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Fracture Zones of the Doldrums Megatransform System (Equatorial Atlantic)

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Abstract—This article presents results of the structural and morphological analysis of the fracture zones that are part of Doldrums Megatransform System (DMS), located in the northern part of the Equatorial Atlantic (6.5°–9° N) that include Vernadskiy and Bogdanov transform faults and the Doldrums and Pushcharovskiy megatransforms. Bathymetric map, based on the multibeam echo sounding data, collected during the 45th cruise of the R/V *Akademik Nikolaj Strakhov* was used for this analysis. It was established that large-scale variations in the width of fracture zone valleys are determined by the distribution of stresses perpendicular to the fracture zone. In the areas with compressive stresses, the fracture zone valleys are narrower and the extension areas are wider. The difference in geodynamic settings within the DMS is due to the difference in spreading directions, which change from ∟89° to ∟93° when moving from south to north. The depth of fracture zone valleys consistently increases from the periphery of the DMS (Bogdanov and Doldrums faults) to the center (Pushcharovskiy fracture zone) in accordance with a decrease in the upper mantle temperature. In each fracture zone, the valley depth decreases from the rift- fracture zone intersections towards the center of the active part to a certain background depth. It is assumed that this phenomenon is the result of the uplift of the valley bottom, which occurred due to the decompaction of the lithosphere, caused by the serpentinization of ultramafic rocks. The violation of the revealed variations in the width and depth of fracture zone valley patterns occurs as a result of various ridges and uplifts formation in the fracture zone. In the axial zones of the active parts of the fracture zone valleys median ridges are widespread, extending parallel to the fracture zone and representing serpentinite diapirs squeezed out above the bottom surface. Transverse ridges that were formed 10–11 million years ago as a result of the lithospheric plate edge flexural bending under extensional conditions are now located in the western passive parts on the southern sides of the of Doldrums and Pushcharovskiy fracture zone valleys. The transverse ridge on the northern side of the Vernadskiy fracture zone, which includes Mount Peyve, was formed between 3.65–2.4 Ma. Due to the frequent jumps of the spreading axis in this region, it was divided into three segments. There are interfracture zone ridges in megatransforms, which in the active part consist of two fracture zone valleys. The times of their formation were in the Pushcharovskiy megatransform, 30–32 million years ago and in the Doldrums megatransform, about 4 million years ago. Due to the curvilinearity of the outlines and under the pressure of moving lithospheric plates, the interfracture zone ridges experience longitudinal (along the fault) compressive and tensile stresses, which are compensated by vertical uplifts of their separate blocks and the formation of depressions, pull apart depressions, and spreading centers (the latter are only in Pushcharovskiy megatransform). The structure-forming processes that determine the patterns and morphology of the fracture zones as a part of the DMS are related in their origin to the spreading and transform geodynamic systems.

Keywords: Equatorial Atlantic, Mid-Atlantic Ridge, Doldrums Megatransform System, transform fault, spreading segment, fracture zone valley, median ridge, transverse ridge, interfracture zone ridge

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INTRODUCTION

This research is based on materials of cruise 45 of the R/V *Akademik Nikolaj Strakhov*, which took place in 2019, and was intended to study megatransforms as a special type of interplate boundaries in the ocean [10, 30].

The Doldrums megatransform system is located in the northern part of the Equatorial Atlantic and is enclosed between the Doldrums transform faults (in the north) and a nontransform displacement crossing the axial spreading zone of the Mid-Atlantic Ridge (MAR) at latitude 6.87° N (South) [9] (Fig. 1a, inset).

The Doldrums megatransform system has a lenticular shape in plan; the total offset is about 630 km, and includes the Doldrums, Vernadskiy, Pushcharovskiy, and Bogdanov transform faults.

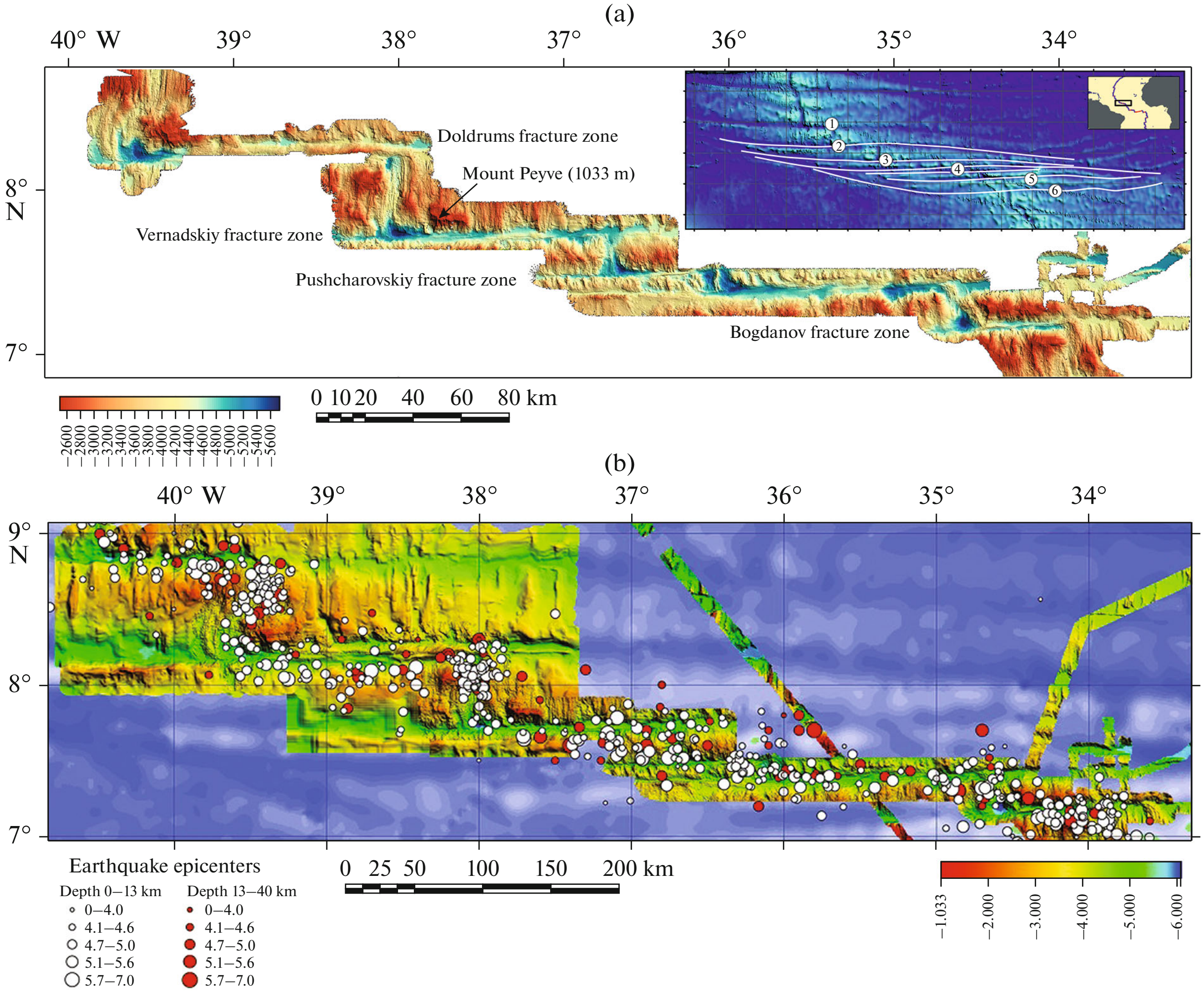

Fig. 1. The bottom relief and seismicity in the area of the Doldrums megatransform system (DMS). (a) bathymetric map constructed according to the data of the 45th cruise of the R/V *Akademik Nikolaj Strakhov* (according to [10]); (b) seismicity (according to USGS data [31]). Inset: DMS position in the structure of the Equatorial Atlantic based on the predicted topography map (according to [28]). Faults (Arabic numerals in circles): (1) Arkhangelsk; (2) Doldrums; (3) Vernadskiy; (4) Pushcharovskiy; (5) Bogdanov; (6) nontransform displacement 6.87° N.

We previously defined this paragenesis as the DMS, but after studying this structural formation in more detail, we came to understing the need to clarify the definition and designated it as the DMS, since we translated some of the transform faults included in the system to the rank of megatransforms.

When describing faults, we will use the generally accepted terminology [1, 2, 5]. For a fault along its entire length, we use the name fault zone or fault zone, in which the following are distinguished:

— the active part of the fault is the segment between the axes of adjacent spreading segments separated by a fault, a transform fault (or transform);

— the passive, that is, western and eastern parts are the parts of the fault that continue from opposite sides of the active part of the fault.

The main structural element of the fault zone is a fault valley or trough. The sides of the valley are built up with structures of various nature: transverse (or transverse) uplifts (or ridges) extending parallel to the fault valley, rift mountains, and oceanic core complexes (OCC).

The internal structure of the valley can be complicated by intra-fault structures:

— median ridges stretching along the axis of the valley;

— transverse uplifts (thresholds) crossing the valley from side to side;

— nodal and other depressions (nodal depressions are formed in the rift and fault intersect zones).

The study of the fault zones structures was carried out on the basis of the bottom relief data obtained from the results of a bathymetric survey carried out on the

45th cruise of the R/V *Akademik Nikolaj Strakhov*, as well as on a bathymetric map constructed during the compilation of the relief according to the data of the 6th, 9th, 22nd, and 45th cruises [9, 10, 30] (see Fig. 1a; Appendix 1: Fig. S1).

The purpose of this article is to study megatransforms as a special type of interplate boundaries in the ocean on the example of the DMS.

THE STRUCTURE OF THE DOLDRUMS MEGATRANSFORM

The DMS is located in the northern part of the Equatorial Atlantic; it includes a separate segment of the MAR, has a lenticular shape and is bounded in the north by the Doldrums transform fault, and in the south by a nontransform displacement of 6.87° (see Fig. 1, inset).

The distance between the Doldrums Fault and the 6.87° nontransform displacement decreases from 170 km in the ridge zone to 110 km (at 31.3° W) on the eastern flank and 30 km (at 41.7° W) on the western flank. The DMS as an independent structure was formed ~30–32 Ma ago as a result of major geodynamic rearrangements in the Atlantic; the system includes the Vernadskiy (7.74° N), Pushcharovskiy (7.40° N), and Bogdanov (7.25° N) faults (see Fig. 1). These faults, being sublatitudinal in the ridge zone, experience changes in strike on the flanks; they either connect or sticks into the Doldrums Fault, or discordant zones of nontransform displacement that limits the system from the south. All faults have large offsets (from 42 to 177 km), and the total offset of the DMS is ~630 km [28].

FIELD DATA AND RESEARCH METHODS

The main methods used in studying the ocean floor in the area of the DMS during cruise 45 of the R/V *Akademik Nikolaj Strakhov* were bathymetric surveys and bottom sampling (dredging). During the survey, 18 latitudinal lines with a total length of 3400 km were completed; the lines were planned with overlaps in such a way as to provide continuous survey coverage of the study area.

We used a deep-sea multibeam echo sounder from Teledyne-RESON A/S (United States, Denmark), model SeaBat-7150 with 256 beams (12 kHz), and a total swath angle of 150°. The processing of the obtained data was carried out in the PDS2000 software (*RESON*) version 3.7.0.53 (United States, Denmark) [33]; in this software a digital elevation model was built with a grid step of 100 m and a bathymetric map with a total area of 29 000 km^2 was obtained (See Appendix 1: Fig. S1).

On the basis of the map, morphostructures and their parageneses were distinguished, as well as their description, morphometry, and, subsequently, genetic interpretation. During dredging, the main structures of the ocean floor in the area were tested. In this study, the results of sampling were used in the genetic interpretation of morphostructures.

THE STRUCTURES OF FAULT ZONES

Doldrums Fault

The length of the active part of the fault is 177 km; its strike is 91°. According to the data obtained during the 6th and 45th cruises of the R/V *Akademik Nikolaj Strakhov*, in the active part of the Doldrums transform fault, two sublatitudinal troughs separated by an extensive inter-fault ridge are recorded [4] (Fig. 2, I):

— northern trough (see Fig. 2, I, **1**);

— inter-fault ridge (see Fig. 2, I, **2**);

— the southern trough was studied with a 15-beam echo sounder on the 6th cruise (see Fig. 2, I, **3**).

The northern trough does not intersect with rift valleys. In the west, it does not reach the 75 km intersect zone, ending at 39° west, where it rests against the structures of the ridge zone of the MAR; in the east it is separated from the rift by an inter-fault ridge (see Fig. 2, I, **4, 5**).

The southern trough extends from the eastern intersect to a nodal depression formed in the western intersect. The data on the seismicity of the region, according to which the main part of earthquakes is confined to the southern trough, indicate that it is currently an active fault, although earthquakes are also recorded in the northern trough [31] (see Fig. 1b).

From the western end of the northern trough towards the western intersect mapped a series of narrow shallow incisions that build on each other in an echelon manner and cut through the structures of the MAR ridge zone (see Fig. 2, I, **6**). Together, they form an arc of a general southwestern strike, practically reaching the southern trough in the area of the 39.4° W.

Most of the earthquakes in the northern trough are confined to this zone. If the northern trough is considered together with the incisions as a whole, then it can be concluded that the northern fault has an arcuate shape in plan view.

The width of the northern trough in the active part fault averages ~7.5 km (hereinafter, the width of valleys, depressions was determined as the distance between the upper edges of their opposite sides). Between 38° and 38.6° W the width is drastically reduced up to 3 km (see Fig. 2, II, sections E–E', F–F').

The trough depth within the active part the fault varies considerably: over long level areas it is 4500 m, in several depressions, which are similar in size and morphology to nodal depressions and, most likely, are their paleoanalogues, it increases to 4650 m (see Fig. 2, II, section A–A'). The depth is sharply reduced to 3850 m at the narrowest point between 38° and 38.6° W.

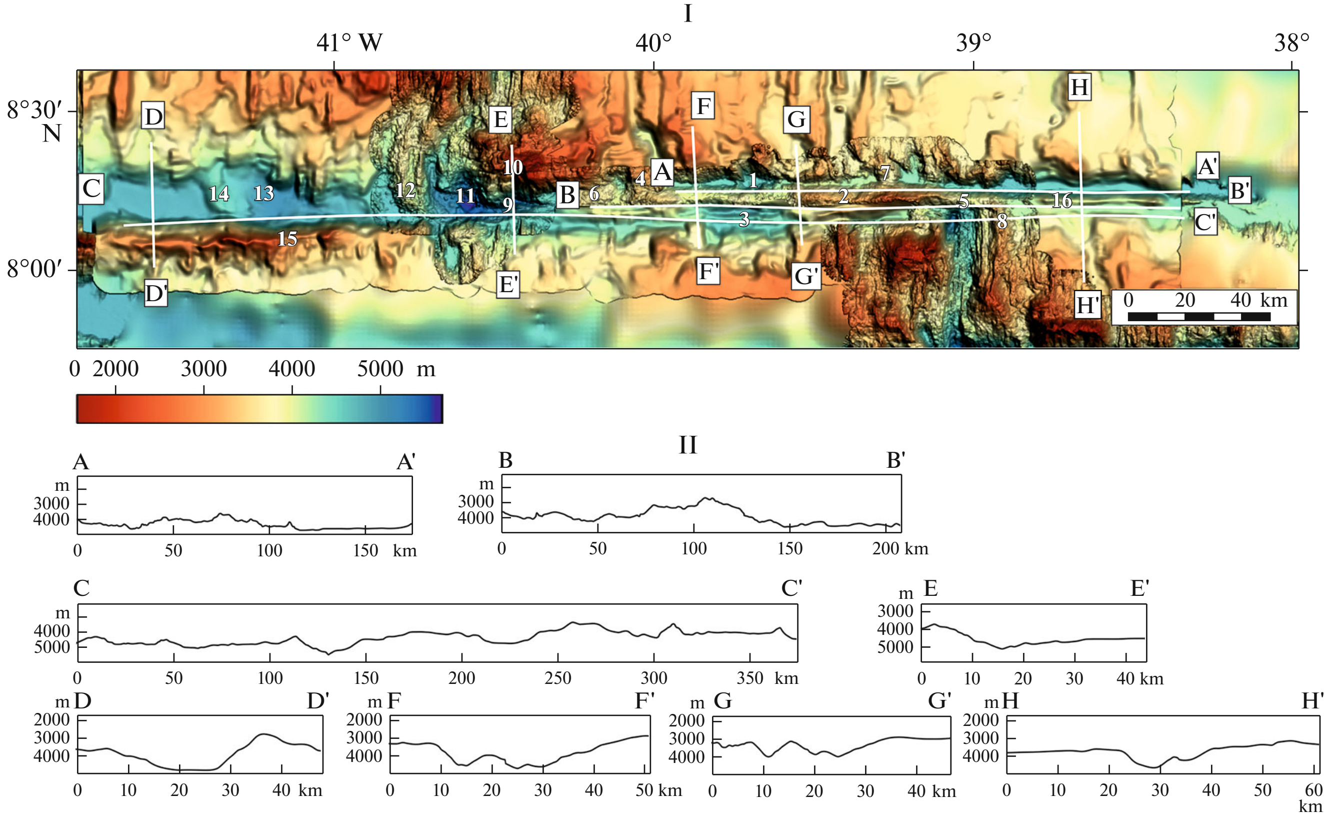

Fig. 2. The bottom relief in the area of the fault zone Doldrums according to cruise 45 of the R/V *Akademik Nikolaj Strakhov*. I, bathymetric map; II, bathymetric profiles: A–A', B–B', C–C' (longitudinal); D–D', E–E', F–F', G–G', H–H' (transverse). Designated (Arabic numerals): **(1)** northern trough; **(2)** inter-fault ridge; **(3)** southern trough; **(4)** ridge zone of the MAR; **(5)** inter-fault ridge; **(6)** cuts; **(7)** transverse submeridional threshold; **(8)** rift ridge; **(9)** cut (in the center of the bottom); **(10)** internal ocean complexes; **(11)** nodal depression; **(12)** rift ridges; **(13)** paleonodal basin; **(14)** transverse threshold; **(15)** transverse ridge; **(16)** inter-fault ridge.

Around 38.25° W the valley is crossed by a transverse submeridional step, ~6-km wide and 500-m high, which is a continuation of the rift ridge north of the Doldrums Fault (see Fig. 2, I **7**). Typically, such massive formations in the axial spreading zone are neovolcanic uplifts. [9]. We believe that this is most likely a dead neovolcanic uplift.

The northern trough has a U-shaped cross section.

The southern side of the northern trough is continuous and rectilinear; its upper boundary is not obvious, since at the same time it is the northern slope of the interfault ridge.

The northern side is built on the structures of the ridge zone, representing alternation of rift ridges and depressions separating them. At the same time, both ridges and depressions end at the level of the upper edge of the side of the fault valley.

Thus, the structures of the MAR zones are located above the bottom of the fault valley and rise to the height of its side. The excess averages 750 m, it increases near the paleonodal depressions up to 1000 m and decreases to 450 m in the area of the bottom rise between 38° and 38.6° W.

The northern wall is absent in areas where submeridional depressions are developed in the ridge zone, morphologically similar to the rift valley, and are connected to the fault valley.

The average width of the valley bottom is 1.5–2 km, with a sharp expansion up to 4 km in the area of paleonodal depressions and narrowing to 0.5–0.8 km in the area of bottom uplifts. The bottom surface is leveled and flat in the region of depressions, which indicates that the bottom is covered by sedimentary strata.

The dredging of the slopes of the northern wall yielded serpentinized peridotites, gabbro, and altered basalts with a noticeable dominance of the former [4, 30].

The interfault ridge, ~130- km long and 3.5 to 5-km wide, has a lenticular shape in plan view and a triangular cross section. It can be traced along the entire strike of the active part of the northern trough and ends in the eastern passive part of the fault zone. The depth of the top of the ridge varies from 4000 m to 2650 m, while the height above the valley floor varies from 500 to 1850 m.

Between 38° and 38.6° W in the area where the northern fault trough sharply narrows and rises, a 3250 m interfault segment ridge up to 1250-m high and ~50-km long occurs. The interfault ridge reaches its maximum width and height in the eastern flank of this segment, where an uplifted block 20-km long was formed, bounded by steep transverse slopes (see Fig. 2, II, sections B–B', F–F'). The slopes of the inter-fault ridge along its entire length are crossed by narrow low transverse ridges. The crest of the ridge is narrow and straight.

The inter-fault ridge in the east smoothly connects with the submeridional rift ridge, its the western end is not obvious, but most likely it is close to the end of the northern trough (see Fig. 2, I, **8**).

The highest and widest part of the inter-fault ridge was sampled on the 6th and 9th cruises of the R/V *Akademik Nikolaj Strakhov*. From its slopes, serpentinized peridotites, gabbroids, basalts, and clastic rocks were obtained: siltstones, sandstones, and gruss [4].

The width of the southern trough of the Doldrums Fault in the active part increases from the eastern to the western intersect from 5 to 12 km (see Fig. 2, II, sections E–E', F–F').

The greatest depth is observed near the nodal depression in the western intersect, but from the mark of 5150 m depth decreases sharply eastward to 4500 m (see Fig. 2, II, section B–B').

In the region of the eastern intersect, the fault valley articulates with the rift basin, the depth here is 5400 m, and the bottom of the fault valley immediately rises sharply to 4500 m in the westerly direction. On extended leveled sections of the southern trough, the depth is 4750 m. The smallest depth of ~4000 m is close to the depth of the northern trough between 38.2° and 38.6° W.

The southern trough in the west of the active zone, where the incision zone extending from the northern trough approaches the southern side, has an unusual structure: a very wide (~12 km) flattened and uneven bottom with a width of the valley itself –17 km, runs along the thalweg in the center of the bottom incision 1-km wide and 200-m deep (see Fig. 2, I, **9**).

The steep northern side, whose height reaches 1100 m, is built by a dome composed of OCC (see Fig. 2, I, **10**).

The southern side is gently sloping and stepped, reaching a height of 750 m (see Fig. 2, II, section D–D'). This section of the southern trough has a northwestern strike, which gives the entire southern fault an arched shape.

A significant part of the southern fault valley is made up of median ridges (length 30–40 km, width 2–2.5 km, and height ~250 m) built on each other (see Fig. 2, I, **3**).

The Doldrums fault zone has a lenticular shape in plan view; as evidenced by morphometric data, the width of the zone is:

— near the eastern intersect – 18 km;

— in the middle part – 22–23 km;

— near the western intersect – 17 km.

Thus, by all indications, the Doldrums Fault is a megatransform fault. It has two arc-shaped transforms, between which there is an inter-fault ridge, which has undergone intense tectonic movements, giving it a block structure.

In the zone of the western rift–fault intersect, a nodal basin up to 9 km in diameter and 5600 m deep was formed (see Fig. 2, I, **11**). The nodal depression is overdeepened relative to the depth of the fault valley by 450 m, which is 200–300 m more than in the cases with paleonodal depressions.

To the west of the nodal basin, a rift ridge enters the fault valley and reaches its opposite side (see Fig. 2, I, **12**).

In the western passive part of the valley located behind the ridge, the depth is 4800 m, with a width of 17 km (see Fig. 2, II, sections B–B', G–G').

At 50 km to the west of the intersect, the valley floor is complicated by a paleonodal basin isometric in plan, 5050-m deep and 10 km in diameter (see Fig. 2, I, **13**).

To the west of this depression is a wide (9 km) transverse step, which reaches a height of 500 m, which is probably a dead neovolcanic ridge protruding from the north (see Fig. 2, I, **14**).

Throughout the western passive part the valley has a trough-like shape, the bottoms of the valleys are wide and flat (see Fig. 2, II, section G–G'). According to seismic profiling data, a sedimentary cover with a thickness of at least 200 m was formed in this part of the fault valley [4].

The southern side of the valley is steep continuous and straight; it is simultaneously the northern slope of the transverse ridge (see Fig. 2, I, **15**, II, section D–D').

The northern wall, whose height reaches 750 m, is similar in structure and morphology to the northern trough in the active part. On the 6th cruise of the R/V *Akademik Nikolaj Strakhov* on the southern side of the valley in the western passive part, a large extended high transverse ridge of sublatitudinal strike was mapped, composed of serpentinized ultramafic rocks and basalts altered and deformed into small folds [4] (see Fig. 2, I, **15**).

The ridge, which is ~12-km wide, stretches for more than 145 km west of the western intersect, and well outside the mapped area. From east to west, the depth of the crest of the ridge decreases from 4000 m to 2000 m and then increases to 2750 m. Thus, its height above the crest of the fault valley varies in the same direction from 50 m to 2050 m.

No distinct nodal depression was formed in the eastern intersect. The valley of the northern fault con-

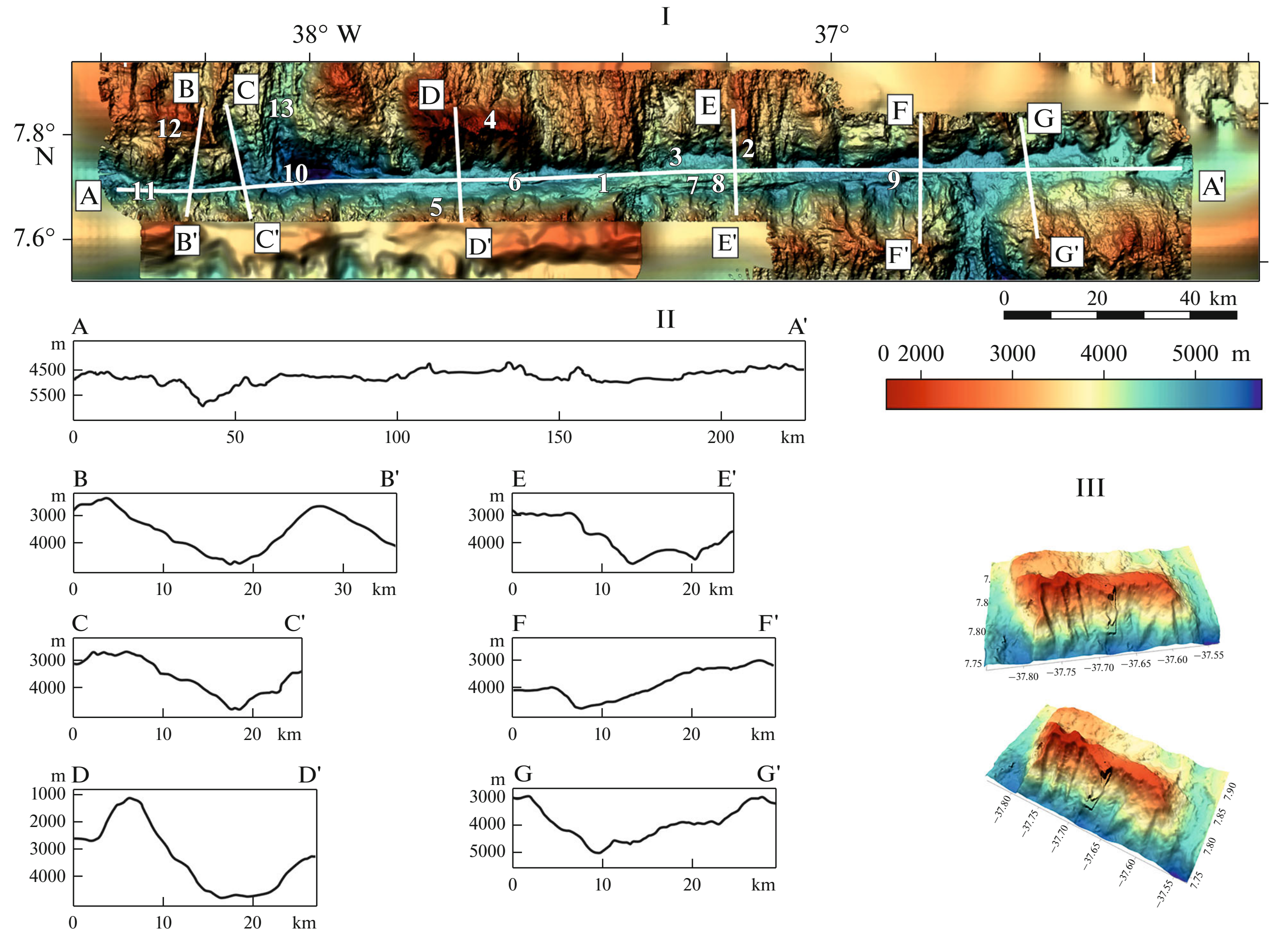

Fig. 3. The bottom relief in the area of the fault zone Vernadskiy according to the data of cruise 45 of the R/V *Akademik Nikolaj Strakhov*. I, bathymetric map; II, bathymetric profiles: A–A' (longitudinal); B–B', C–C', D–D', E–E', F–F', G–G' (transverse); III, Mount Peyve (3D relief model). Designated (Arabic numerals): (**1**), fault valley; (**2**), median ridge; (**3–4–5**), sides of the fault valley; (**6** –7), median ridges; (**8**), intra-fault uplift; (**9**), spurs of the median ridge; (**10**), nodal depression; (**11**), sides of the fault valley; (**12**), transverse ridge; (**13**), rift valley.

tinues into the eastern passive part, where its width is 11 km and depth was 4650 m.

From the intersect to the east for 25 km, a narrow ridge ~50-km long, up to 4-km wide, and about 400-m high, with a peak at a depth of 4000 m, is fixed against the southern side of the valley (see Fig. 2, I, **16**). This ridge could be qualified as a median ridge, but it is located on the eastern continuation of the interfault ridge and is separated from it by a small depression, while their total length is close to the length of the Doldrums fault offset.

We assume that this ridge is the eastern flank of the interfault ridge. This is evidenced by the products of dredging obtained from its slope; they are completely similar to the rocks that were raised from the interfault ridge [4]. Between the inter-fault ridge and the northern side of the valley, the bottom is flat, wide, and covered with sediments (see Fig. 2, II, section 3–3'). The height of the northern side is about 750 m. The valley has a trough-shaped cross section.

The Vernadskiy Fault

A bathymetric survey was carried out on cruise 45 of the R/V *Akademik Nikolaj Strakhov* on the active part of the fault and small fragments of both passive parts (Fig. 3, I).

In the active part, the valley has a sublatitudinal (89°) strike and a length of 146 km. The depth of the valley in the active part noticeably changes (see Fig. 3, II, section A–A').

The maximum depth of the valley is mapped near the western intersect; east of the nodal basin, it is 5150 m; further eastward for 25 km the depth decreases to 4750 m.

From the eastern intersect where the nodal depression is absent, the bottom of the valley rises stepwise from 5000 m to 4750 m over a distance of 35 km to the west. A depth of 4750 m is typical for extended flattened sections of the fault valley. (see Fig. 3, I, **1**).

The minimum depth of 4600 m of the valley is observed between 37.4° W and 37.2° W near a large median ridge (see Fig. 3, I, **2**). Every 20–30 km, paleonodal depressions are located in the active part, the depths of which are 100–150 m greater than the depths of the adjacent parts of the valley.

The width of the fault valley in the active part increases successively from the eastern rift–fault intersect to western intersect from 6 up to 12.5 km (see Fig. 3, II, sections D–D' to F–F').

The northern side of the valley, which has an average height of ~750 m, is steep and discontinuous, since the submeridional depressions of the MAR zone, located opposite some paleonodal depressions, are connected with a fault valley (see Fig. 3, I, **3**). In other areas, it is straight or curved.

Winding areas are observed near other paleonodal depressions, opposite which the fault valley widens, entering the ridge zone, but the edge is not interrupted here, since the submeridional depression of the ridge zone does not reach the fault valley and hovers over it at the level of the upper edge of the side. The northern side of Mount Peyve is complicated by narrow winding ridges up to 8-km long, ~300-m high, and up to 1.5-km wide, extending across the side of the valley, as a result of which its surface has a sawtooth profile (see Fig. 3, I, **4**).

On the southern side of the valley on the eastern flank of the active part up to 37.3° W the wall is absent; here, large rift ridges, which are former neovolcanic uplifts, and the depressions separating them, are associated with a fault valley. In this case, the southern boundary of the fault valley can be drawn along the foot of the rift ridges. West of 37.3° W the southern wall ~600-m high at a distance of ~50 km is continuous, slightly sinuous, or rectilinear (see Fig. 3, I, **5**). In this section, the valley has a U-shaped profile.

Near the western intersect, the heights of both sides increase to 1000–1200 m.

A complex system of median ridges has formed in the active part of the fault in the valley. On the western flank of the fault valley from the nodal depression to 37.5° W five alternating ridges 10–15-km long, 1.5–2-km wide, and 100–150-m high stretch out (see Fig. 3, I, **6**).

Further east a larger median ridge follows, separated from the southern side of the valley by a narrow depression (see Fig. 3, I, II, section E–E'). The greatest width (up to 4 km) and excess above the bottom of the valley (300 m) occurs between 37.4° W and 37.2° W. In this area, the ridge consists of two ridges and is built up on the eastern flank by a rise ~7 km in diameter and up to 500-m high (Fig. 3, I, **8**).

Further to the east, this ridge narrows and continues to the eastern intersect with several narrow (up to 1 km) low (up to 100 m) ridges located on the southern side of the fault and continuing into the eastern passive part of the fault (see Fig. 3, I, **9**).

Located 33 km to the east from the western intersect, Mount Peyve, which is built on the northern side of the valley, stretches parallel to the fault for a distance of 37 km and has a width of 9 km, a height above the crest of the northern side up to 3000 m, and reaches a depth of 1033 m (see Fig. 3, I, II, section D–D'). In the western part of the mountain, its top is flat as a result of erosion when the mountain was above sea level [10] (see Fig. 3, III).

Gabbro and, to a lesser extent, basalts and serpentinized peridotites, are predominantly dredged from the slopes and top of the mountain, while among the recovered samples there are varieties bearing signs of subaerial weathering [4]. Among the deep rocks there are many varieties that are tectonized to various degrees. This range of rocks is close to the rocks that make up the oceanic core complexes (OCC). However, the elongated morphology of the mountain and the absence of tectonic plowing grooves on its corrugation surface do not allow us to classify it as an internal oceanic complex.

Based on the data we obtained and the analysis, we believe that Mount Peyve is a transverse ridge. On both sides, Mount Peyve is bounded by paleorift valleys (see Fig. 3):

— in the west at 37.85° W;

— in the east at 37.58° W.

Between the modern rift valley and the paleorift valley located along 37.85° W and limiting Mount Peyve from the west, the northern side of the fault valley is built on by a wide (up to 4 km) step 6-km long, connecting in the north with the dome-shaped OCC structure (see Fig. 3, I, **13**). This step, which is located on the continuation of Mount Peyve, is most likely its detached fragment.

In the eastern passive part, within the mapped area, the depth of the valley near the intersect is 5000 m. Further to the east, the valley is successively partitioned off by three transverse steps, behind each of which its depth decreases, reaching 4500 m in 30 km from the intersect zone (see Fig. 3, II, section A–A').

The width of the valley here is on average ~5 km, but there are several local widenings on the side of the northern wall, whose height is ~750 m (see Fig. 3, II, section G–G'). The southern wall, which is built on by oval uplifts of the interfault uplift, is straight, its height is 500 m [9]. Throughout its entire length, including the area opposite the rift valley, the bottom of the valley is wide, flat, and probably covered by sediments;

The western intersect contains a nodal depression ~6000-m deep and ~8 km in diameter (see Fig. 3, I, **10**). It is buried, relative to the fault valley, at 850 m. West of the nodal depression, the depth of the fault valley first sharply decreases from 5150 to 5000 m, and then, over 25 km, decreases slowly and stepwise to a depth of

4750 m (see Fig. 3, II, section A–A'). Its width in this section is 4–5 km (Fig. 3, II, sections B–B', C–C'). The valley has a young form:

— a V-shaped section;

— a very narrow rectilinear bottom without sediments;

— steep sides with heights of 650–750 m.

Here, at the bottom of the valley and on its northern side, there are small winding ridges 50–100-m high and 1–1.5-km wide (see Fig. 3, I, **11**) extending across the slope. In this area, on the northern side an unextended (up to 10 km) transverse ridge rising to a depth of 2200 m ends (see Fig. 3, I, II, section B–B'). To the west of the transverse ridge there is a paleorift valley extending along the 38.45° W meridian. [9].

The transverse ridge is located on the western extension of Mount Peyve and is separated from it by several near-rift ridges and the rift valley itself (see Fig. 3, I, **13**). Apparently, this transverse ridge, Mount Peyve, and the step between them, which are on the same line, previously was a single transverse ridge with a total length of ~53 km, which is currently divided by rift and paleorift valleys into three segments.

To the west of the transverse ridge, according to the GEBCO map [21], the fault valley widens sharply up to 18 km; the bottom, covered by sedimentary strata, becomes wide and flat and the transverse profile becomes trough-shaped [21].

The Pushcharovskiy Fault

The Pushcharovskiy Fault is a double fault consisting of two closely spaced fault troughs separated by a lenticular inter-fault ridge cut by a short spreading center (~30 km) [9, 30] (Fig. 4, I).

The total length of the active part of both faults is 186 km (the northern fault is 67 km and the southern fault is 119 km).

The bathymetric survey covers the active part and part of the western passive part of the northern fault, as well as the active and large fragments of the western and eastern passive parts of the southern fault.

The strike of faults in the active part is sublatitudinal 89°. The southern fault is arcuate in plan view, since the strike of the valley in its eastern passive part slightly deviates counterclockwise.

The greatest depths of the northern fault valley are observed in the areas of the rift–fault intersects. In the active part, the depth of the valley gradually decreases from 5300 to 4950 m from the western intersect for 20 km to the east, and then in the area where the median ridge appears decreases sharply up to 4550 m (see Fig. 4, II, section A–A').

On the eastern flank of the active part, the depth gradually decreases to the west from 5200 to 4950 m, and then sharply reaches the minimum values of 4500 m near the median ridge. In the zone of the western intersect is a nodal depression with a depth of 5750 m and a diameter of ~10 km; it is deeper than the bottom of the valley by 450 m (see Fig. 4, I, **1**).

There is no nodal depression in the area of the eastern intersect; here, a large neovolcanic ridge is pushed into the valley, which leads to its narrowing (Fig. 4, I, **2**).

Thus, the central part of the northern trough between the 36.15°–36.45° W is significantly elevated (at a maximum to a depth of 4300 m).

In general, the width of the northern fault valley in the active part varies little and is equal to 5 km. The northern side of the valley is steep, continuous, and straight. The southern wall on the eastern flank of the active part from the eastern intersect to 36.40° W is absent, since the submeridional structures of the interfault ridge go directly into the fault valley.

West of this longitude, the south side is also steep and straightened and passes without changes into the western passive part and is interrupted only in one place at 36.50° W, where the interfault ridge is cut by a wide and deep submeridional depression. The height of both sides near the western intersect is ~1150 m; opposite of the median ridge, it is ~450 m. The sides continue upwards with a smoothed oval relief and uplifts in the north and the contrasting relief of the interfault ridge in the south.

The north side of the valley is indented, because small ridges developed on the surface of oval uplifts descend across the side.

The valley has a young appearance (see Fig. 4, II, section F–F'):

— V-shaped profile;

— narrow straight bottom, not covered with sedimentary rocks;

— steep symmetrical sides.

A narrow (2–2.5-km wide) extended (up to 40 km) slanting ridge 400–500-m high formed in the region of the uplifted part of the valley (see Fig. 4, I, **3**).

In the east, it is confined to the axis of the valley and, moving to the west, is increasingly pressed against the southern side, eventually forming a step in its relief. In general, the strike of this ridge is 75°. In the east, the oblique ridge breaks up into a series of short (5–10 km) and less elevated ridges resting on the northern side.

In the western passive part of the fault a V-shaped valley narrows to 2.5–3.5 km (see Fig. 4, II, sections G–G', E–E'). The depth of the valley sharply decreases to the west of the nodal depression from 5300 to 5000 m and further to the west gradually, stepwise, to 4750 m and even further to the west, to 4450 m (see Fig. 4, II, sections D–D'). The valley from western intersect to 36.85° W over 20–25 km has a young appearance:

— V-shaped cross section;

— narrow rectilinear bottom in the form of an incision without sediments;

— steep sides 600-m high in the south and 380 m in the north.

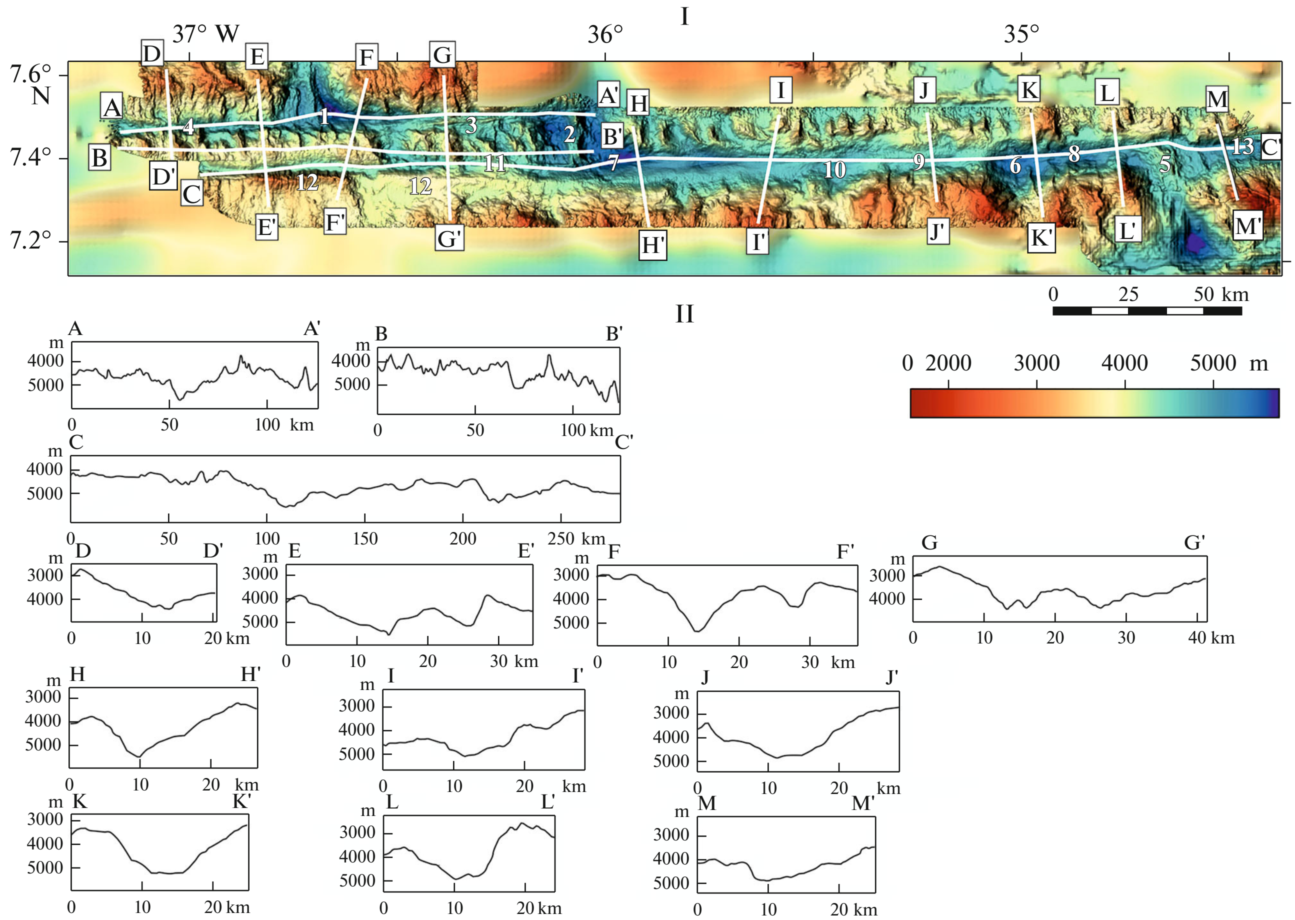

Fig. 4. The bottom relief in the area of the fault zone Pushcharovskiy according to the data of the 45th cruise of the R/V *Akademik Nikolaj Strakhov*. I, bathymetric map; II, bathymetric profiles: A–A', B–B', C–C' (longitudinal); D–D', E–E', F–F', G–G', H–H', I–I', J–J', K–K', L–L', M–M' (transverse). Designated (Arabic numerals): (**1**), nodal depression; (**2**) neovolcanic ridge; (**3**), median ridges; (**4**), combs; (**5**), neovolcanic ridge; (**6**)–(**7**), nodal depressions; (**8**), median ridges; (**9**), intra-fault uplift; (**10**), median ridge; (**11**), transverse step; (**12**), transverse ridge; (**13**), fractured valley.

Further to the west, the bottom expands to 1 km and flattens, apparently due to the fact that it is covered by sedimentary rocks. The height of the sides on both sides is 250 m. At the bottom of the valley there are several short (up to 7 km) narrow (up to 0.5 km) low (50–100 m) winding ridges (see Fig. 4, I, **4**).

The valley of the southern fault in the active part is much wider (6.5–7 km) than the valley of the northern fault and practically does not change in the active part, expanding near the paleonodal and nodal basins up to 7.5 km (see Fig. 4, II, sections H–H'–M–M'). The greatest depths of the southern valley near the intersects (see Fig. 4, II, section K–K').

At 30 km west of the eastern intersect the depth of the valley is 5250 m. Towards the intersect, the depth of the valley decreases, since there is a large neovolcanic uplift here (see Fig. 4, I, **5**). To the west the valley deepens to 5350 m, because here at 35° W is a paleonodal basin (see Fig. 4. I, **6**, II, section K–K').

To the west of this depression, the bottom of the valley rises sharply to a depth of 4450 m, since a longitudinal uplift begins here, occupying almost the entire bottom of the valley. At the western limit of this longitudinal rise of the bottom, the depth of the valley sharply decreases to 4850 m. Further to the west, the bottom gradually decreases to a depth of 5000 m, but in front of the nodal depression, the depth sharply increases to 5350 m (see Fig. 4, I, **7**). The nodal depression is deepened 310 m relative to the valley and has an absolute depth of 5660 m and a diameter of ~11 km.

The cross section of the valley over a significant extent of the active part is trough-shaped with a wide bottom and is asymmetric due to the more gentle southern side. The height of the sides varies (see Fig. 4, II, section H–H'):

— ~1000 m (western intersect);

— 600 m (eastern intersect);

— 250 m (region of longitudinal uplift valley floor).

The northern side is straight and continuous, the southern side (in the eastern half) is winding, in the region of the paleonodal depression on the 35° W meridian it is interrupted by a large submeridional depression that cuts through the ridge zone. West of 35.65° W on the southern side, at the level of its upper edge at a depth of ~4500 m, there is a wide step 3–6-km wide, which is replaced above by an interfault uplift. This step extends to the western intersect and, in its structural position, is similar to a transverse ridge that has not reached full formation.

In the axial part of the valley between the eastern intersect and the paleonodal depression located at 35° west, there are several low (up to 100 m) short (up to 6 km) narrow (up to 0.5 km) median ridges (see Fig. 4, I, **8**).

The large longitudinal uplift of the valley bottom located between 35.1° W and 35.35° W has a length of ~67 km. The height of the uplift varies from 500 m in the east to 150 m in the west. The bottom in the area of this uplift is flat and the thalweg of the valley appears fragmentarily in the form of very narrow and shallow incisions. This rise along its entire length is crowned with a wide low shaft (with an excess of up to 30 m relative to the surface of the rise), extending in the direction 75° (see Fig. 4, I, **9**).

From the west, the uplift is framed by a narrow slanting ridge ~2-km wide and up to 200-m high with a strike of ~70°. Its western part is located in the axial fault zone, while the eastern part is on its northern side (see Fig. 4, I, **10**).

In the western passive part of the southern fault, the width of the fault valley narrows to 6–6.5 km (see Fig. 4, II, section G–G').

Its southern side is steep and straight throughout; the northern side is absent for the first 60 km up to 36.50° west longitude, where, as mentioned above, there is a wide and deep submeridional depression that crosses the interfault ridge, since in this area the valley is completely or partially blocked by several transverse thresholds running both from the south and north from the side of the interfault structures. The largest of these is about 4-km wide and up to 450-m high (see Fig. 4, I, **11**).

West of 36.50° W the valley narrows to 4 km; the north side also becomes steep, straight and continuous, but it is more gentle in comparison with the southern edge over which a transverse ridge is developed in this area (see Fig. 4, II, section F–F').

The height of the sides increases from east to west from 350 to 600 m. The depth of the valley to the west of the nodal depression is 5250 m, but to the west, the bottom of the valley quickly rises to 4850 m, and then gradually (4500 m) deepens to 4800 m in the region of the paleonodal depression (see Fig. 4, II, section C–C').

The most elevated (4300 m) part of the valley is located in the area where the highest part of the transverse ridge rises on the southern side of the valley. In this section, the bottom of the valley is well expressed, flat, probably covered by sediments, and the cross section of the valley has a U-shaped form (see Fig. 4, II, section E–E').

On the south side, starting from the western intersect, a narrow (4–6 km) transverse ridge consisting of two segments separated by a submeridional depression ends. The length of the segments is about 40–50 km (see Fig. 4, I, **12**). The eastern segment rises to a depth of 3750 m, the higher western segment, up to 3000 m; their heights above the crest of the southern side are 150 m and 900 m, respectively (see Fig. 4, II, sections E–E', G–G').

In the area of the eastern passive part of the Pushcharovskiy Fault, we have fragmentary bathymetric data. However, these data are sufficient to state that the fault valley deviates to the north in the east direction, its width is ~7 km, the depth in the studied area is 5050 m, the bottom of the valley is wide and flat, and covered by sediments (see Fig. 4, I, **13**).

The valley has an asymmetric cross-section, the northern side is steep and rectilinear, ~700-m high, the southern side is curved, reflecting the irregularities of the relief of the interfault uplift, gently stepped with an unclear position of the crest (see Fig. 4, II, section M–M').

The two branches of the Pushcharovskiy Fault are separated by an inter-fault lenticular ridge extending along the entire strike of the fault (see Appendix 1: Figure S1). Its structure is largely organized by extensional structures such as pull-apart depressions and paleospreading centers [9]. On the western flank of the inter-fault ridge there is an uplifted block located to the west of a large submeridional basin, elongated along the 36.50° W meridian (see Fig. 4, II, section B–B').

Before the depression, the average depth level of the summit surface of the ridge is 4250 m, while to the west of the depression it is 3750 m; therefore, the amplitude of this uplift is ~500 m.

Thus, by all indications, the Pushcharovskiy fault, like the Doldrums fault, is a megatransform fault. Two arcuate transforms occur in the Pushcharovskiy fault, between which an inter-fault ridge extends, which has undergone intense tectonic movements, giving it a block structure.

The Bogdanov Fault

Bathymetric survey was carried out in active parts and small fragments of the passive parts of the Bogdanov fault (Fig. 5, I).

The offset length is 70 km. The valley in the active part of the U-shaped section and ~10-km wide has a sublatitudinal strike of 85° (see Fig. 5, II, sections D–D'–F–F').

The depth of the valley is the greatest near the intersects (see Fig. 5, II, sections A–A', B–B'). In the region of the western intersect, where the nodal depression is developed, the depth is 5050 m and it sharply decreases to 4750 m in the east direction (see Fig. 5, I, **1**).

The nodal depression up to 6150 m deep and ~10 km in diameter is deepened by 1100 m relative to the val-

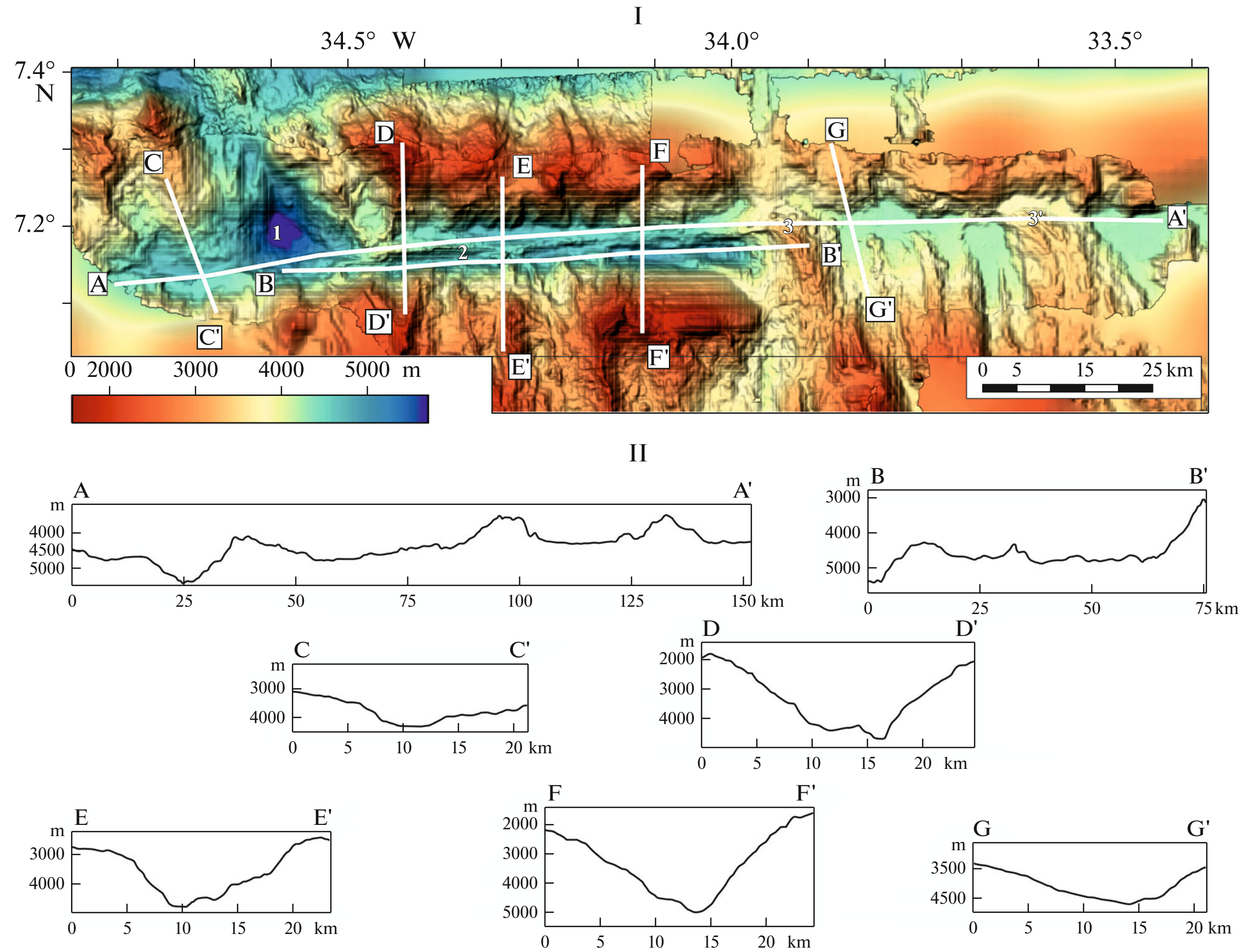

Fig. 5. The bottom relief in the area of the Bogdanov fault zone according to the data of the 45th cruise of the R/V *Akademik Nikolaj Strakhov*. I, bathymetric map; II, bathymetric profiles: A–A', B–B' (longitudinal); C–C', D–D', E–E', F–F', G–G' (transverse). Designated (Arabic numerals): (**1**), nodal depression; (**2**), median ridge; (**3**), transverse step.

ley. In the region of the eastern intersect, the nodal depression is not clearly manifested. Here, in the intersect zone, a depression ~5000 m deep was formed, from which the depth of the fault valley gradually decreases to 4800 m in the western direction.

Depths of 4750–4800 m are characteristic of extended flattened sections of the valley, while in paleonodal depressions the depth can reach up to 4900 m. Near both intersects, fault valleys are blocked by large neovolcanic uplifts penetrating from the ridge zone. Near these rises, the bottom of the valley rises; here, the minimum values of the valley depth of 4550 m are noted.

Both sides are steep, the northern side is continuous, straight, but cut by small ridges descending from oval uplifts. Previously, during the dredging of this side, mainly serpentinized ultramafic rocks were obtained [6]. The southern wall is also continuous, but tortuous; it protrudes into the ridge zone for 2–3 km where large submeridional depressions approach the fault. The heights of both walls are almost the same, along the valley it is 750–800 m, near the eastern intersect it is ~1000 m, near the western intersect, up to 1200 m.

Throughout the active part the valley is 2.5–3-km wide and 300–500-m high, consisting of several echelon-shaped, partially overlapping segments (see Fig. 5, I, **2**).

In the eastern passive parts of the bottom of the valley rises to a depth of 4250 m (see Fig. 5, II, section A–A').

The bottom of the valley is wide and flat, covered with sediments; its generalized width is close to 10 km (see Fig. 5, II, section G–G').

The northern wall, which is 500-m high, is continuous and winding; it protrudes into the interfault uplift in areas where this uplift is intersected by submeridional depressions separating the oval uplifts.

The southern wall is discontinuous, since the depressions separating the rift ridges open directly into the fault valley. The valley has a trough-shaped cross section.

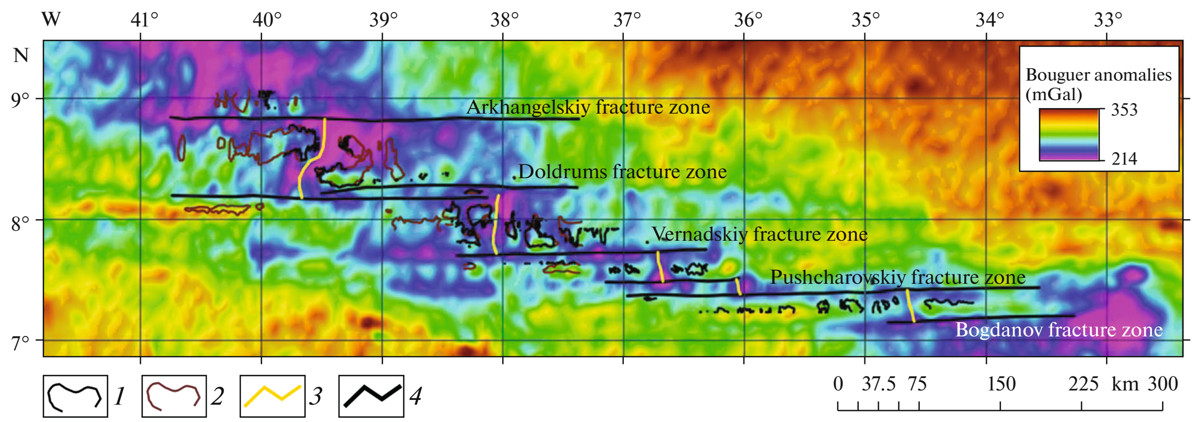

Fig. 6. A map of the anomalous gravity field in the Bouguer reduction in the area of the DMS and its surroundings. Inset: scale of Bouguer anomalies. (*1*), 3000 m isobath (according to the data of the 45th cruise of the R/V *Akademik Nikolaj Strakhov*); (*2*), 3000 m isobath (according to the data of the 6th cruise of the R/V *Akademik Nikolaj Strakhov*); (*3*), axes of spreading segments; (*4*), transform faults

In the studied fragment of the valley, it is blocked by two transverse sills up to 11-km wide and ~750-m high, which are continuations of rift ridges formed to the south of the fault (see Fig. 5, I, **3**). Previously they were identified as former neovolcanic uplifts [9].

In the western passive part, in a section ~25-km long, the depth of the valley near the intersect is ~5000 m, but sharply decreases westward to 4750 m (see Fig. 5, II, section A–A');

— the sides of the valley are weakly expressed (strongly curvy, stepped);

— the height of the lower part of the side is 250 m (the width of the valley at this level is 6–6.5 km);

— the height of the upper part of the wall is also ~250 m (the width of the valley at this level is ~10 km);

— the bottom of the valley is narrow and winding;

— the cross section of the valley is U-shaped.

RESULTS AND DISCUSSION

Transform faults have been confidently distinguished by the bottom topography, the distribution of earthquake epicenters and Bouguer anomalies [11, 31] (see Figs. 1a, 1b). Along their active zones, predominantly shallow-focus strike-slip earthquakes occur, indicating that the transforms are zones of shear deformations [32]. In the Vernadskiy, Pushcharovskiy, and Bogdanov faults, earthquakes often occur in the passive parts of the faults. According to the kinematics, all faults of the DMS are zones of right strike-slips.

In our study, a map of the distribution of Bouguer anomalies for the region of the DMS was constructed according to the data of [21, 28] (Fig. 6).

Deep negative minima of the Bouguer anomalies (up to 214 mGal) are concentrated mainly along the rift valleys and have an inverse correlation with the topography. Along the valleys of transform faults, minima are also observed, but of moderate amplitudes, 270–280 mGal.

Because transform faults are not areas of hot mantle distribution and structures in which sections of crust of great thickness are formed, it is obvious that low-density masses in the sections of faults, in comparison with the MAR flanks and basins, are ultramafic rocks that are serpentinized to varying degrees that predominate among fault-dredged rocks.

Causes of Variations in the Width of Fault Valleys

Data on the width and depth of fault valleys and the height of their sides are given in Table 1. The width of the studied fault valleys varies markedly from 3.5 up to 18 km (see Table 1). It is possible to single out general variations in width, covering its changes on a scale comparable to the active parts of faults and their large fragments, at least 40–45-km long, and local variations in width typical of fault areas of a shorter length.

The general variations in the width of the studied fault valleys have certain regularities, which, in our opinion, are explained in the features of the geodynamic situation in the area of the DMS. It is a fragment of a large connecting link between the South and Central Atlantic, which opened independently, while the directions of spreading were different [12, 23, 26].

When the equatorial segment of Gondwana broke up, then in the newly formed ocean basin that connected the South and Central Atlantic the spreading directions should have compensated for this difference. As a result of the ongoing accommodation in the Atlantic Equatorial segment a variegated, apparently time-varying pattern of the distribution of spreading directions, as reflected in the strikes of transform faults, arises [20].

The consequence is the emergence of transpressional or transtension regimes in various fault zones.

Table 1. The morphometry of transform fault valleys (cross sections)

Fault	**Parts of the fault**	Width, km	Valley bottom depth, m			Side height, m			Height difference, m	Depth interval, m
			max	background	min	max	prevailing	min	*	**
Doldrums	**Active part (northern trough)**	**7.5**	**4650**	**4500**	**3850**	**1000**	**750**	**450**	–	–
	passive part (eastern)	*11*	*4750*	*4650*	*4650*	*750*	*750*	*750*	–	–
	active part (southern trough)	**5–12**	**5150**	**4750**	**4000**	**1100**	**750**	–	**350**	**400**
	passive part (western)	*17*	*5150*	*4800*	*4800*	*750*	*750*	*750*	–	–
Vernads-kiy	**Active part**	**6–12.5**	**5150**	**4750**	**4600**	**1200**	**750**	**600**	**450**	**400**
	passive part (western)	*4–18*	*5150*	*4750*	*4750*	*750*	*750*	*650*	–	–
	passive part (eastern)	*5*	*5000*	*5000*	*4500*	*750*	*750*	*500*	–	–
Push-charovskiy	**Active part (northern trough)**	**5**	**5300**	**4950**	**4550**	**1150**	**750**	**400**	**400**	**350**
	passive part (western)	*2.5–3.5*	*5300*	*4750*	*4450*	*600*	–	*260*	–	–
	passive part (eastern)	–	–	–	–	–	–	–	–	–
Push-charovskiy	**Active part (southern trough)**	**6.5–7.5**	**5350**	**5000**	**4850**	**1000**	**600**	**250**	**400**	**350**
	passive part (western)	*4–6.5*	*5250*	*4500*	*4300*	*600*	–	*350*	–	–
	passive part (eastern)	*7*	*5050*	*5050*	*5050*	–	*700*	–	–	–
Bogdanov	**Active part**	**10**	**5050**	**4750**	**4550**	**1200**	**800**	**750**	**400**	**300**
	passive part (western)	*10*	*5000*	*4750*	*4750*	–	*500*	–	–	–
	passive part (eastern)	*10*	*4250*	*4250*	*4250*	–	*500*	–	–	–

*, the difference between the maximum and prevailing side height; ** is the difference between the maximum and background depths of the valley.

In the area of the DMS the currently observed geodynamic setting is shown in Fig. 7.

The strike of the southernmost Bogdanov fault is 85°, the strike of the northernmost Doldrums fault is 91°, and the next to the north of the DMS, the Arkhangelskiy fault has a large angle of 93°. Inside the Doldrums megatransform system the Vernadskiy and Pushcharovskiy faults have an intermediate value of 89°.

Thus, there is a regular turning of transform faults and, accordingly, directions of spreading from south to north clockwise from 85° to 93°. As a result, in the segment in which the spreading direction is not perpendicular to the transform, the lithospheric plates on one side of the spreading axis can diverge and, therefore, converge on the other side.

Analysis of the bathymetric map allowed us to establish that between the Arkhangelskiy–Doldrums–Vernadskiy faults the spreading axis is orthogonal to the Doldrums fault, and between the Pushcharovskiy and Bogdanov it is orthogonal to the Bogdanov fault.

In accordance with this, compression conditions perpendicular to the fault can occur in the eastern passive and active parts of the Doldrums and Vernadskiy

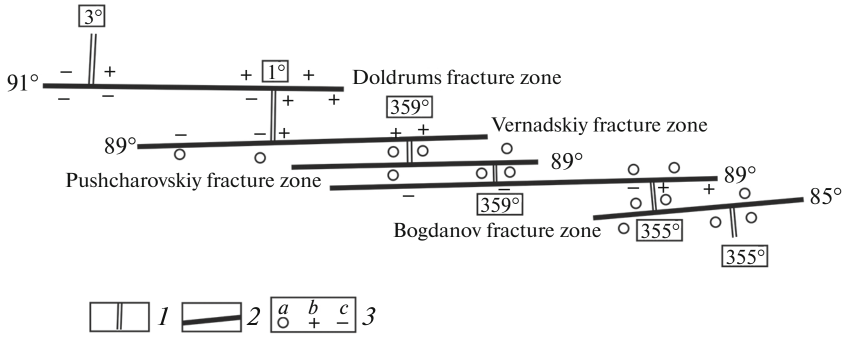

Fig. 7. The scheme of transform faults and rifts in the DMS. Designated: strike of transform faults, degrees; direction of axial spreading zones, deg (in frame). (*1*) are the spreading axes; (*2*), transform faults; (*3*), geodynamic regimes at the boundary of fault zones: *a*, no compression and stretching, *b*, compression, *c*, tension transverse to the fault

faults and in the eastern passive part of the southern Pushcharovskiy fault, while extension conditions are typical for the western passive parts of the Doldrums, Vernadskiy, and southern Pushcharovskiy faults, and also for its active part (see Fig. 1, see Fig. 7). The northern Pushcharovskiy fault and the Bogdanov fault are neutral in this respect.

General variations in the width of the valleys of the studied fault zones as a whole correlate with the studied geodynamic setting. The Doldrums and Vernadskiy Fault Valleys have

— the smallest width in the eastern passive part (11 and 5 km);

— intermediate width in the active part (5–12 and 6–12.5 km);

— the greatest width in the western passive part (17 and 18 km).

We believe that the narrowing of the valleys in the eastern passive parts is the result the fact that they formed under compression, and vice versa, the expansion of the western passive parts is the result of tension. In the active parts of these faults, there are compression conditions, and according to our data, the width of the valley here successively decreases from west to east. In the Bogdanov fault, where there are no compression or extension conditions, the width of the valley is practically unchanged in all parts of the fault and is ~10 km.

This pattern is not characteristic of the Pushcharovskiy double fault. In the western passive parts of its northern and southern troughs the width of fault valleys sharply decreases to 2.5–3.5 km in the northern and to 4 km in the southern faults; the valleys are 1.5–2 times narrower than could be assumed in accordance with the geodynamic scheme (see Fig. 7).

The above facts indicate that another factor is active in the Pushcharovskiy Fault, which determines the width of the fault valleys. We believe that this narrowing of the fault valleys is caused by the uplift of the western segment of the inter-fault ridge separating the valleys of the northern and southern troughs of the Pushcharovskiy fault. On the longitudinal bathymetric profile passing through the middle part of this ridge, it can be seen that west of the 36.50° W the average depth of the top part of the ridge decreases significantly from 4250 to 3750 m (see Fig. 4, II, section B–B').

This gives grounds to assume that the block of the inter-fault ridge in the west of the mapped area has experienced or is undergoing uplift with an amplitude up to 500 m, which led to narrowing of the fault valleys of both branches of the Pushcharovskiy fault in this section of the western passive part.

A similar phenomenon was revealed in the active part of the Doldrums double Fault. Both of its fault valleys narrow significantly (up to 3 km) in the area where one of the segments of the inter-fault ridge experienced a high-amplitude block uplift.

In the western passive part of the Vernadskiy Fault, in the area located to the west of the intersect zone, the fault valley sharply narrows to 4 km, but at a distance of 40–45 km to the west it widens to 18 km [28]. This anomalous narrowing is most likely related to the relatively recent eastward jump of the spreading axis.

Thus, one of the main factors of general variations in the width of fault valleys is the occurrence in fault zones of conditions of extension or compression perpendicular to the strike of the fault. Compressive conditions lead to narrowing, while tension leads to expansion of fault valleys. In addition, the growth of intra-fault uplifts and tectonic phenomena in the adjacent inter-fault areas of the ocean floor have a significant impact.

Local extensions of fault valleys by 1–5 km are observed in the area of nodal and paleonodal depressions and in areas where submeridional depressions are conjugated with the valley from the side of the MAR zone.

Small-scale width variations lead to a sawtooth boundary of the fault valley, which occurs where the valley edge is complicated by a series of narrow (~1 km) low (50–100 m) ridges descending to the valley either from the slopes of Mount Peyve or from the tops of oval uplifts developed on inter-fault uplifts between the Vernadskiy, Pushcharovskiy, and Bogdanov faults.

Causes of Depth Variations of Fault Valleys

The parameter that characterizes fault valleys is their depth. The study of spreading segments revealed a regular increase in the depth of spreading segments from the periphery to the center of the DMS located between two troughs of the Pushcharovskiy Fault [9]. A similar increase in depth is observed for DMS transform faults.

We compared the largest depths of the studied fault valleys, which in each case are observed near nodal depressions (see Table 1). These are the highest in the Pushcharovskiy double fault: 5300 m in the northern and 5350 m in the southern fault. In the Bogdanov and Vernadskiy faults adjacent to it from the south and north, the depths are 5050 m and 5150 m, respectively, and in the Doldrams fault, which is the most distant from the Pushcharovskiy fault, it is 5150 m (in the current southern transform).

In all faults in their active parts, the along-fault variations in the depth of the valley have the same character: the depth of the valley from the maximum values in the area of the rift-fault intersects rapidly decreases to a certain level, let us call it the background level. The background depths are typical for extended and flattened sections of fault valleys, and they are also the largest in the Pushcharovskiy fault, 5000 and 4950 m, respectively, in the southern and northern troughs (see Table 1). In all other faults, they are 4750 m. It was shown that the greater the depth of the axial zone of the spreading segment that is part of the DMS is, the lower the temperature of the upper mantle below it is [9].

Consequently, the depths of the fault valleys that are part of the DMS are also determined by the upper mantle temperatures, and the lower their temperature is, the deeper the fault valley is.

The greatest depths of fault valleys correlate with the greatest depths of rift valleys, which are also observed near nodal depressions. The depths of the rift valleys decrease with distance from the intersect zone with fracture due to an increase in this the direction of the temperature of the upper mantle and the intensity of magmatic accretion of the crust.

In search of the cause of the decrease in the depth of the fault zone in the active part in the direction of the intersect with the rift, we associated low values of Bouguer anomalies in fault valleys with serpentinization of upper mantle rocks, which probably dominate here due to extremely low magmatic accretion in intersect zones. In this case, a decrease in the depth of the fault in the active part in the direction from intersects is a consequence of the increase volume and rise of mantle rocks decompacted during serpentinization.

Transform zones are very favorable for serpentinization processes:

— in these zones, mantle ultramafic rocks are located in the bottom of the valley or near the bottom;

— continuous cracking of rocks and the penetration of sea water, which serpentinizes the lithospheric mantle, are maintained due to constant tectonic movements in this area;

— friction of lithospheric plates moving in the opposite direction leads to warming of their edge parts, and, consequently, heating penetrated deep into the sea water, which accelerates the processes of serpentinization.

According to calculations, the temperature along the surface of the displacer can increase by 200–400°C [18].

Serpentinized ultramafic rocks are essentially no longer mantle but crustal rocks. On seismic profiles crossing transform faults, layers with seismic wave velocities are identified under the fault valley, as in basalts and gabbro (crustal rocks) [7]. However, under the fault valleys there is no such amount of gabbro and basalts, because serpentinized peridotites sharply dominate in the products of sampling of the sides of the valleys [4, 6]. However, experimental work showed that serpentinization of ultramafic rocks leads to a decrease in their seismic velocities, while, depending on the degree of serpentinization, they can correspond to seismic velocities for basalts and gabbroids [19].

Transform faults are also the place where neoformation occurs in oceanic crust, but this is not a magmatic, but a hydrothermal-metamorphic process, which is based on partial or complete serpentinization of the primary mantle material. Thus, the second and third layers of the oceanic crust, as recognizable on seismic profiles under transform faults, are composed of ultramafic rocks, which are serpentinized to varying degrees.

In the active part, the depth of the valley increases compared to the background depth, in the region of depressions and decreases where uplifts have formed, including near the median ridges. We consider the depressions, expressed in the gravity field (Bouguer anomalies) in the form of oval spots and similar to nodal depressions in morphometry and morphology, as paleonodal deprtessions.

The difference in depth between these depressions and the background depth valley is 50–200 m, which is much less than the difference in depth between the valley and the active nodal basin. This may be a consequence of both the fact that the cavities are filled by sediments, as well as a faster rise of the bottom in these areas, compared with other parts of the valley.

Nodal depressions are simultaneously structures of both a fault, with its inherent shear stresses, and a rift, in which is dominated by stretching conditions. The combination of these two factors leads to the formation of deep depressions. Distinct nodal depressions in the area of the DMS have been identified only in the western intersects. In the eastern intersects, nodal basins are superimposed by neovolcanic uplifts or block uplifts of interfault ridges. Nodal depressions are characterized by the lowest values of Bouguer anomalies in fault valleys (~215 mgal) (see Fig. 6).

The reason that the fault valley is not a continuous series of paleonodal depressions, while these depressions occasionally occur in the active and passive parts of the fault zone, is of undoubted interest for research.

We believe that nodal basins are preserved as their paleoanalogues in cases where there was an episode of asymmetric spreading or, possibly, there was a jump in the spreading axis, while a paleorift valley may be located opposite the paleonodal basin.

In the studied passive parts of the faults, the depth of the valley varies to a lesser extent. In the passive parts of the Doldrums Fault and in the eastern passive parts of the Vernadskiy Fault and the southern branch of the Pushcharovskiy Fault, the depths of the fault valleys are 50–250 m greater than the background depths in their active parts (see Table 1).

This difference will be even greater if we take the fact into account that the thickness of the sedimentary cover in the passive parts is much greater than in the active parts. This is consistent with the regular deepening of the ocean floor due to its subsidence due to cooling and an increase in the thickness of the sublithospheric mantle by the distance from the spreading axis increases [29].

In this regard, we can assume that when there is no deepening of the fault valley in the passive parts, we should expect the impact of additional factors or processes. In the Bogdanov Fault zone, the depth of the fault valley in the eastern passive part is 500 m less than the depths of the valley in its active parts (see Table 1).

In the eastern passive part, the bottom of the fault is very wide and flat, which indicates the accumulation of a thick sedimentary cover in the valley, and, most likely, its original bottom was lowered relative to the valley bottom in its acrive part. At the same time, sedimentary strata did not accumulate in the same amount as in the near section of the active part of the valley since the valley at the boundary between the active and eastern passive parts is covered by a large neovolcanic uplift, which may be a barrier to the flow of sedimentary material to the west (see Fig. 5, I, **3**).

In both western passive parts of the Pushcharovskiy fault, the depths of the valleys are 500–750 m less depths in their active parts. Obviously, the uplift of these parts of the fault valleys is associated with the uplift of 500 m of the block of the inter-fault ridge of the Pushcharovskiy fault.

Rift Valley Sides

In the studied area, the fault valleys have distinctly pronounced rectilinear flanks almost along their entire strike. The greatest height of the sides is observed near the nodal basins and is 1000–1200 m, the lowest height is associated with intra-fault uplifts of 250–450 m (see Table 1). The prevailing background height of ~750 m is characteristic of most of the studied fault zones in both the active and passive parts.

The difference between the maximum and background wall heights in each of the faults is in the range of 350–450 m, which is comparable to the difference of 350–400 m between the background and maximum depths of faults in their active parts: (see Table 1). This indicates that the wall height is leveled in the active part of the fault due to a decrease in the depth of the fault valley, as a result of serpentinization mantle rocks.

The edge of the transform fault valley is absent at the point of its intersection with the rift valley.

Outside the intersect zone, at the intersections with paleorift valleys, there is no edge, for example:

— the section of the northern edge in the active part of the Vernadskiy Fault (see Fig. 3, I, **3**);

— in areas on the eastern flank of the active part of the Vernadskiy Fault, where former large neovolcanic uplifts separated by deep depressions adjoin the fault (Fig. 3, I, **9**).

The reason for the absence of the valley wall was jumps of the spreading axis, or asymmetric spreading, as a result of which the axial structures could be preserved in their original form.

There is also no distinct southern edge in the eastern passive part of the Bogdanov Fault in areas where submeridional depressions adjoin the fault, separating rift ridges and the sedimentary cover that fills the fault valley enters submeridional depressions. The sides are absent when the fault valley is blocked by a neovolcanic uplift or its paleoanalogue.

Basically, the sides of the fault valleys are straight, but in some areas they can be winding. If the shape is curved, then the wall goes deep into the ridge zone where a large submeridional depression approaches the fault. In some areas, especially where longitudinal bottom uplifts are developed in the fault zone, the wall can be stepped.

The sides of the valleys can be built up with structures of the ridge zone or transverse ridges, while the relief of the ridge zone is located above the bottom of the valley to the height of the side, especially when the ridge zone is composed of rift mountains. In this case, the rift mountains and submeridional depressions separating them are cut off at the level of the upper side edges.

Uplifts in Fault Zones

The structure of fault zones is complicated by the presence of various types of uplifts, such as:

— transverse steps;

— along-fault uplifts of the valley floor;

— median, transverse and inter-fault ridges.

Cross steps. Most of the transverse sills, which are 4 to 9-km wide and 400–500-m high, are continuations of rift ridges that arose as neovolcanic uplifts that were formed during the most intense impulses of volcanic activity, which led to the fact that they penetrated into the fault valley and blocked it.

Currently, such neovolcanic uplifts are observed in the eastern intersects of the Bogdanov fault and the northern branch of the Pushcharovskiy fault, as well as in both intersects of the southern branch of the Pushcharovskiy fault. There are faults whose connection with neovolcanic uplifts is not obvious, as, for example, in the eastern passive part of the Vernadskiy fault. Perhaps their occurrence is associated with intensive serpentinization processes.

Median ridges. Median ridges are narrow uplifts 10–40-km long, 1.5–4-km wide, and 250–500-m high, as a rule, extending parallel to the fault valley and located in its axial part.

The smallest median ridges (~6-km long, 0.5-km wide, and 100 m) were recorded in both fault valleys of the Pushcharovskiy fault and they have an oblique strike of ~75° with respect to the fault valley. Most often, median ridges are developed in the active parts of the faults.

The median ridges we have not tested, and in order to understand their nature, we took the fact into account that in the Bogdanov fault the lowest values of Bouguer anomalies are associated not only with nodal basins, but also with the entire active part of the fault, in which an along-axial median ridge is developed throughout its entire length, consisting of several segments (see Fig. 5, I, **2**; Fig. 6).

This gives reason to believe that the median ridge is composed of low-density rocks.: basalts, or highly serpentinized ultrabasites. We have not identified any signs that active volcanism occurred in the active part of the Bogdanov Fault valley; it is most likely that the median ridge is composed of highly serpentinized rocks.

This suggests that the median ridges are extended serpentinite diapirs composed of ubiquitous serpentinized ultramafic rocks under fault valleys.

Compressive stresses perpendicular to the fault, which are characteristic of some faults of the Doldrums megatransform system, contributed to the extrusion of these diapirs above the surface (see Fig. 7).

The presence of oblique median ridges in the Pushcharovskiy fault indicates that compression stresses of other directions also existed or exist in this fault. We believe that the cause of these stresses is the lenticular curvilinear in terms of the shape of the inter-fault ridge in the Pushcharovskiy fault. Due to the fact that compressive forces arise when a moving lithospheric plate encounters a ledge of an inter-fault ridge and presses on it, creating local compression stresses, including in the fault valley.

Transverse ridges. Transverse ridges run parallel to the fault and they build on some segments of the sides of fault valleys. The slope of the transverse ridge, facing the structures of the ridge zone, is usually oriented transversely with respect to them. In the area of the DMS, three transverse ridge—two ridges on the south wall in the western passive parts of the faults Doldrums and one range in the south trough of the Pushcharovskiy fault, as well as Mount Peyve on the northern side in the active part of the Vernadskiy fault.

Most the largest of the studied transverse ridges is located in the Doldrums fault zone. According to the results of testing, a significant role in its composition is played by serpentinized ultramafic rocks; there are also altered and deformed basalts. Associated with this spine the field of maximum values of Bouguer anomalies for the region of the DMS (up to 330 mGal) (see Fig. 6). This ridge can be composed of unaltered mantle rocks; dredged serpentinized ultramafic rocks occupy an insignificant place in its section. But it is possible that the ridge is anomalously high, not isostatically compensated, and is currently experiencing lowering.

The genesis of transverse ridges is of particular interest in the scientific community, and most researchers believe that these structures are formed under the action of compressive or tensile forces that arise for various reasons in shear fault zones [3, 7, 13–15, 25, 27].

The transverse ridge, located on the south side in the western passive part of the Doldrums Fault, in terms of its size (width ~12 km and its height above the edge up to 2050 m) is comparable with one of the largest transverse ridges in the Atlantic formed on the southern edge of the Vema Fault valley [15] (see Fig. 2, I, **15**).

As in the Vema Fault, in the Doldrums Fault, the western part of the transverse ridge is uplifted, the length of the ridge (>145 km) is comparable to offset length.

Bonatti and et al. [13] showed that the transverse ridge of the Vema Fault was formed 10 Ma as a flexural bend of the edge of the South American Plate as a result of tensile stresses that arose in the active part of the Vema Fault during a clockwise rotation of the spreading direction in the northern part of the Equatorial Atlantic arrow that occurred 11 million years ago.

The transverse ridge in the Doldrums Fault is located 177 km west of the spreading axis and, in line with the half-spreading rate of 1.5 cm/year [16], it could not have risen earlier than 11.8 million years ago. In this regard, we can assume that the time of formation of the transverse ridge in the Doldrums Fault is comparable in time to the transverse ridge of the Vema Fault and that its formation is associated with an event that led to a change in the direction of spreading, which caused tension conditions in the dextral transforms. Thus, this transverse the ridge is a flexure-like bend of the edge of the South American plate, which arose under conditions of tension about 11 million years ago in the Doldrums Fault.

We believe that a transverse ridge on the southern side of the southern branch of the Pushcharovskiy fault, which is smaller fault (4–6-km wide, 900 m above the edge) similar to the ridges in the Vema and Doldrums faults in many respects also has a similar origin (see Fig. 4, I, **12**). High values of Bouguer anomalies are observed above it, its length (~100 km) is comparable to the offset of the southern Pushcharovskiy fault, the western part is higher than the eastern part and the distance from the spreading axis to the beginning of the ridge is ~160 km, which indicates the age in the region of the ridge is no younger than 10.7 Ma (see Fig. 6).

Mount Peyve, with a width of 9 km, differs from the studied transverse ridges by a significantly shorter length (37 km), higher height (3000 m above the edge of the wall), and noticeably lower Bouguer anomalies (~300 mGal) (see Fig. 3, I, **4**; Fig. 6).

Previously, Mount Peyve was raised above the level sea, as evidenced by its flat top, subsequently, the mountain experienced intense subsidence and is now submerged 993 m below ocean level (see Fig. 3, III).

Analysis of the bottom structural pattern in the area of the western intersect of the Vernadskiy Fault, gives reason to believe that Mount Peyve is the highest and longest segment of a previously unified transverse ridge ~53-km long, divided now by a rift and paleorift valley into three segments.

This means that in this spreading center, the spreading axis was probably crossed repeatedly. This assumption is supported by the presence in the ridge zone between the Vernadskiy and Doldrums faults of several more paleorift valleys.

The complex development of this spreading segment, accompanied by repeated jumps of the spreading axis, confirms the data on the age of the rocks. In accordance with the age of the gabbro, as determined by U–Pb isotope geochronology from zircons isolated from gabbro dredged in the highest western part of Mount Peyve, the rise of the ridge occurred no earlier than 3.65 Ma, when the gabbro was formed [8].

Together with gabbroids, sandy limestones are dredged, in which the sandy component is represented by fragments of gabbroids that have undergone subaerial weathering. The age of these limestones, determined from foraminifera, is 3.2–2.4 Ma [4]. Therefore, the rise of Mount Peyve occurred in the 3.65–2.4 Ma time interval.

Pushcharovskiy [4] also cited the age of the calcareous sandstone as ~3.2 Ma, determined from foraminifera and obtained from the study of the rift ridge overbuilding the eastern side of the rift valley between the Doldrums and Vernadskiy faults, which suggests that the age of the basalt also corresponds to this time.

However, according to the half spreading rate and the distance of this ridge from the spreading axis (~10 km), its age should be no more than 0.7 million years. On the opposite western side of the rift valley, limestones with exactly this age of 0.7 Ma rose. A comparison of these data showed that the modern rift valley was formed as a result of a jump in the spreading axis, which occurred ~0.7 Ma ago, to the bottom region with an age of ~3.2 Ma.

Taking the available age definitions and the prevailing structural paragenesis on this section of the ocean floor into account, we developed the following reconstruction of the development of events during which the transverse ridge and its dismemberment took place (Fig. 8).

Until 3.65 Ma the spreading axis was associated with the paleorift valley at 37.58° W, but 3.65 Ma ago or somewhat earlier, the spreading axis jumped westward to the region of the paleorift valley at 38.45° W, where the age of the bottom was much older, 3.65 Ma (see Figs. 8a, 8b).

Here, under the rift valley, the gabbro of the western part of Mount Peyve was formed in the crustal chamber. Then, 3.65–2.4 Ma ago there was an uplift of the transverse ridge on the northern side in the active part of the Vernadskiy Fault, while only the most heated part of the lithosphere was located between an active and a relatively recently dead rift valley, currently extending along the 37.58° W meridian (see Fig. 8c).

Shortly after 2.4 Ma, the spreading axis jumped into the area paleorift valley at 37.85° W, where the age of the bottom was older than 3.2 Ma (see Fig. 8d). This led to the division of the transverse ridge into western and eastern segments (Mount Peyve).

The western segment turned out to be in the passive part of the fault; however, the fault valley opposite it, in its structural features, corresponded more to the fault valley in the active part of the fault, which it had been until that moment. Moreover, it bore signs of the growth of a transverse ridge, expressed in its narrowing and shoaling and V-shaped cross section. The last jump of the spreading axis to the bottom occurred 0.7 Ma ago with an age of 3.2 Ma, and the western segment of the transverse ridge split into two parts (see Fig. 8e).

Studies still need to clarify the nature of the transverse ridge, of which Mount Peyve is an integral part; however, we present our understanding of its evolution.

— In many respects, it is similar to the other transverse ridges described above in the DMS region, only if it was formed at a later time, 3.65–2.4 Ma ago. Based on this, we can assume that the mechanism of its formation is close to other transverse DMS ridges. It consists in the fact that earlier, at 3.65–2.4 Ma, a global geological event occurred in this region, which led to spreading instability and, as a result, to frequent jumps of the spreading axis. This event may have initiated the formation of an inter-fault ridge in the Doldrums Fault. In this unstable environment, tension conditions could arise in the Vernadskiy Fault and, as reaction to them, there was a flexural bending of the edge of the African plate.

— Some structural features of the space surrounding the transverse ridge in the Vernadskiy Fault zone may indicate that it was formed under compressional conditions, which include:

— a decrease in depth and narrowing of the fault valley opposite the transverse ridge;

— the presence of small low ridges, winding in plan, on the slope of the ridge facing the fault, as well as in the rear part of the ridge in the areas of the ridge zone adjacent to it.

The undulating bends of the ridges are the result of their deformation under the action of compression forces perpendicular to the strike of the fault.

Longitudinal Uplift of the Bottom of the Fault Valley

Longitudinal uplift of the bottom of the fault valley, as an independent positive structure, is fixed only in the southern trough of the Pushcharovskiy Fault (see Fig. 4, I, **9**). The longitudinal uplift rises 500 m above the level of the valley bottom and extends for a considerable distance along the valley (up to 67 km). Unlike median ridges, which are narrow isolated structures, this uplift fills the entire valley. The top part of the uplift is complicated by gently sloping ramparts that strike obliquely.

We believe that in its genesis is the uplift is similar to transverse ridges formed under extensional conditions, with which it is brought together by a large extent and increased Bouguer anomalies relative to the rest of the fault valley (see Fig. 6). This is supported by the fact that to the west the uplift is replaced by a wide step on the southern side of the fault, which, in its structural position, is possibly the embryo of a transverse ridge or an incomplete transverse ridge.

The southern Pushcharovskiy Fault is the only fault of the DMS that is in the transtension mode (see Fig. 7).

The growth of uplifts in transforms in the form of a flexural bend of the edge of the lithospheric plate is possible even under shear deformations alone [27].

Bonatti and et al. [13] claimed that this growth is higher amplitude when tension conditions appear in the transform that are transverse to the fault.

It can be assumed that the formation of longitudinal uplifts differs from the growth of transverse ridges by a lower intensity of tensile stresses.

Inter-Fault Ridges

Within the Doldrums megatransform system, there are two inter-fault ridges in the Doldrums and Pushcharovskiy double faults. These two faults are megatransforms, with which they are united by the presence of a lenticular interfault ridge bounded by two arcuate transforms [9, 24].

The main features of the inter-fault ridge of the Pushcharovskiy Fault are as follows:

— it arose from the beginning of the formation of the Doldrums megatransform system and the Pushcharovskiy Fault ~30–32 Ma ago;

— throughout its geological history, it has been under the influence of two plates moving in opposite directions;

— formation of pull-apart tensile depressions occur in it;

— at the site of tensile depressions of the pull-apart type, spreading centers could emerge.

The inter-fault ridge of the Doldrums Fault is relatively recent. In accordance with the nature of the distribution of earthquakes, the southern branch of the Doldrums Fault is active at present, which replaced the northern branch in this capacity.

On the western extension of the northern fault, a system of small incisions was formed, connecting it with the southern fault, and modern earthquakes are also confined to this zone of incisions. These two facts may indicate that either shear movements periodically occur along the northern trough, or there is a change in the active fault from the southern to the northern one.

The age of one of the gabbroids dredged from the interfault ridge at a distance of ~130 km from the western axial zone of spreading was determined using the U–Pb isotope-geochronological method for zircons, which is ~11 Ma [8]. However, based on the half-spreading rate and the distance from the spreading axis to the dredging point, the bottom age at this point is ~8.5 Ma.

This means that at first the marginal part of the South American plate, which was an inter-fault ridge, moved west relative to the northern fault, then the appearance of the southern fault led to the separation of the inter-fault ridge, which became part of the African plate, and its movement to the east (Fig. 9).

It is obvious that the inter-fault ridge appeared then when the northern fault ceased to be active and the southern fault arose. The time of this event can be determined from the distance between the western end of the northern fault valley and the spreading axis north of the Doldrums Fault or from the length of the section of the inter-fault ridge located in the eastern passive part of this fault, which are close to each other and equal ~60 km.

In accordance with this distance and the half spreading rate ~4 million years ago, the northern fault ceased to be active, a southern fault emerged, separating the interfault from the South American Plate ridge. At this time, spreading instability occurs, expressed by frequent jumps of its axis, between the Doldrums and Vernadskiy faults and the formation of a transverse

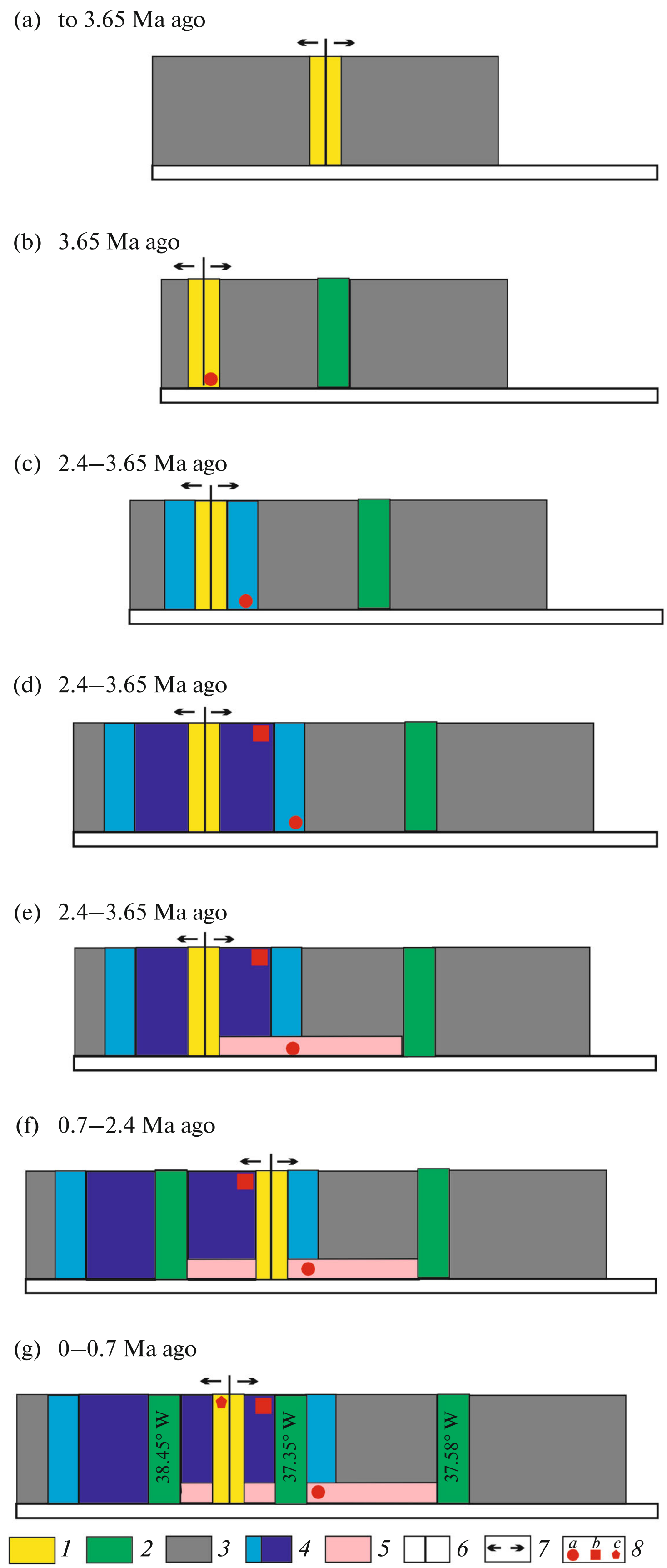
(a) to 3.65 Ma ago
(b) 3.65 Ma ago
(c) 2.4–3.65 Ma ago
(d) 2.4–3.65 Ma ago
(e) 2.4–3.65 Ma ago
(f) 0.7–2.4 Ma ago
(g) 0–0.7 Ma ago
38.45° W
37.35° W
37.58° W
1
2
3
4
5
6
7
a
b
c
8

Fig. 8. The estimated formation scenario and dissection of the transverse ridge on the northern side of the Vernadskiy fault. (a), state of the system before the beginning of the formation of the transverse ridge, (b), jump of the spreading axis to the west about 3.65 Ma ago, emergence of a paleorift valley, which is currently located at the 37.58° W meridian, formation in the axial spreading zone the gabbro that makes up Mount Peyve; (c)–(d) successive expansion of the ocean floor and formation of the oceanic crust in the time interval 3.65–2.4 Ma ago; (e), formation of a transverse ridge on the northern side of the fault valley in its active part; (f), jumping the spreading axis to the east in the interval 2.4–0.7 Ma, the emergence of a paleorift valley, which is currently located at the 38.45° W meridian, the division of the transverse ridge into two segments, with Mount Peyve segment; (g), jump of the spreading axis to the west in the interval 0.7–0 Ma ago, the emergence of a paleorift valley, which is currently located at the 37.85° W meridian, and the division of the western segment of the transverse ridge into two parts. (*1–2*), valleys: (*1*), rift (related to the spreading axis), (*2*) paleorift; (*3*), ancient ocean floor (up to 3.65 Ma); (*4*) uneven-aged bands of the ocean floor (formed after 3.65 Ma ago); (*5*) transverse ridge, (*6*) spreading axis, (*7*) spreading direction; (*8*), position of rocks for which age was determined: (*a*) Mount Peyve gabbro with an age of 3.65 Ma, (*b*) calcareous sandstone with an age of 3.2–2.4 Ma, (*c*) limestone with an age of 0.7 Ma.

ridge on the northern side of the Vernadskiy fault, of which Mount Peyve is an integral part.

Perhaps the same event that occurred ~4–3.65 Ma ago caused structure-forming processes in the area from the Doldrums Fault to the Vernadskiy Fault, including their fault zones. It should be noted that at the same time, a nontransform displacement occurred north of the Doldrums Fault, which has since migrated northward along the spreading axis. Probably, this event had a more global scale, since, according to the study of the anomalous magnetic field, the boundary 4–3.5 Ma ago was characterized by a sharp change in the spreading rate in the Atlantic [17].

Both interfault ridges of the Doldrums megatransform system experienced high-amplitude block vertical movements. Signs of these movements are imprinted on the depth profiles located along the axis of the ridges, in the shallowing and narrowing of the segments of fault valleys adjacent to the segments of the ridges that experienced uplift.

These depth profiles show that in the western passive part of the Pushcharovskiy fault, the more western block of the interfault ridge is uplifted by 500 m above the more eastern block (see Fig. 4, II, section B–B').

In the active part of the Doldrums Fault, the more eastern block of the inter-fault ridge is uplifted by 1350 m above the more western block (see Fig. 2, II, section C–C').

From the uplifted block of the interfault ridge of the Doldrums Fault, along with igneous rocks, relatively well-sorted detrital rocks were dredged, from siltstones to gruss, in which the grains are represented by fragments of serpentinized ultrabasites, gabbroids, and basalts [4]. Their presence indicates that this part of the inter-fault ridge was above the ocean level no earlier than 4 million years ago, from that time to the present day, its intensive subsidence has been taking place, because the modern minimum depths of the ridge are 2650 m.

Let us consider the causes of vertical block movements within the interfault ridges. High-standing inter-fault ridges are found in the northern part of the Sao Paulo polytransform (Atoba Ridge), protruding above the ocean level in the form of Peter and Paul rocks.

Maia and et al. [25] believ that this rise is caused by the action of compressive forces directed along the fault that resulting from a progradation rift north of the Sao Paulo Fault. Taking this point of view as a basis, we believe that the uplift of blocks of inter-fault ridges of the DMS is caused by compression forces directed along the faults. Compressive stresses arise because the inter-fault ridges have a lenticular curvilinear shape in plan.

The moving lithospheric plate in the shear zone collides with the protrusion of the interfault ridge and presses on it, creating local compressive stresses and leading to the uplift of its individual blocks. The subsequent lowering of the raised block is the result of compensating for its isostatic imbalance.

Mechanisms and Factors of Structural and Crust Formation in Fault Zones of the DMS

To analyze the parameters of the structure and morphology of the fault zones of the DMS, we involved various processes, phenomena, and factors, the most important of which are associated with the spreading of the ocean floor; it is spreading that leads to the formation of shear zones connecting spatially separated spreading segments. Geological events occurring in a spreading geodynamic system largely determine the features of the structure transform faults.

Differences in the direction of spreading in neighboring segments of the MAR lead to the appearance of compressive or tensile stresses in fault zones perpendicular to the fault. Under conditions of compression, the fault valleys narrow and contribute to the formation of median ridges found in most of the active parts of the studied faults. Under extension conditions, the fault valleys expand and the longitudinal uplifts of the bottom of the fault valleys (in the active part of the southern trough of the Pushcharovskiy fault) and stepped sides form.

During the opening of the Atlantic Ocean, short-term episodes occurred, during which a change in the direction of spreading, spreading rate, or both could occur [17]. With these changes in the active parts of the transform faults, compression or extension regimes could be established. In the Atlantic, 11 Ma ago, the spreading direction turned counterclockwise,

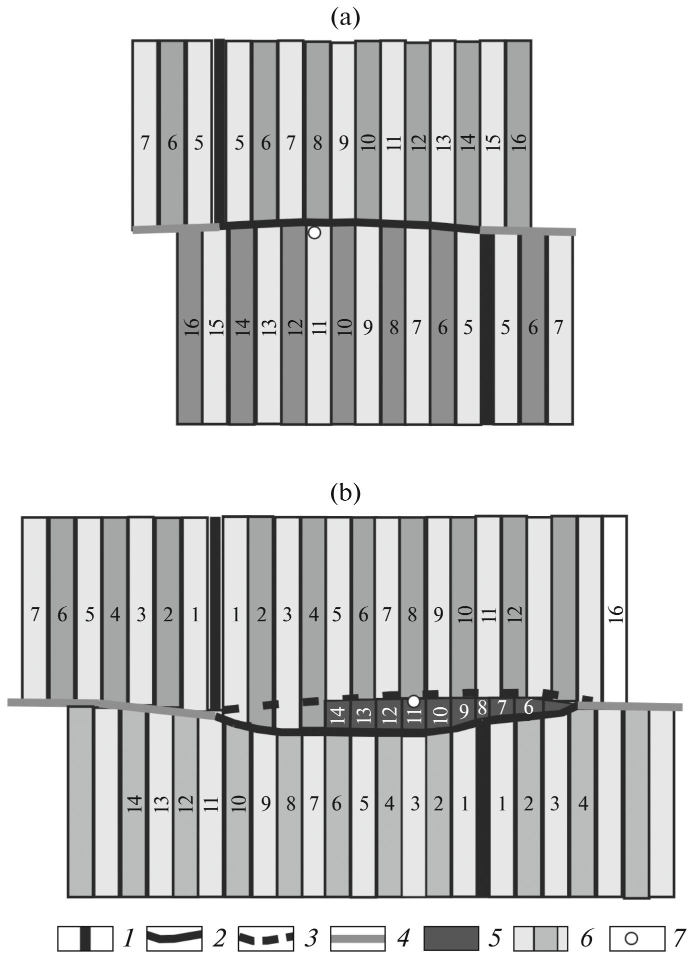

Fig. 9. The scheme of the formation of an interfault ridge in the DMS. (a) the period up to 4 Ma ago, when the northern fault was active; (b) period after 4 Ma ago, when the southern fault became active. (*1*) is the axial spreading zone; *2–3*—transform: (*2*), active, (*3*), not active; (*4*), passive parts of the fault zone, (*5*) inter-fault ridge, (*6*) uneven-aged bands of the ocean floor (the numbers on them are the age in million years); (*7*) is the position of the gabbro, for which the age is determined to be 11 Ma.

which led to the emergence of an extension regime in right-handed transform faults. As a result, in some of these fault zones, large transverse ridges arose, in particular, the Vema and Sao Paulo ridges [13, 25].

According to many structural parameters and the time of formation we believe that transverse ridges are close to these transverse ridges in terms of the mechanism of formation and formed within the Doldrums megatransform system on the southern sides of the Doldrums faults and the southern Pushcharovskiy fault.

In the Atlantic, 3.5–4 Ma ago, there was an episode of a sharp change in the spreading rate, which manifested itself in the region of the DMS in spreading instability, as expressed in frequent jumps of the spreading axis and in spreading asymmetry. We associate the formation of a transverse ridge on the northern side of the Vernadskiy fault, of which Mount Peyve is an integral part, with this episode.

Jumps of the spreading axis and spreading asymmetry are also reflected in the structure and morphology of fault valleys, since in this case nodal depressions, rift valleys, together with neovolcanic uplifts, remain in the rank of the corresponding paleostructures. Near the former nodal depressions, the fault valley widens and deepens. Opposite the former neovolcanic uplifts and rift valleys, the sides of the fault valley disappear and the above structures reach the bottom of the rift valley.

Axial spreading zones are the centers of magmatic accretion of the oceanic crust. At the most intense in the wake of magmatism, large neovolcanic uplifts are formed in the rift valley, which also extend into the fault valley, blocking it: neovolcanic uplifts in the Pushcharovskiy and Bogdanov faults. Recent paleoanalogues of such neovolcanic uplifts form transverse sills in fault valleys.

No less influence on the structure of transform fault zones is exerted by the processes occurring directly in transform faults; they can be attributed to the transform geodynamic system. From what we analyzed based on the example of the Doldrums megatransform system, we distinguish the formation of interfault and median ridges and crust formation associated with the serpentinization of mantle rocks. These transform processes act together with spreading processes and control them.

In the area of the DMS, inter-fault ridges, in accordance with numerical simulation, arose in the Pushcharovskiy and Doldrums faults, which have the largest offsets of 186 and 177 km, respectively [24]. In such fault zones, not one, but two arc-shaped zones of weakening of the lithosphere strength can arise, along which strike-slips occur simultaneously or with a time interval, connecting the spreading segments and isolating the lenticular inter-fault ridge.

The formation of the interfault ridge in the Doldrums Fault ~4 Ma was promoted by the onset of an epoch of spreading instability, which provoked the emergence of the southern trough of this fault. The formation of the interfault ridge in the Pushcharovskiy Fault was also preceded by an epoch of a sharp changes in the direction of spreading ~30–32 Ma ago, which led to the emergence of the DMS and the Pushcharovskiy megatransform with two fault troughs [9].

The curvilinear outlines of the formed interfault ridges influence the movement of adjacent lithospheric plates along the transform. The pressure exerted by moving plates on the curved surface of the interfault ridge leads to the appearance of longitudinal zones of compression and tension within it. Block uplift of ridge fragments occurs in compression zones, which leads to a decrease in depth and narrowing of fault valleys in uplift areas.

Uplifted blocks of interfault ridges are observed in both the Doldrums and Pushcharovskiy megatransforms. Extension zones lead to the formation of submeridional depressions or pull-apart depressions within interfault ridges, which can turn into spreading depression centers. Such morphostructural formations are observed only in the Pushcharovskiy fault.

One feature of the new crust formation in transform faults is the serpentinization of mantle rocks, which then become part of the oceanic crust. An increase in temperature conditions as a result of friction moving in different directions lithospheric plates accelerates the processes of serpentinization. Serpentinized rocks experience uplift throughout the active part of the fault, which leads to a decrease in the depth of the fault valley. In all active parts of the faults, the longitudinal depth profile is the same: from the intersect zones towards the central part of the transform, the depth decreases to a certain background value. In the layer of serpentinized rocks, diapirs are born, which, upon rising, lead to the formation of median ridges.

The structure and morphology of fault valleys is affected by the sedimentary process, which significantly captures the passive parts of fault valleys, which are older than their active parts. The accumulation of sedimentary deposits leads to a decrease in the depth of the valley, to a flattening of its bottom. The transverse depth profile acquires a trough-like shape.

During the formation of thick sedimentary prisms that overlap the sides of the valleys, the boundaries the valleys become winding, connecting with the boundaries of submeridional depressions developed in the ridge zone of the MAR.

CONCLUSIONS

(1) The DMS includes the Vernadskiy and Bogdanov transform faults and Pushcharovskiy and Doldrums megatransforms. The megatransforms have two fault valleys separated by a lenticular inter-fault ridge.

(2) Within the DMS, the direction of spreading when moving from south to north varies from ∟89° to ∟93°, resulting in the emergence of compressive or tensile stresses perpendicular to the direction of spreading in some parts of the fault valleys. On the plots the action of compressive stresses, fault valleys are narrower, while in extension areas they are wider.

(3) The depth of fault valleys successively increases from the periphery of the DMS (the Bogdanov and Doldrums faults) to the center (Pushcharovskiy fault) in accordance with a decrease in the temperature of the upper mantle at the level of the magma generation zone.

(4) In each fault, the valley depth decreases from the zones of the rift-fault intersect towards the center of the active part to a certain background depth. It is assumed that this phenomenon is the result of the rise of the valley bottom, which occurred due to the decompression of the lithosphere caused by the serpentinization of ultrabasic rocks. We regard this serpentinization as a new type of oceanic crust formation.

(5) In the axial zones of the active parts of the fault valleys of the Doldrums megatransform system, median ridges are widespread, mainly extending parallel to the fault; these are serpentinite diapirs squeezed out above the bottom surface.

(6) On the southern sides of the valleys of the Doldrums and Pushcharovskiy faults 10–11 Ma ago, as a result of the flexural bending of the edge of the lithospheric plate under transtension conditions, extended transverse ridges were formed, comparable to the length of the offset, which are currently located in the western passive parts.

(7) The transverse ridge on the northern side of the Vernadskiy fault, which includes Mount Peyve, was formed between 3.65–2.4 Ma. Frequent jumps of the spreading axis in this area led to the division of the transverse ridge into three segments.

(8) The longitudinal uplift of the bottom of the fault valley, encountered in the active part of the southern branch of the Pushcharovskiy fault, is considered as a transverse ridge, which formed under conditions of limited transtension and did not complete its development.

(9) The interfault ridge in the Pushcharovskiy megatransform has existed since the origin of the DMS ~30–32 Ma ago; it was formed in the Doldrums megatransform ~4 Ma ago. Arising under the pressure of moving lithospheric plates, the curvilinearity of the outlines of the ridges led to the fact that the inter-fault ridges experienced longitudinal (along the fault) compressive and tensile stresses, compensated by vertical uplifts of their individual blocks and the formation of depressions, pull-apart depressions, and spreading centers (the latter are found only in the Pushcharovskiy megatransform). The rising blocks could reach sea level, after which they experienced a dive.

(10) In fault valleys, transverse thresholds, most of which are former large neovolcanic uplifts, and oval depressions inheriting nodal depressions occur.

(11) In the active parts of the faults, the valley has a predominantly U-shaped cross section, while in the passive parts of the faults, the valley has a trough-shaped cross section due to its filling with sedimentary cover. The appearance of areas with a V-shaped section indicates tectonic movements of a nonshear nature, which covered these areas.

(12) The structures of the MAR zone adjacent to the fault zones are mainly "suspended" above the bottom of the fault valley to a height of its side, on average, of about 750 m, except for cases where deep submeridional depressions, some of which are paleorift valleys, are directly connected with fault valleys. valleys.

(13) The structure-forming processes that determine the structure and morphology of the fault zones that make up the DMS are related by their origin to the spreading and transform geodynamic systems.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY INFORMATION

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