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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

In the last decade new data on the structure of the sedimentary cover of the Barents Sea shelf northern part have been obtained. One of the promising methods for studing structural and tectonic features, as well as distribution of geothermal parameters in space is three-dimensional modeling. Based on information obtained the paper suggests geological and geothermal three-dimensional (3D) model of the sedimentary cover of the northern part of the Arctic continental shelf of Russia. The model provides an unique opportunity to analyze regional and local geological structure of the sedimentary cover and modern geodynamics of the Arctic region and, in particular, thermobaric regime of the sedimentary cover, creating favorable conditions for maturation of organic matter.

Keywords: sedimentary basin, modeling, oil and gas content, heat flow, temperature, frame model, block model.

Arctic continental shelf of the Russian Federation is considered as strategic reserve of oil and gas industry and basis for the national security. The area of the Russian shelf is 6.5 million km^2, including 4.1 million km^2 of exploration targets within which the initial total recoverable hydrocarbon resources are about 100 billion tons of reference fuel (Varlamov et al., 2011).

The main part of recoverable reserves by operational and infrastructural criteria is related to the Barents (including Pechora) and Kara Seas. The main prospecting operations were focused in here in accordance with scientific advices. As a result, the existence of large Western Arctic oil and gas province was proven (Gramberg et al., 2000).

Until recently, poorly studied areas in the north of the Arctic shelf, in particular the Barents Sea were one of the few places in the northern seas where it was possible to discover large hydrocarbon deposits. Complex geophysical works conducted by JSC MAGE highlighted the structure of the North Barents depression. JSC MAGE has worked out a regional network of complex geophysical profiles totaling 7,000 linear km to clarify geological structure and hydrocarbon potential of the eastern side of North Barents depression during 2006 and 2007 (Fig. 1) (Pavlov et al., 2008).

Complex of geological and geophysical studies included 2D CDP seismic reflection method, above-water gravimetry and differential hydro-magnetometry. Later, in 2009 interpretation of regional network of the profiles with a mesh size of 25x35 km was carried out to construct geological model and reconstruct structural-tectonic evolution in the northern part of Barents Sea (Velichko et al., 2010). This area has the highest potential for hydrocarbons among offshore regions of the Russian Federation (Khlebnikov et al., 2009).

Studies conducted in this poorly studied region obtained new data on structural-tectonic features of this part of the Barents Sea and clarified geological history of the region as a whole. In particular, during the works the sedimentary cover studied to a depth of 17 km; 8 seismic-stratigraphic complexes are allocated and traced, dissected to 14 seismic-stratigraphic subcomplexes and 12 seismic layers (Kazanin et al., 2011).

Based on the results of studies carried out in water area and surrounding land a complex geological and geothermal modeling of the sedimentary cover was performed using software EasyTrace, RockWorks, Surfer, ArcView/ ArcGIS, Micromain, Termgraf, Tecplot (Pavlov et al., 2008; Velichko et al., 2010; Pavlov, 2012; Bogolepov et al., 1990; State geological map..2004a; 2004b; Geology and natural resources ., 2004; Korotaev, Zakirov, 1981; Lebedev et al., 1988; Sorokov, Krasnova, 1993; The structure of lithosphere., 2005; Stupakova, Kiryukhina 2001, Tectonics., 1978; Tectonic map., 1998; Physical

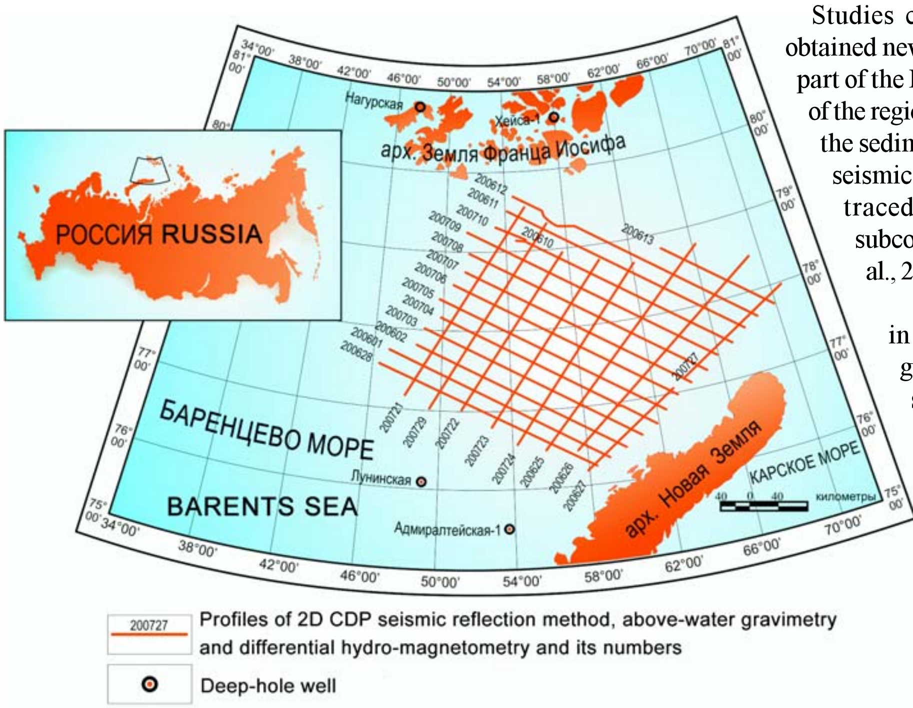

Fig. 1. Overview map of the northern part of the Barents Sea shelf with a network of integrated geophysical profiles.

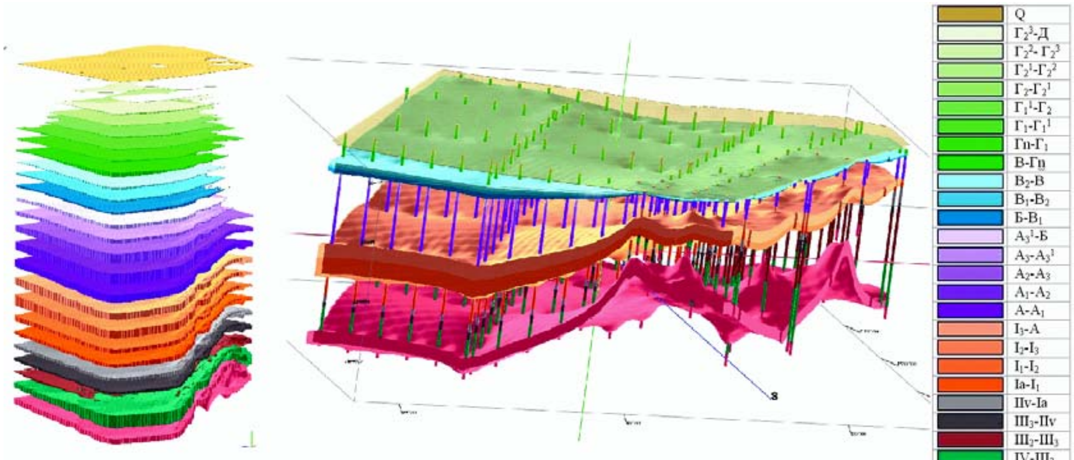

Fig. 2. The results of wireframe model constructed in the Rock Works system.

properties., 1984; Khutorskoy et al., 2008; Shipilov, Tarasov, 1998; Shipilov, Yunov, 1995; Polikarpov et al., 1992; Roslov et al., 2002; Fedukhin et al., 2002 et al.).

Geological structure of the north-eastern part of Barents Sea shelf has two structural-tectonic levels, separated by regional stratigraphic and angular unconformity (Pavlov et al., 2008). Pre-Paleozoic folded basement (sometimes identified as a separate level (Varlamov et al., 2011)) and Lower-Middle Paleozoic lithologic and stratigraphic complex are related to the lower level. The upper floor consists of the Upper Devonian to Quaternary deposits. There are five lithologic and stratigraphic complexes within this level. They reflect significant changes in the structure of sedimentary cover in the area studied.

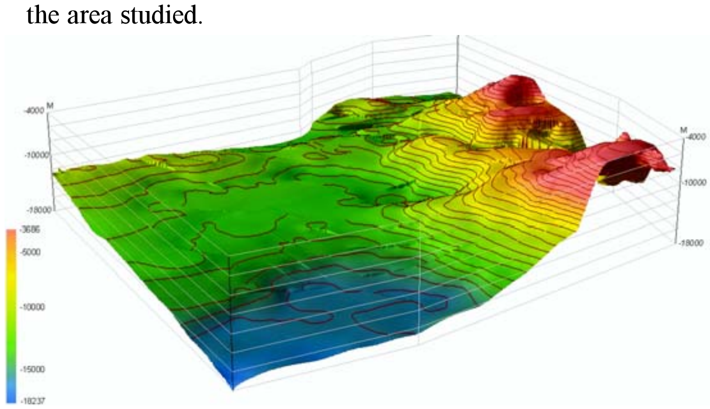

Fig. 3. Digital model of the reflecting horizon VI considering faults. Vertical scale is increased by 5 times.

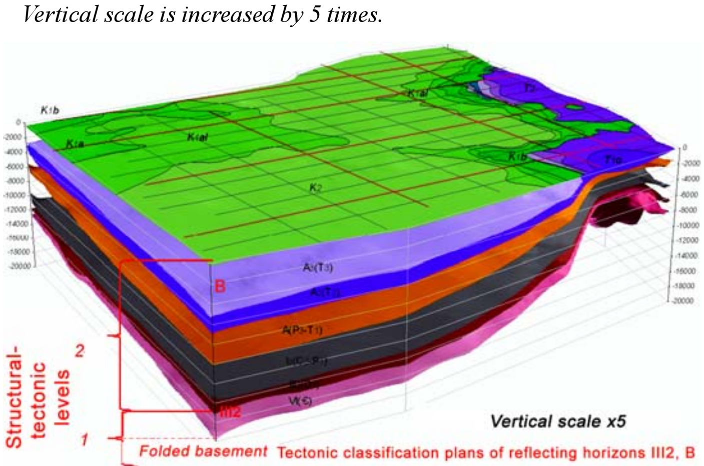

Fig. 4. Structural model of the sedimentary cover in the northern part of Barents Sea shelf combined with the geological basis, based on structural maps of 11 reflecting horizons.

Within the sedimentary cover 26 reflecting horizons are allocated confining conveniently homogeneous seismic and stratigraphic complexes. For 11 reference reflecting horizons there are structural maps with tectonic elements. They are recorded in seismic sections as sub-vertical zones of absence or chaotic reflected configuration and considered as feeding channels for dyke bodies (Varlamov et al., 2011).

Wireframe model of the sedimentary cover was created at the initial stage (Fig. 2). We used 7 seismic geological profiles (200601, 200705, 200709, 200612, 200722, 20625, 200626) (Interpretation: V.A. Zhuravlev, S.P. Pavlov, 2008). Geological structure is defined by 25 isolated and tracked reflecting horizons, limiting conveniently homogeneous seismic and stratigraphic complexes. They are obtained by re-interpreted time sections of CDP reflection method and available geological and geophysical data (Pavlov et al., 2008).

Data for the model formation were prepared by using picket network along the profiles and additional condensation points

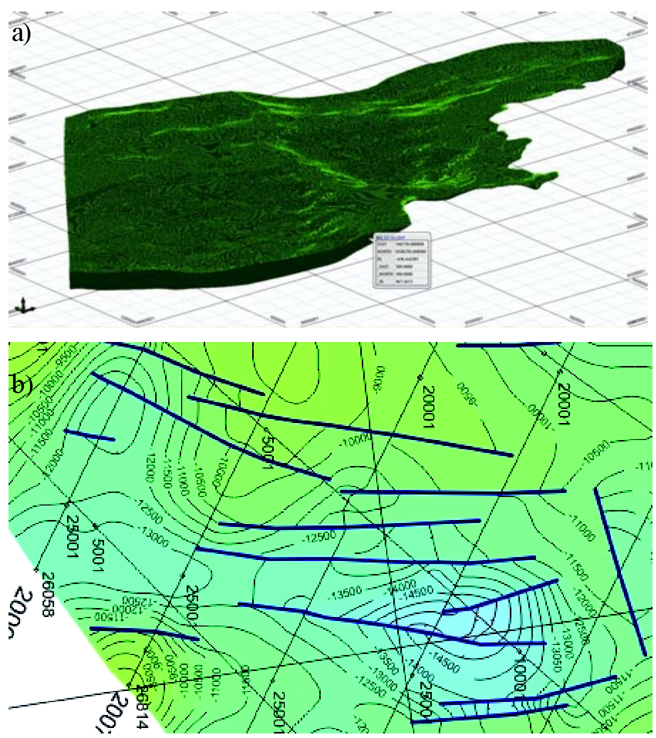

Fig. 5. Example of reservoir block model: a – reservoir block model confined by reflecting horizons G_2-G_n; b – example of processing a complex dislocated surface.

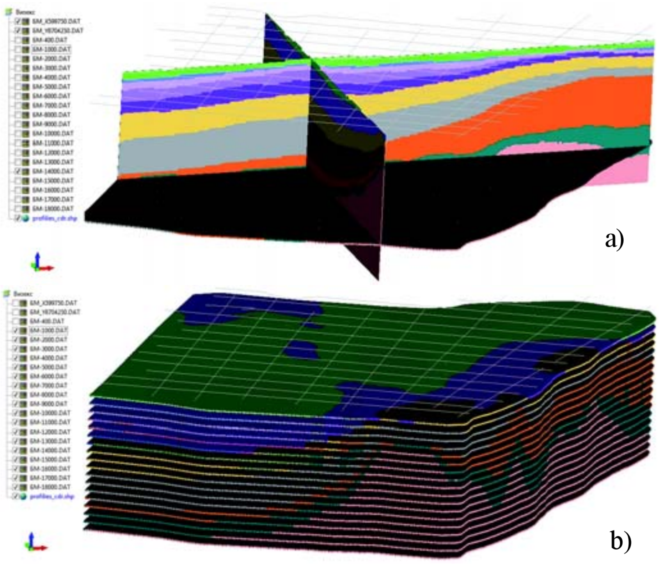

Fig. 6. Regular block model by 11 seismic and stratigraphic complexes: a – orthogonal sections of regular block model; b – horizontal sections of block model with a pitch of 1 km.

with a pitch of 25 kilometers, for which altitude breakdown by reflecting stratified horizons of sedimentary cover were calculated. Conventionally, these observation points were accepted as wells, and the boundaries of seismic and stratigraphic complexes were limited to a thickness of 20 meters. In total, including the sea bottom, 26 numeric structural surfaces confining 25 seismic and stratigraphic complexes were built (Fig. 2).

The model is hollow skeleton type without considering any tectonic elements in the section. The obtained model gives an overview of the occurrence and spatial distribution of seismic and stratigraphic complexes.

The second stage included construction of three-dimensional model. It was made by 11 reference reflecting horizons based on structural maps with tectonic elements.

When creating digital models of surfaces we used minimum curvature method considering faults as interpolation barriers. Elevation calculation is performed independently from the right and left sides of the disruption, making it possible to simulate the block nature of these surfaces. Raster images of seismic and geological sections were linked to three-dimensional environment. It allowed digitizing tectonic fault zones and chaotic reflected configurations on the sectional plane. In conjunction with planned location of these objects, shape modeling of individual tectonic elements in the form agreed with the sections of independent bodies was performed in multi-level maps.

Figure 3 shows the structural map of reflecting horizon VI (O), representing roof of the crystalline basement. 82 interpolation barriers were considered while constructing this surface. Size of established numerical matrix was 794x1162 mesh of 500x500 meters. Faults are clearly identified in the form of steps complicating roof of the crystalline basement.

Figure 4 presents processed structural surfaces, and Pre-Quaternary geological basis is given. These surfaces are

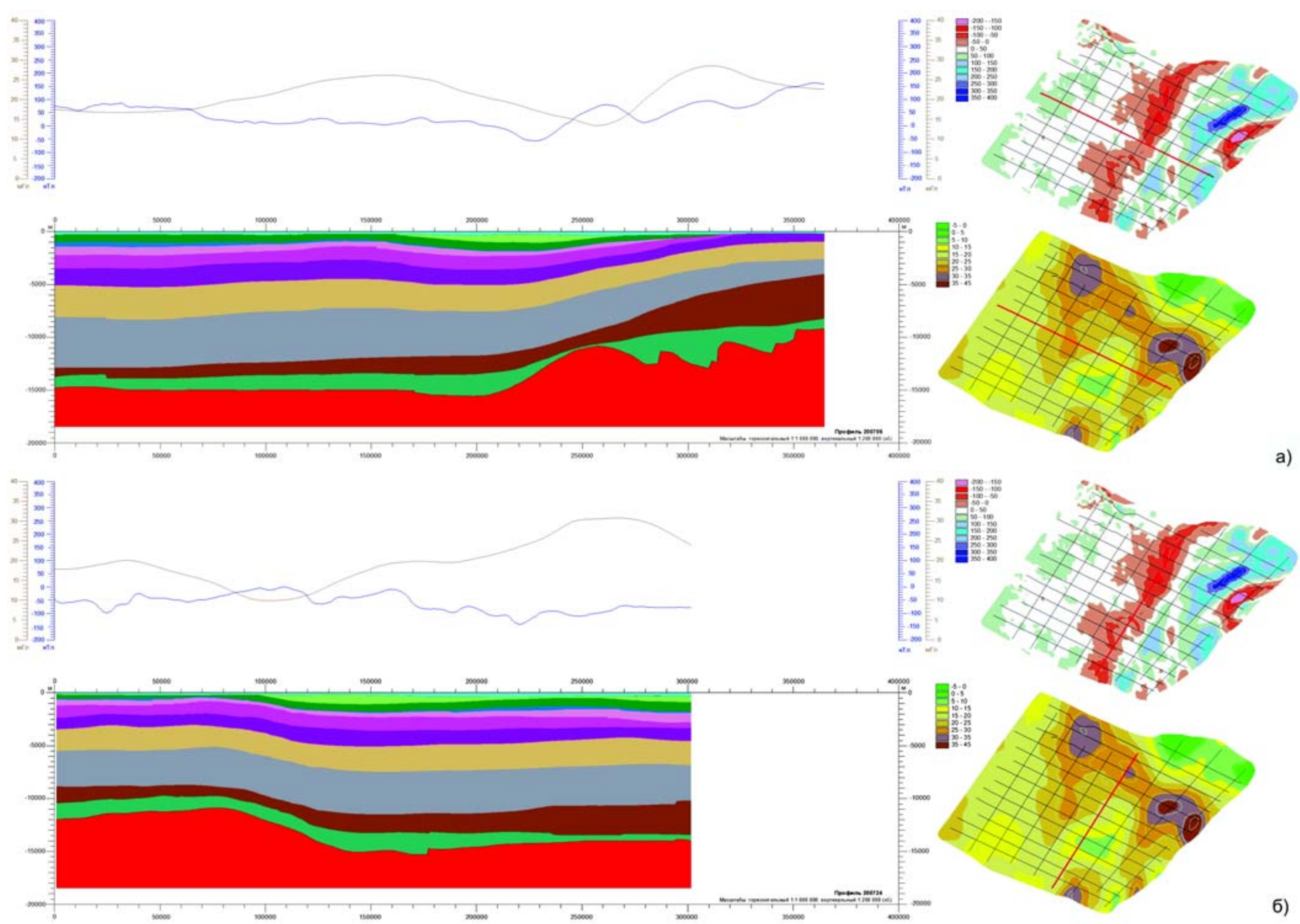

Fig. 7. Sections of block model along the profiles of CDP reflection method: a) 200724; b) 200706. Values of magnetic and gravitaty fields are shown in the form lines above the sections and in the right part of figures in the form of field maps.

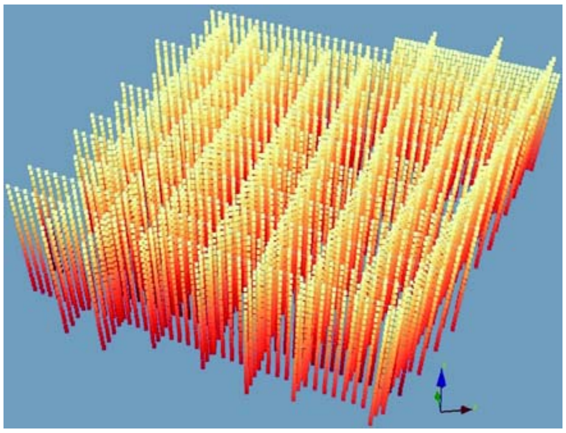

Fig. 8. Estimated temperature model based on seismic and geological profiles.

checked and adjusted for mutual disjointness, as well as agreed with geological boundaries at the level of pre-Quaternary section.

The next step consisted of modifying wireframe model to a set of reservoir block models with a mesh size 500x500 m in plane and total amount of 512,550 pieces for each unit in accordance with applicable softwares (Fig. 5). The height of mesh is equal to the unit thickness.

The fourth stage regularized reservoir block models by altitude of 200 m based on an integrated grid. Under these parameters, the total number of blocks was approximately 46.6 million pieces. The data in the file are in the form of table that assigns to them the petrophysical properties (density, thermal conductivity, residual magnetization, etc.) by the group of attributes or 3B-interpolation, followed by calculation and visualization of distributions along the orthogonal sections. Means of working with tables and three-dimensional interpolation can be involved.

To present the internal structure of block models and significant amount of data, it is easier to visualize the results in a series of sections, orthogonal coordinate axes with individual indicators (Fig. 6).

In the altitude of 0 to -18 km regular block model has 90 pieces of 200 m layers of blocks. Consistent shutdown gives an idea of distribution of properties specified in the model at different levels.

Block model it is a set of a plurality of rectangular unit blocks located in the space on a regular grid. Each block is at least determined by coordinate point of its center (X, Y, Z) and dimensions by the axes. Moreover, various quantitative and qualitative characteristics can be assigned to blocks, in this case – petrophysical properties of seismic and stratigraphic complex. In the transition from reservoir to regular block models, weighted average volume and weighted density characteristics specific calculated for individual layers.

Block model is created in the mining and geological information system Micromain. The model can be visualized in full, and can be exported in random samples in the form of tables, grids, text files. Along the vertical section a comparison of data with different surface geophysical fields is possible (Fig. 7).

Based on vertical sections obtained by vertical sectioning of a regular block model, we carried out a geothermal simulation of sea bottom minus 20 km along 22 structural geotraverses.

To solve the problem of temperature distribution, a numerical end element method with quadratic function approximation of temperature was used between the nodes of a rectangular grid in the plane of each profile, divided by 1681 (41x41) node, implemented in software Termgraf (Fig. 8).

The aim of the project for defining deep temperatures in the sedimentary cover is estimation of the depth of temperature intervals corresponding to varying degrees of catagenetic transformation of organic matter, as well as study of spatial heterogeneity of geothermal field.

According to the results of this simulation, 3D models of deep temperatures and heat flows distribution were built (Fig. 10a, b).

The diagram of temperature distribution (Fig. 9a) shows a «thermal dome» in the depth of 20 to 3 km. Apparently, its origin is connected with the refraction of deep heat flow due to heterogeneity of the structure comparatively to low thermal sedimentary cover. It is significant that localization of this «thermal dome» coincides with location of non-structural hydrocarbon traps allocated by seismic data. Spatial association of «thermal dome» and oil and gas zones is identified.

The model provides map sections of geothermal field at any depth, as well as maps of isothermal surfaces and thus determines particular temperature ranges, namely, isotherms of catagenetic temperature range (110-160°C).

Explorations of the Barents Sea shelf carried out in different

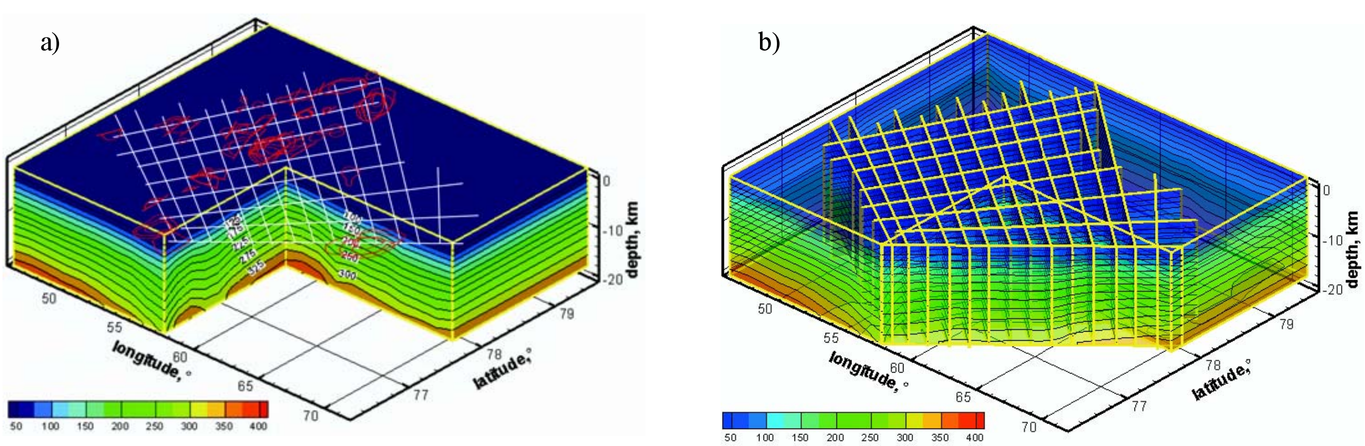

Fig. 9. 3D-model of geothermal field of the sedimentary cover in the north-eastern part of Barents Sea shelf: a) 3D-model of deep temperatures distribution; b) 2D-temperature profiles.

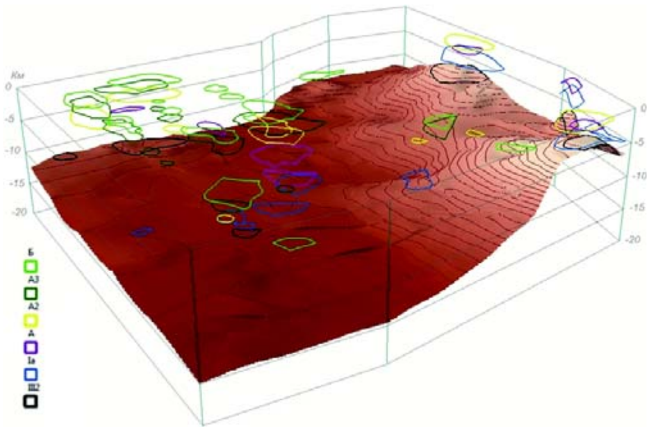

Fig. 10. Spatial distribution within the sedimentary cover of oil and gas potential areas.

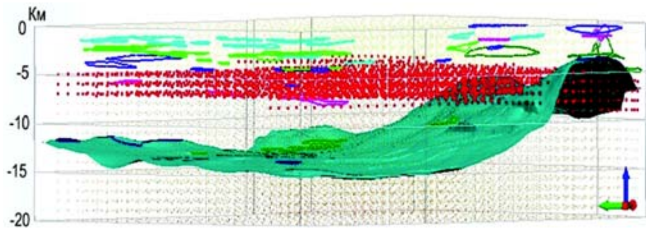

Fig. 11. Spatially combined oil and gas potential areas with catagenetic temperature interval (highlighted in red).

years helped the staff of MAGE to allocate 23 local anticlinal elevations (areas of possible non-structural traps, which include lithological traps associated with depris cones of Phobos and Sedov deflections, stratigraphically in wedging of Triassic deposits under the erosional surface) spaced by corresponding reflecting horizons (Velichko et al., 2010).

Figure 10 shows the spatial distribution of local elevations within the sedimentary cover, on the background of reflector III_2.

Further, temperature range 110-160°C was selected as catagenetic temperature range. Figure 11 shows that this range has local elevations of different ages, and they can be potential for hydrocarbon accumulations.

3D-plot of heat flow shows that its value increases within the section in the north-western direction between 40 and 70 mW/m^2, which can be explained by previously noted thermal activation in the area of Franz Victoria trough (Khutorskoy et al., 2013).

Conclusions

In the process of research authors obtained the following scientific results, the use of which in combination can serve as a basis for studying the sedimentary cover and modern geodynamics of the Arctic region. These results are as follows.

With the use of geo-information technologies we have built: a model of stratigraphic boundaries of the sedimentary cover units considering faults; wireframe model of the sedimentary cover; a regular block model created on the basis of structural surfaces.

A spatial and quantitative correlation of geothermal field, as well as localization of oil and gas potential were performed.

The depth of catagenetic conversion of hydrocarbons in the sedimentary cover was calculated.

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