ORIGINAL RESEARCH ARTICLE

DOI: https://doi.org/10.18599/grs.2018.4.404-412

Complex structural-tectonic zoning of the north-eastern part of the Barents Sea shelf

D.S. Nikitin[1], D.A. Ivanov[2]*

[1]*Geological Institute of the Russian Academy of Sciences, Moscow, Russian Federation*

[2]*Voronezh State University, Voronezh, Russian Federation*

Abstract. The large amount of geological and geophysical data obtained in recent decades for the north-eastern part of the Barents Sea shelf makes their visual comparative analysis difficult, and the use of automated classification methods, in particular, multidimensional statistics, become relevant.

The perspectives of the statistical approach to the processing and interpretation of multi-sign geological and geophysical information are considered. The objective performance of the method of identifying classes (tectonic structures) within the studied area is determined by statistically justified methods that are independent of the subjective factor. The structural-tectonic schemes for reflecting horizons are clarified, at the level of which the main stages of large-scale tectonic reorganizations occur.

Keywords: Barents Sea shelf, statistic analysis, structural-tectonic zoning

Recommended citation: Nikitin D.S., Ivanov D.A. (2018). Complex structural-tectonic zoning of the north-eastern part of the Barents Sea shelf. *Georesursy = Georesources*, 20(4), Part 2, pp. 404-412. DOI: https://doi.org/10.18599/grs.2018.4.404-412

Introduction

In the north-eastern part of the Barents Sea shelf in recent decades, a large amount of geological and geophysical studies have been performed to predict oil and gas content (Pavlov et al., 2008; Velichko et al., 2010; Pavlov, 2012; Tektonicheskaya karta.., 1998; Khutorskoy et al., 2008; Shipilov, Tarasov, 1998; Rostov et al., 2002; Fedukhin et al., 2002, etc.).

The article presents the results of statistical analysis of geological and geophysical information, which helped to clarify the structural-tectonic schemes for reflecting horizons, at the level of which the main stages of large-scale tectonic reorganizations occur. The spatial model (structural and block models, three-dimensional model of faults) of the northeastern part of the Barents Sea shelf, built by the authors earlier (Nikitin et al., 2017; Nikitin, Ivanov, 2016; Nikitin, etc., 2015) served as the basis for the statistical analysis.

New materials obtained by the authors provided the basis for updating and detailing the existing interpretations of previous data on the deep structure of the north-eastern part of the Barents Sea. The article presents new results of a complex structural-tectonic zoning of the north-eastern part of the Barents Sea shelf, obtained as a result of a statistical analysis of geological and geophysical information.

Object of study

The study area is geographically located in the northeast of the Arctic shelf of the Barents Sea between the two archipelagos of insular land – Frantz Josef Archipelago (FJA) and Novaya Zemlya (Fig. 1).

By the nature of seismic records and the distribution of potential geophysical fields, the studied area can be divided into two parts: the north-west and the south-east. The structure of the East Barents depression belongs to the northwestern part. The southeastern part is represented by the Novaya Zemlya forearc structural region, formed by the uplifts of the Admiralty, Pankratiev and Cape Zhelaniya, as well as the deflections of Sedov, Mak, Gulf Stream and Karpov (Fig. 2). The East-Barents depression, made by rocks of Middle Paleozoic-Mesozoic age, has a sedimentary cover thickness of 18 to 20 km. The thickness of the consolidated part of the Earth's crust ranges from 10 to 15 km, the Moho border is located at a depth of 27 to 33 km. The crust is thinned due to reduction of the granite-gneiss layer (Sakulina et al., 2007).

During the transition from the East Barents depression to the Novaya Zemlya forearc structural region, the structure of the Earth's crust, the shape of potential field anomalies, and the nature of magmatism change dramatically. The basement surface is stepped up in a southeastern direction and formed by multi-level

*Corresponding author: Dmitry S. Nikitin
E-mail: ndsnomination@mail.ru*

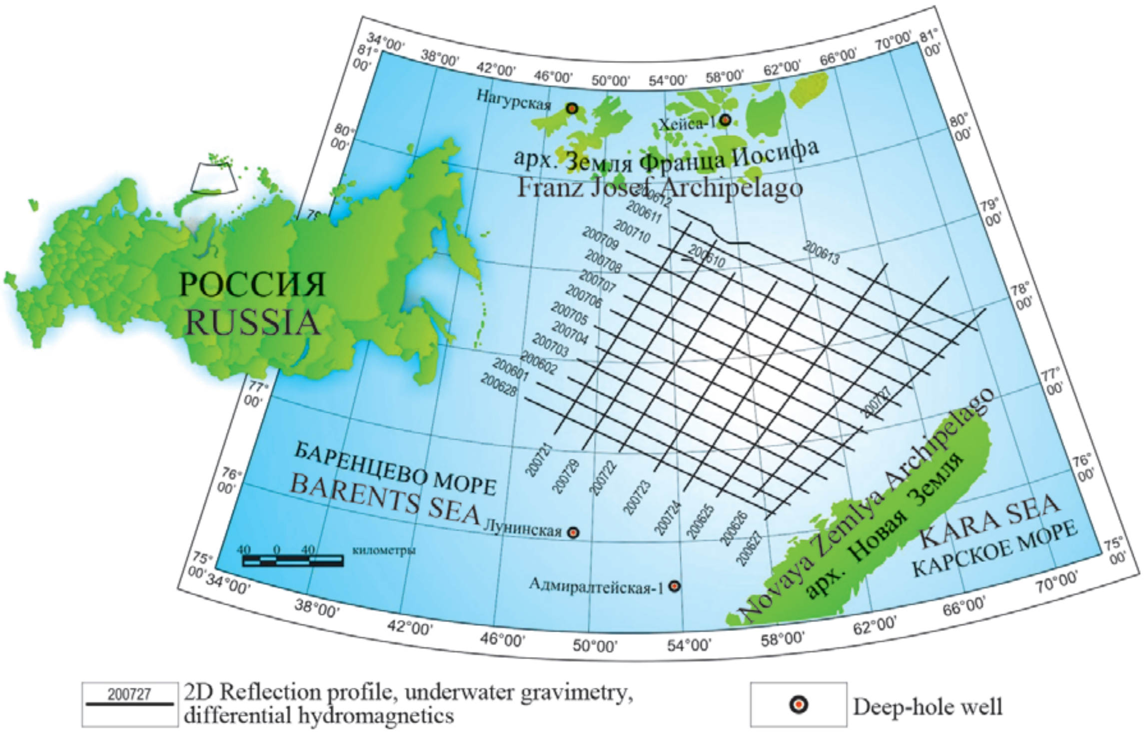

Fig. 1. Location of the study area

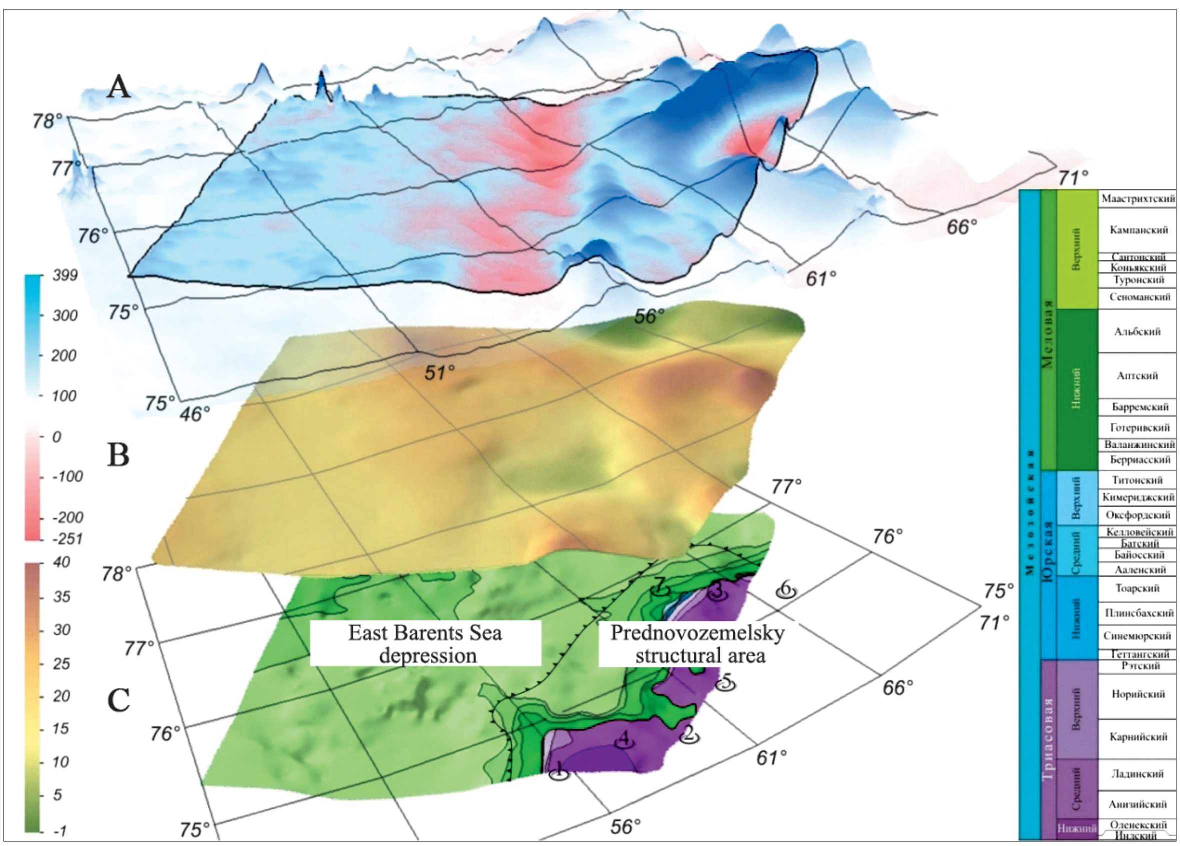

Fig. 2. Map of anomalous magnetic field (A), map of anomalous gravitational field (B), geological map of pre-Quaternary formations (C): 1-3 – elevated blocks of the Earth's crust: 1 – Admiralty, 2 – Pankratiev, 3 – Cape Zhelaniya; 4-7 – subsided blocks of the Earth's crust: 4 – Sedov, 5 – Maka, 6 – Gulf Stream, 7 – Karpov

blocks disintegrated and pulled over the crystalline base of the East Barents Sea depression. The thickness of the crust increases to 36-38 km, but at the same time there are significant fluctuations in the thickness of the sedimentary cover and the granite-metamorphic layer.

The boundary between the East Barents Sea depression and the Novaya Zemlya forearc structural region is traced by zones of deep faults. In the central part of the study area, it is expressed in a magnetic field of a wide, linear negative anomaly of northeast strike. The anomalous zone has a width of 40 to 80 km. Within its limits, the northeastern and sub-meridional thrusts traced from the Novaya Zemlya orogen are replaced by normal faults of the northeastern direction. On the eastern side of the depression, there is an immersion of blocks of the Novaya Zemlya forearc structural region. On reflection-time section of this structural area, the introduction of large intrusions is noted, the upper edges of which are located at depths from 8 to 10 km (Pavlov et al., 2008; Pavlov, 2012).

In compiling the tectonic scheme, the results of thematic works (Verba, Ivanov, 2000), published materials, tectonic maps and charts (Shipilov, Tarasov, 1998) were used. In tectonic terms, the territory under consideration belongs to the Svalbard Plate, which is characterized by a heterogeneous structure.

Within the study area, it is assumed the Grenville age of the basement forming, as well as for the most part of the northern Barents Sea shelf (Shipilov, Tarasov, 1998). According to other authors (Suprunenko et al., 1998), the study area belongs to the epi-Baikal shelf plate, with pre-Baikal rigid blocks soldered into it (Frantz Josef Archipelago).

In the geological structure of the north-eastern part of the Barents Sea shelf, three structural-tectonic levels (STL) are distinguished: the lower – pre-Paleozoic folded basement, the intermediate – lower middle-Paleozoic and upper, which includes sediments from Upper-Devonian to Quaternary. These structural levels are separated by surfaces of regional stratigraphic and angular inconsistencies (reflecting horizon (RH) VI (C) and III2 (D_3)), reflecting significant changes in the structural plans of the sedimentary cover of the study area.

Tectonic zoning patterns are available for the Lower-Middle Paleozoic sediment complex (OG III_2 (D_3)) and on the top of the Triassic sediments (OG B (T-J)) (Fig. 3).

In addition, in the history of the development of the Upper Paleozoic-Mesozoic STL, the stages of large-scale tectonic reorganizations in the Early Permian period, at the Triassic and Jurassic, and in the Neocomian period are also distinguished.

Geometric Analysis

The analysis included the study of the parameters of spatial (strike azimuth) and quantitative (density) distribution of faults, selected according to the results of seismic exploration of 2D CDP seismic reflection method. The study method is the construction of rose diagrams of the strike of faults.

Rose diagrams (azimuth rose plots) are one of the oldest and most widely used methods of graphic representation of measurements of the occurrence of the entire set of different rank disturbances of rock continuity (from microcracks to faults) recorded by various research methods. They can display any one

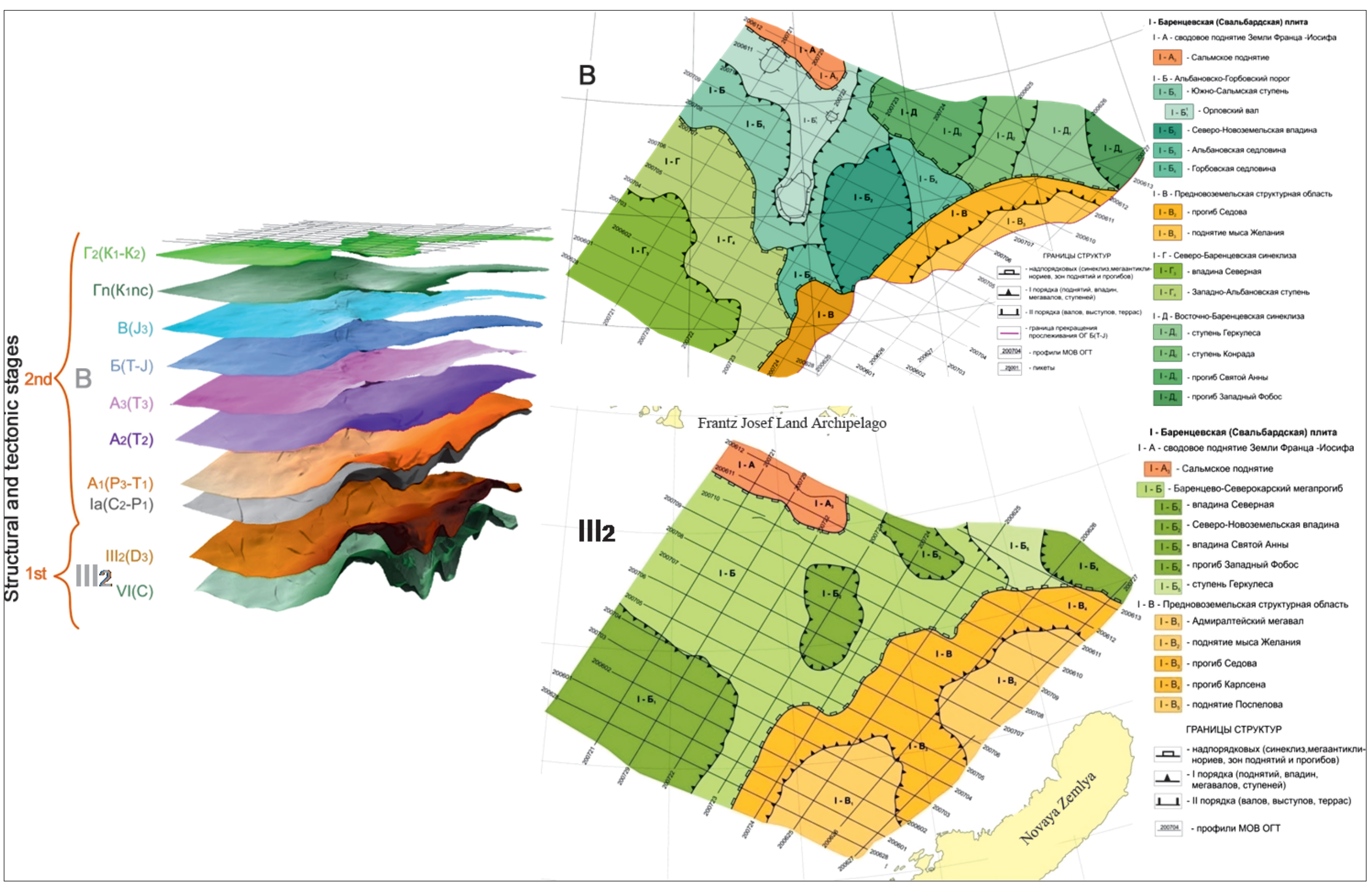

Fig. 3. Schemes of tectonic zoning along the roof of the Triassic deposits (B) and the Lower-Middle Paleozoic complex (III2) (according to the Arctic Sea Geological Expedition with the addition of authors)

measurement element, and with a combination of two or three such diagrams, two or three measurement elements can be shown (strike, direction of fall, angles of fall).

In our case, the number of structural-tectonic disturbances was plotted as a percentage, the total number of measurements was taken as 100%, and the percentage of measurements for each group was calculated.

For the analysis, three levels of structural-tectonic disturbances were used, identified according to the results of spatial modeling (Nikitin, Ivanov, 2016).

The first level in terms of the relative density of the distribution of structural-tectonic disturbances is represented by two fault systems (Fig. 4).

The first system of faults is located in the azimuth range of the NNW 360° – NNE 20° and SSW 190° – SSE 170°. The second system of faults is in the azimuth section of the SE 135° – ESE 120° and WNW 280° – NW 315°.

Fault systems are obliquely crossing each other at an angle of ≈40 °. The identified two fault systems are a consequence of the manifestation and identify two differently oriented regional (?) Stress fields in the history of the sedimentary cover.

The second level in terms of the relative density of the distribution of structural-tectonic disturbances is represented mainly by the north-north-western strike in the azimuth section of the NW 315 ° – NNW 370 ° and SSE 10 ° – SE 135 ° (Fig. 5).

The constancy of the strike of structural-tectonic disturbances is noted, which indicates that the faults are of one genesis and age range. Such a deformation structure is an element of self-organization of sedimentary rocks under conditions of constant exposure to excessive

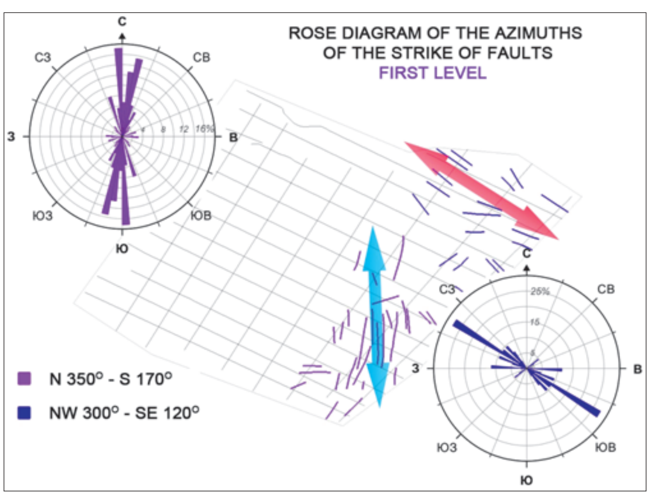

Fig. 4. Scheme of the first level of structural-tectonic disturbances. Rose diagram of spatial orientation of structural and tectonic disturbances. The rose diagram shows the azimuths of the strike of faults in the horizontal plane, the length of the petals corresponds to the total length of the faults with the corresponding strike azimuth in the selected scale

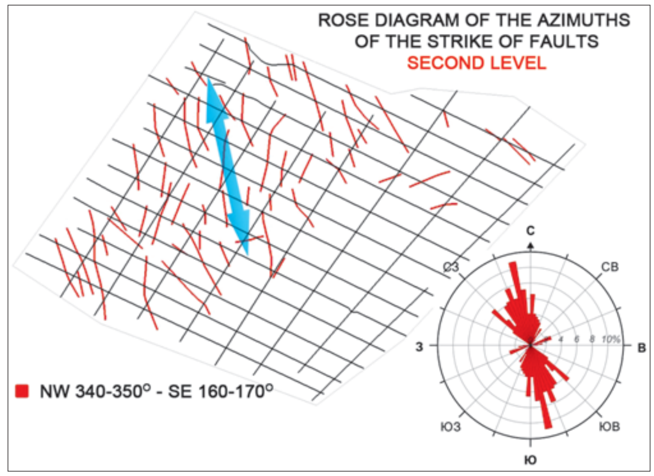

Fig. 5. Scheme of the second level of structural-tectonic disturbances. The detailed description see in Fig. 4

stresses and a natural condition of existence at constant equilibrium.

The third level in terms of the relative density of the distribution of structural-tectonic disturbances is represented by two fault systems (Fig. 6).

The first system of faults is located in the azimuth range of the NW 320° – NNW 360° and SSE 160° – SE 160°. The second system of faults is located in the azimuth range of the SW 225° – SE 135° and NW 315° – 45° NE.

Fault systems are orthogonal to each other and form an angle of ≈90°. The identified fault systems identify two differently oriented regional (?) stress fields in the history of the sedimentary cover.

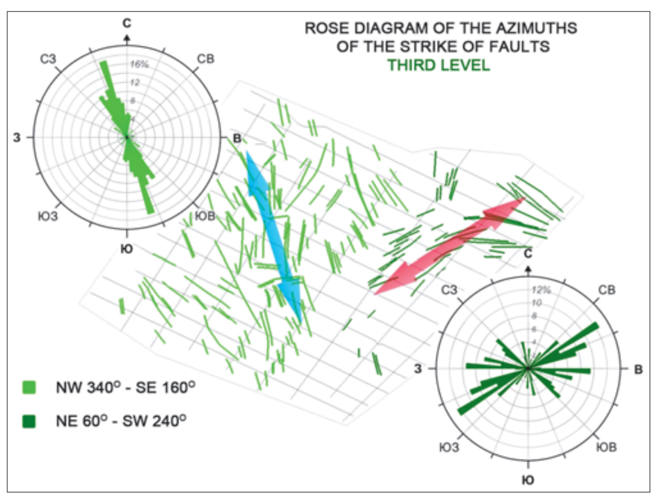

Fig. 6. Scheme of the third level of structural-tectonic disturbances. The detailed description see in Fig. 4

Statistical analysis

Statistical analysis was carried out on 23 signs of different types of geological and geophysical data (information on eleven reflecting horizons, dividing structural-material complexes and geophysical fields). To exclude features that have strong correlations from the processing, a matrix of paired correlations between the values of the absolute marks of reflecting horizons (RH) and the thickness of the structural-compositional sedimentary complexes (SCC) belonging to the Lower-Middle Paleozoic structural tectonic level was calculated.

According to the results of processing, there are strong correlations between the absolute marks of all RH and the thickness of the rocks separating them from the SCC. This indicates the inheritance of the development of the territory and individual structures within the framework of this structural sedimentation cycle. Therefore, for further joint processing with geophysical fields, only the altitude values for RH VI and the power of the SCC between RH VI and RH III2 were used. Moreover, it is precisely for the surface III2 (D3) that there is a structural-tectonic scheme. It is used for a comparative analysis of the results of classification.

As a method of multidimensional classification, a type of cluster analysis method was used – the K-means method. The advantage of the method, as in the whole cluster analysis, is the ability to split objects by several indicators. At the same time, cluster analysis does not impose any restrictions on the type of objects under consideration, which makes it possible to consider sets of initial data of arbitrary nature in various units of measurement.

This classification method is based on dividing the set of the studied objects into statistically homogeneous aggregates or clusters. The resulting clusters consist of statistically similar objects. Objects belonging to different clusters should differ significantly. In our case, the elementary units of a territory of 500×500 meters in size, corresponding to the cells of the constructed mesh surfaces are objects of clustering. The selected clusters will correspond to parts of the territory that are supposed to be interpreted from the standpoint of tectonic zoning. As a result of the classification, for each cell of the territory we get an additional attribute – a class number from 3 to 10, depending on the partitioning parameters. Based on this attribute, a point map of the coordinates X, Y is visualized on the screen and compared with the existing pattern of structural-tectonic regionalization along the surface III2 (D3).

According to the number of clusters formed, zoning schemes of the territory for 4, 5, 6, 7, 8, 9 and 10 classes are sequentially constructed (Fig. 7).

When reviewing the results, it is noted that the boundaries of superorder structures stand out by 70%, starting with the 7th grade and more (Fig. 7c-e).

A complete coincidence of structures, parts and boundaries is noted for superorder structures, for example, for the Salmsk uplift, for the Novaya Zemlya forearc structural region. The structures of the first order clearly delineate the North depression in the southwest, and the Admiralty megaswell in the southeast of the region.

The most optimal, from our point of view, is the result of classification into 8 classes. In Fig. 8 classes are adapted to the color palette of the original map.

After constructing a three-dimensional model of the map obtained as a result of the classification into 8 classes taking into account faults, we can judge that the structures of the first order have a more complicated morphology. So the 3rd class, framing the Novaya Zemlya forearc structural area, is a transitional area with the Barents – North-Kara depression. The region allocated to the 3rd class, allocated in the northern part of the territory, can also be considered as a transitional to the arched uplift of Franz Josef Archipelago (Fig. 9).

For a comparative assessment of the values of the distributions of individual signs, on the basis of which clustering was carried out, “box” diagrams were used. In general, this type of diagram consists of two elements – a “box” and “whiskers” or “tails”. When preparing data for such a presentation, the entire range of available values is divided into quartiles with the boundary values of 25, 50, and 75%. Central quartiles – 25-50% and 50-75% – are graphically placed in a rectangle – box. Extreme quartiles – 0-25% and 75-100% – are depicted as linear forms called tails or whiskers. In the center of the box is a median value in the form of a point or line. The graph allows us to estimate the symmetry of the distributions and the spread of values. In addition, outliers and hurricane values that are significantly different from the normal distribution predicted for a given data set (by mean value and median) and deviations in values of more than three standard deviations are shown in a circle or asterisks. An important advantage of box diagrams is the possibility of simultaneously comparing several distributions.

Figure 10 shows the box diagram for the absolute values of the reflecting horizon VI for all selected classes of objects. Based on the analysis of the diagram (Fig. 10), it is noted that according to the median values and the 50% center line, the classes are individualized 5, 6, 7 and 8, belonging to the depressions of the Barents-North-Kara deflection and the Novaya Zemlya forearc structural region. Statistically indistinguishable classes for this indicator are bordering classes 2 and 3. They correspond to the transition zone between negative and positive superorder structures. Classes 1 and 4 are also statistically similar, however, in terms of their location on the map, the first corresponds to the main bed of the Barents-North Kara deflection, and the 4th corresponds to the structure that separates the uplifts within Novaya Zemlya forearc region.

Figure 11 shows the box diagram of the thickness of the deposits between RH VI and III2 for all selected classes of objects.

By the nature of the distribution of power and the median value (2900 m), 3rd class is sharply

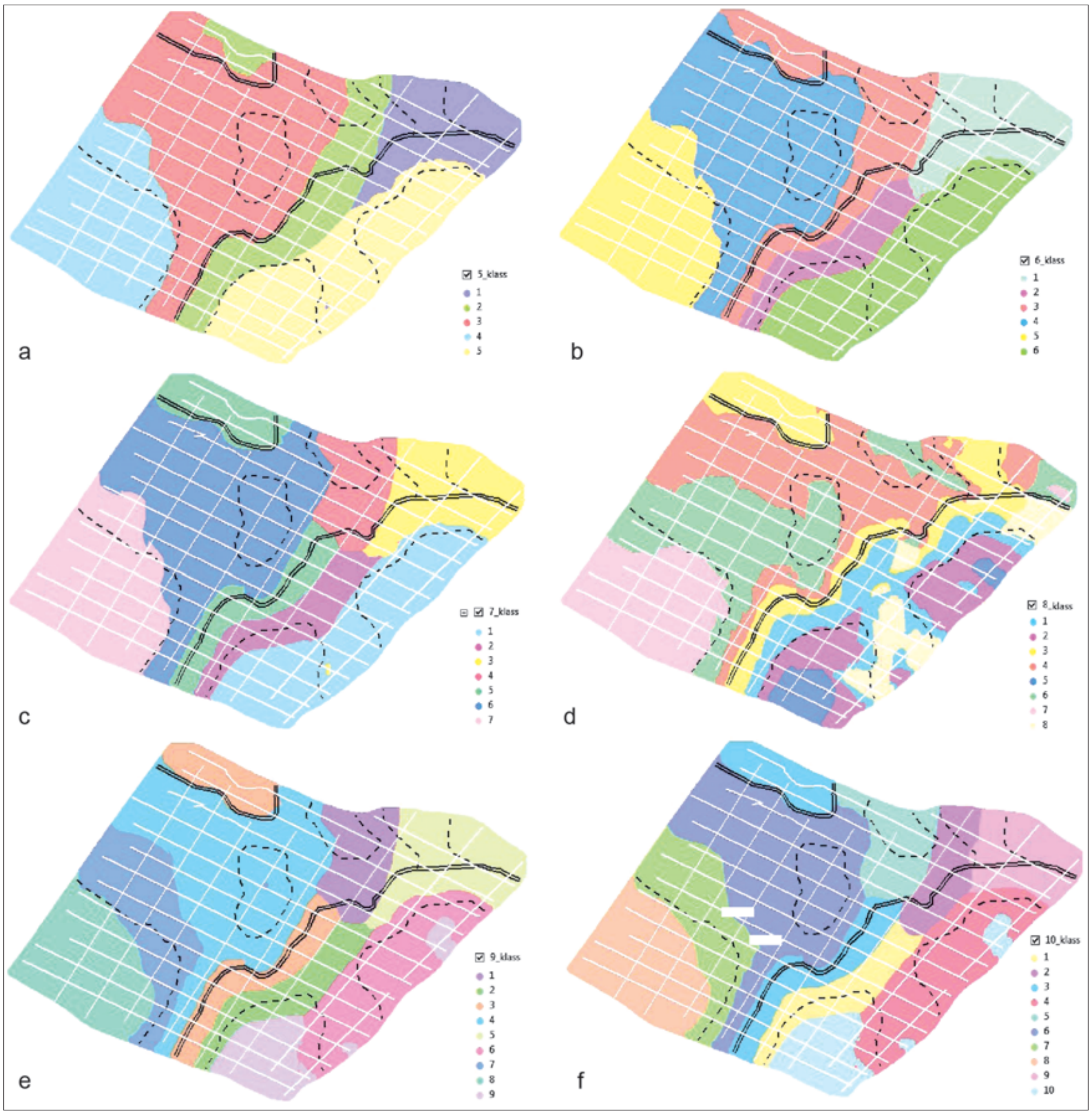

Fig. 7. The result of clustering by the K-medium method of the Lower-, Middle Paleozoic structural-tectonic: a – 5 classes; b – 6 classes; in – 7 classes; g – 8 classes; d – 9 classes; e –10 classes; - - - – the boundaries of the structures of the first order; === – boundaries of superorder structures

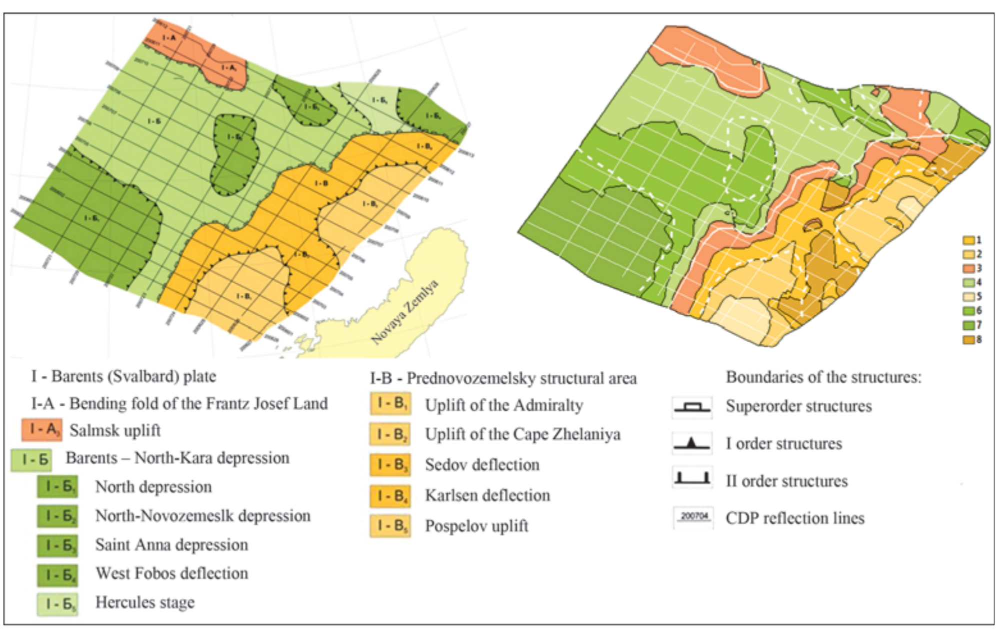

Fig. 8. Example of comparison of the initial structural map and a map constructed using multidimensional analysis. Shows the division into 8 classes

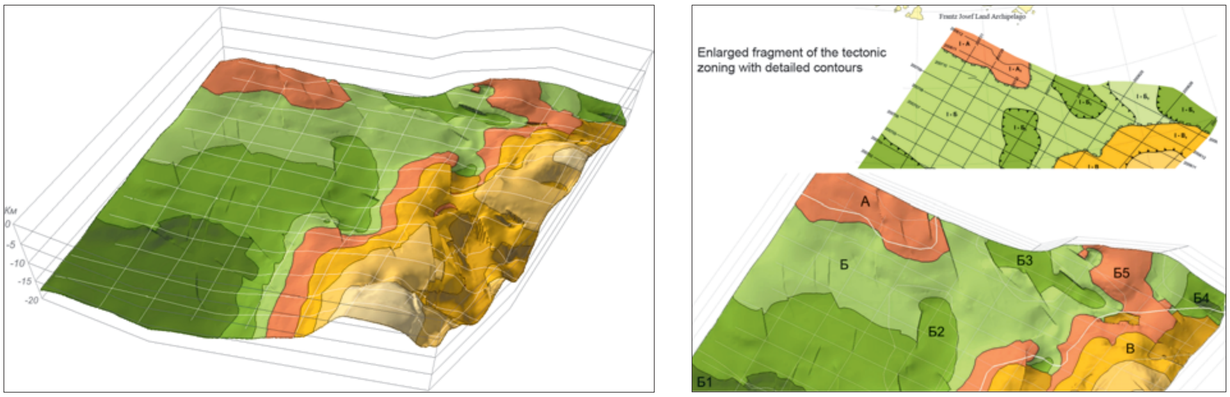

Fig. 9. Volumetric model of the RH VI with superimposed boundaries of tectonic structures obtained according to the statistical processing

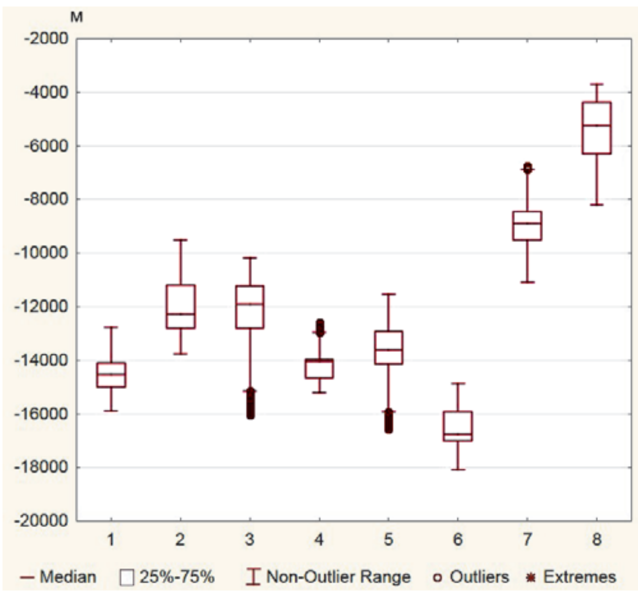

Fig. 10. Box diagram of the distribution of absolute marks for selected classes of objects

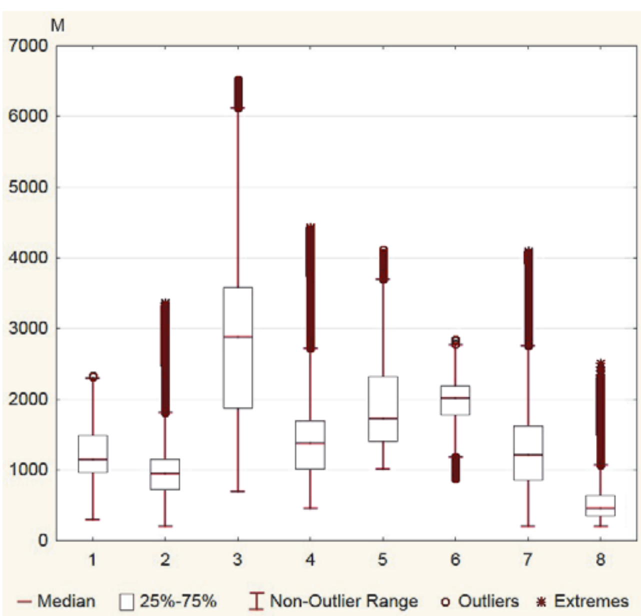

Fig. 11. Box diagram of the distribution of power between RH VI and III2 for selected classes of objects

distinguished. According to these parameters, it is unambiguously separated from the 2nd class (the median value is 1000 m), despite the fact that they are statistically similar in the values of their absolute marks (Fig. 10). The characteristics of the power distribution also clearly allow us to distinguish the 8th and partially 2nd classes, the first corresponds to the areas with the maximum absolute marks of the territory, the last – with the minimum. The remaining classes – 1, 4, 5, 6 and 7th – provide significantly overlapping distributions and can be interpreted only with the help of information about their spatial distribution.

Characteristics of geophysical fields

In the distribution of the absolute values of the magnetic field for the selected classes of objects, distinctly individualized groups are absent (Fig. 12).

In Figure 12, several groups of classes with a close distribution of the magnetic field are distinguished by span and median values. These are classes 1, 2 and 4, spatially corresponding to the slope parts of the uplift of the Novaya Zemlya forearc structural region and the flattened part of the Barents – North Kara deflection. The second group of classes (3 and 5) has a similar range of distributions with a higher median value for the 5th class. These classes are distinctly separated spatially: the 3rd corresponds to the near-slope parts of positive supra-order structures, the 5th corresponds to their apical parts. The nature of the distributions and the absolute values of the magnetic field for the 7th and 8th classes are very close, with different spatial localization within the site. The smallest scatter of values or a uniform character has a magnetic field within the 6th class – 30-50 nT. This class corresponds to the intermediate depths of the Barents – North Kara deflection.

The box diagrams of the distribution of the gravitational field values for the selected classes of objects in Fig. 13 are ranked by median values.

According to the absolute values of the gravitational

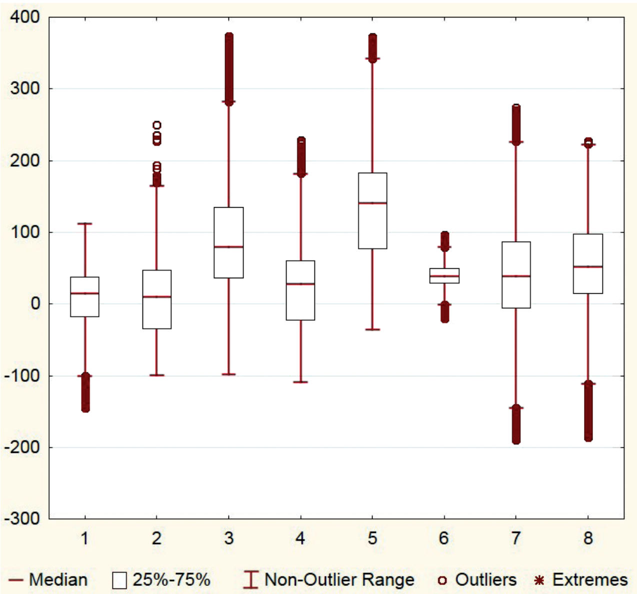

Fig. 12. Box diagram of the distribution of magnetic field values for selected classes of objects

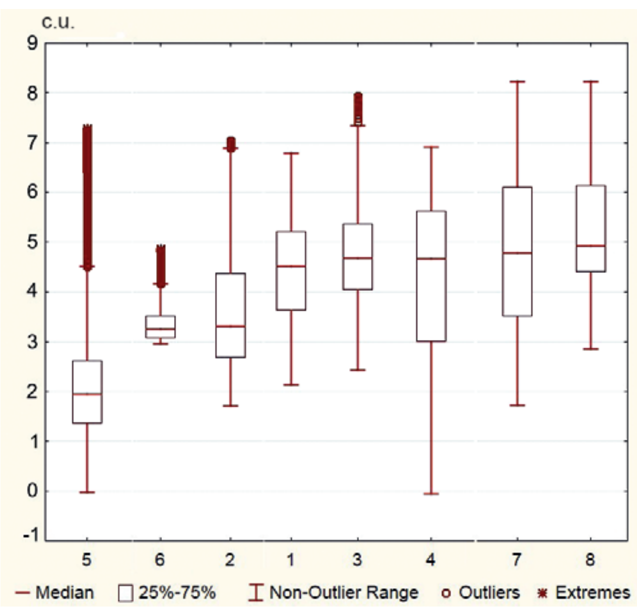

Fig. 13. Box diagram of the distribution of gravitational field values for selected classes of objects

field, only the 5th class can be distinguished, which corresponds to the apical part of the Novaya Zemlya forearc structural region. It has minimal absolute field values, a symmetric distribution, and an average 50% of the distribution, overlapping with other distributions only in the tail portions. The minimum dispersion, as in the case of a magnetic field, has a gravitational field for the 6th class. The distributions of the gravitational field for the other selected classes largely overlap and have close median values.

Thus, none of the individual signs of a structural nature or a geophysical field makes it possible to unambiguously regionalize the territory with the necessary degree of detail. For this, it is necessary to share the complex of features and methods of multivariate statistical analysis. The classification values of individual signs can be estimated based on factor loadings.

Conclusions

The objective performance of the method of identifying classes (tectonic structures) within the study area by statistically sound methods independent of the subjective factor has been determined.

The result of the zoning of the Lower Middle Paleozoic complex of rocks is quite comparable with the existing tectonic schemes, moreover, he specifies them. The boundaries of the superstructure are programmed at 70%, starting with 7 or more division classes. The boundaries of the structures of the 1st order are represented by a more complex morphology with a detailed internal structure and are partially outlined by discontinuous disturbances.

The most important basis for tectonic zoning of a sedimentary cover are structural maps of reflecting horizons taking into account tectonic disturbances.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (grant No. 18-35-00236 mol_a) and the program of the Presidium of the Russian Academy of Sciences P47.

References

Fedukhin N.V. et al. (2002). Model' stroeniya litosfery Barentsevskogo shel'fa po dannym glubinnoy seysmorazvedki [The model of the Barents shelf lithosphere structure according to the deep seismic studies]. Murmansk: Fund of the Marine Arctic Geological Expedition (MAGE). (In Russ.)

Khutorskoy M.D., Viskunova K.G., Podgornykh L.V. et al. (2008). Geotemperaturnaya model' zemnoy kory Barentseva morya: issledovaniya vdol' geotraversov [Geotemperature model of the Barents Sea crust: research along geotraverses]. *Geotektonika = Geotektonics*, 2. pp. 55-67. (In Russ.)

Nikitin D.S., Gorsky P.P., Khutorskoy MD, Ivanov D.A. (2017). Analysis and numerical simulation of the potential fields in Barents sea Northeastern part. *Monitoring, nauka i tekhnologii*, 1(30), pp. 6-15. (In Russ.)

Nikitin D.S., Ivanov D.A. (2016). Structural and tectonic conditions of oil and gas content of Northeast part of the Barents sea shelf. *Monitoring, nauka i tekhnologii*, 2(27), pp. 48-54. (In Russ.)

Nikitin D.S., Ivanov D.A., Zhuravlev V.A., Khutorskoy M.D. (2015). Three-dimensional geological and geothermal model of sedimentary cover in the north-eastern part of the Barents Sea shelf in connection with the development of hydrocarbon resources. *Georesursy = Georesources*, 1(60), pp. 13-19. https://doi.org/10.18599/grs.60.1.3 (In Russ.)

Pavlov S.P., Shlykova V.V., Grigor'eva B.M. et al. (2015). Otchet po ob'ektu «Utochnit' geologicheskoe stroenie i perspektivy neftegazonosnosti vostochnogo borta Severo-Barentsevskoy vpadiny» [To clarify the geological structure and petroleum potential of the eastern side of North Barents depression. Report]. Murmansk: MAGE JSC. (In Russ.)

Pavlov S.P. (2012). Geological structure and petroleum potential of the north-eastern part of the Barents Sea according to geophysical data. *Diss. cand. geol.-min. nauk* [Cand. geol. and min. sci. diss.]. Murmansk. (In Russ.)

Roslov Yu.V. et al. (2002). Otchet o sozdanii modeli glubinnogo geologicheskogo stroeniya Barentsevomorskoy neftegazonosnoy provintsii na osnove novoy tekhnologii kompleksnoy obrabotki dannykh MOV, MPV i GSZ na opornykh profilyakh v perekhodnoy zone «susha-more» [Report on the modelling of deep geological structure of the Barents Sea oil and gas province on the basis of new technologies for data integration]. St. Petersburg: GNPP «Sevmorgeo». (In Russ.)

Sakulina T.S., Verba M.L., Ivanova N.M., Roslov Yu.V., Belyaev I.V.

(2007). Glubinnoe stroenie severnoi chasti Barentsevo-Karskogo regiona vdol' profilya 4-AR [The deep structure of the northern part of the Barents-Kara region along the 4-AR profile]. Sbornik materialov 7-go foruma: Toplivno-energeticheskii kompleks Rossii [Coll. papers: 7th forum «Fuel and Energy Complex of Russia»]. St.Petersburg, pp. 371-374. (In Russ.)

Shipilov E.V., Tarasov G.A. (1998). Regional'naya geologiya neftegazonosnykh osadochnykh basseynov Zapadno-Arkticheskogo shel'fa Rossii [Regional geology of oil and gas bearing sedimentary basins of the Western Arctic shelf of Russia]. Apatity: «KNTs RAN» Publ. 306 p. (In Russ.)

Suprunenko O.I., Evdokimov N.K., Shkola I.V., Bro E.G., Dibner V.D., Makar'ev A.A., Stolbov N.M., Ustinov N.V. (1998). Perspektivy neftegazonosnosti arkhipelaga Zemlya Frantsa-Iosifa [Oil and gas potential of the archipelago Franz Josef Land]. *Geologo-geofizicheskie kharakteristiki litosfery arkticheskogo regiona* [Geological and geophysical characteristics of the lithosphere of the Arctic region], 2, pp. 153-168. (In Russ.)

Tektonicheskaya karta morey Karskogo i Laptevykh i Severa Sibiri [Tectonic Map of the Kara and Laptev Seas and the North of Siberia]. (1998). Scale 1:2 500 000. Ed. N.A. Bogdanova, V.E. Khaina. Moscow: Federal Service for Geodesy and Cartography of Russia. (In Russ.)

Velichko B.M., Shlykova V.V., D'yachenko A.B. et al. (2010). Otchet po ob'ektu «Kompleksnoe geologo-geofizicheskoe issledovanie severo-vostochnoy chasti Barentsevomorskogo shel'fa» [Integrated geological and geophysical studies of the northeastern part of the Barents Sea shelf. Report]. Murmansk: MAGE JSC. (In Russ.)

Verba M.L., Ivanov G.I. (2009). Tektonicheskaya karta Barentsevo-Karskogo regiona masshtaba 1:2500 000: neftegeologicheskii i geoekologicheskii prognoz [Tectonic map of the Barents-Kara region of 1: 2500 000 scale: oil-geological and geo-ecological forecast]. *Trudy 9-i konferentsii RAO/CIS Offshore* [Proc. 9th RAO/CIS Offshore Conf.]. St.Petersburg: KhIMIZDAT, V.1, pp. 19-23. (In Russ.)

About the Authors

Dmitry S. Nikitin – Researcher, Laboratory of Heat and Mass Transfer

Geological Institute of the Russian Academy of Sciences

7, Pyzhevsky lane, Moscow, 119017, Russian Federation

Dmitry A. Ivanov – PhD (Geology and Mineralogy), Associate Professor, Department of Historical Geology and Paleontology

Voronezh State University

1, Universitetskaya sq., Voronezh, 394018, Russian Federation

Manuscript received 25 July 2018;
Accepted 12 Ocotober 2018; Published 30 November 2018