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GEOLOGY

Shear Tectonic Fabric in the Atlantic Ocean and Its Relation to the Geodynamic Condition of the Upper Mantle and Intraplate Deformations

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Abstract—The tectogenesis of the Atlantic Ocean segments is complicated by the axial difference in spreading half-velocities, which causes additional shear displacements between the lithospheric blocks along the transform faults. The intensity of these processes and density of the fault zones iis related to the presence of "cold" sublithospheric lenses along the MAR at a depth of 500 km.

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The postulate of rigidity of the lithospheric plates moving along the Earth's surface on the asthenospheric layer with a reduced viscosity does not correspond to the real geological structure. As defined in [9], the lithosphere is laterally divided into large and small plates that are not uniform in both the vertical and horizontal sections. The major tectonic activity is manifested at the plate boundaries, but it is also typical of the intraplate space. The energy that is necessary to implement the full range of tectonic processes in the lithosphere is estimated at (1–2) × 10^{11} W [1], while the total energy considered in the Earth is estimated at (5.3–7.2) × 10^{13} W [4]. It means that the energy release exceeds the needs of the lithospheric tectonic processes (including horizontal plate movements) by more than two orders of magnitude. Thus, the main problems are the mechanisms of energy conversion to work related to tectonic deformation of the lithosphere both on its boundaries and inside the plates.

The major driving forces for plate movement in the Atlantic region are not completely clear. The subducted plate pulling (slab pull) into the mantle is unlikely in this ocean, because, except for the relatively small arc systems of the Scotia and Caribbean seas, there are no subduction zones with a slope from the Mid-Atlantic Ridge (MAR), the pulling in of which could support the opening process. The lithosphere transfer by the asthenospheric current should form a well-recognizable dynamic relief related to the MAR. But according to [12], the dynamic relief is related not to the MAR, but to the system of localized regions of ascending plumes detected by the seismotomography data also not evidencing continuation of the MAR axial anomalies deeper than 250–300 km [11]. Hence, the formation of the MAR structure cannot be clearly explained in terms of classical mechanisms and additional options are needed. This can be a rotational mechanism that forms the tangential forces affecting each element of "loose" plates and blocks [6] analogous to volumetric forces. In addition, the action of such forces can lead to block movements within the large plates and various tectonic deformations in the intraplate space and can also contribute to the differentiated horizontal displacements.

The different spreading velocity for the even-aged areas along the isochrons in parallel to the MAR may be an indicator of horizontal differentiated displacement within the plate. According to [3], the spreading velocities for the South Atlantic segment between 12° and 17° S, at ages from the present up to 20 Ma, obtained from the correlation of anomalous magnetic fields (AMFs), show a difference of more than twice in the kinematics of adjacent spreading segments separated by transform faults. These conditions can cause shears not only in the active fault areas under the standard conditions at the same velocity, but also outside of them on both sides of the MAR due to the additional shear amplitude caused by the velocity difference. This amplitude should decay or dissipate at an increasing distance from the MAR [8]. The decay process needs an additional space that is comparable to

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the size of the shear segment. Shears can cover intraplate areas, passive parts of transform faults with adjacent areas, and also the sedimentary cover. Evidence for deformations in the seismic records of the sedimentary cover, which can be formed by paragenesis of the shear zones, can be found in [10] and many other works. The first assumption of the possible shear nature of intraplate deformations in the Atlantic Region is likely given in [2].

Let us consider a compilation of geophysical attributes along the MAR between 55° S and 80° N (Fig. 1). The attributes are compared in the section of variations in the ratio of longitudinal and transverse wave velocities *Vp/Vs* from the surface to the mantle bottom along the MAR (Fig. 1-6), calculated in [7]. This seismic attribute is interpreted as an indicator of tectonic "mobility" in the mantle, and its minima are lower "mobility" zones circled with dotted areas, which correspond to the "cold" lenses located largely in the range of 400–700 km. Figure 1-5 shows the density of the fault zones along the MAR with an envelope curve. Modulations of the total lengths are well-defined as the chain of maxima coinciding in general terms with the position of the "cold" lenses under the MAR. The geodynamic effect of these lenses on tectonic fragmentation of the lithosphere and crust is also based on the mantle thermal condition in the layer with a thickness of about 300 km right above the 670 km section and is retained when moving away from the MAR during spreading. It can be explained by the fact that the thicker (up to 400 km) surface layer can be involved in the movement of lithospheric plates, the bottom of which, characterized by increased friction within the "cold" lenses, contributes to enhanced macrofracturing. In the space between the lenses, the mantle is less viscous and the number of large faults and their length decrease.

Figures 1-2 and 1-3 show spreading half-velocities along the 16 and 4 Ma isochrons, respectively, in pairs for the western (a solid line) and eastern (a dashed line) MAR flanks, constructed after [13] without an interval filtration from 8°S to 15°N. These diagrams were obtained by the cross section of the matrix of half-velocities along the position profiles of these isochrons. Due to the fact that the equatorial segment of the Atlantic (ESA), which for a number of reasons, contains the highly fragmented AMF. This interval is therefore not shown in the diagrams characterized by the following features. A regular increase in the spreading velocities is clearly seen when the plates become more and more distant from the rotation pole of the plates separated by the MAR (about 60° N). Against this background the local variations in half-velocities reach 100% along the strike of the MAR and 250% in the difference between the western and eastern flanks. The dimensions of the segments with local variations of half-velocities are comparable with the depths of the top of the "cold" lenses.

The velocity asymmetry is well-defined on the western and eastern flanks (Figs. 1-2, 1-3). This asymmetry is reduced to almost zero difference in some MAR segments, the position of which (Fig. 1-4) is coincident with the "cold" lenses and the transform fault modulation maxima. The asymmetry of spreading half-velocities reaches its maximum between the lenses, and the western flank of the MAR in the Southern Hemisphere is characterized by greater values than the eastern flank. Velocities are occasionally predominant on the eastern flank in the Northern Hemisphere. A negative correlation of the half-velocity maxima on the western flank and the minima on the eastern flank should be noted. The 16 Ma isochrone in the east is characterized by a northward shift of the whole data system relative to the west. The data curve in Fig. 1-2 therefore looks displaced along the latitude. A northward shift of the western curve by about 120 km would result in a negative correlation close to 1 for this isochron, as well as for the 4 Ma isochron. It means that the total spreading movement accompanied by some horizontal accretion of the crust, despite the half-velocity asymmetry, remains more or less the same, and no rapid jump in productivity of the magmatism supplying material to form the crust is observed. Within the plate there are segments with different kinematics and a predominant trend of this process (horizontal "keyboard"). In other words, the MAR segments have different kinematic and independent characteristics. This fact confirms the thesis of a heterogeneous "non-rigid" structure of the plates and possible independent motion of their parts under the action of volumetric forces with a horizontal component. These processes are more intensive in the regions between the "cold" sublithospheric lenses and within deep anomalies such as the "plume" in the MAR.

Having compared the half-velocity profiles for the 16 and 4 Ma isochrons, we observe segments where the western predominance of higher velocities underwent inversion, and at 16 Ma, the predominance was in the eastern flank and vice versa. For example, the segment from 52° to 49° S 4 Ma was characterized by an eastern half-velocity predominance, whereas at 16 Ma, the predominance was western. On the other hand, the segments from 41° to 37° S and from 17° to 15° S 4 Ma were characterized by the western half-velocity predominance, whereas at 16 Ma, the predominance was eastern. These inversions occur between the "cold" sublithospheric lenses. It is evident that the zones with a reduced mantle viscosity contribute to instability and variations in the predominant trends of the spreading process as compared to the "cold" zones.

As noted above, under the nonuniform velocity profile along the MAR segments, there should be shifts between the blocks, expressed as deformations in the basalt layer top, and, respectively, in the covering sedimentary cover, where it is already formed. Figure 2 shows the residual relief of the MAR axial zone and

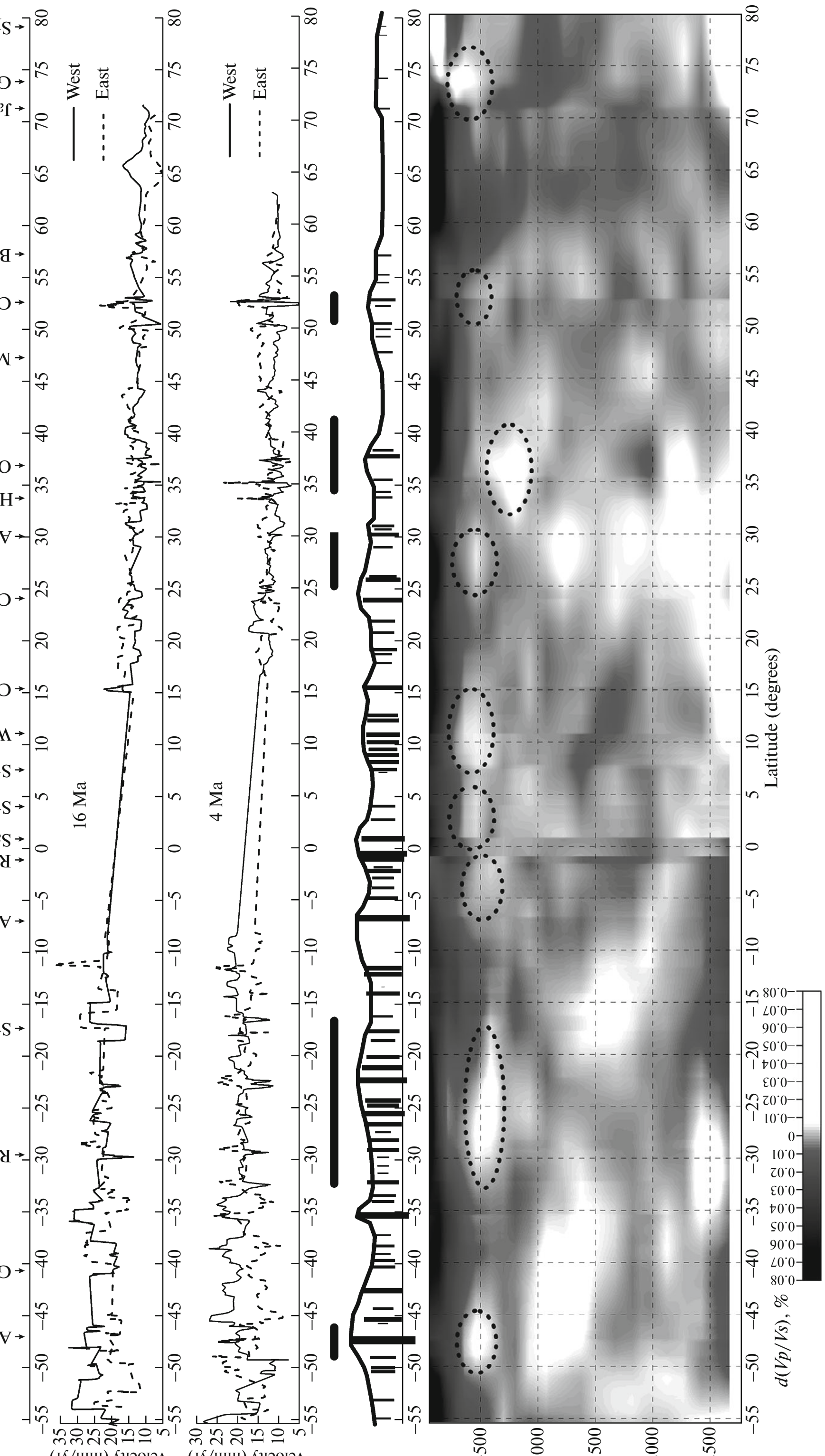

Fig. 1. Compilation of geophysical attributes along the MAR. (1) Position of intersections with the largest faults on the MAR axis and their names; (2, 3) spreading half-velocities (mm/yr) along the 16 Ma and 4 Ma isochrons, respectively, shown in pairs for the western (solid line) and eastern (dotted line) flanks of the MAR, constructed after [13], with interval filtration from 8° S to 15° N; (4) position of the zones with a minimum asymmetry of spreading velocities in the areas with reliably identified linear magnetic anomalies; (5) positions of intersections of the transform faults with the MAR with a symbol the size of which is linearly proportional to the total length with passive parts, and their envelope curve; (6) variations in Vp/Vs calculated from seismotomographic data on the P- and S-waves [11, 14]; dotted circles indicate “cold” anomalies in the upper mantle of the Atlantic Region under the MAR zones and flanks.


1
Agulhas
Gough
Rio Grande
Saint Helena
Ascension
Romanche
San Paulu
Strakhov
Sierra Leone
Vema
Cape Verde
Kane
Atlantis
Hayes
Oceanographer
Maxwell
Charlie Gibbs
Bight
Jan Mayen
Greenland
Spitsbergen
2
Spreading half-rate (mm/year)
16 Ma
3
West
East
4 Ma
4
5
6
Depth
Latitude
d(Vp/Vs),(%)

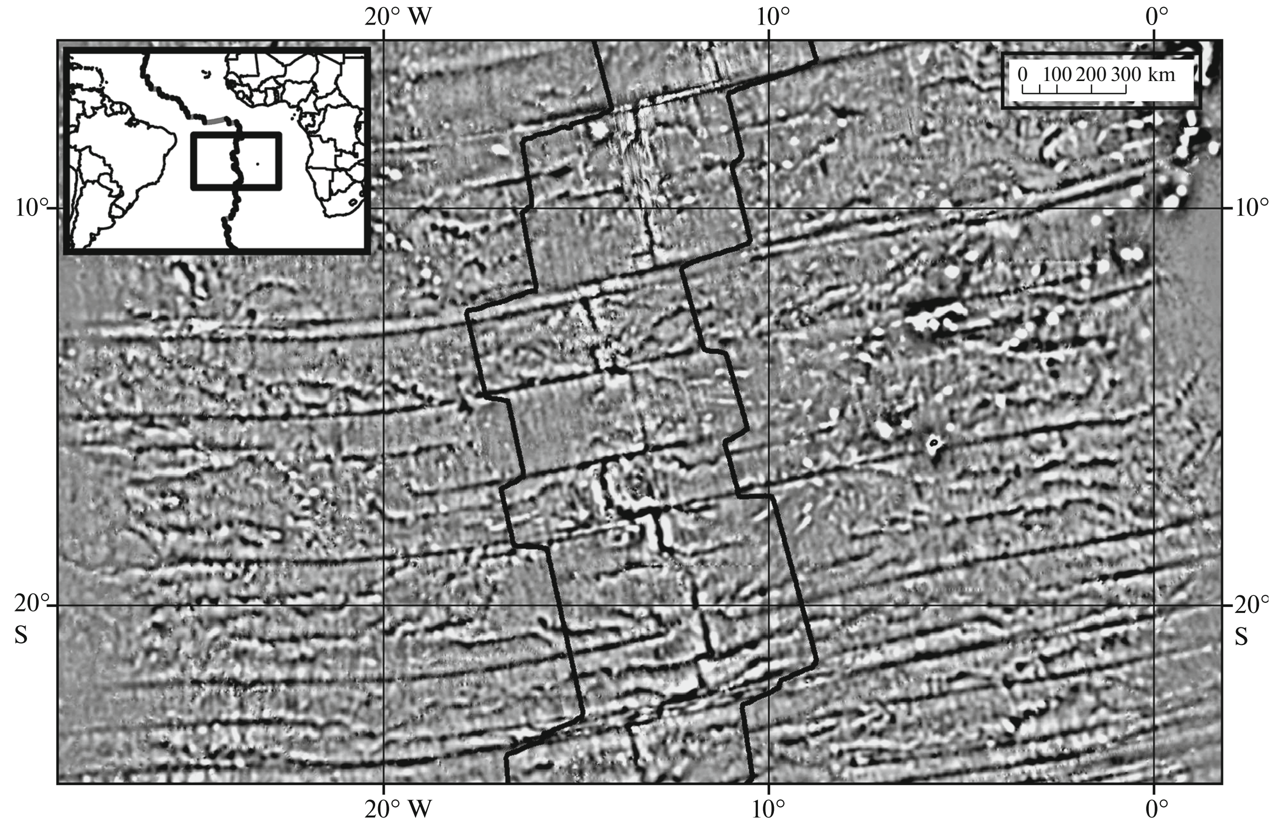

Fig. 2. Residual relief of the MAR axial zone and flanks between 7° and 24°S obtained by high-frequency filtration of the full GEBCO relief (http://www.gebco.net/, sampling date August 21, 2013) in the 30-second matrix for waves of less than 75 km in length. Bold lines show the position of the 16 Ma isochron from both MAR flanks. The root-mean-square dispersion of residual relief values is ±232 m, while the minimum and maximum values reach about ±5000 m.

flanks between 7° and 24° S obtained by high-frequency filtration of the full GEBCO relief (General Bathymetric Chart of the Ocean, http://www.gebco.net/, sampling date August 21, 2013) in a 30-second matrix for wavelengths of less than 75 km. For comparison with Fig. 1-1, Fig. 2 shows the position of the 16 Ma isochron. Figure 2 shows well-defined troughs of the transform faults, expressed as the extended and almost straight relief anomalies between which, in a number of interfault segments, there are multiple winding troughs of similar amplitude. It is difficult to explain their trajectory under the general trajectory curving of the transform zone (flow line) due to migration of the plate rotation pole. Their origin can be interpreted by the difference in velocities of adjacent segments, leading to shears along the transform faults and the related tensile zones at an angle of 25°–45° to the shear rupture in the segments that are adjacent to it. It should be noted that discordant structures develop in the segment with a lower velocity. This phenomenon is most demonstrative in the interval from 17° to 13° S on the MAR western flank in the 16 Ma isochron: the half-velocity value to the south of 15° S (Fig. 1-1) exceeds that to the north of this latitude at smaller deformations of the higher velocity segment (Fig. 2).

The disappearance of a "hermit" fault, as defined in [2] within the interval from 17 to 15° S at a distance of about 400 km west of MAR can be regarded from the standpoint of the alignment of spreading half-velocities in adjacent segments. Meanwhile, velocities were higher in the northern part judging by discordant faults in the southern part. Frequent changes in the relative velocity conditions in numerous MAR segments led to the formation of a mosaic oceanic substrate as alternating areas with discordant faults and without them. Thus, in addition to the AMF, the residual relief is the basis for reconstructing the detailed kinematic evolution of the spreading substrate. These processes can occur in each fault-based segment of the Atlantic lithosphere, but the presence of "cold" sublithospheric lenses and a less viscous mantle between them can activate the processes in these intervals and enhance the motion asymmetry.

The average thermal flow is 52 mW/m^2 in the zones with lenses and 67 mW/m^2 in the intermediate lower viscosity zones. Hence, the surface macrofracturing parameters, deformation-based lithosphere zoning, energy release through the surface, and seismic tomographic anomalies are connected in a more or less consistent cause-and-effect chain, which makes it possible to estimate the effect of the mantle geodynamic condition on the surface structures.

The following conclusions can be made:

(1) The geodynamic influence on the tectonic fragmentation of the lithosphere and crust is caused by the mobile mantle at a depth of 500 km. It means for the MAR zone that the surface layer with a thickness of up to 400 km is involved in the motion of the lithospheric plates. This layer is characterized by a higher friction at its bottom in the region of "cold" lenses contributing to an increased density of macrofractures. Between the lenses, the mantle is less viscous and the number of large faults and their length decrease.

(2) The asymmetry of spreading half-velocities is reduced almost to zero in the MAR segments located above the "cold" lenses. The asymmetry reaches a maximum between the lenses. The MAR segments have different kinematic characteristics. This suggestion confirms the thesis of a "nonrigid" structure of the plates. The lower viscosity mantle zones likely increase the instability and variations in the predominant spreading trend relative to the "cold" zones.

(3) The nonuniform velocities cause shifts between the blocks along the MAR segments, expressed as deformations in the basalt layer top. The difference in velocities of adjacent segments causes strike-slips along the transform faults, which form the pattern of discordant troughs. The residual relief reflects the kinematic evolution of the spreading substrate accretion.

(4) The surface macrofracturing, energy release through the surface, and the rheological state of the mantle are connected in a more or less consistent cause-and-effect chain, which makes it possible to estimate the effect of the mantle geodynamic condition on the surface structures.

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