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The tectonics of the Mid-Indian Ocean Ridge and the petrography of the solid rocks of its rift zones

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Introduction

The structure of the Mid-Indian Ridge has been studied by many authors. Especially active investigations relate to the period of activity of the International Indian Ocean Expedition (1960 to 1965), and results of this work are well known from numerous papers cited in bibliographical list edited by Fox (1967), especially those by Matthews (1966), Vine (1966), Cann (1968), Cann & Vine (1966), Laughton (1966), Fisher (1965) and Engel & Fisher (1969). Russian expeditions in the area of the Mid-Indian Ridge (figure 1) paid particular attention to the correlation between different geophysical and geological features of the rift zone. These results are not so well known for language reasons and because there are few publications. In this report we would like to concentrate on the approach to the understanding of the mechanics of the tectonic development of the rift zone on the basis of petrographical studies of solid rocks. This mechanism is very important for the interpretation of the process, which determines the spreading of the oceans' floor and continental drift.

1. Block structure of rift zones

The general scheme of tectonic features of the rift zone of the Mid-Indian Ridge is more complex than that of the Mid-Atlantic Ridge. Very typical is the orientation of rift valleys and ridges at 45° to the main direction of axis of the Ridge. It is often difficult to differentiate rift valleys and transform faults which cross the Ridge. During the first phase of our investigations it seemed to us that the deepest troughs such as the Vema trench, Vityas trench and other deep valleys were typical rift valleys, but now on the basis of comparison with the M.A.R., I must agree with Laughton and Matthews in the interpretation of such deep valleys as transform faults.

The most important tectonic feature of the rift zone of the Mid-Indian Ridge (in our opinion) is the block structure (figure 2). This means that the structure of the crust represents some kind of mosaic of blocks of different origin. This idea is based on the whole complex of geophysical and geological data; it originates from the topographic features, the heterogeneity of deep-structure revealed by seismic refraction, magnetic and gravity anomalies, values of heat flow, seismicity, and heterogeneity of petrography of solid rocks. On the basis of numerous dredge hauls it is clear that we have different petrographical blocks in the rift zone of the Mid-Indian Ridge.

It is very typical that in each dredge haul we usually find only one of the two main types of solid rocks:

(1) The first is a more ancient and more complex series which consists of peridotites, usually lherzolites and more or less serpentinized harzburgites, sometimes very fresh and at other times completely serpentinized, together with intrusions of gabbro and dykes of dolerite.

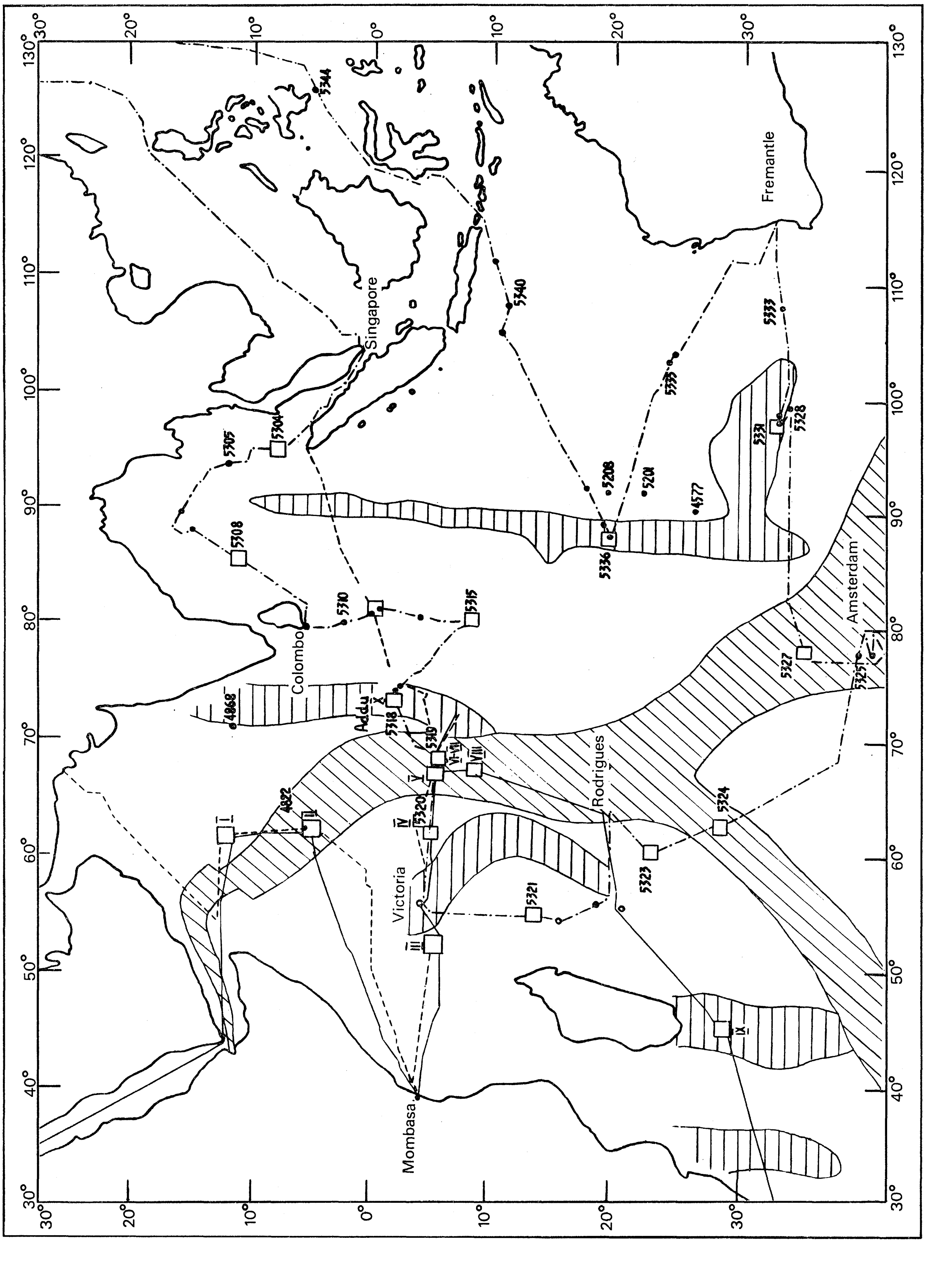

FIGURE 1. Map of tracks of cruises of Soviet research vessels in Indian Ocean on Upper Mantle Project in 1964–7. —, track of *Akademik Kurchatov*, 2nd cruise, 1967; - - -, track of *Vitjaz*, 41st cruise, 1967; -·-·-, track of *Vitjaz*, 36th cruise, 1964–5; ▨, mid-oceanic ridges; ▤, other ridges; □, areas of detailed survey; ● 5208, station number.

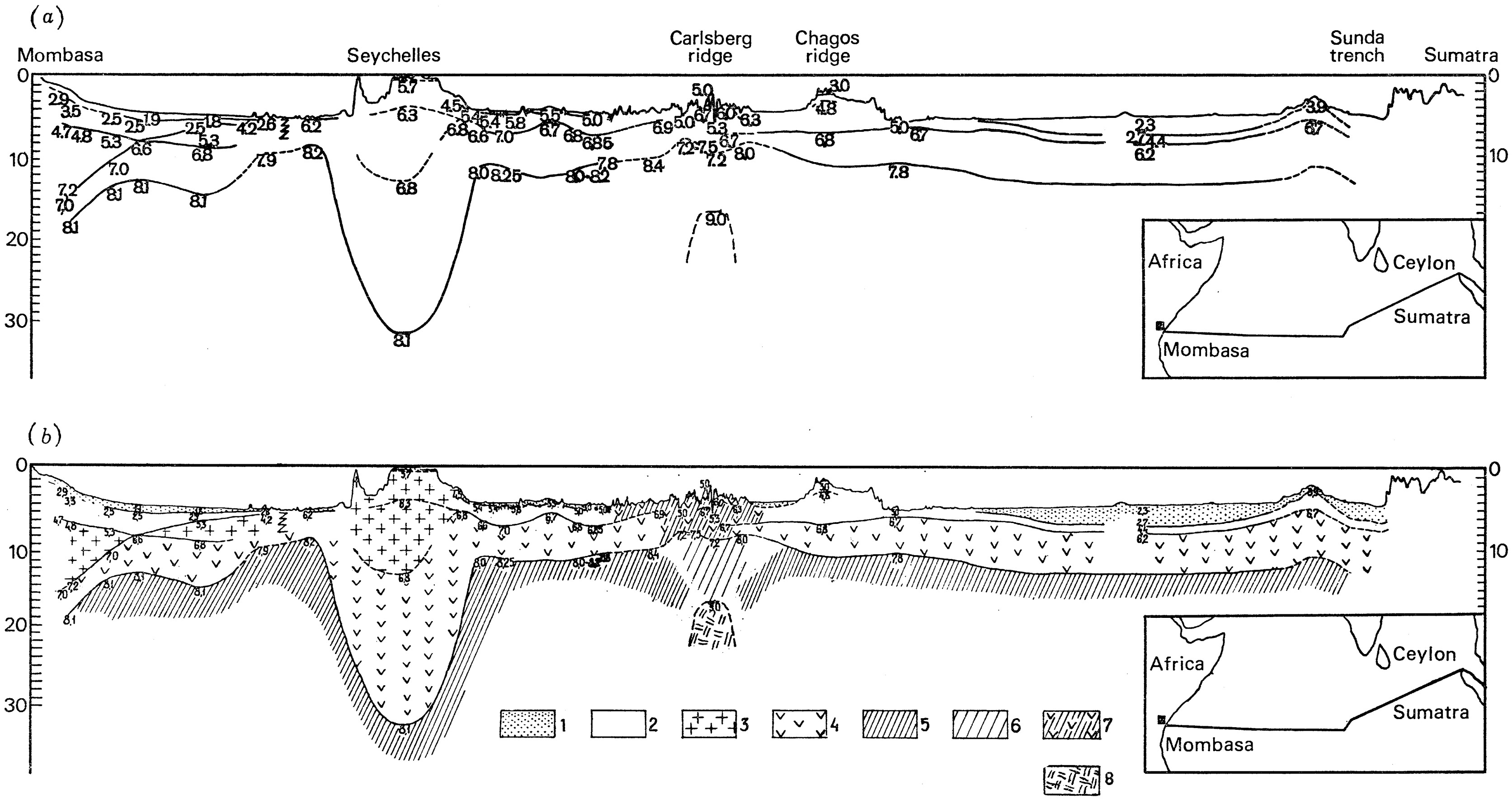

FIGURE 2. Cross sections of Earth's crust and upper mantle of the Indian Ocean floor along the line from Mombasa, Africa, to Sumatra Island, Sunda arc. Generalized sketch on the basis of published data. (*a*) on the base of deep seismic sounding only, (*b*) on the basis of full complex of data. Numbers on figure correspond to seismic velocities. 1, unconsolidated sediments; 2, 'second' layer; 3, 'granite-metamorphic' layer; 4, 'basalt' layer; 5, upper mantle rocks with normal density; 6, upper mantle rocks with reduced density; 7, mosaic crust of mid-oceanic ridge; 8, uprisen rocks of the lower mantle.

(2) The second is more recent and consists of basalt in the form of pillow lavas, mainly of tholeiitic type, and gabbro.

It is possible to recognize the existence in the rift zone of clearly contoured blocks formed by one of these types of solid rocks. Outcrops of ultramafic rocks are common enough in the central part of the rift zone and they are more rare on the slopes of the ridge; but we have also samples of ultrabasic rock from the slopes of the Mid-Indian Ridge as well as from the slopes of the M.A.R.

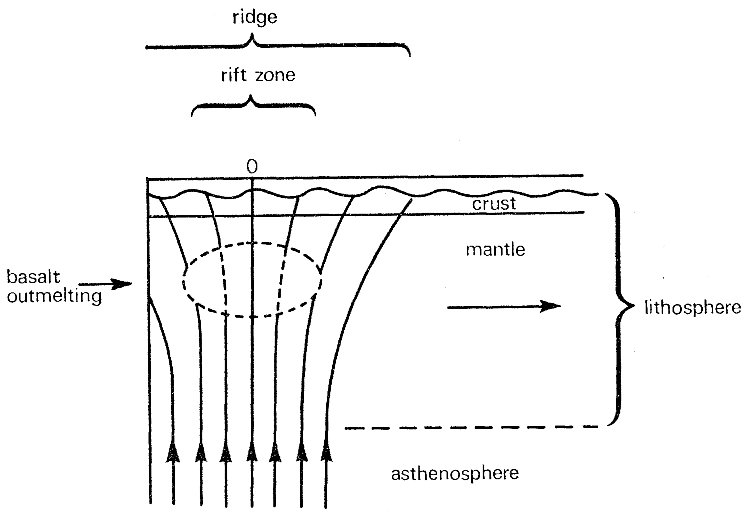

FIGURE 3. Scheme of development of structure of rift zone as result of uprise of deep material of mantle.

2. Process of formation of block structure

The processes of creation of block structure of the rift zone can be imagined in the following way (figure 3).

(1) The most important process is the uprise of deep material from the Upper Mantle in the form of protrusions of blocks of ultrabasic rocks. This process is complicated by serpentinization of peridotites, and by the outmelting of basalts from them, as well as by the strong cataclasis and mylonitization. The wide distribution of peridotites, serpentinites and gabbro on the surface of the ocean floor in the rift zone, and sometimes on the crest of the rift ridge, can be best explained by the following mechanism. The most convincing evidence of such an uprise is the stability of magnetization determined for samples of serpentinites and corresponding to the depth of serpentinization of the order of 10 to 14 km. It corresponds very well to the position of the isotherm 450 °C. Geochemical investigations of samples of serpentinites have shown the juvenile origin of the water which is involved in the serpentinization of peridotites of the rift zone.

The absence of garnet peridotites in the rift zone can be used as evidence of their uprise from a depth not greater than 60 km, or as evidence of a very slow rise accompanied by a process of slow transformation of garnet peridotites into the spinel type of harzburgites. The second idea seems to us to be the more attractive.

The suggested process of the uprise of peridotites of the rift zone does not offer good conditions for a normal development of the magmatic process or for the long-term existence of the magma chambers which are necessary for normal differentiation of the rocks. The evidence of such unstable conditions is based on the primitive and very constant composition of basalts of the rift zone which corresponds to the composition of medium mafic magmas. The basalts are mainly tholeiites; high-alumina and subalkali basalts are much more rare, and all versions of their composition do not exceed the limits of the medium mafic magmas, as shown by Kuno (1960) and Nockolds (1954).

It seems to us that under the rift zone, basalts have no time for complete outmelting in the course of the uprise of the ultrabasic rocks and so they have no time for complete differentiation. The primary mantle material not touched by differentiation is in our opinion lherzolite which is more close in composition to the pyrolites of Ringwood & Green (1966).

In contrast to such a situation there are areas of the ocean floor where volcanic cones with highly differentiated lavas are typical. It is clear that there are conditions for long-term existence of lava chambers in such tectonic areas.

The process of uprise is also accompanied by intensive cataclasis and mylonitization of ultrabasic rocks, by contact metamorphism of the rocks along the boundary of different petrographical blocks, and by regional metamorphism at the base of stable and relatively older basaltic blocks.

It is possible to recognize that there are three types of metamorphism:

(*a*) Dynamic metamorphism without considerable changes in the contents of trace elements, which is typical of contact zones.

(*b*) Hydrothermal metamorphism with rather large changes of content of trace elements, which is typical for the zone of degassing of mantle material in blocks of ultrabasic rocks.

(*c*) Regional metamorphism involving the base of gabbro-basaltic blocks of the crustal mosaic.

(2) The process of uprise of ultrabasic rocks naturally leads to a forcing apart of more ancient blocks of the ocean floor in the rift zone and in the whole area of the mid-oceanic ridge. The lateral displacement of such blocks will be accompanied by a continuous outmelting of basalts and it will determine the smoothing out of tectonic topography by lava flows; the prevalence of basalts in the area of slopes of the mid-oceanic ridges and rarity of outcrops of ultrabasic rocks are typical of slope areas.

(3) It is an interesting question, which process is the most active in creating the structure of the rift zone: protrusions of deep upper mantle material and the resulting displacement of crustal blocks, or the extension of the crust which is accompanied by an isostatic uprise of deep material in the form of protrusion or in the form of dykes of melted basaltic lavas filling the fractures of the extended crust?

After considering the evidence of strong cataclasis and mylonitization of ultrabasic rocks, intensive contact dynametamorphism of basic rocks and the localization of seismic activity in the narrow rift zone, it seems to us that the prevailing role belongs to the protrusion of deep upper mantle material which disjoints more ancient parts of ridge's slopes. As a whole the process of formation of specific structures and formation of the rift-zone rocks is so peculiar that it is possible to give it a special name: the georiftogenal process, that is to say the process which characterizes the development of the georiftogene (Udintsev 1968).

Additional evidence is provided by the extreme depth of the troughs along the transform faults. It is well known that the greatest depths of the rift zone occur along the transform faults (figure 4). It is difficult to explain this by the extension version of this process—in this version the filling of the fracture would have occurred in the same way in rift valleys as in transforming fractures. It is much more easy to explain it by protrusion which takes place irregularly and creates displacements of crustal blocks. Such protrusions create along transforms fault conditions for extensions and for opening.

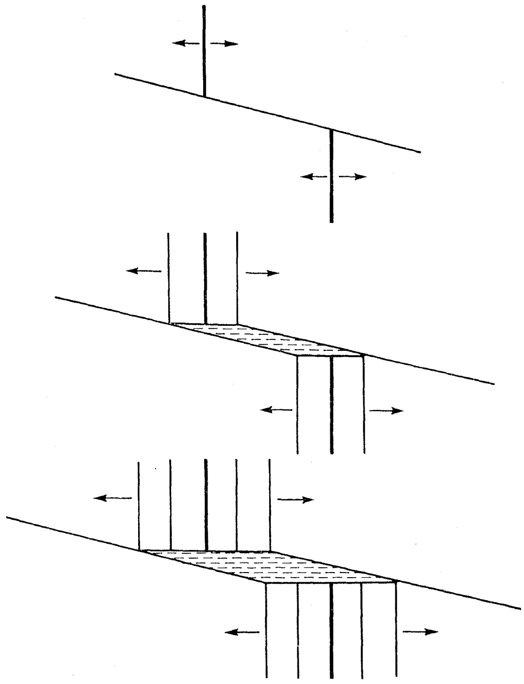

FIGURE 4. Scheme of development of fractures of rift zone as result of crust's spreading.

The scheme (figure 4) is very similar to Van Andel, Phillips & von Herzen's (1969) scheme explaining the origin of the Vema Fracture Zone in the M.A.R.—but we do not believe in the existence of so many ancient rift zones as would be needed on their hypothesis to justify the origin of so many faults across the ridge.

3. Magnetic anomalies and rate of sea-floor spreading

Closely linked to the petrography of the solid rocks of rift zones is the idea about the nature of linear magnetic anomalies and the rate of sea-floor spreading. The most popular idea was proposed by Vine & Matthews (1963) and is based on the assumption that magnetic anomalies were created by the axial intrusion or effusion of melted basalts which became magnetized with the polarity of the Earth's magnetic field. As it is known that polarization of the Earth had inversions through its history it is possible to believe that whole sequences of magnetic anomalies of mid-oceanic ridges reflect the rate of spreading of axial effusions of basalt lavas.

In the process of investigation of the rift zones of Mid-Indian Ridge and especially of the rift zone of the M.A.R., we obtained some interesting data (analysis by Mizlin & Pechezsky):

(1) On all occasions we were unable to estimate direct correlation between the topography and the anomalous magnetic field; only displacements of linear anomalies have real correlation with transform faults.

(2) Measurements of the intensity of remanent magnetization of basalts give very high values —up to 0.06 (c.g.s. (m) units).

If we use such intensity, 3 to 60×10^{-3} (the modal value for basalts, on average, is 0.01), for the calculation of the magnetic effect of a layer which has as upper boundary the surface topography of the ocean floor, and as lower boundary a certain horizontal surface at the maximum depth of the rift valleys, then the amplitude of anomalies will be from 400 to 700 γ. This means that irregular topography of the rift zone must create a magnetic effect similar to the one observed and it must be in correlation with topography—but such correlation was not clear.

(3) Studies of basalt give an opportunity to determine the polarity of magnetization. We measured the direction of magnetization in relation to glassy surfaces of lava fragments and obtained for 24 large fragments from different depths evidence of direct and reversed polarization: direct polarization for specimens from depths of 0 to 2.5 km, and reversed for specimens from depths of 3 to 5 km.

It is possible to propose that in the same sites we met basalts of different age and that the upper layer of the crust is stratified—and this upper part of the crust has very small effective magnetization.

(4) Magnetization no less intense is typical for serpentinites—from non-magnetic to 0.01; an average for numerous samples is 5 to 7×10^{-3}.

(5) Gabbros in all cases are practically non-magnetic. It is possible to think that in this case the effect of magnetization must be defined by the upper part of the crust.

(6) The investigation of basaltic samples from the rift-zone permitted us to determine that the magnetic intensity decreases with increasing depth of the layers from which the samples were taken. Together with the data for the inversion of polarity of magnetization this fact enables us to reject the supposition about vertical basalt dykes as a cause for the formation of linear magnetic anomalies.

(7) Close study of the magnetic intensity of basalts and serpentinites has shown the genesis of linear magnetic anomalies. It follows from this that the correlation of these anomalies with isochrons associated with the crust formed in the rift-zone is doubtful.

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