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Structure Formation in the Rift Zones and in the Tranvers Offset of the Spreading Axes: Results of Physical Modeling

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Abstract—The paper presents the results of experimental modeling of the specific features in the structure formation within the rift zones and also within lateral displacements of the spreading axes such as transform faults and nontransform displacements. The experiments were conducted on materials consisting of liquid and solid hydrocarbons; the similarity conditions were taken into account.

The parameters, which were varied in the experiments, included (1) the thickness of the model lithosphere in the rift zone, the thickness of the lithosphere in the zone of the nontransform displacement, and the thickness of the ambient lithosphere; (2) the value of displacement between the rift segments; and (3) the spreading rate. The modeling revealed the specific features in the structure formation and segmentation of the spreading axes in case of the orthogonal and oblique extension of the model lithosphere; also, the critical values of the lateral displacement of the spreading axes, which cause changes in the pattern of the structure formation within zones of transverse displacements, were estimated.

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INTRODUCTION

The global system of the rift zones within the mid-ocean ridges, extending by about 70 thousand kilometers, is interrupted throughout its extension by various morpho-tectonic structures, which divide the spreading axis into separate segments [Macdonald, 1998; Dubinin and Ushakov, 2001]. The most distinctly expressed structures, which displace the spreading axis in the transverse direction, are the transform faults (TF) and nontransform offsets (NTO) and overlapping spreading (OCS) centers of spreading of different types (Fig. 1).

Transverse dislocations (offsets) are the characteristic structures of the midocean ridges with low rates of spreading. They correspond to the along-axial maxima in depths and are the zones, where the conjugated segments of spreading with the different tectonic patterns and different levels of magmatic activity may coexist with each other. On the nontransform offsets, the horizontal shear between the displaced segments of the ridge is not confined to a narrow localized and stable valley as is the case with the transform faults. The nontransform offsets include a broad variety of structures, governed by volcano-tectonic processes within the rift zone and also by the length of the nontransform offset located between the neighboring spreading segments. The off-axial passive traces of the transform faults indicate that they are long-living and stable in time structures (tens of millions of years). The traces of nontransform offsets are usually inclined to the axis of spreading. The latter are indicative of the axial migration of these structures, which, as judged by the length of off-axial traces, have a limited lifetime of a few million years.

The present work addresses the experimental modeling of the processes of structure formation in the shear and extension zones within the oceanic lithosphere. Modeling was carried out in two directions: (1) structure formation and segmentation of the rift fault during its formation and propagation with the different rates and directions of spreading and different thickness of the model lithosphere, and (2) structure formation in the zones of lateral offsets of the spreading axes.

EXPERIMENTAL TECHNIQUE

The model material used in the experiment was a mixture of liquid (mineral oils) and solid (paraffin series) hydrocarbons. Its physical characteristics strictly satisfy the principal criterion of similarity $\Omega = \tau_s/\rho g H = \text{const}$, where τ_s is the shear yield strength, ρ and H are the density and the thickness of the layer, respectively [Shemenda, 1983]. This material shows viscoelastic plastic properties, and at a certain temperature and deformation rate it may fail as a brittle or plastic body, i.e., with the formation of separate fractures or a zone of localized deformation in the form of thinning. The materials for this type of model experi-

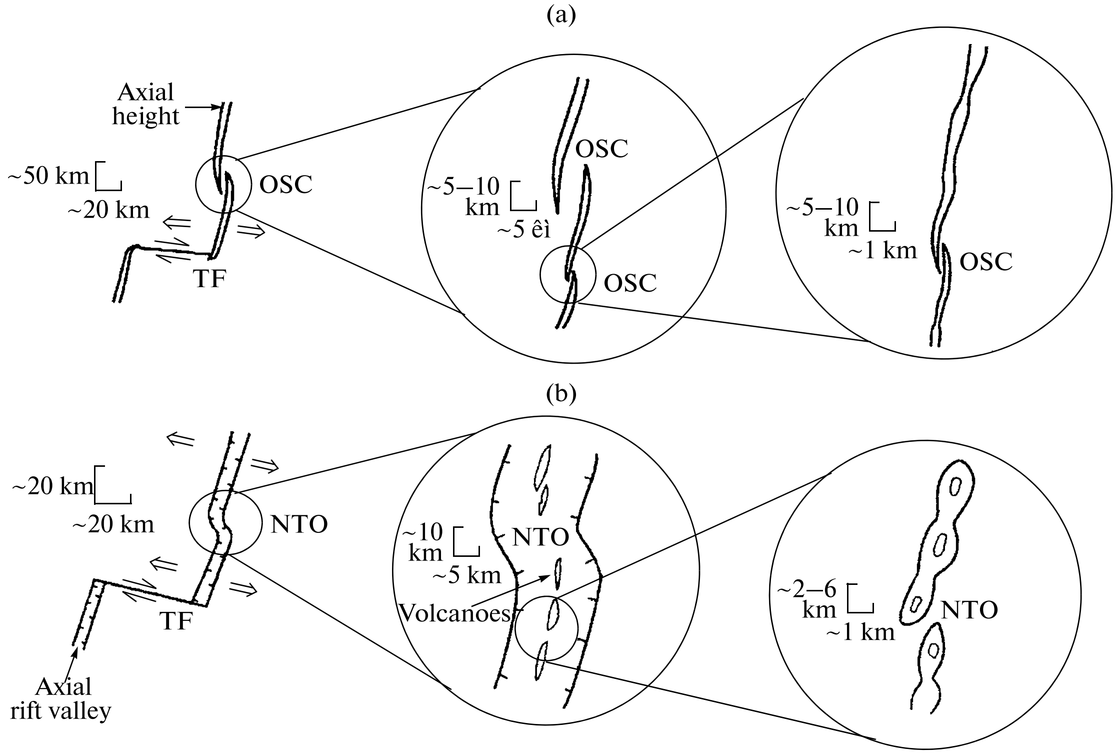

Fig. 1. The morphostructure discontinuities of different scales in the rift zones of midocean ridges with different rates of spreading [Macdonald, 1998, with small changes]: (a) with overlaps of the spreading centers and (b) with the nontransform off sets.

ments, their rheological characteristics, similarity conditions, instrumentation, and experimental procedures are described in more detail in [Shemenda and Grokholskii, 1988; 1994; Grokholskii and Dubinin, 2006].

The experiments were conducted with a unit which consists of a textolite bath with a piston and a system of internal heating. The frame with a piston, being driven electromechanically, moved in the horizontal plane at a given speed.

The model substance was placed into the bath and heated. Once the required temperature had been reached, the model material was cooled from above by a fan. The desired temperature of the melted model substance was maintained at the bottom and on the sidewalls during the preparation and conducting of the experiments. The solidification of the melted material from above formed the model lithosphere on the surface of the melt, which was "welded-on" to the piston and to the opposite wall of the bath. Within this zone, the heterogeneity was cut in the form of a linear weakened (thinned) zone with a width W and a thickness H, simulating the rift zone lithosphere. This process was controlled, and after the model plate within and outside the weakened zone had reached the thicknesses necessary for the given experiment, its horizontal stretching at a rate V had started.

EXPERIMENTAL RESULTS AND DISCUSSION

Structure Formation during the Orthogonal and Oblique Spreading

The modeling of structure-forming deformations in the axial zones of the spreading ridges showed that within the considered range of the extension rates in the model, a discontinuity of the brittle lithospheric layer occurs and the rift rupture is formed by the mechanism of propagation of a "running" fracture [Grokholskii and Dubinin, 2006].

The experiments carried out in the conditions of orthogonal tension showed that if the zone where the deformation develops is relatively narrow and has a small thickness, the nascent fractures mainly form small off sets and the overlaps with a width less than or equal to the thickness of the model plate . The fractures themselves form straight lines within the weakened zone. With an increase in the width of the deformation zone, the size of the displacements increased, too. The total displacement of the groups of the echeloned fractures also increased. An increase in the thickness of the layer also affected the pattern of the structures being formed. Within the overlap region, the fractures forming the structures were more strictly linear. These structures also differ in shape in a horizontal plane and in the ratio of the width of the offset to the length of the overlapped fractures. In experiments with a relatively thinner layer in the weakened zone, this

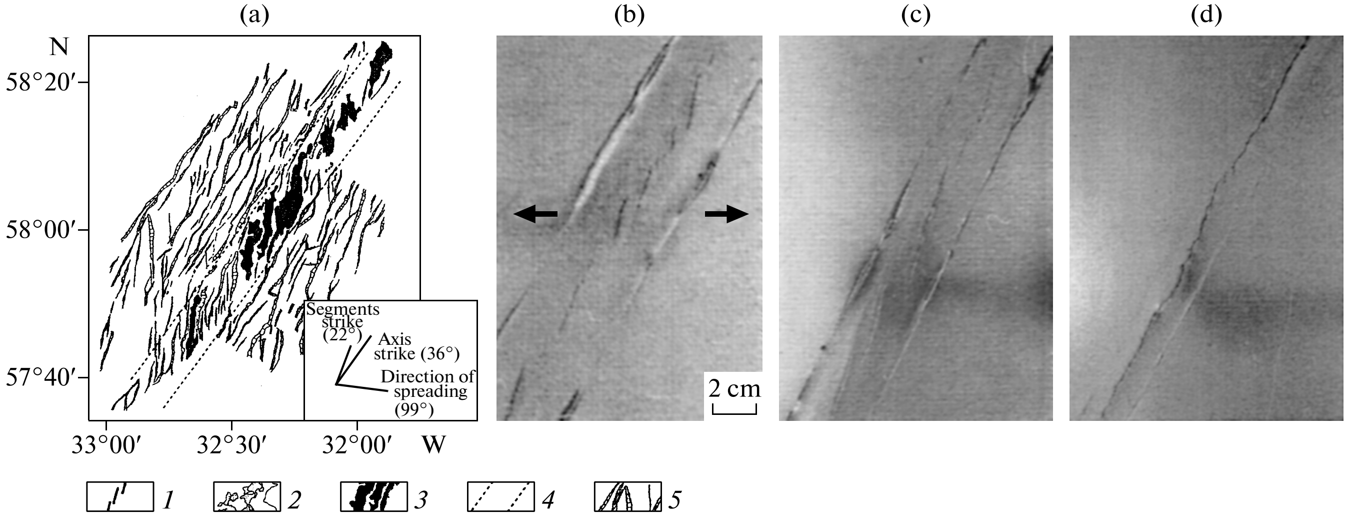

Fig. 2. Specific features in the morphostructure segmentation of the sections of the axial zone of oblique spreading according to the results of physical modeling (on the example of the Reykjanes spreading ridge): (a) the observed segmentation on [Tuckwell et al., 1998], (b)–(d) the structure formation under tension of the model plate ($V = 1.7 \times 10^{-5}$ m/s) with the inclined weakened zone ($\angle\alpha = 60°$). Photos, top view. Sections of the rift zone of the Reykjanes ridge: (b) northern ($H = 10^{-3}$ m, $W = 4 \times 10^{-2}$ m), (c) central ($H = 10^{-3}$ m, $W = 3 \times 10^{-2}$ m) and (d) southern ($H = 3 \times 10^{-3}$ m, $W = 2 \times 10^{-2}$ m), (*1*) the axis of spreading, (*2*) bathymetry, (*3*) axial volcanoes, (*4*) axial weakened zone, (*5*) faults and fractures.

ratio is 1 : 3, whereas with a layer that is thrice as thick, it is 1 : 5. Such structures are typical for fast- and slow-spreading ridges, respectively [Grokhol'skii and Dubinin, 2006].

In the experiments with oblique tension, we also observed the dependence of the structures being formed on the width of the weakened zone (in the region of the heated rift and thinned lithosphere). For example, this was the case at the Reykjanes ridge where, with a very oblique spreading between the strike azimuths of the rift zone and displaced segments, the difference amounts to ~15°(Fig. 2) [Tuckwell et al., 1998].

The influence of the Iceland plume is reduced to the heating of the Earth's crust, thinning of the lithosphere, and shortening of the thickness of its brittle layer in the course of the motion from south to north. The distinguishing feature in the morphology of the axial zone is the presence of echeloned volcanic ridges that are S-shaped in the plane.

When modeling the structure formation on the Reykjanes ridge in the conditions of the oblique tension influenced by the hot spot, we took into account the fact that the width of the heated zone decreased and the thickness of the lithosphere increased south off Iceland. The experiments reproduced the geodynamic conditions of three provinces recognized within the ridge, namely the northern, the central, and the southern ones (Figs. 2b, 2c, and 2d), which differ in the pattern of segmentation, the axial topography, the width of the rift zone and the thickness of the lithosphere.

The northernmost part of the ridge was reproduced in experiments with the minimum H and maximum width of the heat penetration zone W. The conditions of the transitional central province of the ridge were modeled in the experiments with intermediate values of the parameters. And, finally, the southern province, exhibiting the morphology of an axial valley was reproduced in the experiments with the maximum H and the minimum W. The angle α between the direction of spreading and the strike of the weakened rift zone was 60°.

Within the northern province of the model considered, the axial volcanic ridges are considerably extended, being somewhat spaced from each other (Fig. 2b). Within the southern province of the ridge, where the lithosphere is stronger, the number of fractures increases, whereas their lengths decrease; the fractures become more segmented here (Fig. 2d), and the space between them is occupied by smaller fractures, whose counterparts are the nontransform offsets. In the experiments reproducing the transient zone between the northern and the southern portions of the region, the structure formation pattern was also transitional (Fig. 2c). At a considerable dip, although tending to orthogonality, the fractures still propagate obliquely due to the large shear component on one side and due to the influence of the general oblique strike of the weakened zone. The experiments revealed reasonably good agreement between the experimental and natural patterns of distribution of axial fractures and segmentation at the Reykjanes ridge (Fig. 2).

A somewhat different geometry of the axial cracks is typical for the region of the Azores thermal anomaly.

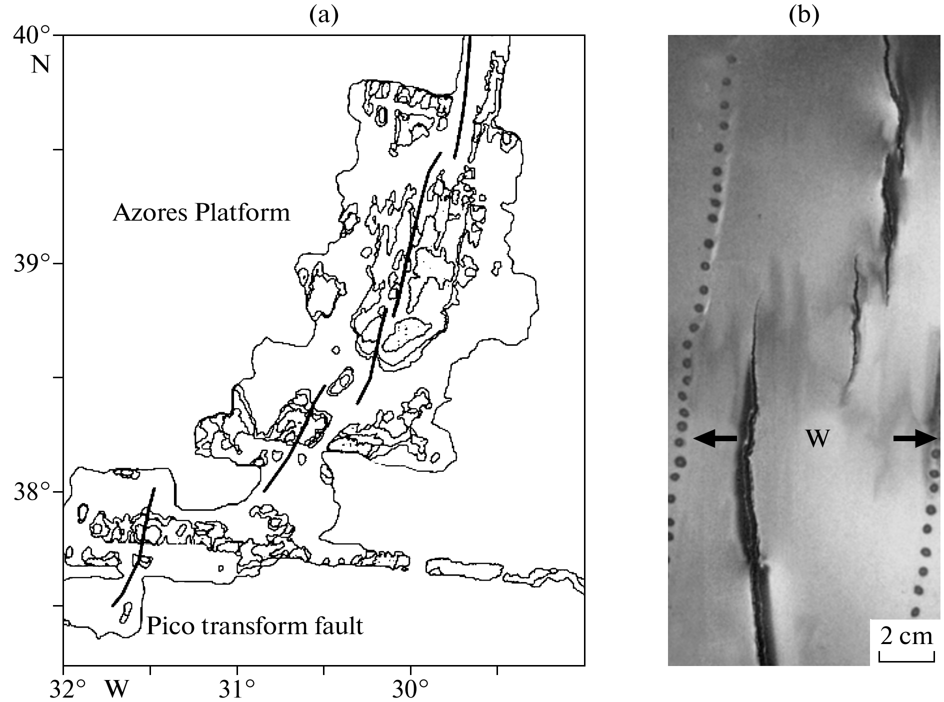

Fig. 3. Specific features in the morphostructure segmentation of the sections of the axial zone of oblique spreading with a wide zone of heat penetration: (a) segmentation of a section of the midocean ridge in the region of the Azores platform [Detrick et al., 1995], (b) structure formation under tension of the model plate with the inclined weakened zone of spreading and a wide axial heated zone ($H = 2 \times 10^{-3}$ m, $D = 8 \times 10^{-2}$ m, $V = 2.15 \times 10^{-5}$ m/c). Photo, top view. Designations are the same as in Fig. 2.

To the north of the Azores plateau, the area of heating within the rift zone is relatively narrow. The spreading is almost orthogonal here. Therefore, the segments forming the nontransform offsets in this section are scattered within a sufficiently narrow zone. To the south of the Azores, on the contrary, the heat penetration zone is wide, and the spreading is substantially oblique [Detrick et al., 1995]. This led to the formation of a series of large nontransform offsets here with a significant total offset (Fig. 3) [Grokholskii and Dubinin, 2006].

The simulation yielded the qualitative picture of the formation of faults and fractures in the rift zone, revealed the specific features of segmentation of the rift fissure, and also elucidated the formation mechanism of different structures (bending of the axis, the echelons of fractures, the nontransform offset, the small and large overlaps, etc.) in different geodynamic conditions of spreading. The experiments showed that at the stage of the nucleation of the rift fracture, the formation and the development of a different type of structures is controlled by the thickness of the lithosphere at the rift axis, by the width of the zone of lithospheric heating, by the direction and, to a lesser degree, the rate of spreading. If the axial heat zone, localized as a result of the presence of axial magmatic chamber, is narrow, and if the thickness of the lithosphere is small (fast spreading), the formed rift fracture is relatively linear, divided into segments, bounded by small offsets with a minor overlap, if any.

If the heated zone produced by the elevation of the asthenospheric wedge or by the influence of mantle plume is wide, the offsets on the rift fractures become more distinct, and the deformations involve a wider area. Being controlled by the thickness of the lithosphere, the configuration of the inclination rift fracture in a plane depends also on the inclination of the rift zone relative to the direction of tension: the larger the oblique angle, the more clearly expressed is the echeloned pattern of the fractures.

With any type of spreading, the formation of macrofractures is preceded by the formation of the propagating front of the linear microfractures, which disturb the upper more brittle layer of lithosphere, thus forming the general strike of the rift zone. This indicates that the propagating of the fractures occurs simultaneously on the different scales.

Structure Formation in the Offset Zones of the Spreading Axes

The second group of experiments concerned the identification of specific features in the structure formation within the regions of nontransform and transform displacements of the rift zones in the midocean ridges.

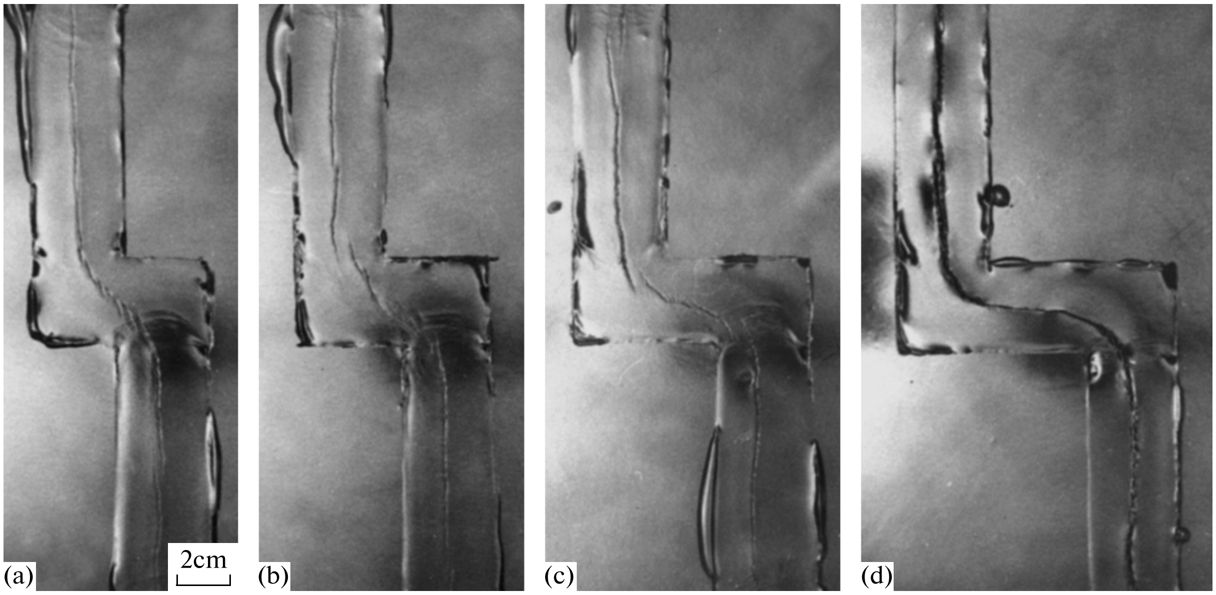

Fig. 4. Structure formation with different thicknesses of the model lithosphere in the offset zone and in the rift segments. Photo, top view: $H_p = 6 \times 10^{-3}$ m; $H_r = 10^{-3}$ m; $H_c = 2 \times 10^{-3}$ m; $V_{spr} = 3.75 \times 10^{-5}$ m/s; (a) $L = 3 \times 10^{-2}$ m; (b) $L = 4 \times 10^{-2}$ m; (c) $L = 5 \times 10^{-2}$ m; (d) $L = 7 \times 10^{-2}$ m.

In terms of the amount of the spreading axes offset, three types of nontransform offsets are distinguished [Sempere et al., 1993]: (a) large scale nontransform offsets with a length of about 15–30 km and distinct off-axial traces indicative of their long existence, (b) intermediate nontransform offsets with a displacement length of the order of 4–7 km, characterized by a simple displacement of segments without any distinct off-axial traces; (c) small scale nontransform offsets, which are the displacements within the neo-volcanic zone with a length less than 4 km; they correspond to the faults between the isolated seamounts.

The morphology of large and intermediate offsets significantly differs; therefore, Spencer with her coauthors [1997] proposed a morpho-tectonic classification of the nontransform offsets (NTO's). This classification also includes three types of the nontransform offsets: (a) type 1, nontectonic NTO; (b) types 2A and 2B, characterized by the existence of the "septa" (or closure) type of structures in the intrasegmental region; (c) type 3, which is characterized by the echeloned shear zones under brittle/dutile tension.

To reveal the specific features of the structure formation under the brittle-plastic failure of the lithosphere, we carried out the experiments on studying the lateral offsets of the spreading axes. These series of experiments were prepared in the same way as those described above. The only difference was that the configuration of the weakened zone in the model plate was set as the rift–offset–rift. In the experiments, we varied the amount of offset (L) and the thickness of the layer within the rift segments (H_r) and within the transverse offsets (H_c). The direction of tension coincided with the offset direction in the model, i.e., it was orthogonal.

The results of different experiments, which differed in the value of the rift segment offsets in the model and in the thickness of the weakened zone, are shown in Fig. 4. The model thickness within the offset region was twice as large as in that within the rift segments. In the case of small offsets, a staircase of the displaced fractures was formed in the region of the nontransform offset (Fig. 4a). As the distance between the rift segments increases, the inclinations of these fractures became steeper, their number decreased due to the increase in their length, and the width of the offsets formed by them also increased (Fig. 4b). Further on, they passed into oblique shear fractures, which connected the internal angles of the zones of the intersection of rift segments with the offset region (Fig. 4c). The transition occurred when the length of the offset exceeded the width of the weakened zone (the width of the axial heated zone). The inclination of the region of oblique shear relative to the strike of the offset decreased with an increase in the length of the latter. Actually, this shear is the zone of the main shear strains whose strike in the real transform faults does not always coincide with their own strike. With a further increase in the length of offset L, a single shear fracture was formed in the model (Fig. 4d).

Next, we carried out a series of experiments on a model with very small thickness (1 mm) in the zones of the rift segments H_r and in the region of offset H_c. The other parameters and the mode of their change in all experiments were the same as in the previous series.

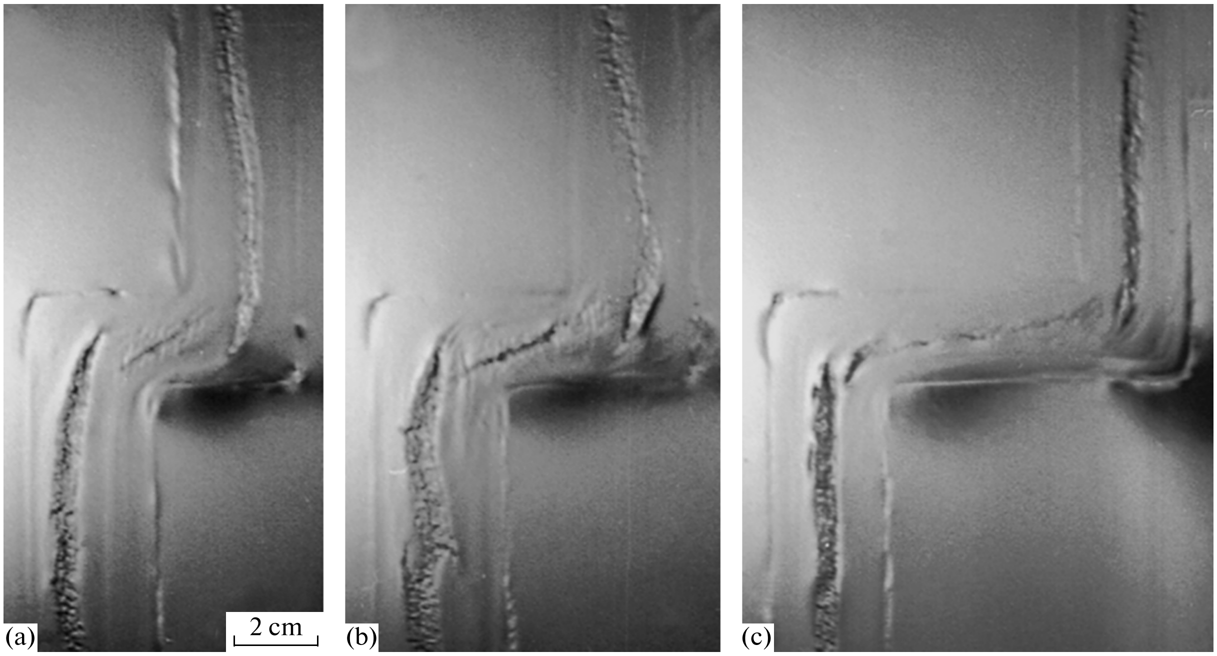

Fig. 5. Structure formation with different lengths of the offset in the model with more plastic properties. Photos, top view: $H_p = 4 \times 10^{-3}$ m; $H_r = 10^{-3}$ m; $H_c = 10^{-3}$m; $V_{spr} = 3.75 \times 10^{-5}$ m/s; (a) $L = 5 \times 10^{-2}$ 2 m; (b) $L = 7 \times 10^{-2}$ m; (c) $L = 1.1 \times 10^{-1}$ m.

The results of these experiments (Fig. 5) showed that the dipping zone of shear strains, which intersects the nontransform offset at a certain angle, is formed earlier than in the previous series, when the offset L is 5 cm. It is obvious that the failure of this thinner model lithosphere was rather more plastic. This is supported also by the fact that no segmentation in the form of small displacements comparable with the thickness of the layer was observed within the rift segments. The fractures, which had originated on the segments, propagated as unit fractures. In the offset region, they propagated with a smooth turning towards each other and had advanced by 2/3 of its width farther than in the previous series. Then, they stopped propagating and a bidirectional network of fracturing was formed in the zone of the offset. The fractures, which are normal to the direction of the tension, passed into smooth S-shaped fractures. Further, the shears with small offsets relative to each other were formed along the fractures, which were subparallel to the direction of tension. In the experiment shown in Fig. 5a, there were two of them and in Figs. 5b and 5c, a few. In the course of the tension the shears merged with each other via a network of fractures, and then with the fractures of the rift segments. In case of a significant offset (Fig. 5c), the zone of shear strains had a zigzag shape in the plane due to the connection of relatively short shear fractures. In case of a more plastic failure such a picture was observed in all experiments with a offset larger than 5 cm. With the increasing length of the offset, the zone of main shear strains became also oriented at smaller angles relative to the strike of the offset.

CONCLUSIONS

Based on the experiments, we may conclude that a regular variation of the structure formation occurs in the zones of transverse offsets depending on the length of the offset and the ratio between the thickness of the lithosphere in the rift zone and that in the offset zone. A successive change in the length of the offset in the experiments showed that there are critical values, with which the behavior of the failure of the lithosphere and, thus, the type of the forming structures changes. Primarily, such a critical value is the length of the offset (less than 1.5 cm in the model and 5–10 km in nature), with which the nontectonic nontransform offsets (type 1 according to the classification by Spencer) pass into offsets of types 2 and 3. Another critical value of the length of the offset is 5 cm in the model (35 km in nature), with which the nontransform offsets of types 2 and 3 are changed by the transform faults with a distinct localized zone of shear strains. This critical offset appears at those places where the age of the lithosphere, and, therefore, its thickness/mechanical strength prevent the segments from propagating through the dislocation.

Thus, the lateral offsets of the spreading axes, belonging to the type of nontransform offsets, may be formed and develop either due to the propagation of the axes of the spreading segments towards each other (type 1–2) in case of a change in the relative motion of the plates, or during the advance and retreat of the neovolcanic zones (type 3), caused by the axial migration of the melt flows during the magma uplift in the hot spot regions (the Azores thermal anomaly), or in the regions of the focused mantle upwelling under the centers of the segments. On the other hand, physical modeling shows that the formation of nontransform offsets can be linked with local jumps of the axis of spreading within the rift zone and with the deformation of the lithospheric wedge during the accretion of the new crust [Malkin and Shemenda, 1991; Shemenda and Grocholsky, 1994]. Finally, the experiments showed that the structures of nontransform offsets and overlaps of the centers of spreading can be formed during the original nucleation and segmentation of the rift fracture (Figs. 2 and 3). The traces of these dislocations may be inherited in the subsequent evolution of the lithosphere.

Our results showed that the character of these structures' formation is governed by the thickness of the lithosphere at the rift axis, by the width of the zone of its heating, caused by the presence of the axial magmatic chamber or the asthenospheric uplift (the focused mantle upwelling), and by the direction and the rate of the tension.

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