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The Southeastern Flank of the Knipovich Ridge (Northern Atlantic): The Basement Structure and Neotectonics from Geophysical Data and Experimental Modeling

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Abstract—The acoustic basement of the Knipovich Ridge southeastern flank was interpreted on the time-domain CDP seismic sections and calibration of Bouguer gravity anomalies to depth was done with construction of basement structural map for the area with an oceanic crust type. On this map, to the east from Knipovich Ridge, there is a longitudinal uplift, which is the northern continuation of the Senja fracture zone and interpreted as a transverse ridge on the transform fault board. This uplift is framed by linear clusters of the off-axis seismicity epicenters, indicating the activation of this area structures. The CDP seismic data above the identified uplift show deformations of the Pliocene–Quaternary sedimentary cover with reverse fault and shear kinematics. Physical modeling of structure formation in the area of the Knipovich Ridge clearly demonstrated the features of the main tectonic elements during oblique spreading. The result, which is especially close to reality, was obtained by conducting combined experiments with bending the weakened zone to large angles between the direction of stretching and perpendicular to the axis of the weakened zone. At the same time, the appearance of typical accretion swells and nontransform axis displacements simulating the structures of the southeastern flank of the Knipovich Ridge is close to reality. The series of experiments conducted to study the possible formation of the spreading axis jump in an easterly direction to the continuation of the Senja fracture zone showed the fundamental possibility of this structure activation, which we consider as one of the reasons for the formation of features observed in geophysical data. The current position of the active zones of the region, seismicity, the structure of the basement and the structure of the sedimentary cover indicate a shift in the activity of the main tectonic elements in the eastern direction relative to the current position of the extension axis. A likely scenario for further development of the region is the transformation of the Knipovich Ridge into one or the series of transform faults parallel to the western edge of the Barents Sea shelf and the series of short spreading segments between them.

Keywords: Knipovich Ridge, transform fault, spreading, physical modeling, sedimentary cover deformations, seismicity, Bouguer anomalies, structure activation

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INTRODUCTION

The Knipovich Ridge is located in the eastern part of the Norwegian–Greenland Basin at a distance of 40 km to the north and 200 km to the south from the western edge of the Barents Sea shelf, which is a source of terrigenous material and avalanche sedimentation in the basin (Fig. 1).

The sediment-leveled topography of the eastern flank of this segment of the Mid-Atlantic Ridge (MAR) and the partially leveled topography of the western flank do not reflect the primary structure of the oceanic basalt basement, as is known from observations in other segments of the MAR that are not located so close to the sources of sedimentary material [17].

According to the data of expeditions of the Geological Institute of the Russian Academy of Sciences (GIN RAS, Moscow, Russia) from 2006 to 2010 numerous neotectonic dislocations were identified on the R/V *Akademik Nikolai Strakhov* near the Knipovich Ridge in the upper part of the sediment section according to seismoacoustic data, which were used to build a map of vertical amplitudes of sedimentary cover faults [18]. The interpretation of their spatial distribution and genesis was carried out taking into account the presence of a strike-slip component in the kinematics of the rift structure.

The presence of neotectonic faults on the southeastern flank of the Knipovich Ridge indicates the recent activity of the area outside the axial part of the

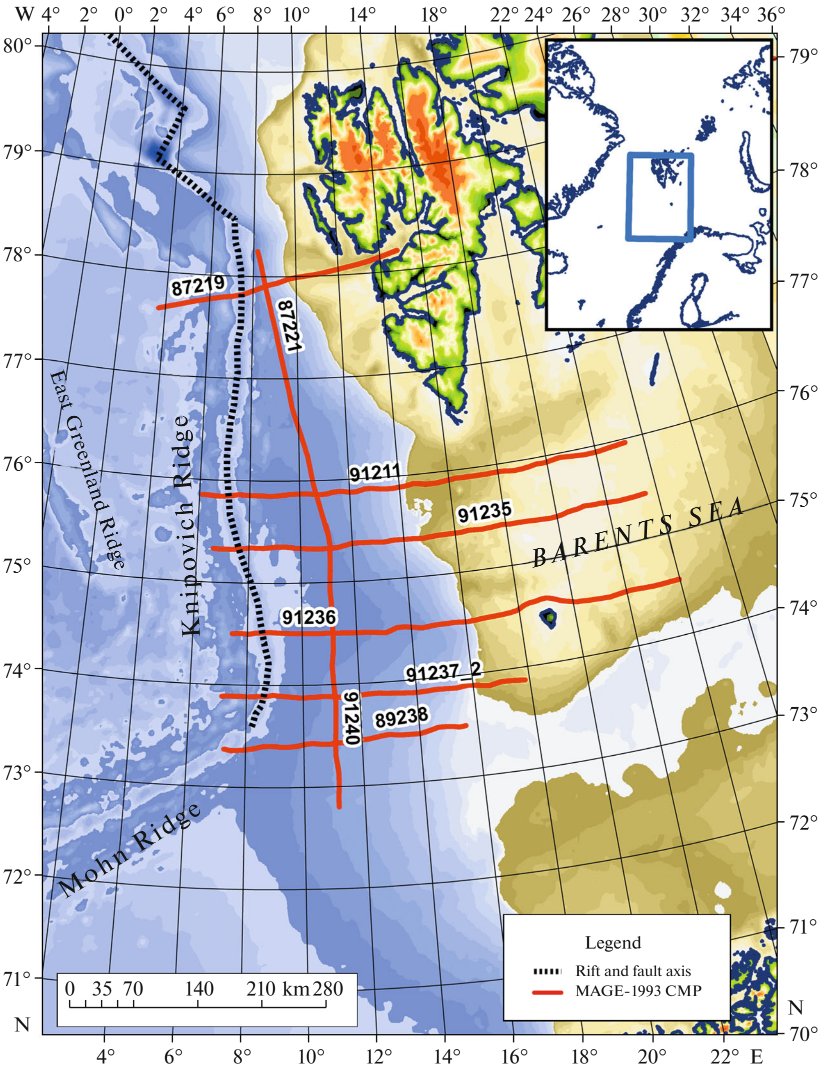

Fig. 1. The Knipovich ridge area and the position of the MAGE-1993 seismic sections used in this work. Inset: study region shown. The map shows the axis of the rift and fault (dotted line); time sections MAGE-1993 (line in red); numbers of time sections (Arabic numerals).

rift. This is a confirming factor for the possible activation of the basement structures, since it is the consolidated part of the earth's crust and upper mantle that is the carrier of the movement, which forms deformations and faults mapped by seismoacoustic methods in the weakly consolidated sedimentary stratum covering it.

The proximity of the rift to the source of avalanche sedimentation creates a unique opportunity to confidently identify modern tectonic faults from sediments deposited on a basement with a mobile block structure.

The oceanic basement without a sedimentary cover is represented by a surface with an uneven morphology of a ridge relief, in which it is difficult to distinguish the primary relief formed by accretion during the spreading process from the irregularities that arose under the action of tectonic faults.

One of the signs of deformations superimposed on the primary structure of the basement is their discordant orientation with respect to the main structural elements of the rift and its flanks. Analysis of the basement map reveals such structures.

With the good seismic knowledge of the area, there are no structural maps of the basement in open sources. The only information about the structural surface of the basement in the southeastern frame of the Knipovich Ridge is [24], which was carried out on the basis of the 1993 survey. In this paper, we present the position of the used sections of this survey [24] (Fig. 1).

The information of the Bouguer reduction of gravity in the oceanic part of the area [28], which was built on a grid with a step of 2 arc minutes, is detailed and uniform. It is used in this work to obtain an analogue of the structural surface of the basement by the method of its calibration according to seismic sections. The result we obtained is compared with the anomalous magnetic field and seismicity, as well as the literature data, to detect the currently activated basement structure, which forms the pattern observed in geophysical fields. The assumption obtained from this comparison about the nature of the geodynamics of the area and the nature of the observed transformation on the southeastern flank of the Knipovich Ridge is verified by physical modeling of spreading processes under conditions similar to its southeastern framing.

The task of modeling is to elucidate the conditions, as well as the geometry of the influence of mantle thermal heterogeneities, under which the initiation of a jump of the ridge axis and activation of its flanks is possible. It is planned to physically simulate the process of displacement and determine the conditions necessary for the implementation of a rift axis jump, and mantle plume anomalies as effective triggers for a change in the configuration of the main tectonic elements of the Knipovich Ridge.

REGIONAL GEODYNAMICS

Modern ideas about the beginning of the opening of the Norwegian–Greenland basin agree that at the initial stage of the divergence of Greenland and the Svalbard Plate ~54 Ma ago the process occurred along the transform interplate boundary represented by the echeloned system of the Hornsund and Senja faults and the Vestbakken volcanic province between them [31–33].

In [33], a very logical mechanism for the further tectonic evolution of the region was proposed, consisting in the fact that the spreading that formed the magmatic basement initially passed along the direction subparallel to the transform boundary with a slight deviation towards Greenland. This model was based on the assumption that the Knipovich Ridge at one of the stages in the development of geodynamics provided the opening of the basin along a shorter rift structure crossing the initial spreading segments of the young oceanic basin with a formed sedimentary cover [33]. However, the modern tendency to consider the Knipovich Ridge as the original center of spreading has led to a significant diversity of ideas about the geodynamics of the region.

Most studies of the Knipovich Ridge point to the anomalous nature of its tectonic structure compared with other MAR structures with a typical configuration of structural elements. This anomaly lies in the following facts:

— The axial zone of the ridge with the sides limiting the rift, according to the data of the anomalous magnetic field, has an angular relationship with segments of linear magnetic anomalies between 35° and 50°, which is too large for conventional oblique spreading with angles of no more than 15° [35] (Fig. 1). This indicates that the dynamics along the divergent boundary at such angles between the accretion direction and the perpendicular to the rift axis will most likely have a strike-slip component [19].

— Bottom sampling of the western side of the Knipovich Ridge showed the presence of Oligocene mudstones in the bedrock [1]. This indicates that the Knipovich Ridge was not the center of spreading in which loose sediments accumulate on the flanks and compact as they move away from the axis. This is also seen in the seismic sections, which show the displacement of lithified sedimentary strata along normal faults in the rift shoulders [8, 26].

— Slope angles in places where sediments displaced by faults reach 35°, which is physically unrealizable for the accumulation of loose watered sediments in a seismically active zone [16].

— Seismic event frequency curves along the ridge are also anomalous and are in an intermediate position between the typical slopes for rifts and transform faults [9].

These facts point to a jump in the spreading center, which in this case is also accompanied by a turn of its axis by 45°. Known cases of jumping of northern segments of the MAR occurred as a subparallel shift of the spreading axis [32].

Other ideas about the development of the region are represented by diagrams according to which the modern axis of the Knipovich Ridge is the initial center of oblique spreading, along which accretion of the crust occurred along a system of short rift segments with an oblique direction of oceanic crust growth relative to the normal to its modern axis [10, 13, 23, 30].

In [30], an attempt was made to identify short mosaic fragments of the anomalous magnetic field of the Knipovich Ridge in such a way that the current position of its axis became the initial spreading center, which, in our opinion, does not remove the contradiction with the facts we presented [30].

Other assumptions about the tectonic development of the region, to different extents, take the existing inconsistencies between the listed facts and simplified model representations into account, which explains the existing diversity of these ideas.

Most significant reconstructions are based on the fact that the Knipovich Ridge is not a classical spreading ridge, but a strike-slip transform structure with spreading elements [2, 29, 6], which coincides with the definition of pull-apart structures formed as a chain of amagmatic depressions separated by igneous necks with volcanic edifices of the central type [9, 29]. One geodynamic phenomenon that would eliminate the contradiction in the observed facts without considering oblique spreading could be a jump of the divergent boundary with a 45° turn and the beginning of rifting in a completely new position with the split-

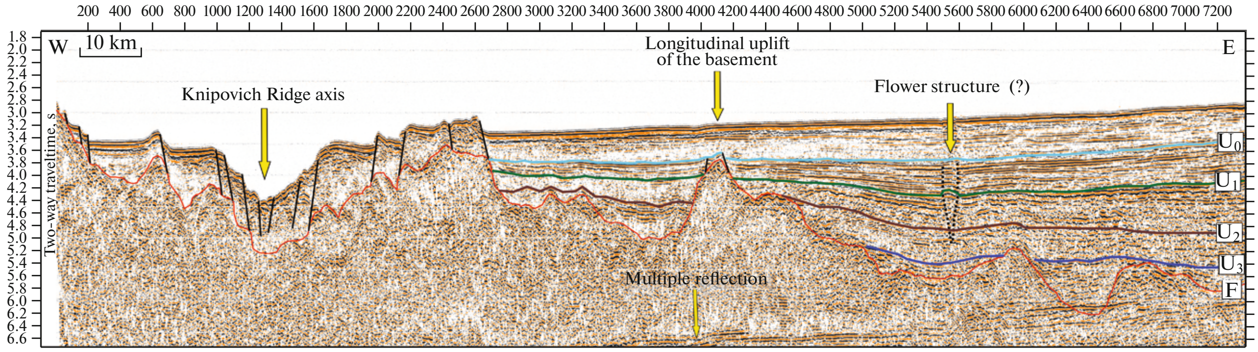

Fig. 2. Interpretation of a fragment of the time seismic section 91236 (according to [24], with modifications). The position of the cut see Fig. 1. *faults*: highlighted confidently (line black), assumed (dotted line); acoustic foundation F (line in red). *Roof of seismic complexes*: U_3, Middle Oligocene–Lower Miocene (32–22.5 Ma); U_2, Miocene (22.5–9.8 Ma); U_1, Upper Miocene (9.8–6.6 Ma); U_0, Upper Miocene–Pleistocene (6.6–2.8 Ma). The bottom of the seismic complex: U_0, Pleistocene (2.8–0 Ma).

ting of the previously formed spreading basement with a sedimentary cover.

According to [6], the structural plan of the new rift structure has not been completed, but this process began in the Miocene. The absence of an axial magnetic anomaly along the entire Knipovich Ridge, except for a small area in the north, in our opinion, indicates that the jump could have occurred in the Quaternary [15].

This may mean spreading along the Knipovich ridge has not yet occurred, but rifting has begun in the chain of pull-apart depressions that represent this ridge. The appearance of such faults, which straighten the interplate boundary, is most likely the simplest solution to the discharge of the system of tectonic stresses [19].

The available petrological data on hafnium and neodymium isotopes in basic rocks also point to the unique structure of the Knipovich Ridge, which, according to the isotope ratios of these elements, can arise only during the repeated melting of the previously depleted mantle, which confirms the jump of the axis of the divergent boundary in the region [36, 37].

At present, the Knipovich Ridge has hybrid properties of a rift and a transform fault [9]. The analysis of seismic tomography data indicates the presence of low velocity values of seismic waves, most likely associated with a local "hot" anomaly in the upper mantle near the southern tip of the Knipovich Ridge, which theoretically can be a trigger for the observed transformation [25].

DATA USED

This work used time domain seismic reflection CDP sections obtained by JSC "MAGE" in 1993 [7, 24] (Fig. 1). We have given an example of seismic data with interpretation of the basement top and Cenozoic seismic complexes (Fig. 2).

Gravity anomalies in the Bouguer reduction (Fig. 3).

The positions on the plan of the peaked basement are shown in the segments of the sections, where it is distinguishable up to a superposition with multiple waves (Fig. 3). Separately, the isoline of the Bouguer anomalies 240 mGal is shown, which conditionally separates the continental lithosphere from the oceanic one for this field [28]. The seismicity of the Knipovich Ridge and its flanks is considered from the data in the NORSAR catalog [34]. The map of the anomalous magnetic field ΔTa is given according to the data of [35].

Data Processing and Primary Interpretation of Results

A comparison was conducted and a correlation was made of the basement depths on time sections with the values of the Bouguer anomaly. This made it possible to obtain a linear approximation basement depth dependence from the value of the gravity reduction (Fig. 4).

A sparse network of stacked time seismic sections, on which the acoustic basement corresponding to the top of the second basaltic layer of the oceanic crust, made it possible to link the basement depths to the values of the Bouguer anomaly on these sections. The cross-plot based on the obtained pairs of numerical values for the part of the water area with the oceanic lithosphere is dense enough to obtain the linear dependence for the recalculation of the reduction field into the structural surface in isochrones. A sparse network of direct seismic observations of the basement calibrates the field of Bouguer anomalies, which has a uniform coverage in the area under consideration, in such a way that after recalculation to the depths of the basement it creates a realistic structural plan of the second oceanic layer top (Fig. 5).

We note that for the area in which the segments of sections 89238 and 91237_2 go east beyond the isoline of 240 mGal, which conditionally separates the oceanic lithosphere from the ocean-continent transition

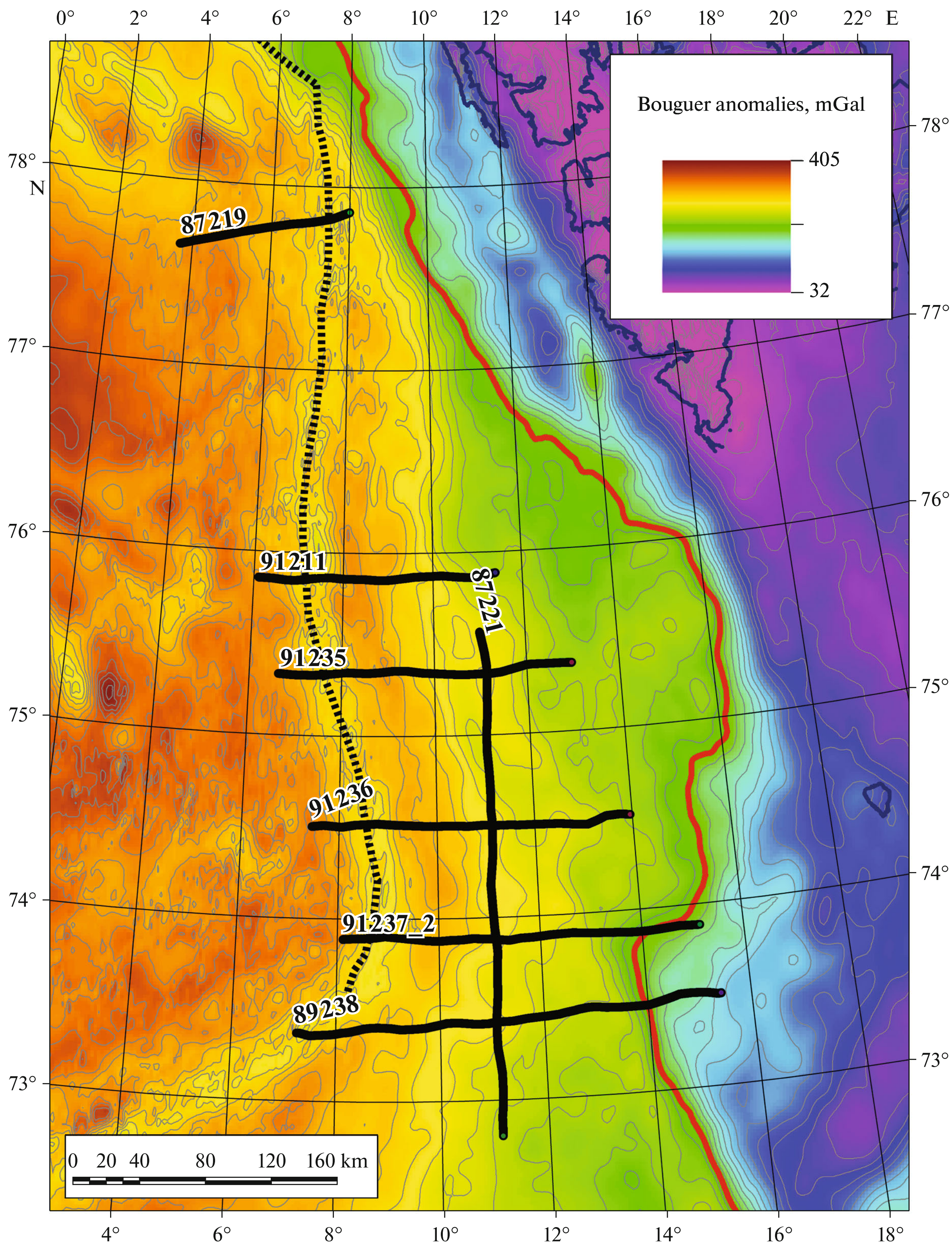

Fig. 3. The position of the interpreted acoustic basement depths along the MAGE-1993 seismic profiles and the 240 mGal isoline separating an area with oceanic crust from a transitional area to a continental-type crust. Designated: Bouguer anomalies (according to [28]) (scale); rift and fault axis (dotted line); peaked basement (black lines); isoline 240 mGal (red line); isolines at 10 mGal intervals (grey lines).

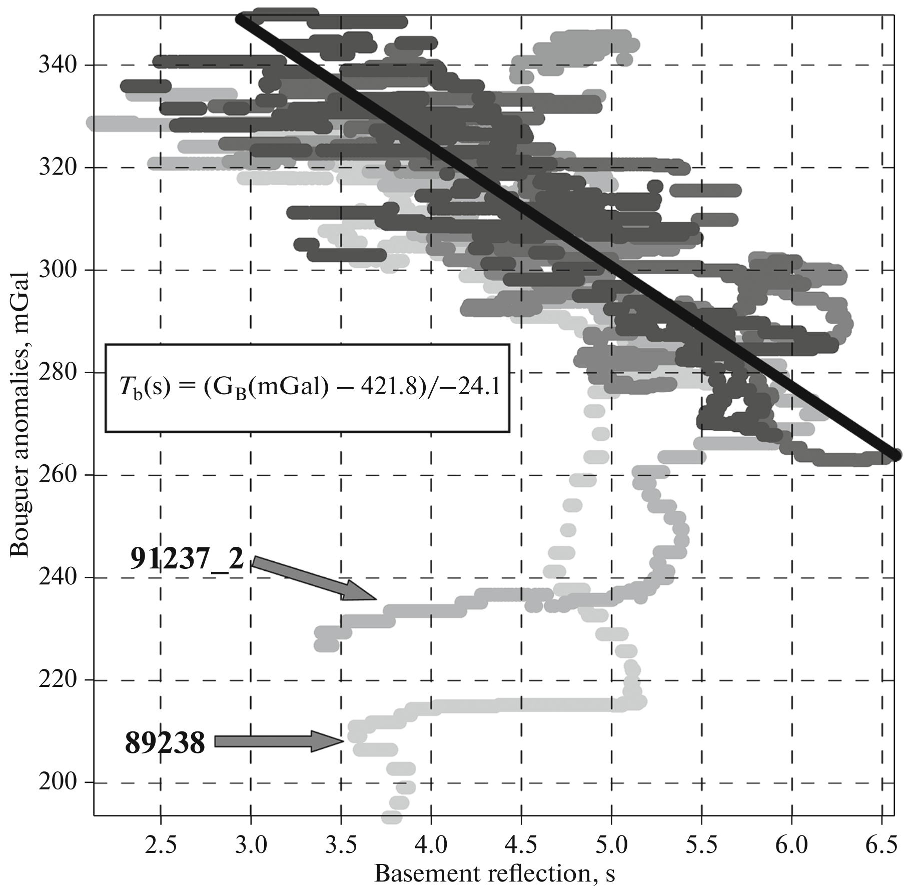

Fig. 4. Correlation of basement depths in double travel time with the values of Bouguer anomalies (according to [28]). The formula shows a linear approximation of the dependence trend of depths from the gravity reduction. Arrows show strong bounces of values along sections where the position of the interpreted basement goes beyond the 240 mGal isoline.

zone, rebounds from the main cloud with a linear trend are formed on the cross-plot (Fig. 3, Fig. 4).

This indicates the inapplicability of the obtained approximation to the continental and transitional regions with the presence of a volcanic plateau. The main structural features of the seismic sections, after recalculating the entire area of the study area into the surface, remain in the nature of the local basement relief, but acquired in a uniform display, which makes it possible to adequately assess the structure of the entire area. This is possible due to the fact that the most contrasting density boundary is displayed in the Bouguer anomalies, which is exactly the top of the basement that separates the basalt and sedimentary parts of the section.

Comparison of the calculated structural surface with seismicity according to NORSAR data shows that off-axis events that indicate the recent activation of the Knipovich Ridge flank are grouped into linear clusters, which are located on the flanks of the longitudinal uplift adjacent to the ridge from the east to the north of 76° N (Fig. 5). This uplift is located on the continuation of the Senja Fault, along which the opening of the oceanic basin initially took place along the interplate boundary of the transform type.

Events along the axis of the Knipovich Ridge are gathered into groups that are isolated from each other, which does not contradict the assumption that the Knipovich Ridge was formed in the form of a chain of pull-apart depressions that arose under the action of tension with shear.

Comparison of the calculated structural surface with an anomalous magnetic field (AMF) ΔTa shows a discrepancy between the orientation of the basement relief structures and the mosaic of linear segments of magnetic anomalies adjacent to it (Fig. 6).

This indicates a different genesis of the structures that emerged during spreading accretion of the basement and reflected in the linear fragments of the anomalous magnetic field, and the structures that emerged in the basement to the east of the linear anomalies. It is with these structures that the activation of the Knipovich Ridge flank in recent times, at the present stage accompanied by seismic activity along the northern extension of the Senja fault, is spatially associated. The resulting structural pattern

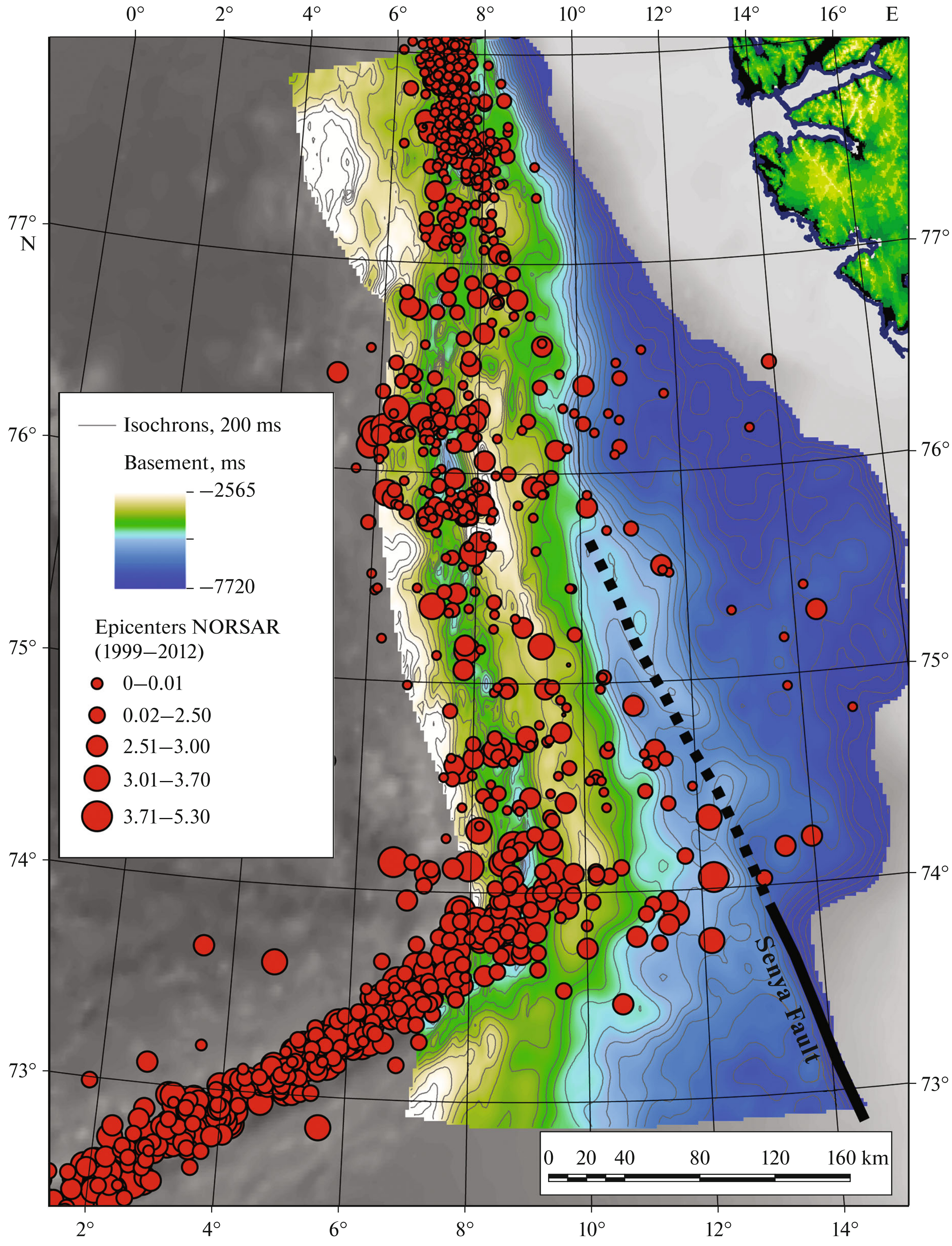

Fig. 5. The structural map of the acoustic basement in isochrones in the region of the southeastern flank of the Knipovich Ridge and the seismicity of the area (according to [34]). Shown: position of the Senja fault (solid line in black), its probable modern continuation (dotted line).

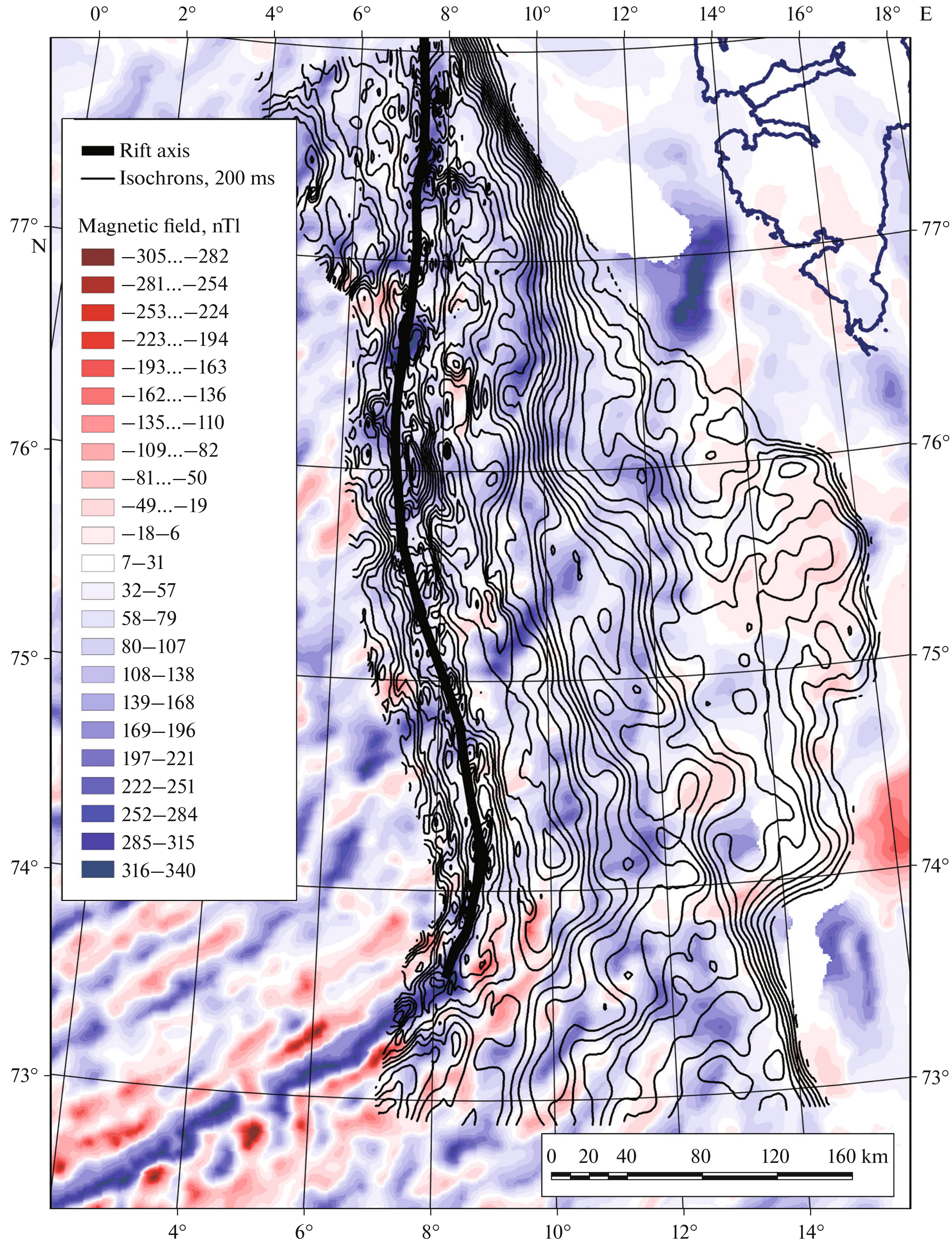

Fig. 6. The structural map of the acoustic basement in isochrones in the region of the southeastern flank of the Knipovich Ridge and the anomalous magnetic field ΔTa (according to [35]).

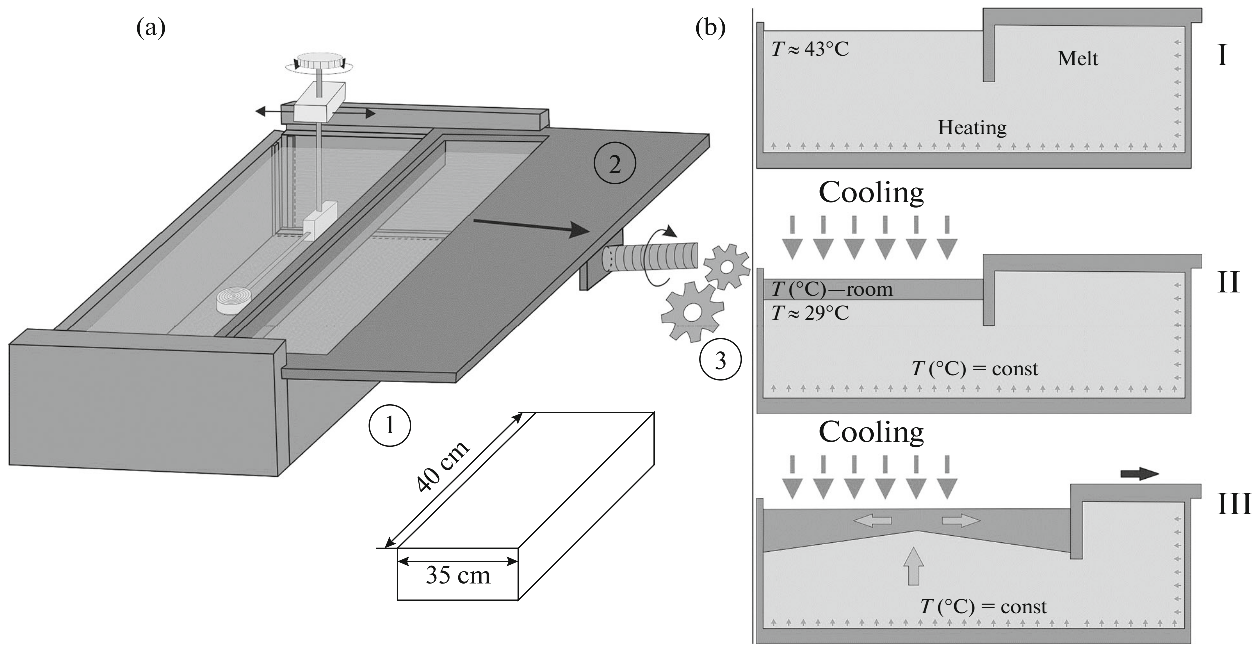

Fig. 7. The experimental setup (a), preparation of the model in the section (b). On (a): 1, textolite bath; 2, a frame with a piston; 3, electromechanical drive. On (b): I, stage of heating of the working substance; II, formation of a cooled layer; III, start kinematics modeling.

determines the direction and primary geometry to be modeled experimentally.

EXPERIMENTAL MODELING

Setting Up and Methods of Conducting Experiments

Experimental studies were carried out in the laboratory of physical modeling of geodynamic processes of the Museum of Earth Science, Moscow State University (Moscow, Russia) in accordance with the methods described in [3, 4, 7, 38]. The model substance is a complex colloidal system based on liquid (mineral oil) and solid (ceresin and paraffin) hydrocarbons with various surface-active additives. The substance meets the criterion of similarity in shear modulus:

$$F = \tau_s / \rho g h = \text{const}, \quad (1)$$

where τ_s are the characteristic overhydrostatic stresses; ρ, h are the density and thickness of the lithosphere, respectively; and g is the free fall acceleration [22]. For its implementation, it is required that the ratio of stresses in the lithosphere that cause its deformation (suprahydrostatic stresses) to hydrostatic stresses in the plate, in nature and in the model be the same.

The experimental setup is a textolite bath with a piston moved by an electromechanical drive (Fig. 7).

A uniform temperature field of the model substance is created due to the heating circuit located along the walls and bottom of the model. The electromechanical drive allows one to vary the rate of deformation of the model plate (Fig. 7, item 3).

The methods we used make it possible to create conditions for orthogonal or oblique tension of the model plate. Changing the duration of its cooling during preparation provides a different ratio of its brittle and plastic layers [3]. When preparing the experiment, the substance is heated in the setup to a certain temperature, provided that a fixed temperature regime is maintained in the laboratory (Fig. 7a).

The process of cooling of the molten model substance begins, a crust (model lithosphere) is then formed, which is welded to the piston and the opposite wall of the pool (Fig. 7b).

After the model plate reaches the thickness required for this experiment (parameter h in the description of experiments), its horizontal stretching begins (Fig. 7c).

If it was necessary to create a weakened or stronger zone, a part of the plate was cut out or additionally cooled. Within the framework of this study, in a number of experiments, a local heating source (LHS) was used, which, at the stage of preparing the experiments, was placed in the model asthenosphere at the desired location and turned on at the required moment during the experiment. A local heating source is a device that allows one to simulate the activity of a hot spot by locally raising the temperature and melting the model substance.

Within the framework of this study, two main goals were set for physical modeling, according to which all experiments were divided into two series:

— study of features of structure-forming deformations during the formation of the Knipovich Ridge

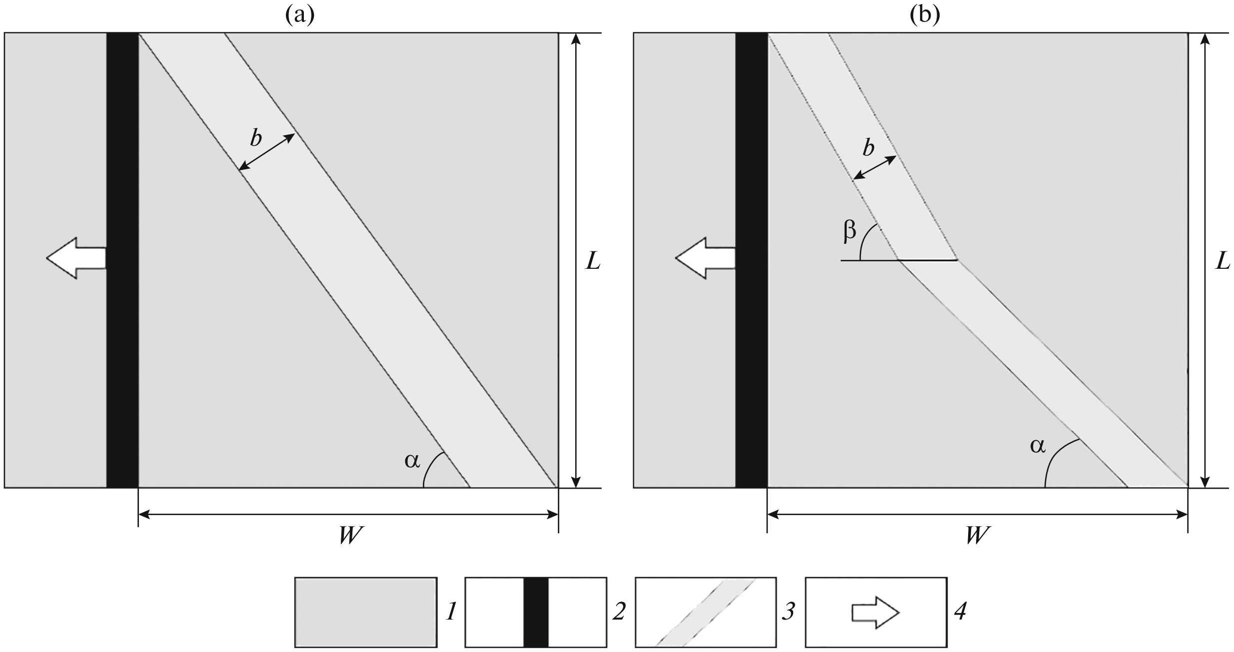

Fig. 8. Schemes and experiment parameters. (a) weakened zone without bending; (b) weakened zone with a bend. On (a)–(b): b, width structural heterogeneity; α and β are the angle between the weakened stretching zone and direction; *W* and *L* are the initial dimensions of the model area installation. (*1*), model plate; (*2*), piston; (*3*), structural heterogeneity with reduced thickness of the model lithosphere; (*4*) is the direction of stretching.

under conditions of oblique extension between Svalbard and Greenland;

— modeling of possible reactivation of the Senja fault zone, manifested in nature by a linearly elongated zone of modern seismic activity on the continuation of an ancient fault.

SERIES OF EXPERIMENTS

Series 1

Within the framework of the first series, the Knipovich Ridge was divided into two parts according to the angle between the direction of extension and the strike of the ridge:

— the upper segment determined by the values of the angle of inclination of the tension axis in within ∟35°–45° (Fig. 8a; Fig. 9, exp. No. 2397);

— the southern segment defined by values in within ∟50°–60° (Fig. 8a; Fig. 9, exp. No. 2407).

After obtaining the results in these two groups of experiments, a combined group of experiments with bending of the weakened zone was carried out (Fig. 8a; Fig. 9, exp. No. 2416).

To simulate oblique tension within the framework of the experimental setup in the model lithosphere, at the stage of preparing the experiment, a weakened zone was set to localize stresses at the required angle to the direction of tension. After this, the electric motor was started, due to which uniform stretching began. We consider Experiments Nos. 2397, 2407, and 2416.

Experiment #2397. At the first stage, the initially specified weakened zone is visible in the model lithosphere at an angle of ∟40° and a width of 2 cm (Fig. 9). For creating this zone during the formation of the model lithosphere at the stage of preparation, the zone was cleared of frozen matter, after which recooling was performed, due to which a difference in the thickness of the lithosphere was created within the weakened zone (h_2) and the main model lithosphere (h_1). At the beginning of tension, a series of cracks are initially formed within the zone of focused stresses, which are connected into a single axis through transform faults.

At the second stage, the process of accretion of the new oceanic model crust along the spreading segments begins.

At the third stage, uneven accretion along the ridge is more clearly observed; transform faults have already partially compensated. All geomorphological features of the rift valley are clearly visible under conditions of oblique spreading; a narrow rift valley with an anomalously large depth for orthogonal spreading is clearly pronounced.

This experiment clearly demonstrates the features of oblique spreading with an extension slope less than ~45, expressed in the almost complete absence of accretion swells characteristic of orthogonal or slightly

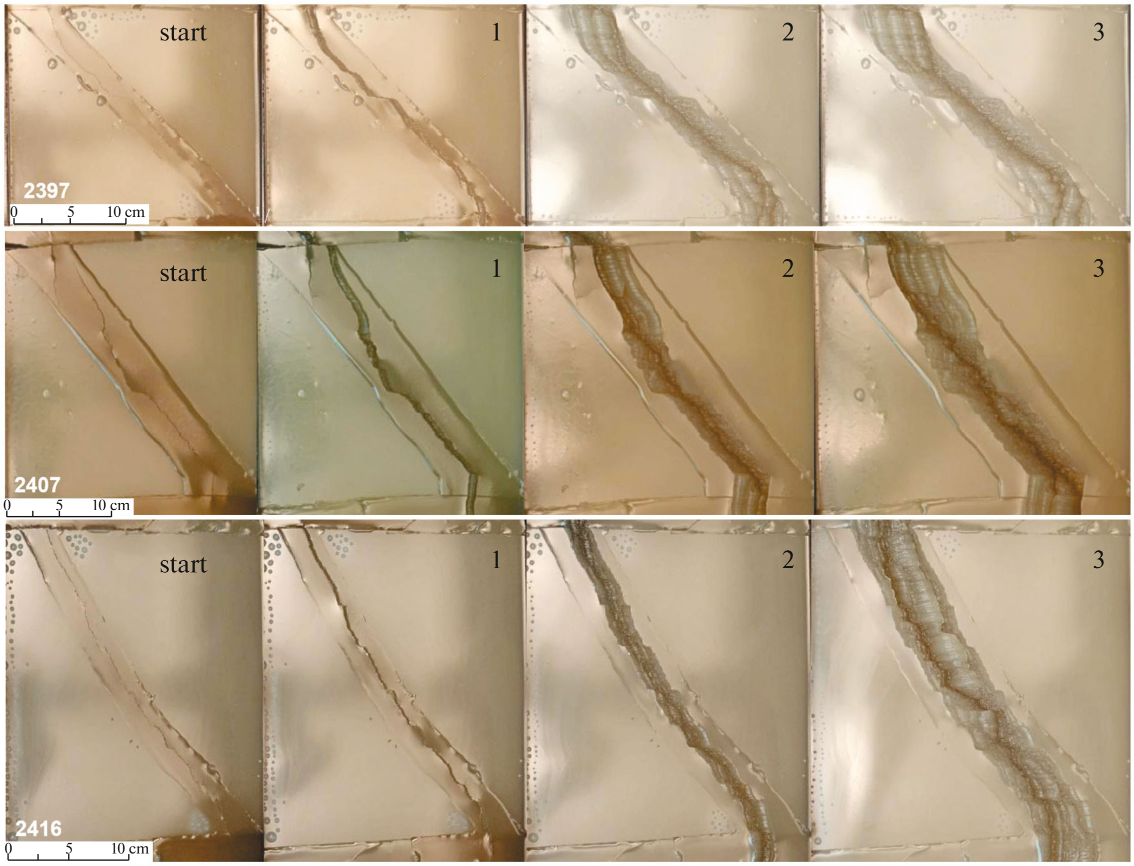

Fig. 9. Experiments Nos. 2397, 2407, and 2416. Features of structure-forming deformations along the strike of the Knipovich Ridge at different angles of oblique spreading (No. 2397, 40°; No. 2407, 50°) and when bending weakened zone (No. 2416, $h_1 = 3 \times 10^{-3}$ m; $h_2 = 1.5 \times 10^{-3}$ m; $V_1 = 1.87 \times 10^{-5}$ m/s). Labeled: experiment number (numbers in white); stage of the experiment (numbers in black).

inclined spreading, a narrow and anomalously deep rift valley, and the presence of transform faults.

Experiment No. 2407. In the second group of experiments within this series, the angle of inclination of the tension axis was increased to ∟50°, which corresponds to the values of the northwestern segment of the Knipovich Ridge (Fig. 9).

At the first stage, during the initiation of a crack, differences are seen: the fracture segments are more elongated and less displaced along the transform faults.

At the second stage, it is also seen that the accretion of a new oceanic crust begins. Note that in comparison with experiment No. 2397, accretion swells form along most of the ridge strike.

At the third stage, most of the transform faults were compensated, and the formation of accretion swells continues in the central part of the experiment. Similar deformations were not observed in experiment No. 2397 with a different stretching angle at this stage.

The final photo clearly shows that, in comparison with experiment No. 2397, as a result of changing the angle of inclination of the stretching axis not only has the ∟10° rift the valley has become less deep, but it continues to be quite narrow (Fig. 9). The second important difference is the pronounced accretion swells in the central and northern segments, which is also associated with a change in the angle of inclination of the extension axis.

Experiment No. 2416. This experiment clearly demonstrates the difference in structure-forming deformations along the Knipovich Ridge with a change in the angle of inclination of the axis stretching by ∟10° (from 40° to 50°) along its strike from the southeast to the northwest (Fig. 9).

By analogy with experiments No. 2397 and No. 2416, a weakened zone 2-cm wide was initially set in the model lithosphere, after which the electric drive was started, due to which its stretching began.

At the first stage of the litosphere splitting and the initiation of a system of cracks within the weakened zone, a difference is seen in the northern and southern segments. In the north segment, a series of large linear fractures with short transform faults formed, while in the southern segment the length of the segments is less and the displacement is greater. This is also observed

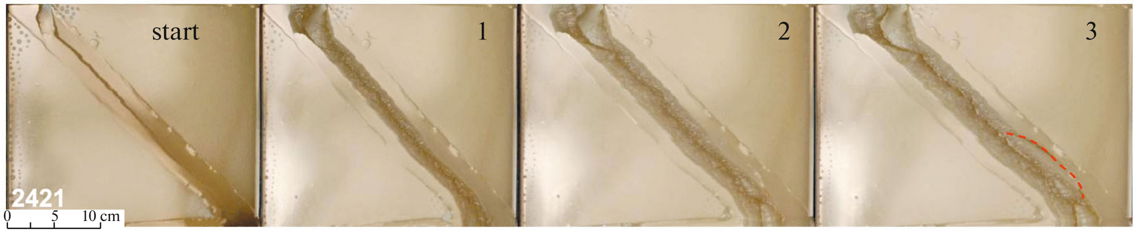

Fig. 10. Experiment #2421. Modeling the formation of the southeastern segment of the Knipovich Ridge and possible formation of a jump in the spreading axis (red dotted line) towards the Senja Fault ($h_1 = 3 \times 10^{-3}$ m; $h_2 = 1.5 \times 10^{-3}$ m; $V_1 = 1.87 \times 10^{-5}$ m/s). Labeled: experiment number (numbers in white); stage of the experiment (numbers in black).

in the later stages of stretching, which is observed from the first to the third stages.

As well, the northern and southern segments differ in the amplitudes of newly formed structures, which are expressed in the upper part of the model fracture with larger amplitudes. This experiment clearly demonstrates the difference in structure-forming deformations with a change in the angle of extension along the strike, which is confirmed by geological and geophysical data [8].

Series 2

The second series was carried out to study the possible reactivation of the Senja fault and structures located on its northern extension and adjacent to the Knipovich Ridge, followed by a change in the geometry of structural extension elements without introducing thermal and, as a result, density heterogeneity into the experiment (Fig. 10).

The initial conditions of the experiments of this series are similar to the experiments of series 1 (Fig. 8a). A weakened zone of 50°–55° was set in the model lithosphere, after which the engine was started. One feature of this series is the introduction of structural heterogeneity at the boundary of the newly formed lithosphere, which corresponds to the Senja fault in nature. In some experiments, this inhomogeneity was the reason for the formation of a jump in the spreading axis, which can be seen by the example of experiment No. 2421.

Experiment #2421. At the preparation stage, a weakened zone was set at an angle ∟55° and a width of 2.5 cm. The first part of the experiment is similar to the previous series (Fig. 9, Fig. 10). At the first and second stages, a series of cracks is formed, which, when connected, form a single rift axis, nonorthogonal transform displacements and the structure of the valley is clearly expressed and is almost missing accretion shifts.

At the end of the second stage, the engine was stopped and structural heterogeneity was set to recreate natural conditions. After restarting the engine, the given structure affected the geometry of the rift crack, initiating an axis jump, which can be seen at the third stage of the experiment, that is, a new fragment of the rift axis that is marked with a red dotted line (Fig. 10).

The obtained jump of the spreading axis due to the changed geometry of structural inhomogeneities in the area of rifting is not the only scenario in which such changes are possible. In [5] in experiment No. 1997 and [21] in experiment No. 1967 was shown that a change in the position of the spreading axis is possible due to density inhomogeneity, or a thermal anomaly in the lithosphere, which occurs during the experiment in the presence of a plume in the vicinity of the rift.

DISCUSSION OF THE RESULTS

Geodynamic Interpretation

The manifestation of modern tectonic activity in the axial part of the rift structure with the deformation of the sedimentary cover deposited in it by alluvial fans from the Barents Sea shelf is a process with an obvious geodynamic substantiation. Tectonic activity on the flank, recorded in seismicity, requires a different interpretation (Fig. 5).

Linear groups of epicenters, elongated mainly along the western side of the submeridional uplift, indicate the modern activation of this structure (Fig. 5, Fig. 6). Since breakup of Norwegian–Greenland basin, starting from 54 Ma, passed along the transform strike-slip boundary with the change of an additional component from transpressional to transtensional 36 Ma ago, this process should have been accompanied by the formation of near-fault structures, typical for this geodynamic setting, that is, transverse ridges [11, 24, 31–33].

An uplift on one of the sides of transform faults can form both under compression and under tension after isostatic compensatory uplift of one of the sides due to the removal of the load on the mantle substrate. Many transform faults in the Atlantic (Vema, Romanche, São Paulo, Andrew Bain, etc.) have transverse ridges on one of the sides with an excess of up to 3 km or more from the base, whose occurrence can be interpreted as an isostatic reaction to a change in the type of strike-slip mode kinematics. [17].

It should be noted that the listed faults have a relatively long offset part, at least 300 km, within which even deviations of the trajectory from a rectilinear shape can create conditions for both transtension and transpression, not to mention variations in the parameters of plate kinematics that the transform fault separates. The modern total length of the displacement between the head parts of the Mohn and Gakkel ridges is 1030 km, and variations in the types of geodynamic regime along its length are quite real.

The interpretation of the longitudinal uplift described in this paper, which is located on the continuation of the Senja fault, can be formulated as a transverse ridge, which can be confidently traced on the structural map of the basement (Fig. 5). In addition to its geometry and relationship with the main structural elements of the basin, including the East Greenland Ridge from the west of the Knipovich ridge, our interpretation also explains the overlap of the U3–U2–U1–U0 sedimentary complexes on its slopes without strong deformations, charachteristical for the active tectonics of the axial part of the rift (Fig. 2).

Small plicative deformations are traced along the U2 horizon, although these can also be box folds (Fig. 2). A positive flower structure is observed, shifting deposits between the U0 and U2 horizons (Fig. 2). This form of the wave field is usually revealed near slip-strike zones. We also see a low-amplitude uplift over the rise along the U0 horizon, which has a amplitude of ~100 ms (Fig. 2).

This indicates that before the beginning of the Quaternary period, a transpression setting could have arisen in the area, which is displayed in the wave field by a positive flower structure and a slight vertical movement along the uplift buried under modern sediments. Since a step of about 35 m is observed above it in the bottom topography, it can be assumed that the vertical component of the movement, which arose at the beginning of the Quaternary, is also active at the present time, leading to the appearance of seismicity between the axis of the Knipovich Ridge and the flank of the uplift, as well as to the east of it. The inflow of a large volume of glacial material formed a smoothed topography above this uplift.

Experimental simulation of spreading processes in the area of the Knipovich Ridge and its flanks with geometric parameters of movement that are close to those observed in reality showed that the spreading basement buildup strongly depends on the angle between the rift axis and the direction of movement. The most realistic reproduction of modern rift structures near the Knipovich Ridge is achieved with a variable angle between these directions (see Fig. 9, experiment No. 2416).

In this series, the model in the southern segment of the rift shows, at the third stage, near-rift arcs on the flanks, as in the real transition to the Mohn Ridge, and the occurrence of the most pronounced transform and nontransform displacements of the axis of the simulated rift compared to other series.

An experiment with the addition of structural heterogeneity on the eastern flank showed that its activation with a potential transfer of the extension center is quite plausible (Fig. 10). Thus, the variable kinematics of plate movement in the presence of a weakened zone can lead to migration of the tension center and to the appearance of additional spatial displacements of the axis.

Experiments simulating the effect of a plume have shown that the effect of a hot spot can also initiate a jump of the extension center to another position close to the projection of the plume onto the surface [5, 21]. Since, according to the data of regional seismic tomography, there is such a heated zone in the southeast of the Knipovich Ridge, we can assume that the activation trigger can be complex [25]. The modern scheme of geodynamics of the Knipovich Ridge and its flanks can be displayed as follows (Fig. 11a).

The space between the head parts of the Mohn and Gakkel ridges is a wide dextral strike-slip zone, in which a separation fracture has formed at present, which is the Knipovich ridge. The data on the sedimentary rocks [1] and the structure of the relief and sedimentary cover [16] show that the Knipovich Ridge is most likely not the original center of spreading, but arose as a result of rifting along a straightened trajectory on an already formed oceanic basement with a lithified sedimentary cover. The ridge on the northern extension of the Senja fault is a heterogeneity that has been activated as a result of the development of a trend towards a straightening of the transition between the Mohn and Gakkel ridges. An additional source of feeding for this process can be a mantle plume identified according to seismic tomography data [25].

Data on deformations in the upper part of the section of the sedimentary cover obtained during expeditions of the R/V *Akademik Nikolay Strakhov* from 2006 to 2010, allowed us formulate ideas about modern tectonics on the southeastern flank of the Knipovich Ridge [8, 18].

Previously, the idea was proposed that the logic of development in a tectonically complex area may consist in straightening the configuration of the divergent boundary in the Atlantic [17]. If we consider the process on the flanks of the Knipovich Ridge from these positions, we can assume the following events (Fig. 11b). The head part of the Mohn Ridge will move towards the Barents Sea, involving the sedimentary cover in the deformation of the original structure that appeared in the remote parts of the alluvial fan. Transformation of a single separation crack in Knipovich ridge will occur by highlighting several short spreading segments, perpendicular to the shelf crest, and the appearance of several long transform faults parallel to it simultaneously with the general narrowing of the shear zone.

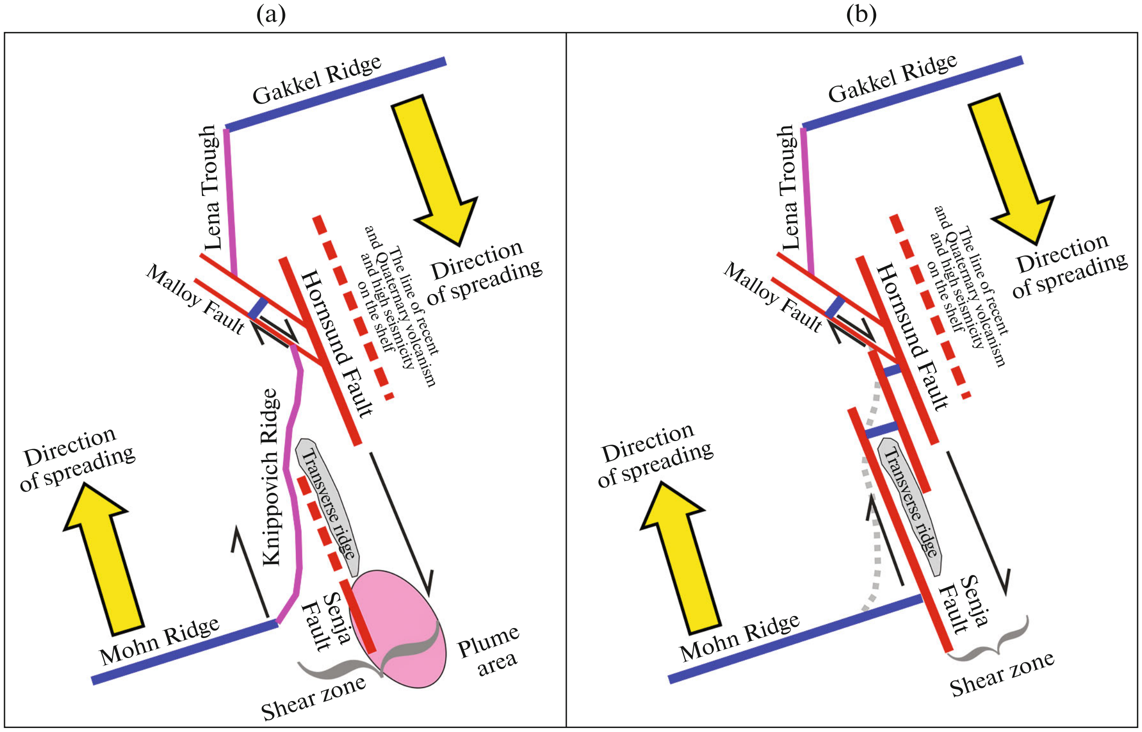

Fig. 11. The principal diagram of the modern geodynamics of the Knipovich Ridge area (according to [16], with modifications). (a) current state; (b) forecast transformation of tectonic elements.

The scenario of transition of activation to the shelf also confirms the area between the shelf edge and the eastern flank of the Knipovich Ridge with strong seismicity parallel to these structures [27]. In addition, Quaternary volcanism [14] and rift heat flow [20] are known in Svalbard. These facts indicate the possibility of changing the trajectory the transition of spreading activation from the Mohn Ridge to the Gakkel and further to the shelf.

Tectonic processes that can occur north of the Knipovich Ridge in the fault region Molloy are of interest for research, but we note that, according to [12], a situation has developed in this region that is potentially dangerous in the possibility landslide and tsunami waves; therefore, further studies of tectonic evolution of this region remains relevant.

CONCLUSIONS

(1) Interpretation of the acoustic basement on the CDP time sections on the southeastern flank of the Knipovich Ridge and their comparison with the Bouguer gravity anomalies made it possible to calibrate the anomaly values in terms of depths and build a basement map in isochrones for an area with an oceanic type of crust, determined by the level of the anomalous field.

A longitudianl uplift is distinguished on the map, which is the northern continuation of the Senja fault and is interpreted as a transverse ridge that appears on the sides of long transform faults. A transform interplate boundary ran along the uplift at the beginning of the opening of the Norwegian–Greenland basin. In an anomalous magnetic field, the uplift separates the regions with the presence of linear anomalies from the region with a mosaic structure of the field.

(2) The uplift identified on the southeastern flank of the Knipovich Ridge is framed by linear groups of epicenters outside the axial seismicity, indicating the presence of deformations in the upper part of the sedimentary section and activation of the region's structures. CDP data over the identified uplift show faults in the Pliocene–Quaternary sedimentary cover, which are probably currently active. These faults have signs of reverse and strike-slip kinematics.

(3) Physical modeling of structure formation in the region of the Knipovich Ridge clearly demonstrated the features of the main tectonic elements during oblique spreading with a difference in the extension direction angle of 10°–15° (or more) from the perpendicular to the axis of the weakened zone. A result close to reality was obtained during combined experiments with bending of the weakened zone, which is necessary for stress localization. The main discrepancies in the results of these experiments are the different frequency and amplitude of transform faults, as well as the appearance at a bigger angle of full-fledged accretion swells and nontransform displacements imitating

the structures of the southeastern flank of the Knipovich Ridge, are close to reality.

(4) A series of experiments carried out to study the conditions for the eastward jump of the spreading axis to the continuation of the Senja fault showed the possibility of activation of this structure, which we consider as one of the reasons for the formation of the features observed in geophysical data.

(5) The current position of the active zones of the region, seismicity, the structure of the basement and the structure of the sedimentary cover indicate an eastward shift in the activity of the main tectonic elements relative to the current position of the extension axis. A probable scenario for the further development of the region is the transformation of the Knipovich Ridge into one or a series of transform faults parallel to the western edge of the Barents Sea shelf and a series of short spreading segments between them. Of particular interest is the potential impact of strike-slip tectonics on large sedimentary masses in the Molloy fault region.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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