

Geodynamics of the Russian Arctic Shelf and Relief-Forming Processes in the Central Kara Basin

N. O. Sorokhtin^{a,*}, S. L. Nikiforov^a, R. A. Ananiev^a, N. N. Dmitrevskiy^a, E. A. Moroz^b, E. A. Sukhih^b,
N. E. Kozlov^c, I. V. Chikirev^c, A. I. Fridenberg^d, and A. A. Koluibakin^d

^a Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia

^b Geological Institute, Russian Academy of Sciences, Moscow, Russia

^c Geological Institute of the Kola Science Center, Russian Academy of Sciences, Apatity, Russia

^d LLC “RN-Exploration”, Moscow, Russia

*e-mail: nsorokhtin@ocean.ru

Received August 19, 2021; revised March 4, 2022; accepted April 14, 2022

Abstract—The article deals with the issues of the geodynamic evolution of the Kara–Barents Sea shelf and influence of structure-forming processes on the nature of relief formation. The aggregate data obtained allows us to assume that the relief of the western part of the Russian Arctic formed as a result of polycyclic processes of closing of the Proto-Atlantic, Paleoural, and Iapetus oceans. A systematic analysis of paleogeodynamic reconstructions of the evolution of the continental crust of the Arctic region makes it possible to identify with a high degree of reliability the spatiotemporal patterns of relief formation, predict areas of localization of hazardous phenomena on the seafloor, and substantiate geomorphological criteria for searching for hydrocarbon deposits in shallow bedding.

Keywords: geodynamics, geomorphology, Arctic shelf, bottom topography, hazardous processes, graben, Kara Sea, local extension

DOI: 10.1134/S0001437022040117

INTRODUCTION

The continental crust of the western part of Russia's Arctic shelf differs sharply from oceanic crust, both in composition and structure. It is mainly formed in plate subduction zones. Part of “young” platforms could also have been formed due to the collision of island arcs and entraining of fragments of ancient oceanic crust, which includes not only mafic, but also serpentinized ultramafic rocks.

Studies of the areal characteristics of the bottom topography of a number of shelf areas, which include the formations of the Barents Sea Plate and parts of the West Siberian Plate (young platform), make it possible to solve fundamental problems, the most important of which is to determine the heterogeneous structure of the basement and geodynamic nature of the lithospheric sections buried under the sedimentary cover with oceanic crust framed by continental crustal formations. The Barents and Kara basins, as well as sections of the West Siberian Young Platform (WSP) can serve as an example of such formations. To date, there are no unambiguous ways to categorize them. The importance of this is difficult to overestimate, because it is the basis for constructing the spatio-temporal parameters of the further geodynamic evolution of the regional continental-crustal system, the recon-

struction conditions and the nature of accumulation of the sedimentary cover, the spatiotemporal distribution patterns of reservoirs and traps, as well as forecast the accumulation of economic concentrations of hydrocarbon raw materials [7, 8]. In addition, adequate reconstruction of the cause-and-effect relationships of exogenic and endogenic processes of the regional geodynamic system will make it possible to substantiate a forecast of probable catastrophic events on the seafloor and quantitatively assess them.

One novel method that confirms geodynamic constructions can be geological and geomorphological analysis aimed at solving the inverse problem [6]. This method was not chosen at random, since the parameters of its origin, the scale of manifestation, and age of consolidation were taken into account in the relief-formation processes. Therefore, the nature and features of manifestation of structure-forming processes in modern landforms of different genesis reflects the individual stages (parameters) of its past geodynamic evolution. This technique involves a geodynamic analysis of the main patterns of evolution of the lithosphere of this region and saturating the general model with textural geological, geophysical, and geomorphological data. Based on the proposed methodology, the problem of interpreting the data obtained during

the study of the bottom topography during the expeditions of the R/V *Akademik Nikolai Strakhov* in 2019–2020 is solved.

GEODYNAMIC EVOLUTION

The ancient East European Platform (EEP) in the Proterozoic repeatedly underwent breakup and collision processes with the North American Plate [11, 19]. During closing of the Svecofennian Paleoocean and formation of the Megagaea Shtille supercontinent (1.9–1.8 Ga ago), the structural–material complexes of Svecofennides of the Baltic Shield and the Ketylides of southern Greenland and Canada were formed. Owing to this, subsequently, a diamond-bearing province in the eastern part of the Baltic Shield and Arkhangelsk oblast was formed [18]. There are no reliable geological data on geodynamic processes in the Early and Middle Riphean (1650–1030 Ma ago) in this region. It is known that in the Peri-Timan region and in the Kandalaksha–Dvina basin, structures of basement subsidence and accumulation of continental terrigenous sediments with an admixture of volcanic rocks developed in the interval of 1350–1050 Ma [11]. At the same time, shelf and slope sedimentary complexes of the passive continental margin began to form at the northeastern end of the EEP [4, 9]. Apparently, the opening of the Paleoyapetus Ocean, which separated the Canadian–Greenland continent and the structural–material complexes of the Baltic Shield, took place at that time. About 1.7 Ga ago, the Megagaea Shtille supercontinent broke up, which continued until the Late Riphean (about 1000 Ma ago), when the next supercontinent in Earth’s history, Mesogea (Rodinia), formed [2, 19]. At that time, the Dalsland fold zone was formed in the northwestern part of the EEP, which is a continuation of the Grenville belt in Canada and Greenland and marks the closing zone of the Paleoiapetus Ocean [1, 19]. In the Vendian (600–535 Ma), the processes of its leveling led to the formation of continental terrigenous sediments with traces of tillites in the northwest [12] and coastal marine formations in the north near the Varanger Peninsula in Norway [17]. At the same time, shelf and continental-slope sediment accumulation continued on the northern and northeastern passive margins of the EEP. The Dalsland orogeny led to the formation of a number of regularly spaced graben structures in its northeastern regions. At the same time, the tectonic conditions of their development are characterized by an almost complete lack of magmatism in the sections, which reflects the nature of these processes. The conditions of relative tectonic quiescence in the eastern and northeastern parts of the EEP for a long time period, namely, about 815 Ma (i.e., from 1350 to 535 Ma ago), indicate the possible accumulation of huge sediment masses on the slope and foot of the continent [9].

The closing of the Paleoural Ocean and the formation of the Ural Fold System took place in the Early

Carboniferous–Early Triassic periods and was accompanied by a multistage and uneven approach of the EEP passive margin from the West Siberian Plate (WSP). At the same time, the western part of the WSP was thrust over the ancient continent, which led to the formation of the collisional structure of the Urals with a complex configuration. Spatiotemporal migration of collisional processes developed sequentially from the Early Carboniferous (about 350 Ma ago) in the south to the Early Triassic (about 245 Ma ago) in the north [3]. At the same time, the main part of the Barents Sea–Pechora Plate subducted under the South Kara segment of the WSP, forming the uplift of the Novaya Zemlya archipelago. As well, its northern part (North Kara segment) was obducted onto the Siberian Craton and formed the Taimyr fold system. The complete closing of the Paleoural Ocean is marked by the development of postcollision granites with an age of about 264 Ma [5]. As a result, the orogenic structure of the Polar Urals, the Novaya Zemlya archipelago, and Taimyr Peninsula was formed between the EEP and the WSP. At the same time, the once unified Barents Sea–Pechora Plate finally split into the Barents (Svalbard), Pechora, and North Kara plates (Fig. 1).

The Caledonian and Hercynian stages of tectogenesis resulted in a single supercontinent, Pangea, in the northern part of which the lithospheric plates of the North American, East European, and Siberian ancient cratons collided. Young lithospheric plates with the Grenville and Hercynian basements were sandwiched between them, which include the West Siberian and Barents Sea–Pechora young platforms [7]. Apparently, the Eurasian Oceanic Basin was formed at the same time, the majority of which is occupied by the Canadian or Amerasian Basin.

The collision of noncoeval lithospheric plates and folding at their boundaries led to systems of discontinuous faults with regular spatial location and specific folding. Figure 2 shows the regularities of their distribution within the Barents Sea–Kara region, which inevitably had to occur due to closing of the Iapetus and Paleoural oceans. Very important factors in understanding the evolutionary history of the region are the nature of plate collision and the geometry of interacting geological bodies. In the same period, the formation of the Norwegian–Mezen rift system occurred, which were overprinted on aulacogens of the Grenville stage of tectogenesis. As a result of the collision of Greenland, the Barents Sea Plate, and the Baltic Shield in the triple junction zone, and a little later, “the northern part of the West Siberian Platform being dragged onto the eastern part of the Barents Sea Plate, the modern structural appearance of the western part of the Russian Arctic was basically formed. As well, the fold system of the Northern Urals, the Novaya Zemlya archipelago, and the Taimyr Peninsula acquired a bizarrely curved geometric shape, which, in turn, influenced the development of a deep-seated fault system and the distribution of magmatic activity zones in

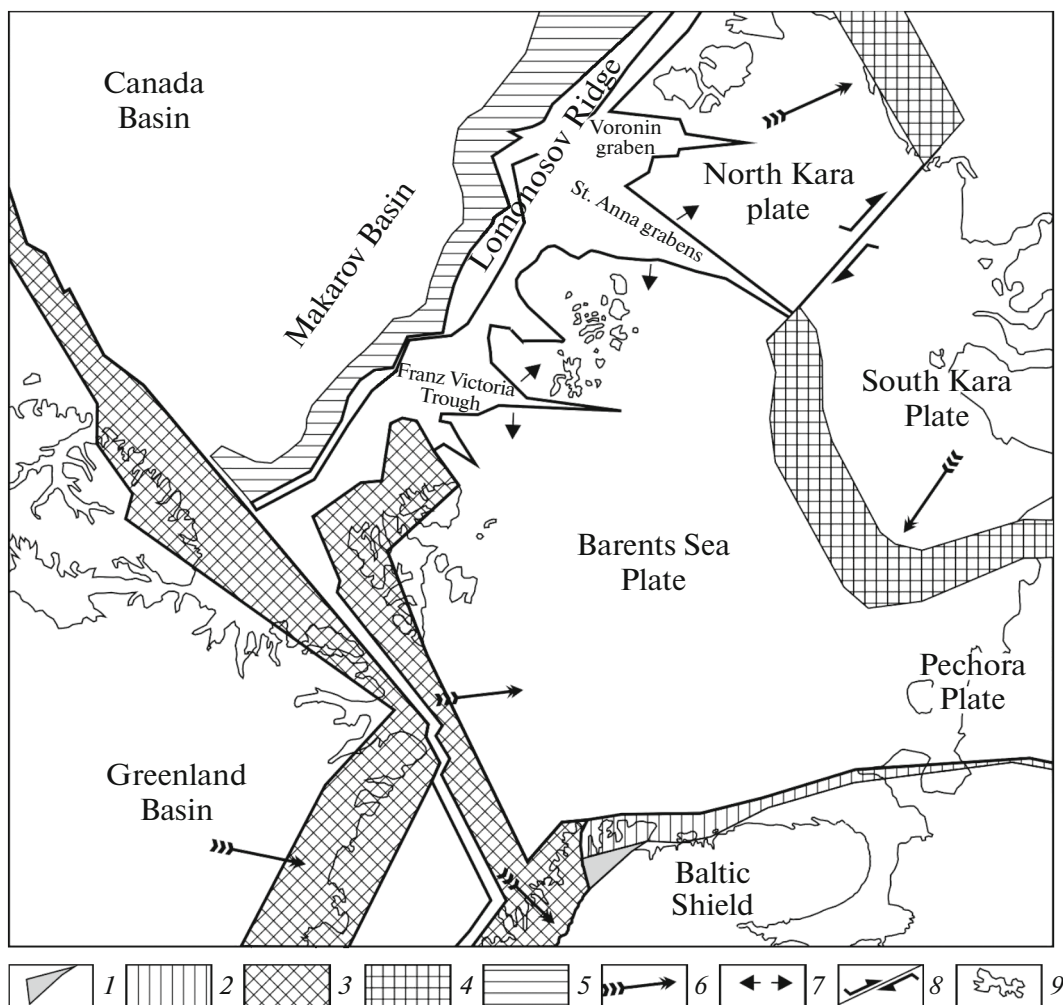


Fig. 1. Paleogeodynamic reconstruction of western part of Arctic for Paleozoic–Early Mesozoic stage (535–241 Ma ago) [5]: (1) continental terrigenous sediments of Vendian (600–535 Ma ago); (2) Middle–Upper Riphean and Vendian sedimentary complexes of shelf and continental slope of passive margin of northeastern Baltic Shield and Russian Plate; (3) fold formations of North Atlantic Caledonides in Early Ordovician–Late Devonian (480–362 Ma ago); (4) fold formations of Polar Urals, Novaya Zemlya, and Taimyr Peninsula in Early Permian–Early Triassic (290–241 Ma ago); (5) passive margin of continent; (6) generalized direction of lithospheric plate movement; (7) stress field vectors in continental lithosphere; (8) transform fault; (9) contour of modern coastline.

the region [7]. At that time, a number of specific sub-parallel wedge-shaped rifts formed on the periphery of the Barents and North Kara plates. The largest of them are the St. Anna and Voronin grabens in the east and the Franz Victoria Trough between Franz Josef Land and the Svalbard archipelago in the west (Fig. 2). The morphology of these structures indicates extension processes of the northern part of the Barents Sea Plate with clear signs of rotation. This is indicated by the fact of their wedge-shaped opening during the active phase of formation. The origin and further development of these structures are closely related to the dynamics of lithospheric plate interaction during closing of the Paleoural Ocean.

It should be noted when lithospheric plates of the same type collide, the older one always subducts under

the younger [10]. In our case, the basement of the Barents Sea Plate is composed of multifold formations of pre-Riphean and Riphean structural-material complexes, while similar structures of the West Siberian Plate are represented by Paleozoic–Triassic formations. Meanwhile, the northern part of the Siberian Craton was formed by ancient Archean and Lower Proterozoic granite-gneiss complexes.

The closing of the northern part of the Paleoural Ocean in the Permian–Early Triassic led to the collision of several lithospheric plates. The collision of the Barents Sea and West Siberian young lithospheric plates was complicated by their collision with the ancient Siberian Platform. As a result, the Barents Sea Plate subducted under the younger WSP in the south and simultaneously thrust over the ancient Siberian

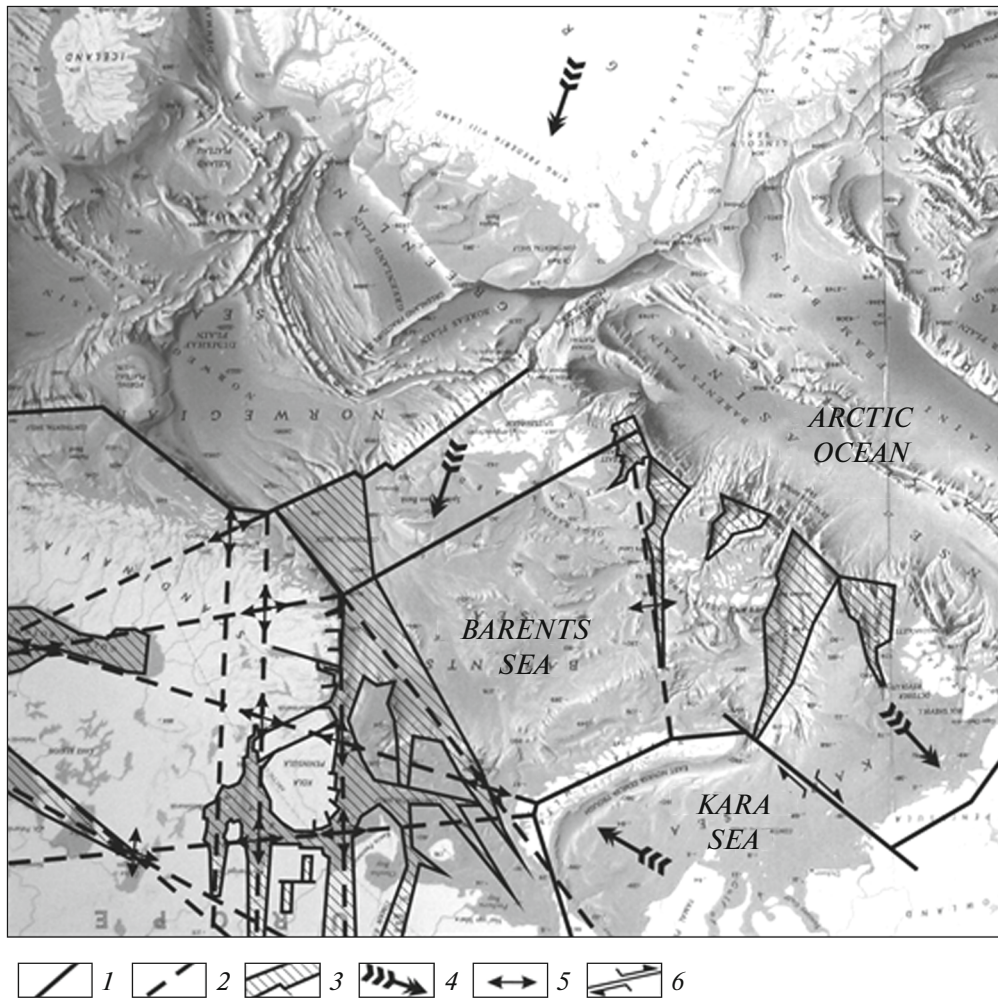


Fig. 2. Scheme of faults in western part of Russian Arctic in Paleozoic–Early Mesozoic (535–241 Ma ago) [6]: (1) lithospheric plates boundary; (2) main lineaments formed in continental lithospheric plate; (3) continental rifts; (4) generalized vector of lithospheric plate movement; (5) stress field vectors in continental lithosphere; (6) transform fault.

Plate in the north. Such a complex configuration of the triple junction of the collision zone formed a right-lateral strike-slip transform fault that displaces its Novaya Zemlya and Taimyr segments (Fig. 2).

The principal kinematic diagram of this relief-forming geodynamic process is shown in Fig. 3. If we assume that the Barents Sea Plate moved progressively and rectilinearly with respect to the immobile and eastwardly located lithospheric plates, and the friction coefficient in their interaction zone was equal to zero, then in the ideal case, the kinematic scheme shown in Fig. 3a will occur. In reality, the lithospheric plate plunging into the mantle always experiences a much greater friction force than the obducting one. Consequently, the rate of thrusting of the southern part of the Barents Sea Plate was much lower than that of its northern part. This indicates that the geodynamic conditions shown in Fig. 3a is fundamentally unachievable in nature. It turns out that the velocity V_1

is always greater than velocity V , which must inevitably cause tensile and compressive strains regularly distributed in the body of the studied plate. Thus, the northern segment of the Barents Sea Plate must inevitably move at a higher speed than its southern part, and wedge-shaped fractures must have appeared in its body, which fanlike divided the northern part of the plate into smaller segments (Fig. 3b). In addition, the transform fault formed at the plate boundary, which is represented by the North Siberian sill, should have been accompanied by compression and buckling deformations, leading to isoclinal folding in the area of its development [13]. In addition, the difference in the rates of movement of individual lithospheric blocks in the body of the plate should have caused their rotation with respect to each other. According to this scheme, the northern end of the southern segment of the Barents Sea Plate curved to the right following the northern segment (Fig. 3b). If we consider the geographical map, then this is exactly how the fold axis behaves in

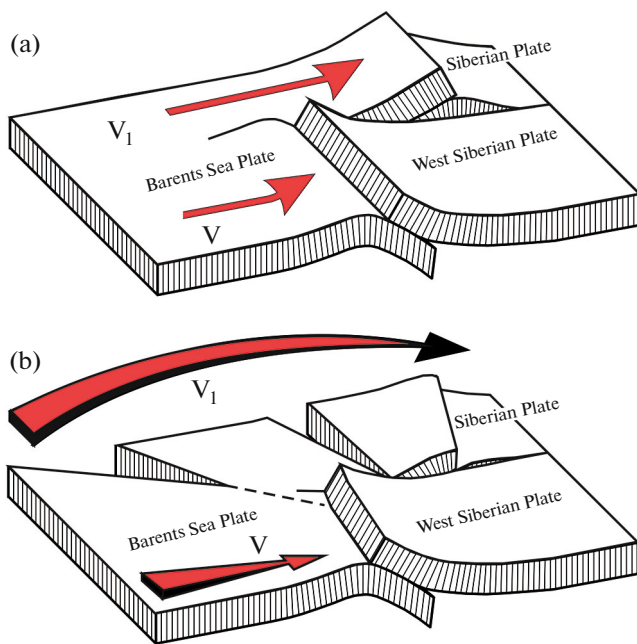


Fig. 3. Schematic diagram of triple junction of noncoeval continental lithospheric plates. See text for explanations.

the northern terminus of the Novaya Zemlya orogenic structure (Fig. 2). It should be noted here that the North Kara segment of the Barents Sea Plate after the emergence of the large St. Anna rift was almost completely separated from it and could have subsequently moved independently in space.

During the translational movement of the Barents Sea Plate towards the young West Siberian and ancient Siberian platforms, the formation age of wedge-shaped rifts should have changed from west to east at present-day points from ancient to young. This is because their successive origin and development are associated with the configuration of the triple junction zone and distance from the collision zone. The most ancient wedge-shaped rifts of the studied region should have originated at an early stage of collision and in the rear of the Barents Sea Plate, while later ones, at its front and at the final stage, i.e., about 245 Ma ago. These conclusions are quite consistent with the data that substantiate the age shift from west to east of the formation of wedge-shaped rifts framing the Barents Sea Plate from the north [14].

The formation processes for the structural ensemble of the described region, on the one hand, have a regular shape of the collision zone of the junction of several lithospheric plates, and on the other hand, reflect the conditions of their evolution at the early stages (Fig. 4). The cover complexes of the Barents Sea (Svalbard), Pechora, and South Kara plates have different structural organization, which is due to the uneven spatiotemporal tectonic influence of the collision zone. Thus, the East Barents Sea region is char-

acterized by a regular spatial distribution of fairly wide and elongated anticlinal uplifts parallel to the suture of the Ural Hercynides (Perseus and Central Barents), which are separated from it by the East Barents and St. Anna synclinal depressions (Fig. 4). The North Cape trough was mainly formed as a result of the development of structures in the Caledonian, and its southern part is a typical piedmont trough. It should not be forgotten that the uplifts of the Franz Josef Land archipelago, as well as the Severnaya Zemlya and Svalbard archipelagos, were formed not so much due to these processes, but as a result of later isostatic alignment of the continental margin during opening of the Arctic Ocean in the Cenozoic.

The massive subsidence of the basement of the Barents Sea Plate and formation of the East Barents Basin, on the one hand, was caused by the development of a foredeep, and, on the other, reflects its heterogeneity and presence of oceanic crust. This was apparently the reason for the development of such a wide basement deflection in terms of its parameters, since depressions of this type usually have a rather narrow, elongated shape. Often, as the cover warps, characteristic saddle-shaped formations arise, dividing them into segments. As an example of such a structure, we can consider the Ludlov saddle, which divides the East Barents Basin into the North and South Barents basins. They arose, most likely, as a result of a change in the strike angles of the collision zone and, as a consequence, the development of shear deformations. It should be noted that the listed structures are complicated by the development of a rift system overprinted in a later era, which only intensified the basement subsidence processes.

Analyzing the results, we can conclude that the basement subsidence structures developing within the Barents–Kara region have different natures. Some of them formed due to the stretching of the lithosphere, while others were formed as a result of the evolutionary subsidence of the basement. The structures of the Norwegian–Mezen rift system and the Voronin, St. Anna, and Franz–Victoria grabens can be attributed to the former, and the South Barents Basin, the Medvezha–Edzha trough zone and a number of linear troughs of the southern and central parts of the Kara Sea, to the latter.

Naturally, the first type of structures, as a rule, is characterized by magmatism with normal alkalinity, comparable to oceanic basalts, and the second type is represented by subalkaline varieties [5]. At the stage of extinction of the active collision phase in the era of tectonic relaxation of the system and breakup of the orogenic structure, it is at the boundary of contrasting media that deep-seated faults should form, along which mantle magmatites are intruded. This is because the isostatic alignment of crustal blocks of different composition, density, and specific gravity leads to their vertical displacement relative to each other at different

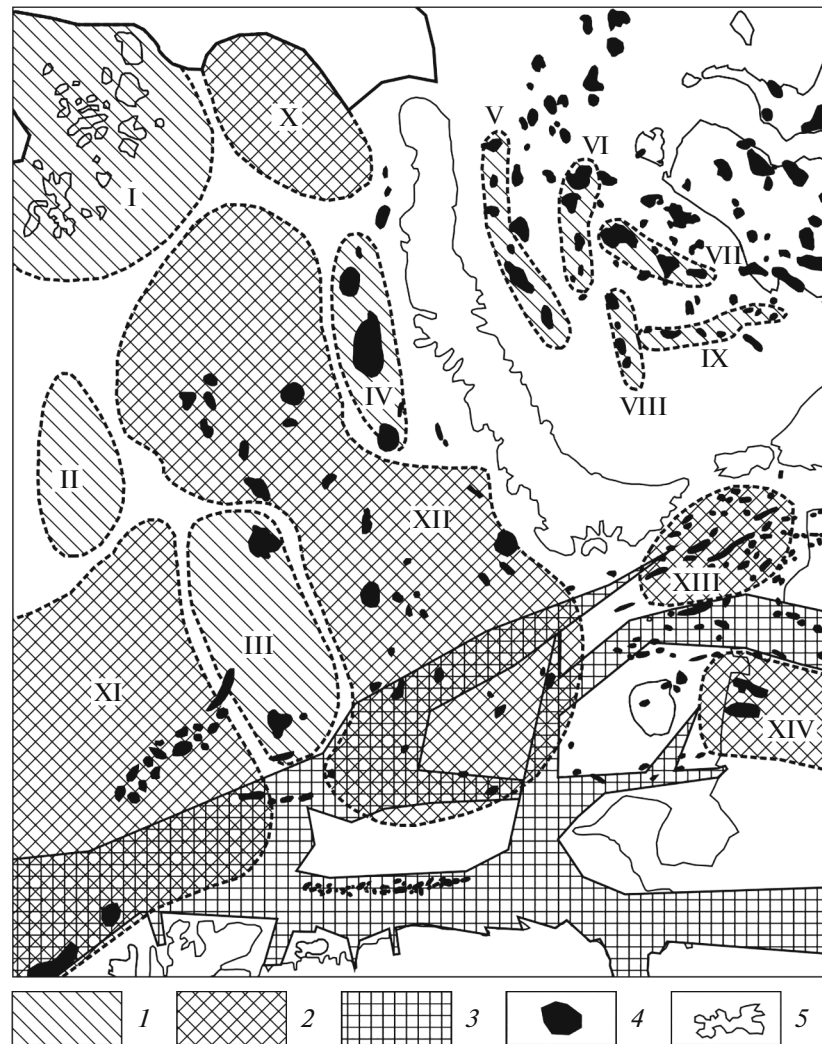


Fig. 4. Superimposed structural organization of Barents–Kara region [4]: (1) uplifts and rises: I–IV, uplifts of Barents Sea Plate: I, Franz Josef Land; II, Perseus; III, Central Barents; IV, Admiralty; V–IX, megarises of South Kara Plate: V, Vikulov; VI, Kropotkin; VII, Rusanov; VIII, Voronin; IX, Obruchev; (2) deflections, depressions, and synclises: X–XIV, Svalbard and Pechora plates: X, St. Anna; XI, North Cape; XII, East Barents Sea; XIII, Pechora; XIV, Izhmo–Pechora; (3) Norwegian–Mezen rift system; (4) potential oil and gas bearing structures and discovered hydrocarbon deposits; (5) contour of modern coastline.

rates. The alkalinity of the magma compositions in this case depends on the depth of their origin, and, consequently, on the thickness of the lithospheric plate, which is always higher than in actively developing rift systems.

As noted above, during closing of the Paleoural Ocean 290–241 Ma ago, the fold system of the Urals, Novaya Zemlya, and Taimyr Peninsula was formed. Attention is drawn to the concavity of the Novaya Zemlya segment of the fold system, characteristic of island arcs, which naturally affected the distribution of stress fields in the southern and central parts of the back-arc space, which is the Kara Sea (Fig. 5). It is known that the direction vectors of compression forces are always perpendicular to the long axis of folding and shear deformations are realized along them.

The geometry of the rear paleosubduction zone within the Novaya Zemlya archipelago is such that they intersect in the central part of the South Kara Sea Basin (Fig. 5).

Outside the zone of intersection of the vectors of the compressive stress fields, local tensile conditions may arise because shear deformations in these zones form characteristic detachment fissures, which often form under normal stresses exceeding the tensile strength of rocks. The displacement angles along faults formed in this way should correspond to the angles of the extreme vectors along which they form. Thus, we can conclude that the described vectors of the internal force fields realized in space are actually macroscale analogs of the change in stress tensors, which are accepted for unit volumes of a continuum.

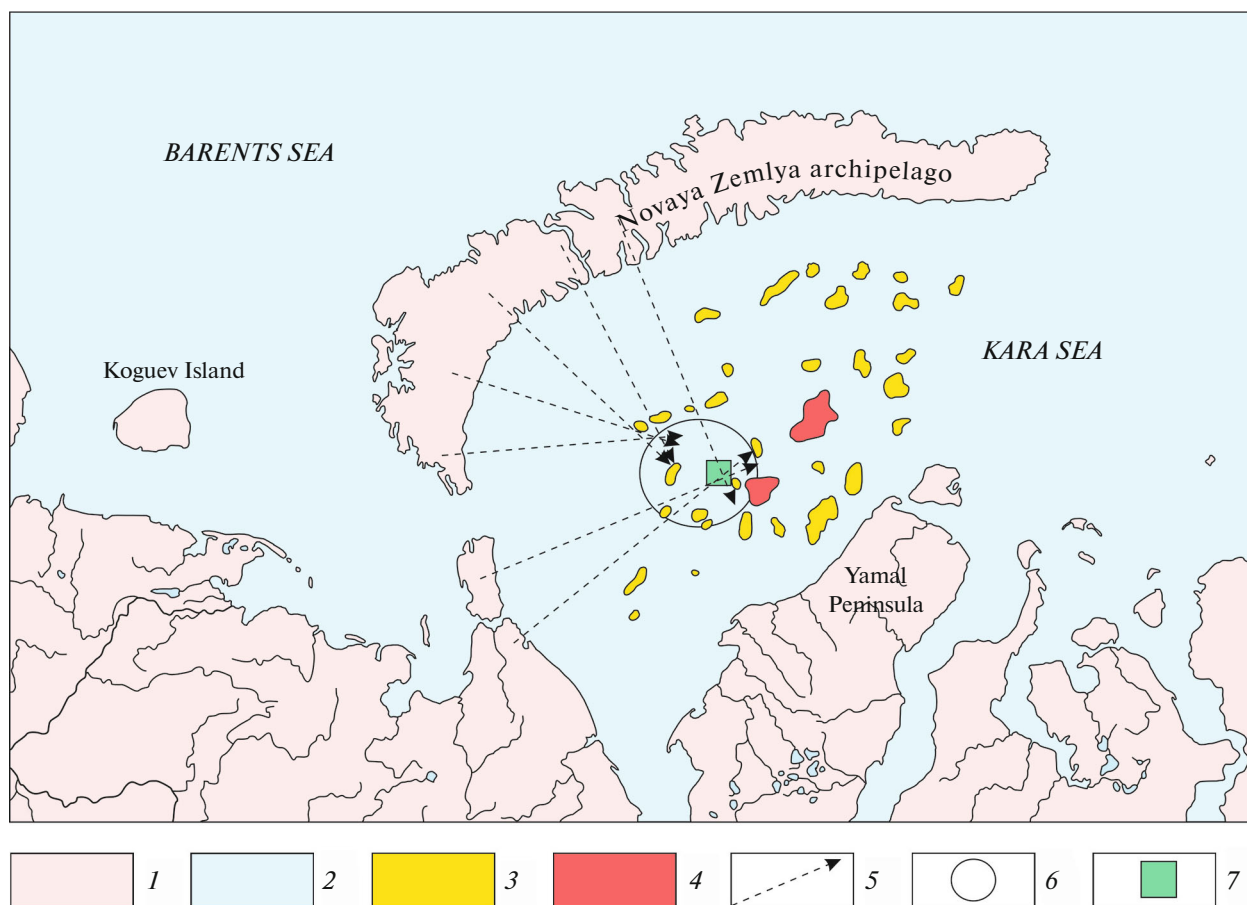


Fig. 5. Scheme of distribution of stress field vectors in Kara Sea: (1) land; (2) shelf; (3) oil and gas fields; (4) gas condensate fields; (5) stress field vectors; (6) zone of intersection of stress field vectors; (7) survey area where detailed studies were carried out.

STUDY METHODOLOGY AND MORPHOSTRUCTURAL ANALYSIS

Comprehensive geological and geophysical studies were carried out on the Kara Sea shelf during cruises 41 and 49 of the R/V *Akademik Nikolaj Strakhov* in 2019–2020 [15, 16]. Bathymetric sounding was carried out with a Reson Seabat 8111 multibeam echo sounder, which is part of the ship's standard hydroacoustic seafloor mapping system. Data were collected and processed using the Teledyne PDS program. The surveys made it possible to identify several characteristic areas within which relief-generating processes associated with Phanerozoic regional geodynamic events.

One of these survey areas is located within the central Kara Sea at depths from 50 to 240 m, 60–90 m on average (see Fig. 5). The depth difference in the area is 190 m. Subhorizontal surfaces and very gently dipping slopes (up to 4°) predominate. On the slopes of grabenlike depressions and erosion cuts, the slope angles vary from 8°–15° to 35°. Thermokarst depressions are characterized by slopes of medium-steep and gently dipping slopes (4°–8°). The survey area is an

erosion-denudation plain modeled by water–glacial and cryogenic processes with subsequent Holocene marine accumulation overprinted on an older and deeply (up to 160 m) dissected grabenlike structure (Fig. 6).

Within the survey area, several distinct zones can be distinguished. In the lower tier of the relief, a deep graben-shaped valley is found, complicated by numerous channels and the accompanying remnant relief forms on the sides (Fig. 6, A). In the north, several wedged-out “sleeves” branch off from it (Fig. 6, B, C), and in the southern part of the survey area there is a narrowing channel that extends beyond the study area (Fig. 6, G). In the southeastern part of the survey area, at depths of 100–125 m, there is a large field with numerous negative landforms, presumably of thermokarst origin, enveloping the remnant forms of the background plain (Fig. 6). In morphological features, it can be assumed that thermokarst fields inherit the structural forms of the relief and are located in the zone of more intense sedimentation, which covered the linear basement subsidence zones with a thick column. In the northern part of the survey area, an elevated plain is distinguished, with a depth of 45–70 m,

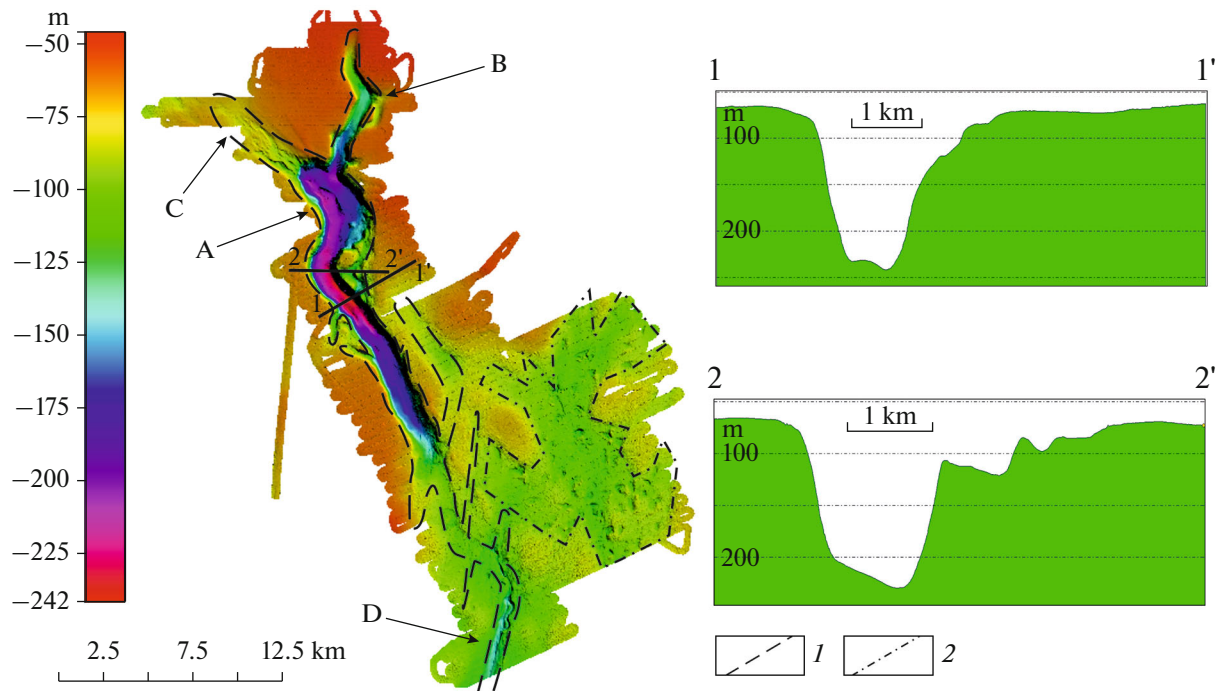


Fig. 6. Digital elevation model of bottom topography of detailed survey area with profile lines and boundaries of zones (see Fig. 5). Scale of transverse profiles is 1 : 10. (1) Generalized graben development zone; (2) generalized thermokarst development zone. Other notation explained in text.

while in the southern part it is relatively low (85–100 m) with numerous traces of small and medium forms of iceberg ploughing (Fig. 6).

The dominant landform is a graben-shaped valley, a linear depression 18 km long and up to 160 m deep (Fig. 6, profile 1-1'). The angles of its slopes reach 15°–20° on average and up to 27°–30° in the steepest segments. The width of the depression along the crests is 1.5–1.7 km in the southern and central parts and 2.8–3 km in the northern.

In the bottom part of the graben, rises, hills, and troughs are found, complicating its relief forms. The most significant is the rise, which stretches 7 km along the bottom of the depression in its central part. It has a height of 5–8 m and a width of 300–400 m. Small troughs encircle the rise on both sides. In the northern part of the survey area, on the eastern side of the bottom part of the grabenlike structure, two terracelike surfaces can be found at relative heights of 30 and 60 m and a width of 300–1000 and 400–600 m, respectively. The higher terraced platform is more pronounced, because has an almost flat surface. The lower terrace has a surface at an angle of 1°–2°, and in some places, up to 4°.

The slopes of the graben on both sides are complicated by eroded surfaces, consisting of relict hills and channels, creating troughs 30–50 m deep around them (Fig. 6, profile 2-2'). The channels on these surfaces form a meander-like pattern. The slopes of hills

of medium steepness are 5°–8°, up to 10°, and the tops are flat. The absolute heights of the tops of all hills correspond to the heights of the background plain. The stepped nature of slopes may be associated with slope collapse, landslide processes, and subsidence of large blocks along fracture zones, which is also inherited by the erosion network.

CONCLUSIONS

The data obtained during the research make it possible to reconstruct the spatiotemporal system of manifestation of relief-forming processes in the central Kara Sea.

The earliest include tectonic processes associated with closing of the Paleoural Ocean and the formation of a fault system in the crust of the northwestern terminus of the West Siberian Young Platform, which includes the South Kara Basin. The kinematic scheme constructed by us within the studied survey area allows us to state that local extension zones can form in the regional compression domain (Fig. 7). Figure 7 shows that in the rear zone of the intersecting vectors of the regional compression fields, a characteristic grabenlike structure appears, resembling a detachment fissure with obvious traces of tension and shear.

The process of formation of spatially localized extension zones in the central South Kara Basin is natural, since it reflects the geometric variability of the collision zone of the Novaya Zemlya archipelago, Vai-

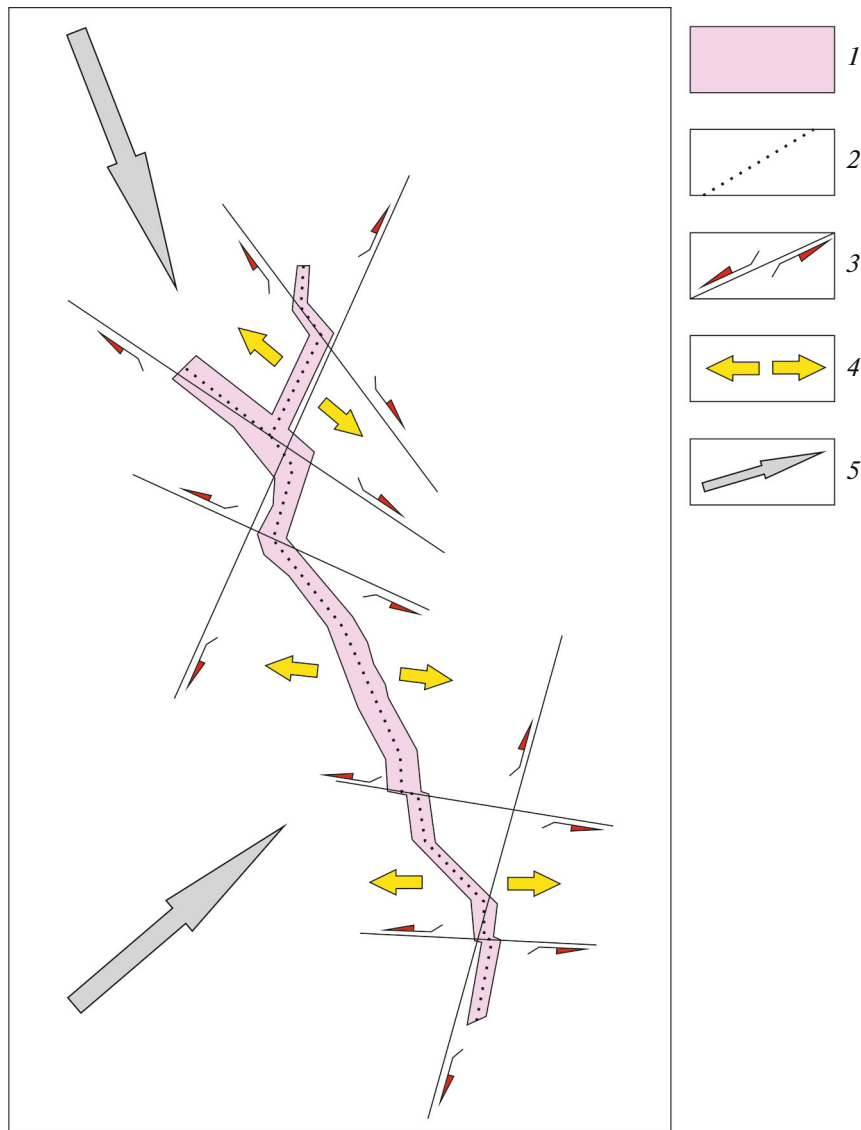


Fig. 7. Kinematic diagram of deformations of grabenlike structure shown in Fig. 6: (1) contours of grabenlike structure; (2) axis of graben; (3) strike-slip faults; (4) directions of local extension field vectors; (5) directions of regional compression field vectors.

gach Island, and the northern terminus of the Polar Urals. A systematic approach to the problems of studying the structural organization of such geodynamic settings allows us to assert that for regional compression of natural geological systems, there will always be zones and areas of local extension, characterized by graben formation and even rifting. These studies are most important in the localization areas of oil and gas fields, because such processes lead to hydrocarbon degradation of the sedimentary cover of individual zones in the region.

FUNDING

The study was carried out within a state task (topic nos. FMWE-2021-0005, FMWE-2021-0004, FMWE-2021-

0015, FMWE-2021-0016, FWWZ-2019-0053, FWWZ-2019-0052, and 0135-2019-0076).

OPEN ACCESS

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the

permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

REFERENCES

1. V. A. Vernikovskii, N. L. Dobretsov, D. V. Metelkin, et al., “Problems of tectonics and tectonic evolution of Arctic,” *Geol. Geofiz.* **54**, 1083–1107 (2013).
2. D. V. Metelkin, V. A. Vernikovskii, and A. Yu. Kazanskii, “Neo-Proterozoic stage in the evolution of Rodinia in the context of new paleomagnetic data on the western edge of Siberian Craton,” *Geol. Geofiz.* **48**, 42–59 (2007).
3. E. E. Milanovskii, *Geology of Russia and CIS Countries (Northern Eurasia)* (Mosk. Gos. Univ., Moscow, 1996) [in Russian].
4. V. Z. Negrutsa, A. A. Basalae, and I. V. Chikirev, *Barents Sea Phosphate Basin* (Kola Research Center RAS, Apatity, 1993) [in Russian].
5. *Description of the Tectonic Map of the Barents Sea and Northern Part of Russia's European Part, Scale 1 : 2500000*, Ed. by N. A. Bogdanov and V. E. Khain (Inst. Litosfery, Moscow, 1996) [in Russian].
6. N. O. Sorokhtin, S. L. Nikiforov, S. M. Koshel', and N. E. Kozlov, “Geodynamic evolution and morpho-structural analysis of the western part of Russia's Arctic shelf,” *Vestnik MGTU* **19**, 123–137 (2016).
7. N. O. Sorokhtin and N. E. Kozlov, “Geodynamic evolution of the western part of Russia's Arctic shelf,” *Vestn. RAEN* **10**, 32–41 (2010).
8. N. O. Sorokhtin, N. E. Kozlov, V. N. Glaznev, and I. V. Chikirev, “Potential oil and gas occurrence in the western part of Russia's Arctic shelf and prognostic criteria for the search of hydrocarbon raw materials in the coastal zone of the Kola Peninsula,” *Vestnik MGU* **13**, 736–750 (2010).
9. N. O. Sorokhtin, N. E. Kozlov, V. N. Glaznev, and I. V. Chikirev, “Geology and potential oil and gas occurrence of the Rybachii peninsula,” *Geolog., Geofiz. i Razrabotka Neftyanykh i Gazovykh Mestorozhdenii*, No. 5, 14–19 (2011).
10. O. G. Sorokhtin, *Global Evolution of the Earth* (Nauka, Moscow, 1974) [in Russian].
11. V. E. Khain, *Tectonics of Continents and Oceans (Year 2000)* (Nauchnyi Mir, Moscow, 2001) [in Russian].
12. N. M. Chumakov, “Pre-Cambrian tillite and tilloids (Problems of pre-Cambrian glaciation),” *Trudy GIN*, No. 308, 202 (1978).
13. E. V. Shipilov and V. A. Vernikovskii, “Structure of the area of junction of the Svalbard and Kara platforms and geodynamic environment of its formation,” *Geolog. Geofiz.* **51**, 75–92 (2010).
14. *Geology of Franz Josef Land*, Ed. by V. D. Dibner (Norsk Polarinstitut, Oslo, 1998), No. 146, p. 190.
15. S. L. Nikiforov, R. A. Ananiev, N. N. Dmitrevskiy, et al., “Geological and geophysical studies on cruise 41 of the R/V Akademik Nikolaj Strakhov in Arctic Seas in 2019,” *Oceanology* **60**, 295–296 (2020).
16. S. L. Nikiforov, N. O. Sorokhtin, R. A. Ananiev, et al., “Comprehensive research in the western Arctic seas on cruise 49 of the R/V Akademik Nikolay Strakhov in 2020,” *Oceanology* **61**, 439–441 (2021).
17. M. E. Raaben, V. V. Lubtsov, and A. A. Predovsky, “Correlation of stromatolitic formations of northern Norway (Finnmark) and northwestern Russia (Kildin Island and Kanin Peninsula),” *Nor. Geol. Unders. Spesial Publ. Trondheim*, 233–246 (1995).
18. N. O. Sorokhtin, *The Origins of Natural Diamonds* (Scrivener Publ. Wiley, 2019). <http://www.scrivenerpublishing.com/cart/title.php?id=470>.
19. N. O. Sorokhtin, N. E. Kozlov, V. N. Glaznev, and E. V. Martynov, *A Study in Earth's Geological Evolution (The Baltic Shield)* (John Wiley & Sons, 2020).