies, whose dimensions are smaller than the minor axis of the ellipses. So, in the field of anisotropic anomalies, it will be predominantly anomalies whose strike coincides with the direction of the ellipses' major axes. Also, isometric anomalies as well as elongated and linear anomalies will be weakened more. Their strike coincides with the symmetry axes of the difference averaging window (A-A, B-B), called the "butterfly window" (Fig. 6, c). In accordance with the selected example of the location of ellipses in the butterfly window, the field of difference anomalies will contain mainly anomalies of the northwest and northeast directions.

Return to the transformation of Andreev – Klushin. Algorithms of transformations (3) and (4) for the case $\gamma = 0^0$ (Fig. 5) can be rewritten as follows:

$$\Delta_1 = \Delta\overline{g}_{Ant}(x,y)_{\gamma=0} = \frac{2}{3}[\overline{g}_{e2}(x-\Delta x,y)+\overline{g}_{e3}(x,y) + \overline{g}_{e4}(x+\Delta x,y)] - \overline{g}_{e1}(x-2\Delta x,y) - \overline{g}_{e5}(x+2\Delta x,y) \quad ;(6)$$

$$\Delta_2 = \Delta\overline{g}_{Terr}(x,y)_{\gamma=0} = \overline{g}_{e1}(x-2\Delta x,y) - \overline{g}_{e5}(x+2\Delta x,y) + \overline{g}_{e2}(x-\Delta x,y) - \overline{g}_{e4}(x+\Delta x,y) \quad ;(7)$$

where P $(x,\ y)$ – the center of the transformation window, Δx – the size of the small axis of the ellipse.

The anisotropic anomalies obtained because of the transformation according to variant (6) are called anomalous fields of the anticline type; anomalies according to variant (7) – anomalous fields of terrace type, actually, transformations are: according to first variant – A-transformation; according to second variant – T-transformation [Anikeyev, et al, 2021].

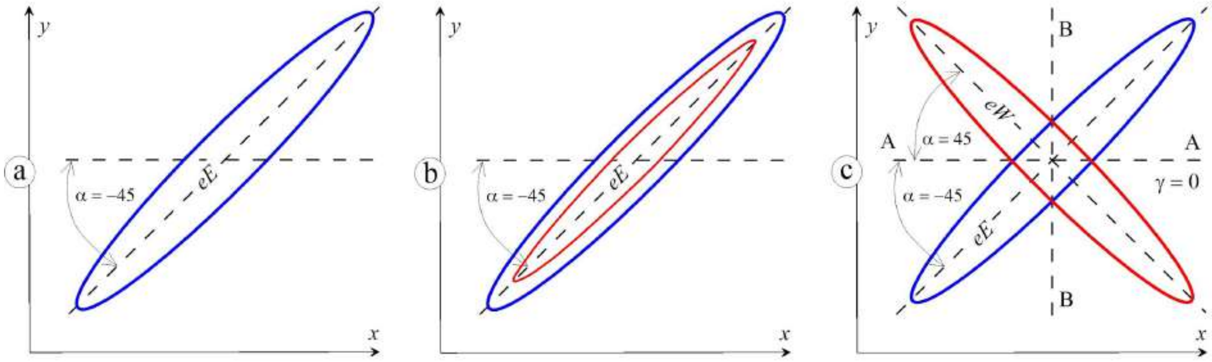

Fig. 6. The anisotropic transformation windows of averaging and residual averaging with incline angle α = ±45⁰

Estimating the parameters of anisotropic transformations

The sizes of anomalies depend on the depth of their sources and on the size and degree of horizontal extension of these sources. With a fixed depth and other constant parameters, point (or isometric) source anomalies have minimum sizes. Obviously, the extension of anomalies from extended horizontal layers, elongated structures or linear dislocations (thrusts, landslides, faults) is equal to or greater than the extension of these sources (in the direction of their extension). From these two critical cases (three-dimensional and two-dimensional), it is possible to estimate the range of possible sizes of anomalies (within the half-maximum):

$(2/1.31)\times h \div L$ (for gravitational anomalies);
$h \div L$ (for magnetic anomalies); (8)

where h – the depth of the source; L – dimensions of highly elongated structures.

The dependence between the radius of the averaging window R and the depth h of the occurrence of isometric sources (see formula (1)), whose anomalies will be weakened in the transformed field by more than 60 %, follows from the above relations and from the depth characteristics of the isotropic averaging transformation (Fig. 4).

The anisotropic windows parameters (Fig. 5, 6) depend on the assumed sizes of linear zones and noise-anomalies. The width of the combined window should be small, but not less than the width of the zones to be selected. With an increase in the length of the palette, the reduction of small variations increases. However, the length of the palette must be at least twice less than the minimum extension of these dislocations for reliable mapping of linear disloca-tions.

Here is a formal approach to estimate the parameters of the windows of anisotropic transformations.

On the contrary, to reduce anomalies from linear structures of length L, the radius of the averaging window should be:

$$R > L. \quad (9)$$

It is important to estimate the degree of attenuation of elongated anomalies (two-dimensional anomalies from cylindrical bodies) by the transformation of averaging along the profile, across their extension. According to the classical approach, the depth characteristic for three-dimensional anomalies is defined as the dependence of the degree of attenuation of a point source (or sphere) anomaly on the depth of its occurrence, normalized to the averaging radius (Fig. 4). Similarly, it is possible to determine the depth characteristic for two-dimensional anomalies (for example, an anomaly from a horizontal cylinder), but along a profile perpendicular to their extension. It is easy to verify that the depth characteristic of averaging for two-dimensional gravitational and magnetic anomalies is identical:

$$\varepsilon(h) = \mathrm{arctg}(P)/P, \qquad (10)$$

where $P = R1/h$.

Comparison of the depth characteristics of the averaging transformations of isometric and substantially elongated anomalies (Fig. 7, 8) shows that the degree of attenuation of elongated anomalies (in the transverse direction of their extension) in the range of practical values (0.4–0.8) will be the same or greater, provided (compare with formula 1):

$$R > 2 \cdot h. \qquad (11)$$

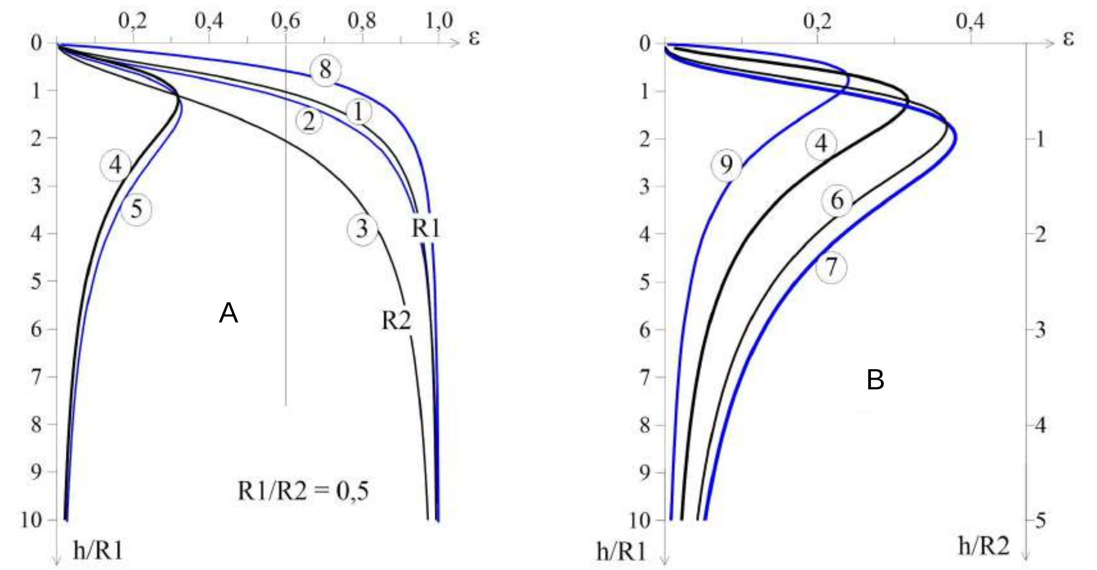

Fig. 7. The relative depth characteristics of the transformation

Symbols: 1, 3 – for averaging of gravity anomalies of isometric sources (ratio of averaging radii $R2 = 2R1$); 2 – averaging of magnetic anomalies of isometric sources; 4 – difference averaging of gravity anomalies of isometric sources; 5 – difference averaging of magnetic anomalies of isometric sources; 6 – Saxov –Nigaard [Saxov and Nygaard, 1953] transformations of the gravitational field; 7 – Saxov – Nigaard transformations of the magnetic field; 8 – (anisotropic) averaging of gravitational and magnetic anomalies in the direction perpendicular to the extension of cylindrical bodies (almost coincide); 9 – (anisotropic) difference averaging of gravitational and magnetic anomalies in the direction perpendicular to the extension of cylindrical bodies; other symbols – in Fig. 4

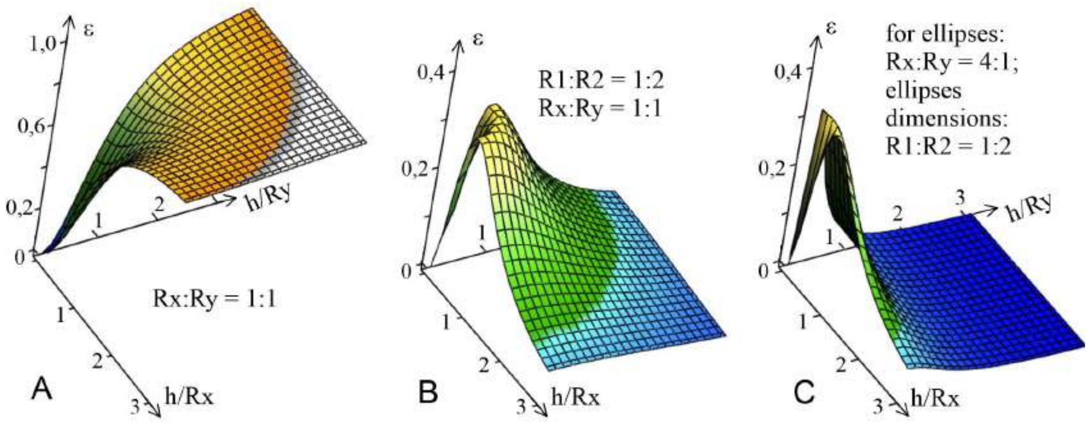

Fig. 8. A three-dimensional image of the depth characteristics of isotropic averaging (A), difference isotropic averaging (B) and difference anisotropic averaging (C)

The purpose of anisotropic transformations is to isolate anomalies of linear dislocations; therefore, inequality (9) shows what dimensions of linear dislocations will be predominantly reflected in anisotropic anomalies, and the estimate (11) indicates a limitation of the depth of their occurrence. The sizes of the ellipses are parameters for anisotropic transformations. The size of the major axis is determined by the estimate (9) and the minor axis of the ellipse is determined by the estimate (11). The smaller the minor radius of the ellipse is, the narrower the anomalies will stand out in the observed field against the background of others, and, therefore, linear sources of shallower depth will be reflected in the anisotropic anomalous field. It is important that the dimensions of the major axis of the ellipses be significantly larger than the maximum size of the anomalies to be attenuated. But they should be smaller than the useful linear anomalies, or networks of interconnected isometric or elongated local anomalies to be traced (emphasize) in potential fields.

In our opinion, the parameters of other combined anisotropic transformations based on averaging procedures (for example, Andreev – Klushin) are estimated similarly. The ellipses in the window are tight, so the distance between them is equal to the size of the minor axis of the ellipses. Of course, each type of combined transformation has its own depth characteristics, according to which estimates may differ (1, 8, 11).

In theory, the transformations of potential fields are represented by mathematical filters, which have their own frequency characteristics. The averaging transformation is a low-pass filter. Its frequency characteristics (analog of the spectrum of a rectangular pulse) depends on the size of the averaging window *R*. Examples of frequency characteristics of isotropic transformations of averaging and difference averaging (or anisotropic, but along the extension of elongated anomalies) are given for comparison in Fig. 9, the same frequency characteristics in the version of the three-dimensional image are presented in Fig. 10 [Anikeyev, et al, 2019].

Note that the Saxov – Nygaard transformation and the difference averaging are bandpass filters. Comparison (Fig. 7B) of depth characteristics provides an opportunity to evaluate the relations between the depth bands of anomaly sources localized against the background of the intense attenuation of other anomalies and different $R1/R2$ ratios, as well as to see a greater resolution of difference averaging compared to Saxov –Nygaard transformation.

The characteristics of anisotropic transformations are essentially direction-dependent of the main axis of the window and therefore are evident in 3D (Figs. 8, 10).

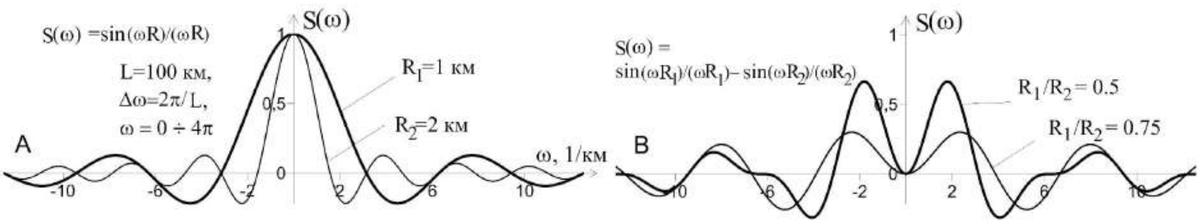

Fig. 9. The frequency characteristics of averaging (A) and difference averaging (B)
$S(w)$ – the spectrum of the transient characteristic of the filter; w – frequency;
$R_{1,2}$ – different radii of the transformation window; L – signal length selected

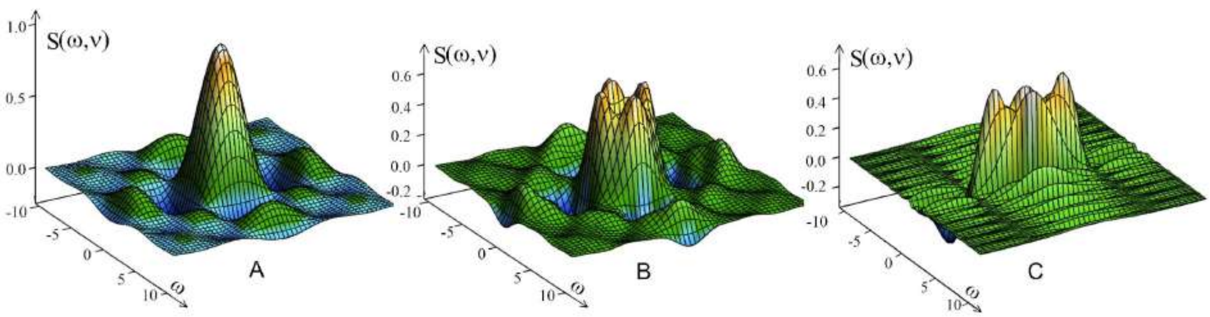

Fig. 10. A three-dimensional image of the frequency characteristics of averaging (A), difference averaging (B), and anisotropic difference averaging (C) transformations

Test examples of anisotropic transformation

An example of successful testing of the algorithm of anisotropic transformation according to the variant of B. O. Andreev, I. G. Klushin is given in their work [Andreev, Klushin, 1962]. The background mosaic field and isometric anomalies are filtered from a morphologically complex field, while the extensions of linear dislocations are emphasized by isolated anisotropic anomalies.

A field in which there are useful anomalies of the north-western extension, a background linear anomaly of the latitudinal extension and a narrow anomaly elongated in the northern direction was selected to test the difference anisotropic transformation with a butterfly-window (Fig. 11, a). Parameters of the butterfly window are as follows: the ratio of the axes of the ellipses 1:10, the angle of the symmetry axis of the combined window $\gamma = 0^0$ (Fig. 6, c). Regional latitudinal anomaly and narrow local northern anomaly are completely absent in the field of difference anisotropic anomalies (Fig. 11, b). However, practically invariant linearly elongated anomalies with northwestern extension are present. This coincides with the major axis of one of the two ellipses. The transformed field is smaller than the original one to eliminate the edge effects.

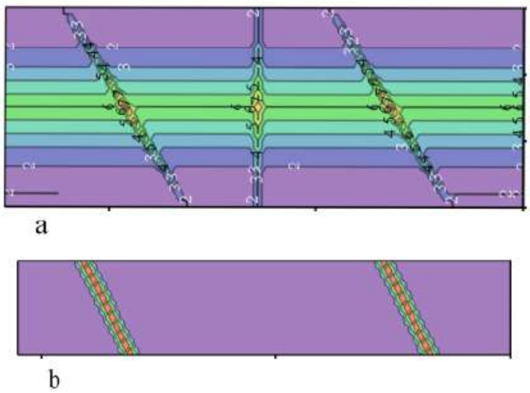

Fig. 11. Sample test anomalous field (a) and the result of the difference anisotropic averaging (b)

Andreev –Klushin transformations, as well as anisotropic difference averaging are combined transformations and have the property of smoothing interference and attenuation of various signs of small anomalies. It is important that the size of their windows be larger than the size of the major axis of small anomalies in the practical application of these transformations.

Characteristic features of the reflection of the region tectonic structure in gravimagnetic fields

The intensity of the gravitational field of the southeastern Ukrainian Carpathians decreases noticeably approximately to the Dolyna-Yaremche line, where the known Carpathian gravity minimum is observed. It gradually increases further towards the Transcarpathian trough (Fig. 2). Isoanomals are generally directed from southeast to northwest in the direction of the strike of tectonic zones. Gradient zones are caused by deep faults. Complications of isoanomales reflect the morphology of the Kolomiya paleovalley, branches of the Precarpathian fault, intersection of longitudinal and transverse deep faults, as well as changes in their extension (Fig. 2).

The intensity of the magnetic field within the study area decreases in the same direction and for the same reason: under the influence of an increase in the depth of the basement surface of the East European Platform. There is an insignificant increase in the field intensity within the zone between the platform and the Folded Carpathians. The contours of this anomaly have a complex morphology and are explained by the influence of a large-amplitude fault – the Precarpathian fault and its branches. Complications of isodins are caused by the block structure of the basement, the topography of its surface and the influence of fault systems (Fig. 3).

Sometimes significant differences between the morphology of gravimagnetic fields and fault tectonics and the contours of tectonic zones are explained by a number of factors. One of them is the integral nature of the influence of the geological and tectonic structure of the geological section on potential fields (inclination angle of deep faults, thrust geometry of thicknesses of certain tectonic zones, inclination angle of magnetic field vector, and also rocks magnetization vector, etc.). Other aspects include the principles and views that were used as the basis for determining the projections of tectonic zones on the earth's surface during the construction of a tectonic map [Tectonics of the Ukrainian Carpathians ..., 1986].

Anisotropic transformations of gravimagnetic fields in the southeast of the Ukrainian Carpathians

In the anisotropic transformations of the gravitational and magnetic fields of the southeast of the Ukrainian Carpathians and the Precarpathian trough, the dimensions of the windows are determined by the depth characteristics, taking into account the depths of the basement surface. The ellipses in the windows are as follows: large radius – 5000 m, small – 500 m (map scale 1:50000); orientation of the ellipses: northwest and/or northeast.

The features of the morphology of anisotropic anomalies are highlighted in comparison with local anomalies obtained using isotropic averaging of fields (Figs. 12, 13); and also all maps are compared with tectonic zones.

Local anisotropic gravitational anomalies are presented in Fig. 14. They are obtained by extracting from the observed field as the result of anisotropic, averaging with a window-ellipse of northeastern and northwestern direction. According to the observed field, large isometric anomalies and anomalies of clearly northeastern (Fig. 14A) or northwestern extension (Fig. 14B) were removed.

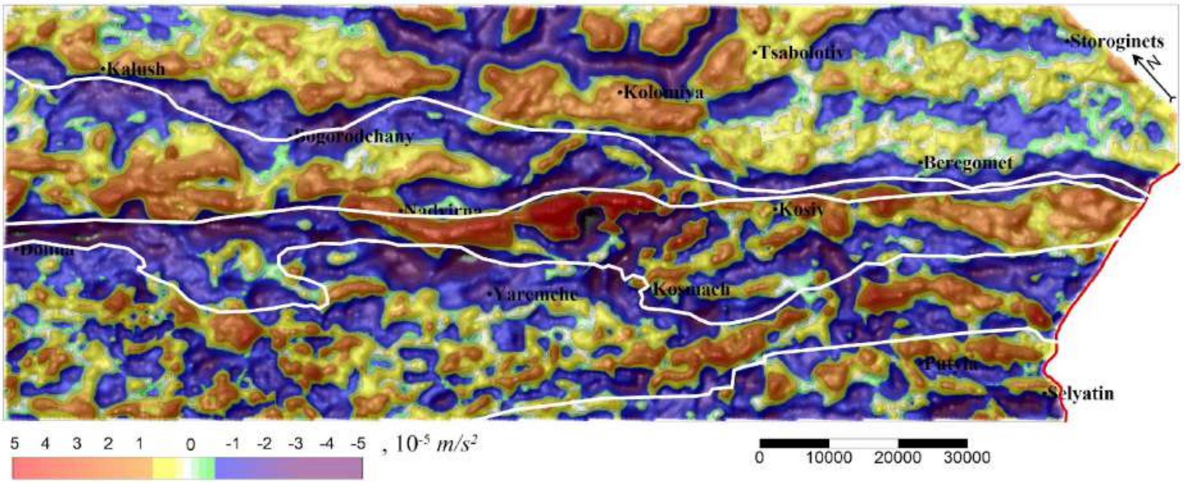

Fig. 12. Local anomalies (window radius of isotropic averaging R = 5000 m) of gravity field of the southeast of Ukrainian Carpathians [Anikeyev, et al, 2020]

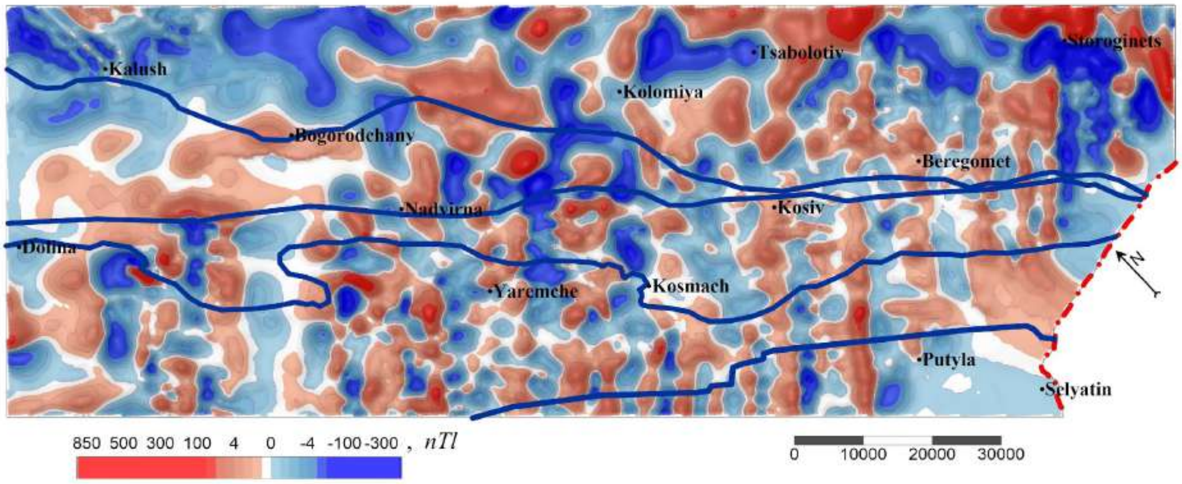

Fig. 13. Local anomalies (window radius of isotropic averaging R = 5000 m) of magnetic field of the southeast of Ukrainian Carpathians

Rather wide bands of groups of positive anomalies of the north-western extension predominate within the slope of the platform (Fig. 14A). The nature of the anomalous field within the Boryslav – Pokutsky cover (BPC) is somewhat different from its morphology within the rest of the Folded Carpathians. Here, the impact of basement complications is less due to the strong sedimentary cover. Also, the influence of tiers of folds, extended mainly in the transverse direction (north-west) to the thrust, prevails here. A comparison of the south-western contour of the BPC (Skyba front) and the morphology of the negative anomaly strip suggests a significant extension of it near Skyba sometimes at more than 10 km, but except for the Maidan and Pokut – Bukovynian ledges, with covers, which may be due to the deep protrusion of the platform basement.

If we remove the bands of groups of anomalies of the north-western extension (Fig. 14B), the picture of the anisotropic anomalies distribution changes acutely. Here, the change in morphology and directions of elongated anomalies can be clearly traced along the line. This line in some places coincides with the front of the BPC, more precisely with the zone of the Precarpathian fault. Also, nodal anomalies related to the influence of the Berezivka structure [Zayats, Anikeyev 2008, Anikeyev et al., 2013] and the Precarpathian fault have been revealed in the center of the study region. According to changes in the morphology of anomalies, the region can be divided into three sections. The first (north-western) extends to Nadvirna, the second – the central one (from Nadvirna to Kosiv) and the third – from Kosiv to the border with Romania. Within the Folded Carpathians, the central area can be divided into two with conventional names – Yaremche zone and Kosmach zone.

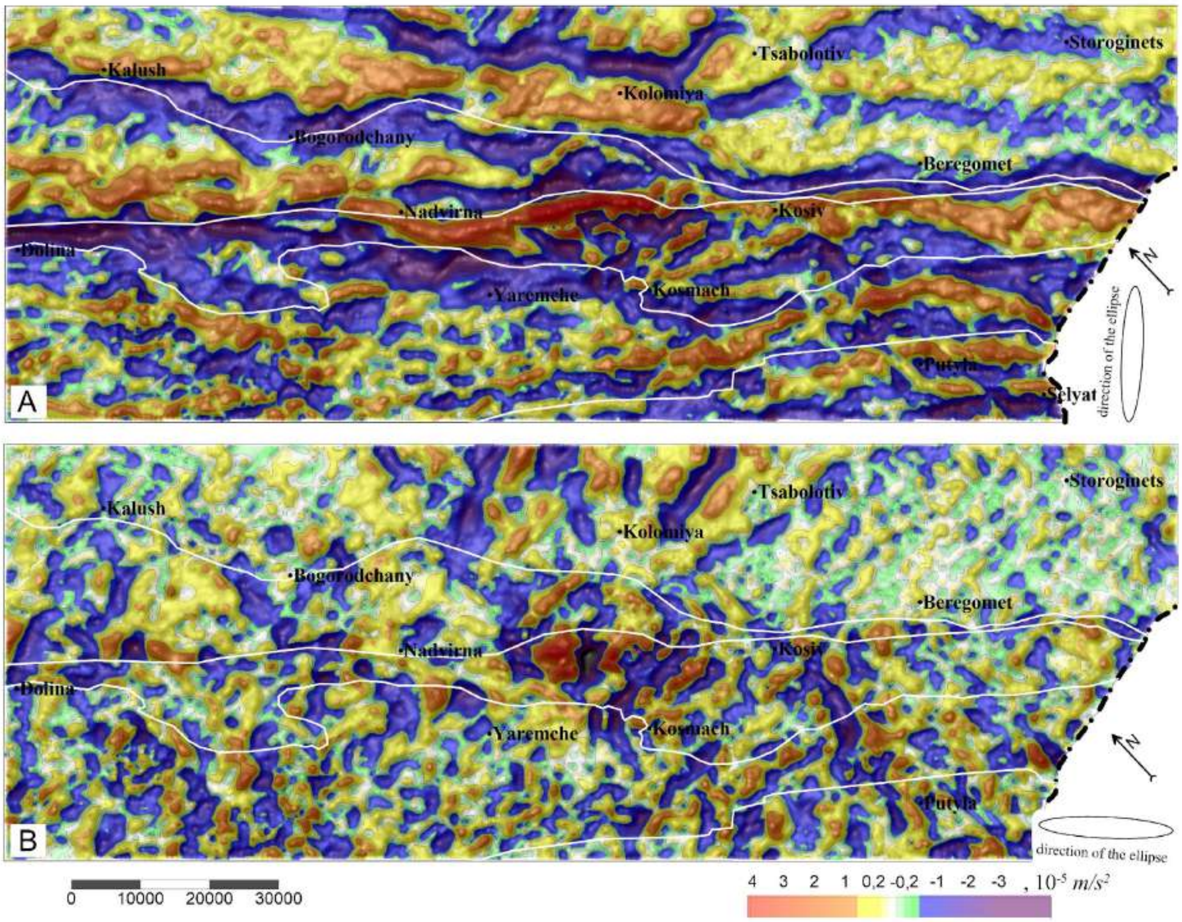

Fig. 14. Local anisotropic anomalies (observed field minus anisotropic averaging) of the gravity field of predominantly non-northeastern extension (A) (direction of window-ellipse is northeast) and predominantly non-northwestern extension (B) (direction of window-ellipse is northwestern) with the presence of small isometric anomalies (the size of which is much less than 5000 m)

In anisotropic magnetic anomalies, which are obtained in a similar way, there is also a division of the region by morphology and size of anomalies into platform and geosynclinal almost along the BPC front. The Yaremche area is also well distinguished (Fig. 15A). On the other hand, the anomalies, strongly elongated in the transverse (northeast) direction, clearly prevail in the field, according to the variant of extraction of large isometric anomalies and anomalies of the north-western direction (Fig. 15B). Their extension can be traced from the Folded Carpathians far to the slope of the platform. They weakly "react" to the intersection of the high-amplitude Precarpathian fault and probably reflect a network of deep transverse faults of the basement.

Difference anisotropic anomalies of the gravitational field contain mainly those anomalies that are elongated in a different direction than the ellipses. They are obtained by a combined transformation with a window in the variant shown in Fig. 6, b (radius of ellipses: 500 m – 2500 m, 1000 m – 5000 m). In addition, there are suppressed anomalies caused by linear dislocations, the length of which is clearly larger than the large axis of the small ellipse, as well as large (larger than the large ellipse) and small isometric anomalies (smaller than the small axis of the small ellipse). Fig. 16 presents the difference anisotropic anomalies with the north-eastern and north-western directions of the ellipses. The result of the transformation generally meets expectations within both the slope of the platform and the Folded Carpathians. The sources of most anomalies lie in a certain depth band, probably in the range of small ellipse parameters according to the content of the depth characteristic of the combined transformation of anisotropic difference averaging (Figs. 7, 8) (averaging with a small ellipse minus averaging with a large ellipse).

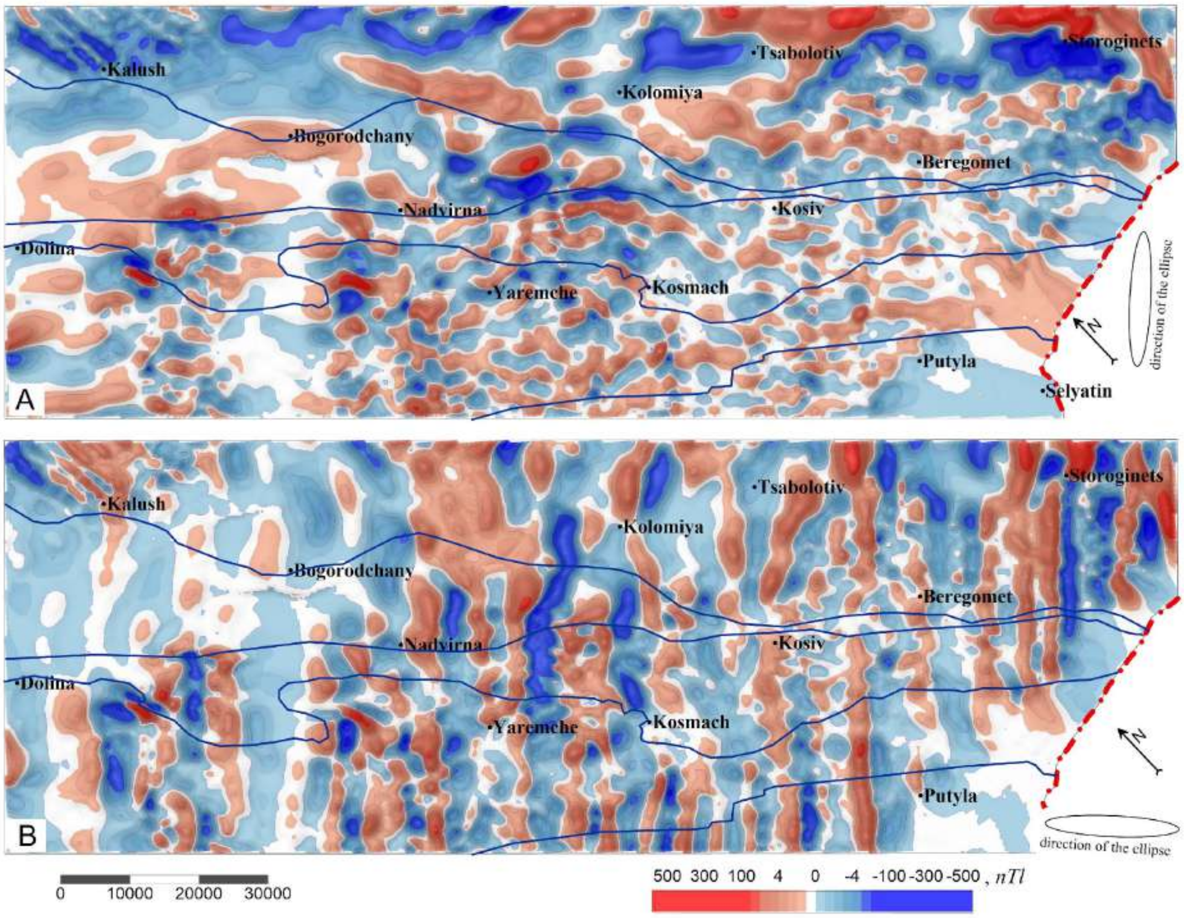

Fig. 15. Local anisotropic anomalies (observed field minus anisotropic averaging) of the magnetic field of predominantly non-northeastern extension (A) (direction of window-ellipse is northeast) and predominantly non-northwestern extension (B) (direction of window-ellipse is northwestern) with the presence of small isometric anomalies (the size of which is much less than 5000 m)

Bands of positive (negative) values of difference anomalies are caused by long uplifts (depressions) of the basement surface (platform slope) or uplifts (depressions) of long tiers of Paleogene-Cretaceous folds (Folded Carpathians) (Fig. 16A). They are absent in the transformant, which is shown in Fig. 16B. Instead, large uplifts of complex forms are manifested (Sambir cover) and within the Folded Carpathians there is a practically continuous wide positive band, which in the rear part of the Krosno zone is complicated by chains of small negative anomalies of the south-western extension. There are relatively large anomalies elongated in the north-eastern direction only in the south-eastern part of the Carpathians and in front of the Maidan half-window front [Tectonics of the Ukrainian Carpathians…, 1986].

Difference anisotropic anomalies of the gravitational field, which are the result of the transformation in the variant of the butterfly window (Fig. 6, c, radius of ellipses: 500 m – 5.000 m), should contain mainly anomalies elongated in the directions of the butterfly window ellipses and larger than the semi-major axis of the ellipses.

Figs. 17 show the results of the combined isotropic-anisotropic transformation (empirical formula):

$$2\cdot\underline{U}_R - \underline{U}_E - \underline{U}_W; \qquad (12)$$

where $2\cdot\underline{U}_R$ is a double isotropic averaging with radius R that equal to the small axis of the ellipses; $\underline{U}_E$ – anisotropic averaging in the northeast direction of the window-ellipse (500×5.000 m), which in combination is a butterfly window (Fig. 6, c).

Anisotropic anomalies were obtained by Andreev-Klushin T-transformations (see formula 7) in two variants (Fig. 18, radius of ellipses: 500 m; 5.000 m). According to the first (Fig. 5) variant the main axis of the transformation window has a transverse direction (northeast) to the extension of the main tectonic zones and deep faults of the southeast of the Ukrainian Carpathians (see Fig. 1). According to the second variant, the direction of the transformation window (north-west) corresponds to the extension of tectonic zones and longitudinal deep faults. According to T-transformations, gradient anomalies (or zones of high gradients) elongated in the direction of the main axis of the transformation window are singled out.

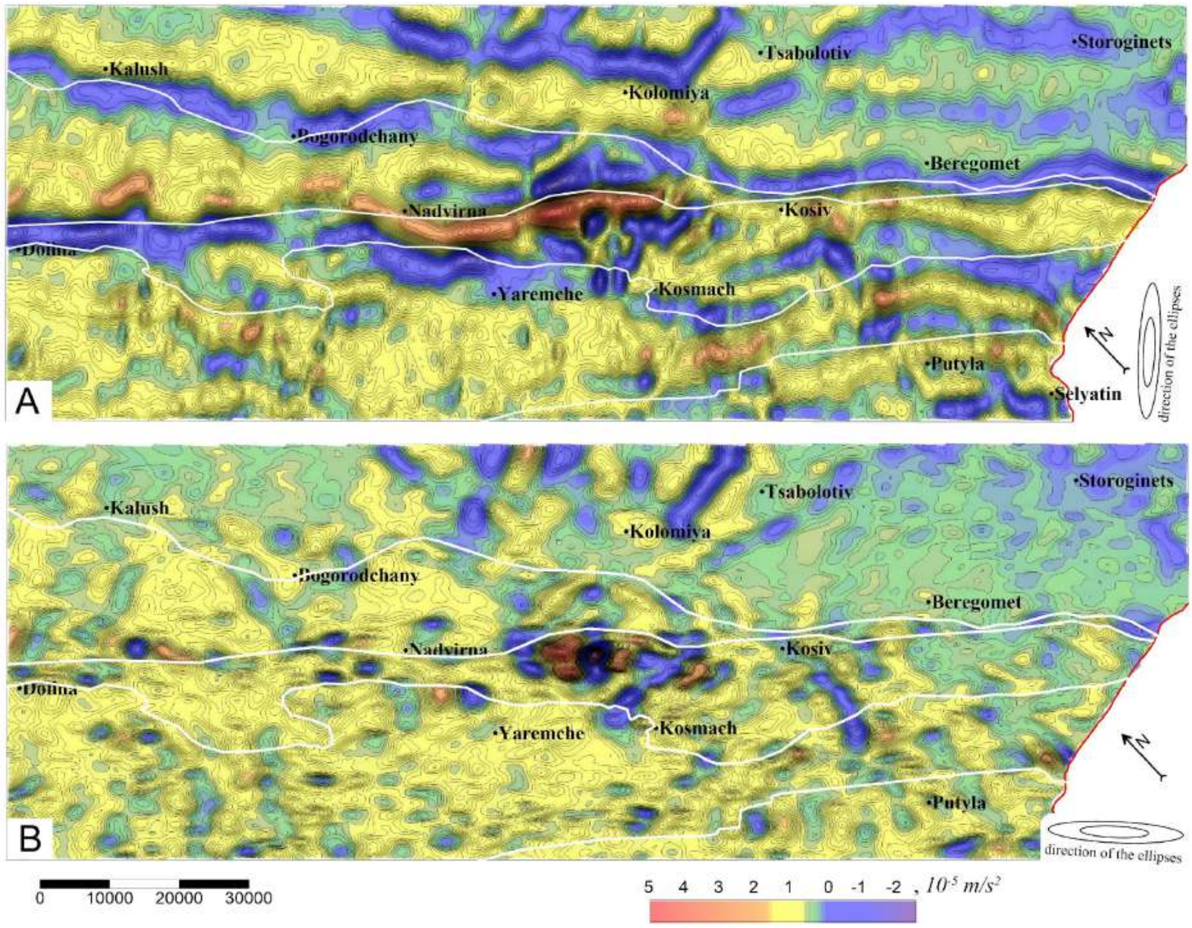

Fig. 16. Difference anisotropic anomalies of the gravity field: A – the direction of the window-ellipses northeast; B – the direction of the window-ellipses northwest

The result of this transformation is local anomalies, the sources of which are located in a band of depths from the first kilometers to 5,000 m (magnetic anomalies – up to 7,000 m).

Anomalies of significant extensions, except for extended bands of positive or negative anomalies, are practically absent. Regional isometric anomalies and anomalies smaller than 2000 m are also significantly attenuated. Brachyanticline structures (see Fig. 1), only in some cases correlate with positive anomalies. More often they are located on their periphery (Fig. 17). The structures, located within the positive anomalies of the gravitational and magnetic fields, are formed above the projections of the basement. In the case when the anomalies in the plan do not coincide, the folds are formed as a result of the slide in the frame of the projections of the basement. Concerning the faults, let us pay attention only to the following results: the transverse faults near Bohorodchany have a linear extension in the Folding Carpathians.

The gravitational T-anomalies of the northeastern extension (Fig. 18A) reflect a network of transverse structures and faults. Here you can select the transition zone between the slope of the platform and the Folded Carpathians. The negative anomalies predominate towards the south-west, closer to the edge of the strip (the Skyba front line). The transitional zone, in our opinion, is a manifestation of the nature of the platform deepening under the thrust front of the sedimentary cover of the geosyncline. According to its morphology, the slope of the platform has a significant continuation under the thrust in the areas of the Maidan knot and the Pokutsko – Bukovina Carpathians. A large positive anomaly is noticeable in front of the Maidan half-window within the slope of the platform. T-anomalies of the north-western extension (Fig. 19A) reflect the complications of the basement surface along the extension of tectonic structures and longitudinal deep faults (platform slope) or the behavior of Paleogene-Cretaceous folds (Folded Carpathians).

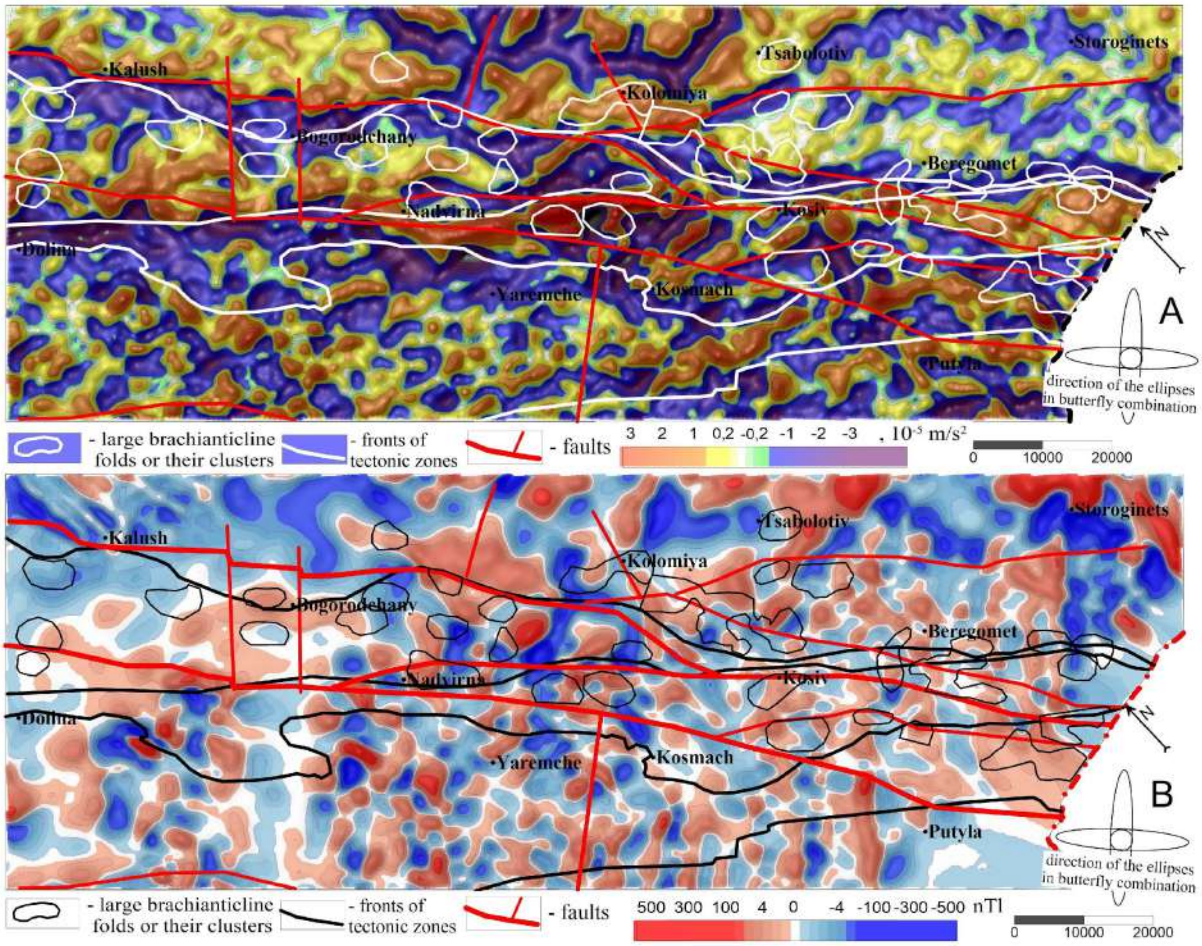

Fig. 17. Local difference anomalies of the gravity field (A) and the magnetic field (B) of the south-east of the Ukrainian Carpathians

In magnetic T-anomalies, the expansion of negative anomalies and the increase of their intensity are also noticeable in the areas of the Maidan half-window and the Pokutsko – ukovynian Carpathians in the transition zone (Fig. 18B). In the direction of the Kolomyia Paleo-Valley, the invasion of low intensity (Fig. 19B, Fig. 3) has a certain correlation with the schemes (which were built by A. M. Kononsky and O. S. Gula) of decreasing interval resistance according to MTS at depths of 5 km and, especially, 30 km, [Zayats, 2013].

The influence of transverse faults can be traced in the schemes of linear magnetic field anomalies (Figs. 15B and 18B). In our opinion, transverse faults belong to the regional system of basement faults (K. F. Tyapkin's rotational hypothesis of structure formation [Tyapkin, et al, 2000]).

Fault tectonics maps and schemes [Tectonic map of the Ukrainian Carpathians…, 1986; Dolenko, et al., 1976; Dolenko, 1986; et al.] indicate the complexity of the tectonics of the region. On the schemes, the basement of the trough is divided into blocks by a network of deep faults of longitudinal and transverse directions (Figs. 1, 20).

The network of linear dislocations developed in the northeast of the Ukrainian Carpathians is most clearly manifested in the gravimagnetic local anisotropic anomalies of the terrace type (the Andreev – Klushin T-transformation). Such anomalies are a reflection of deep transverse (Fig. 18) and longitudinal (Fig. 19A) dislocations or complex basement shapes with predominantly longitudinal orientation (Fig. 19B). To a certain extent, gravimagnetic local anisotropic anomalies of the terrace type are devoid of the influence of shallow complications (in comparison with anisotropic anomalies in Figs. 14, 15). This is due to the design of the transformation window (field variations within the central ellipse are not taken into account - formula 7). Also, in Figs. 18, 19, a number of changes in the morphology of anomalies are traced, for example, along the Dolina – Bogorodchany, Nadvirna – Kolomiya – Tsabolotiv, Kosmach – Kosiv – Beregomet or Bogorodchany – Nadvirna – Yaremche line. The lines of these changes have an extension that roughly corresponds to the direction of the Radekhov or Pokut faults (Fig. 20). Perhaps this is a manifestation of another network of regional faults, deployed at an angle to the network of longitudinal-transverse, which is consistent with the K. F. Tyapkin's rotational hypothesis.

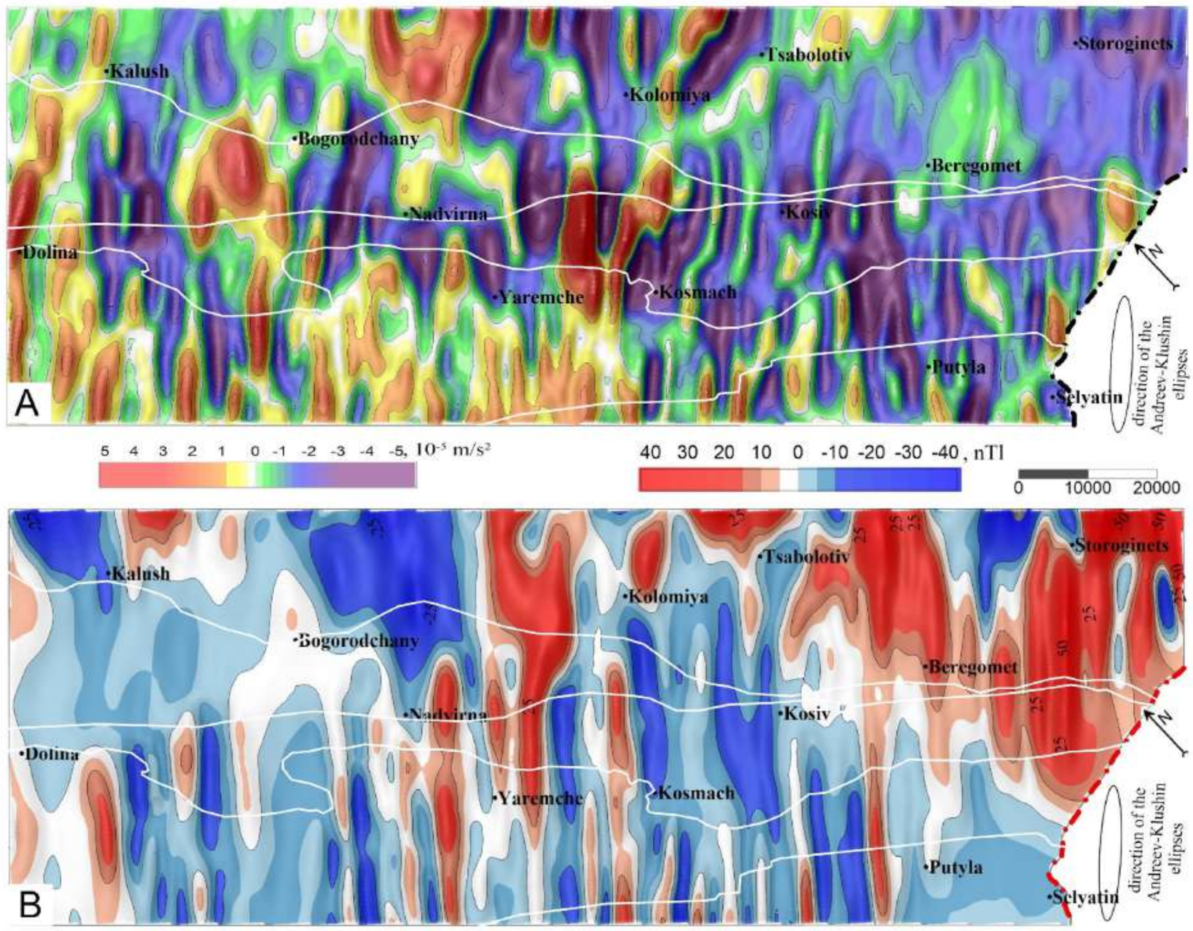

Fig. 18. The result of anisotropic T-transformation: gravity (A) and magnetic (B) anomalies of the terrace type; direction – northeast

Structural features of predominantly nonlinear character are successfully reflected in local difference anomalies of the gravitational (Fig. 16B) and the magnetic field (Fig. 17B).

Scientific novelty

The study gives definitions and presents the basic properties of a number of transformations based on anisotropic averaging. It also substantiates the geological and tectonic informative value of the morphology of anisotropic transformations of potential fields in the studies of fault tectonics of the Ukrainian Carpathians and adjacent depressions. Schemes of anisotropic gravimagnetic anomalies complement the existing views on the deep structure of the region. In particular, linear anomalies of the magnetic field (see Figs. 15B and 18B) show the probable influence of a network of regional faults, which was developed according to the rotational hypothesis of K. F. Tyapkin's structure formation.

Practical significance

Reliable isolation of local gravimagnetic anomalies and successful study of their nature requires the use of transformations with justified characteristics.

There is an indisputable meaning in the application of different methods of transformations with variation of their parameters. Comparison of transformed fields and search for common morphological features of the manifestation of geological and tectonic structures is an effective approach to identify and refine the parameters of these structures [Andreev and Klushin, 1962].

The application of anisotropic transformations of potential fields increases the reliability and detail of tracing regional faults and the geometry of foundation blocks which are associated with the forecast of prospects for deep oil and gas deposits.

Conclusions

Anomalous gravitational and magnetic fields are extremely informative in solving problems of studying the deep structure, detecting and mapping faults, tracing tectonic zones, as well as in isolating structural forms. The degree of reliability of the study of the nature and morphology of local gravimagnetic anomalies depends on the possibility of comparing the results of a number of transformations, including anisotropic ones, the practical application of which has a theoretical basis. Also, the transformation fields should be determined by means of different parameters, including different angles of anisotropic transformations, in order to increase the meaningfulness of their qualitative interpretation. Obviously, this is the basis for more reliable detection and tracing of tectonic elements in comparison of localized anomalies (in sufficient scale and detail) with structural-tectonic maps, built on seismic and drilling data.

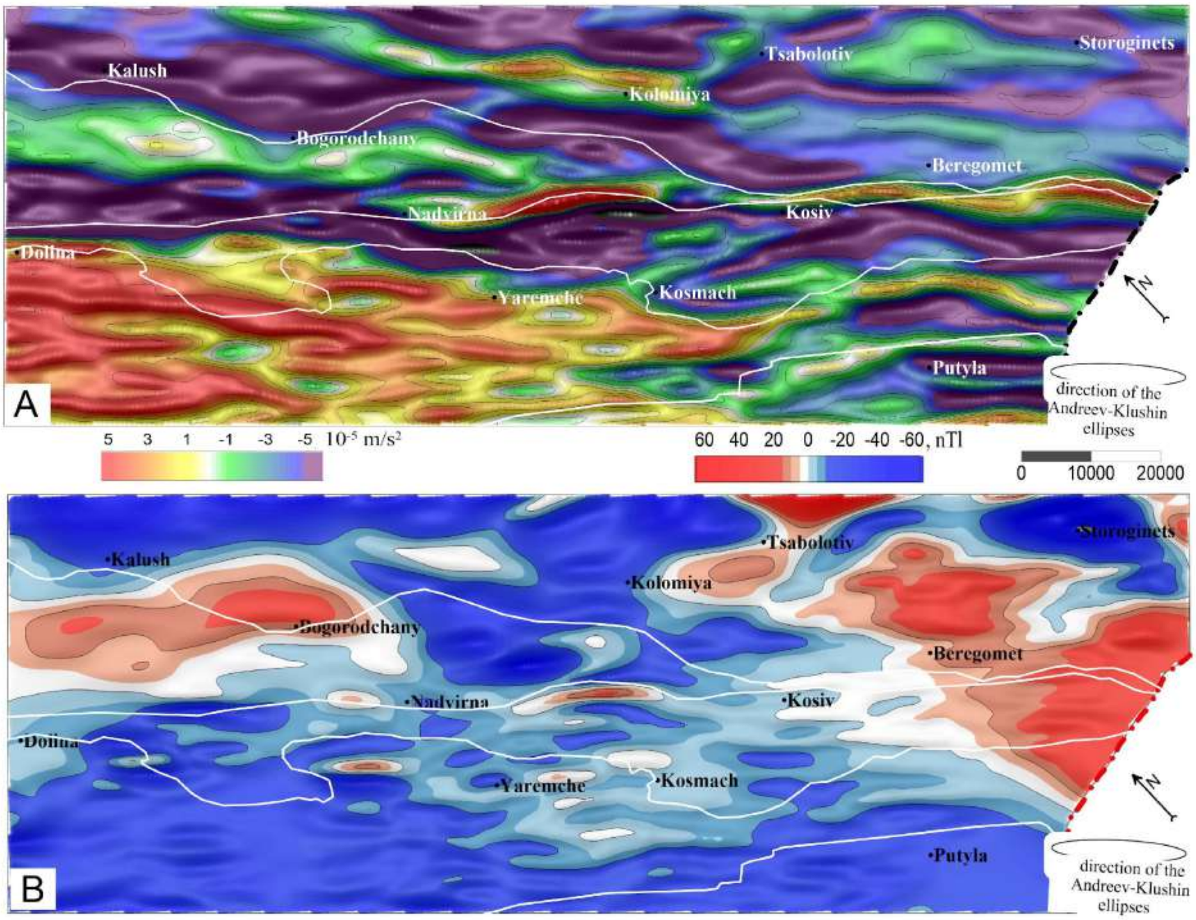

Fig. 19. The result of anisotropic T-transformation: gravity (A) and magnetic (B) anomalies of the terrace type; direction – northwest

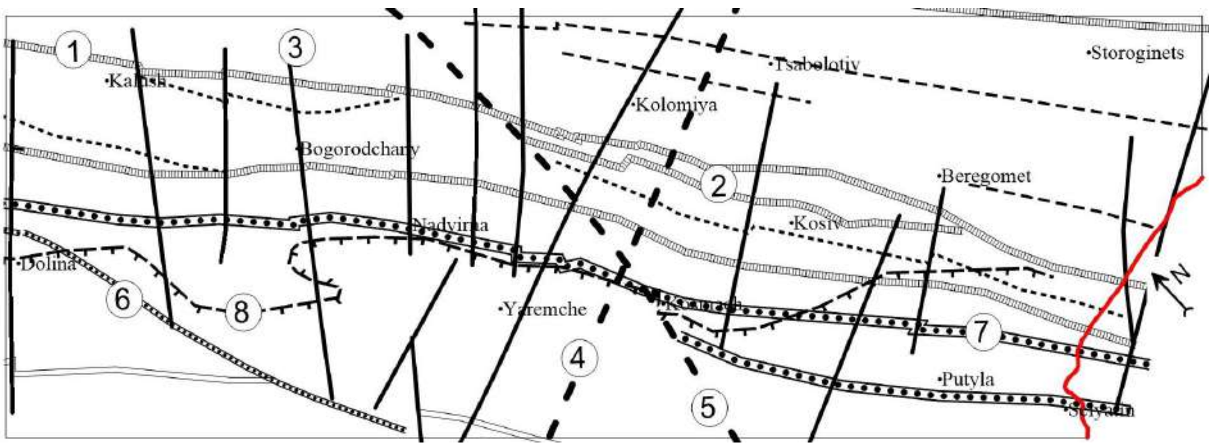

Fig. 20. Scheme of fault tectonics of the Precarpathian Depression (fragment) [Dolenko et al., 1976], supplemented by elements of tectonics of the Folded Carpathians [Dolenko, 1986]

Faults: 1 – Kalush fault; 2 – Kosiv; 3 – Manyavsky; 4 – Pokutsky; 5 – Radekhiv; 6 – Krakovetsky; 7 – northeastern border of the Pre-Carpathian deep fault; 8 – the thrust line of the Coastal Carpathians (Skiba front)

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АНІЗОТРОПНІ ТРАНСФОРМАЦІЇ РЕГІОНАЛЬНИХ ГРАВІМАГНІТНИХ ПОЛІВ ПІВДЕННОГО СХОДУ УКРАЇНСЬКИХ КАРПАТ

Мета досліджень проаналізувати властивості та геологічну інформативність низки анізотропних трансформацій гравітаційних і магнітних полів, у яких використано процедури осереднення, зокрема способу Андреєва – Клушина. Анізотропні перетворення потенціальних полів необхідні для виявлення та простеження витягнутих у певному напрямку аномалій або їх ланцюжків, які спричинені глибинними лінійними дислокаціями у геологічному розрізі. Вивчення властивостей анізотропних трансформацій ґрунтується на аналізі їхніх глибинних характеристик та теоретичних і практичних експериментах. Методика аналізу особливостей відображення розломної тектоніки, зокрема, на прикладі південного сходу Українських Карпат, у анізотропних аномаліях гравімагнітних полів ґрунтується на пошуку морфологічних ознак прояву глибинних розломів та інших протяжних великих структурно-тектонічних елементів у анізотропних аномаліях гравітаційних і магнітних полів, а також у простеженні цих елементів на основі зіставлення морфології, інтенсивності, розмірів та напрямку простягання анізотропних аномалій із опублікованими тектонічними і геологічними картами регіону. Наведено визначення та алгоритми таких анізотропних трансформацій, як способи Андреєва – Клушина антиклінального та терасового типів, анізотропного осереднення та анізотропного різницевого осереднення. Виконано дослідження геологічної інформативності анізотропних трансформацій потенціальних полів на теоретичних і практичних прикладах. Показано, що у морфології анізотропних гравітаційних і магнітних аномальних полів на території південного сходу Українських Карпат простежуються протяжні локальні аномалії, які зумовлені розломною тектонікою, зокрема глибинними поздовжніми та поперечними розломами, а також лінійними ускладненнями осадового покрову. У результаті аналізу анізотропних аномальних полів виявлено низку характерних ознак відображення великих тектонічних зон, регіональної поведінки поверхні фундаменту, глибинних розломів, на основі яких можна побудувати схеми розломної тектоніки південно-східного регіону Українських Карпат. Також простежено значне простягання фундаменту східноєвропейської платформи від Майданського вузла та Покутсько-Буковинських Карпат під Складчасті Карпати. Надано визначення низки анізотропних трансформацій та розглянуто їхні властивості. Обґрунтовано геологічну інформативність морфології анізотропних трансформацій потенціальних полів у дослідженні розломної тектоніки Українських Карпат та прилеглих прогинів. Застосування анізотропних траснформацій потенціальних полів сприятиме підвищенню достовірності й детальності простеження глибинних розломів, а також інших лінійних дислокацій як у фундаменті, так і в осадовому чохлі. Вивчення розломної тектоніки є важливим чинником успішного вирішення завдань із пошуку та розвідки площ, перспективних щодо покладів нафти і газу.

Ключові слова: Передкарпатський прогин; розломна тектоніка; лінійні дислокації; трансформації гравітаційного і магнітного полів; анізотропне осереднення; глибинні характеристики трансформацій; анізотропні аномалії.

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