Nordic Energy Research Programme Norwegian U. of Science and Technology

Petrophysical Properties of the Rift Zone Rocks at Triple Point Bouvet

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Abstract
The basalts occurring at the triple point are mainly of ophitic texture. Characteristics of the given basalts are great density values, high velocities of the elastic waves and drastically different values of magnetic susceptibility. The lowest values of magnetic susceptibility are specific to the rocks occurring far away from the rift zone and subjected to secondary transformation. The highest ones are typical of the rift zone basalts of microdiabasic texture. In the other region the encountered basalts exhibits markedly diversified texture. Here, holohyaline rocks, transitional varieties and totally crystalline basalts are found. In this connection their properties differ greatly. The anisotropy type of the studied rocks in the above regions has been estimated using the acoustopolarizational measurements of the amplitude of transverse waves. What is more, the values of acoustic dichroism have been defined in three directions. The measurements indicate that a greater degree of anisotropy is characteristic for the rock samples taken at triple point Bouvet.

1. Introduction

Studies to gain insight into the conditions and dynamics of movement of the lithosphere platforms seem to be most favourable in the areas of junction of several tectonic structures. One such area, which are few in number, is the triple junction in proximity to the Bouvet Island in the South Atlantic (Mc Kensie, Morgan, 1969; Sclater *et al*., 1976).

The location of the triple junction point Bouvet has been first defined from seismologic data in the area of latitude 55° south and longitude 0° east (Forsyth, 1975). The American-Antarctic, Mid-Atlantic and West-Indian mid-oceanic ridges form the junction. The Bouvet volcanic island is located in the near vicinity of the last-named ridge. To the north of the island there is a zone of the Bouvet transform fault stretching at an angle of 45° and displacing the ridge by 150 km at 55° south south-east from the Bouvet fault which is named the Shpiss ridge.

To obtain comprehensive information of the mentioned area the joint Russian-Italian investigations have been carried out in 1994 from the Russian ship “Academic Nikolai Strakhov” (trip 18). The work program included magnetic and gravimetric studies in order to forecast the possible direction and velocity of plates spreading. Later studies have been conducted on the petrophysical properties of rock samples dredged out at several locations in the triple junction area. Part of the data is presented in the report; the data are tentative and contain mainly the information on the petrophysical properties of rock samples taken directly from the rift zones and away from them. It is the first attempt to assess the anisotropy of sampled rocks.

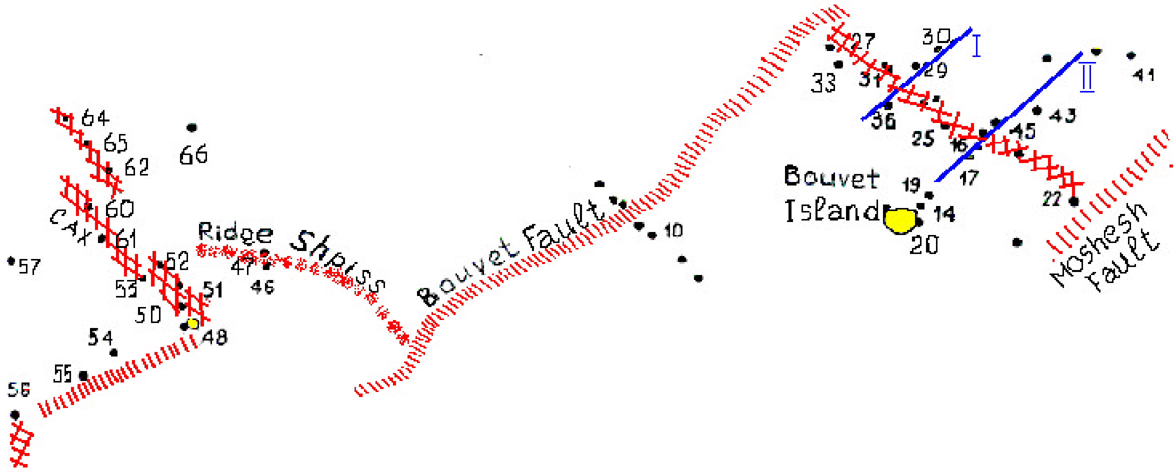

Figure 1. Scheme of dredging stations location: left - Triple point (junction) area, right - Bouvet island area.

2. Brief characteristics of the area of studies

The geological-geophysical studies in the said area have been performed mainly by American researchers (Sclater *et al*., 1976; Hays, 1991). The joint analysis of identified paleomagnetic anomalies and the ocean floor relief made it possible to draw a conclusion that the triple junction is of the fault-fault-ridge type and can be considered kinematically stable (Patriot, Coustillot, 1984; Nurnberg, Muller, 1991).

For the kinematic analysis the data of the best studied areas in the vicinity of the transform faults at 54°-56° South (Bouvet, Konrad and nameless faults on the Mid-Atlantic ridge) have been used. The velocities of spreading to both sides perpendicular to the axis of the ocean-floor spreading have been defined through the simulation of paleomagnetic anomalies in the internal of chrones of 0-2A. According to the analysis, the ocean-floor spreading at the Mid-Atlantic ridge is going on at an angle 65°±5° with the velocity being 0.8±0.1 cm/year. The building-up of the Mid-Atlantic ridge along its axis is going on with a velocity of 1.6 cm/year. The location of the triple junction at present is determined by the coordinates of latitude 54°50′ south and longitude 0°40′ west.

The petrographic studies have been performed on the samples taken at the depth of 750 m to 3300 m in three regions:

1. Directly in the area of the triple junction of the lithosphere plates, where within the rift zone of the Mid-Atlantic ridge there are three rift troughs: northern, central and southern (Peive *et al*., 1995);
2. The environs of the Bouvet island where dredging has been carried out as two crossings (I and II) of the rift zone;
3. The West-Indian ridge slope.

The data presented in the report refer to the first two areas (Fig. 1).

3. Applied methods

The petrographic properties have been defined using both the standard technique and new methods, including the description of rocks in microsections, the definition on density, water absorption, strength, magnetic susceptibility and of the velocity of longitudinal waves; the assessment of the anisotropy type and definition of the acoustic dichroism value. Since all the definitions of the properties, except for the anisotropy, are practically standard techniques, we will dwell briefly on the method of its study.

The anisotropy of rock samples is commonly studied using acoustopolarimetry (Gorbatsevich, 1995). For this very purpose the rock samples (1.5-4 cm test cubes) are placed between two linear-polarized converters of transverse waves - a radiator and a receiver. If then we start to rotate a sample around the axis of the wave propagation direction and record therewith the change of the amplitude of shear vibrations with polarization vectors coinciding (parallel vector - PV) and with vectors crossed (CV), one can observe the change of peak amplitudes. The above change is recorded and named the envelopes. The values of the peak amplitudes with parallel (A_{pvm}) and crossed (A_{cvm}) polarization vectors depend on the angle of rotation and phase difference. If an ideally isotropic sample is under study, then at PV one and the same amplitude is recorded and the envelopes configuration (acoustopolarigram) will be a circle; when CV - amplitude is equal to zero. Provided an anisotropic sample is under study and when being rotated the configuration of the envelopes (A_{cvm}) constitutes a symmetrical quadripetalous, hexapetalous etc. (depending on the phase difference) figure-rosette. The straight lines drawn through the minimum of such a figure determine the space position of axes and planes of symmetry of the anisotropic medium which the sample is made of.

It should be emphasized that neither the method of selection of the tested samples nor the samples themselves admit unfortunately no orientation whatever in the usual geological sense. The said fact in turn does not allow one to prepare the samples for tests in such a way that the sample axes follow the anticipated rock symmetry axes. Therefore the studies of anisotropy of the dredged-out rocks can be considered qualitative only as regards its detection. At the same time the acoustic dichroism quantity (linear anisotropic effect of absorption - LAEA) can serve as the quantitative characteristics of anisotropy degree, insofar as it depends upon the structural elements of rock, which is the polarizer for the passing shear waves bundle. The LAEA turns out to change to the most extent the configuration of acoustopolarigrams at the parallel polarization vectors. From the technological viewpoint the measurements are taken on the sample rotation every 10°.

The amplitudes of the shear waves are defined at PV and CV of the stationary converters in three mutually perpendicular directions. The amplitude value in decibel is recalculated into relative coefficients, which are used to build polarigrams (Fig. 2-3). Taking the acoustopolarigram as the base at PV the degree of acoustic dichroism D is defined, the acoustic dichroism being computed with regard to the values of the peak and minimum coefficients (A_{max1}, A_{max2}, A_{min1}, A_{min2},). The direction of the anisotropy axes and planes is determined from the CV diagram, provided the sample is oriented. It is impossible in the given report to present a more detailed description of all utilized methods, equipment and the obtained data processing technique; those who are interested may refer to the voluminous literature presented in the monograph (Gorbatsevich, 1995).

The analysis of 72 acoustopolarigrams of the samples dredged out in the area of the rift zones has shown that by the outline character they are analogous to those described for the volcanogeneous rocks of the Ural superdeep borehole (Gorbatsevich, 1995; Panasiyan *et al.*, 1983). All the studied basalt samples may be classified under three groups - with poor, pronounced and strong anisotropy.

4. Petrophysical properties of the studied rocks

The studied rocks and their properties differ greatly from each other even within the source area, that is why the characteristics of samples will be given in compliance with their mineralogic-petrographic peculiarities and with reference to the sampling area.

4.1. Samples from Triple Point Bouvet

Samples from this area (see Fig. 1) have been taken both from the rift of the southern and northern troughs and from their environs at depths below 2300 m.

The rift zone rocks are basalts. The texture of the groundmass is microdoleritic, almost totally crystalline with rare small sections of black glass. Plagioclase and olivine crystals are encountered in the form of phenocrysts; the basalts of the rift northern part contain 3 mm glomeroporphiric phenocrysts. The pyroxenes of the groundmass are found in the form of small skeleton structurized lath-like crystals, which are greater in amount than plagioclase. The rock contains many <0.05 mm crystals of titanomagnetite (prevailing) and ilmenite as well as thinnest (<0.01 mm) ore dust, which cannot be visually defined. There is a great amount of equally spaced isometric pores (mm fractions). These are young basalts not subjected to secondary transformations. They feature (see Table 1) high density (ρ) over 2.8 ton/m^3, small water absorption (w) up to 0.6% and values of velocities of elastic longitudinal waves (v_p) 5-5.3 km/s not typical for samples with such density, the said values on saturation increase as much as by 5-20%. The latter is likely connected with microfracturing (Ladygin, 1980) of rock or with microporosity. The uniaxial compression strength R is over 240 MPa. It has the highest value (among all studied samples) of magnetic susceptibility (χ) equal to (8.9-10)$\cdot 10^5$ SI units.

Table 1. Sample properties from the two areas.

	sample	depth	ρ	w	v_p	R	$\chi \cdot 10^{-5}$
cross	No	km	ton/m^3	%	m/s	MPa	SI unit
	Area Bouvet Triple Point						
	51-26r	2.3	2.80	0.5	5.3	240	8.9
	54-19	2.9	2.74	1.2	5.8	283	2
	55-24	3.3	2.83	0.6	6.6	206	0.6
	-43	3.3	2.82	0.6	6.1		0.5
	57-16	2.3	2.68	1.3	5.6	148	2.1
	63-6r	2.7	2.83	0.7	5	283	10
	Area Bouvet island						
I	29-54	2.6	2.72	1.3	5.3	246	1.5
	30-26r	2.8	2.65	0.9	5.2	162	9.1
	31-54r	2.9	2.64	1.1	4.8	238	2.9
	32-2	2.1	2.84	0.3	6.9	161	0.4
	32-11	2.1	2.79	0.8	6.2	265	35
II	16-33r	1.8	2.29	2.5	5.2	129	2.1
	-45r	1.8	2.15	3.6	4.8	76	2.5
	-48r	1.8	2.34	2.7	4.7	196	5.5
	-55r	1.8	2.28	2.2	4.6	144	5.3
	19-16	0.8	1.99	3.7	4.2	87	2.8
	21-6	2.7	2.38	3.8	5.3	173	2.1
	-10	2.7	2.39	3.8	5.3	178	2.2
	-19	2.7	2.39	4.4	5.2	152	3.4
	-21	2.7	2.38	4.4	5.1	119	1.9
	41-1	1.4	2.37	3.4	4.7	107	0.8

r - samples of the rift zone

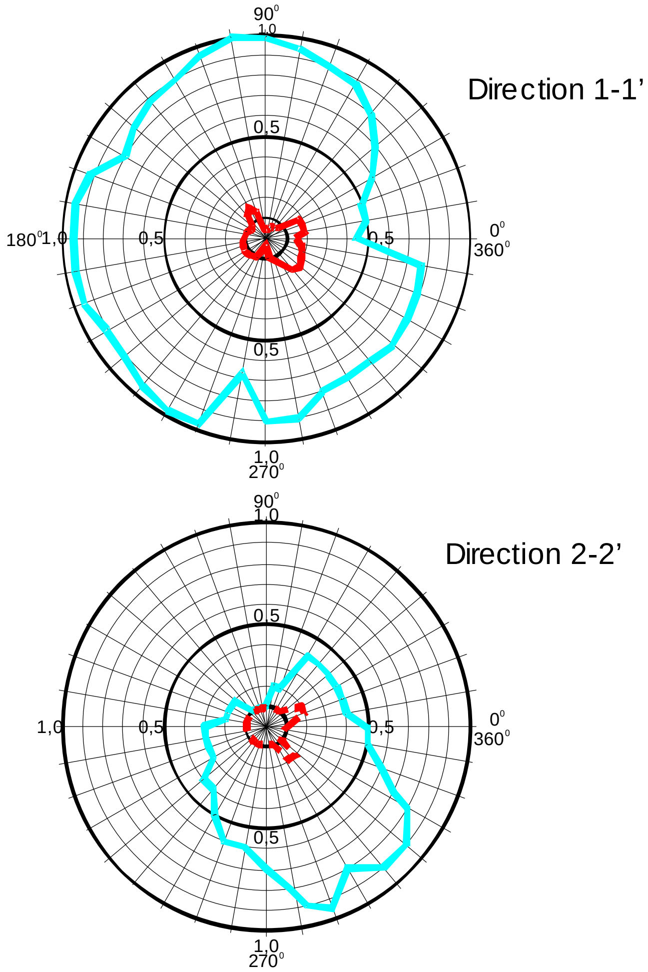

Figure 2. Typical acoustopolarigrams of isotropic sample 63-6: blue line - diagram PV, red line - diagram CV.

The young basalts from the northern and southern rifts have the similar acoustopolarigrams (Fig. 2). A relatively small size of petals at CV compared to those in the PV diagram and their configuration attest that rocks appear to be practically isotropic or have a certain transition form towards the anisotropic ones. That can also be associated with a circumstance that in one of three directions there is a very strong effect of absorption. The acoustic dichroism value in the samples averaging 0.15 and not more may reach 0.69 in one of the directions. The CV polarigrams therewith remain feebly masked. The anisotropy absence or its weak manifestation is likely associated with the rock youth.

Samples dredged out in the neighbourhood of the southern part of the rift zone are also composed of the porphyritic basaltic with pyroxene phenocrysts, the groundmass texture is ophitic. Visually, the basalts are dark grey, with no visible pores and traces of secondary transformations, yet one can see in microsections a greet amount of round chlorite filled pores to 0.5 mm in size. As a result of the secondary transformation of the rock, some sections of glass have decomposed and are replaced by chlorite; there is saussuritization over plagioclases which has affected olivines and pyroxenes. There are prenite filled joints in the rock. The absence of ore minerals results in a lower χ value. The density and velocity of longitudinal waves are high ρ > 2.85 ton/m^3, v_p > 6.0 km/s, except for sample 54-19 (Fig. 3). Porosity, apart from small pores under 1 mm in size, are scattered through the whole rock and the pore concentrations which probably is the cause of some reduction of ρ to 2.74 ton/m^3 and v_p to 5.8 km/s.

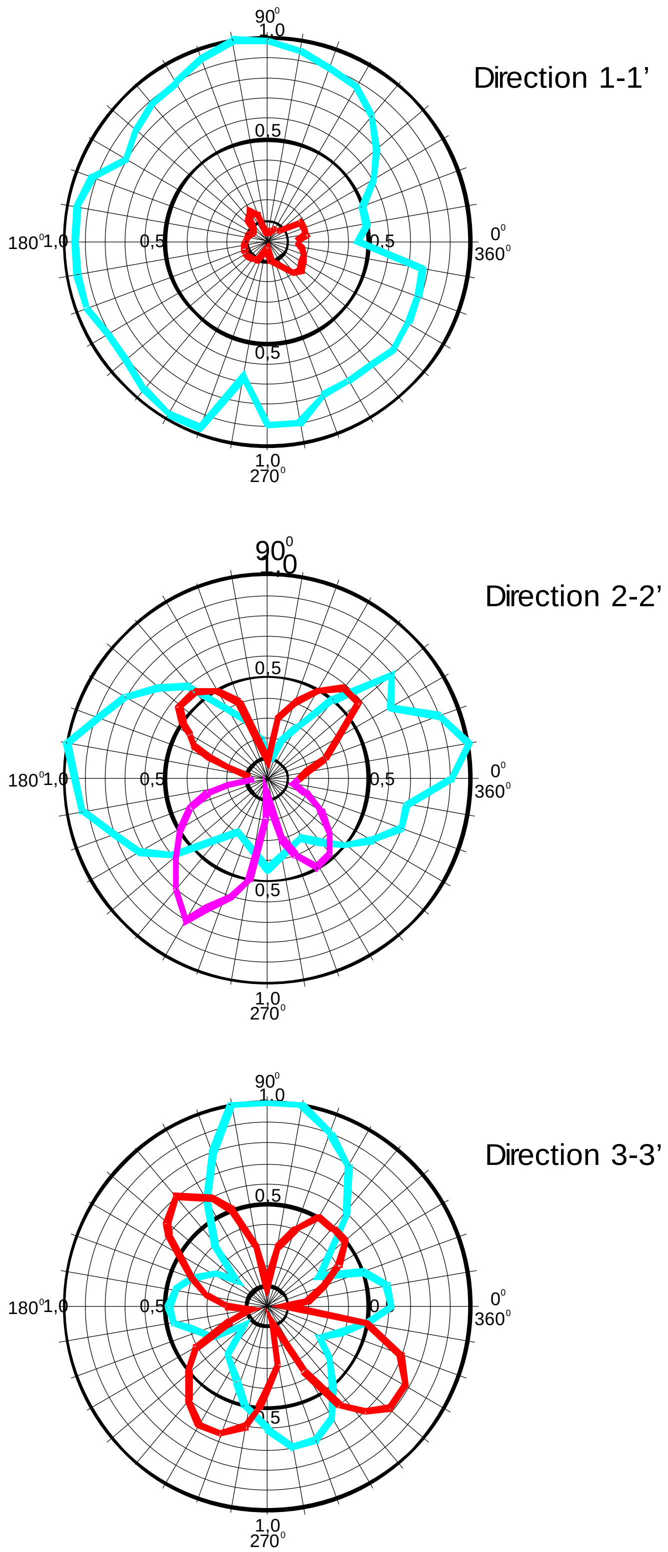

Figure 3. Typical acoustopolarigrams of the anisotropic sample 54-19: blue line - diagram PV, red line - diagram CV

Samples taken in the triple point area near the southern transform fault and to the west of the central one feature a pronounced strong anisotropy. The said basalts may be referred to the transversal anisotropic media. Typical for them and similar by the outline to the theoretical ones are acoustopolarigrams displayed in Fig. 3. Here, in one of the directions the "rosette CV" is hardly distinct, while in he other two directions it has well-defined symmetrical petals. What is more, in directions 2-2′ and 3-3′ the LAEA shows up and the value D in such samples in the like directions equals 0.35-0.45. The said effect appears to be dictated by the ordered micropores and microfractures, which orientation in microsection is hardly visible. Besides, the basalts have already undergone the hardening stage and have probably experienced great stresses in the spreading zone, what has entailed the formation of anisotropy.

4.2. The northern crossing (I) of the Bouvet Island area

This area (see Fig. 1) has been characterized by samples taken on the west and east sides of the rift zone and its surroundings.

The basalts from the rift zone are grey and dark grey, with rarely scattered 1-2 mm round pores. The groundmass of the rock has a doleritic and microdoleritic texture with section of noncrystallized black glass, what is often confined to pores. Rare phenocrysts are composed of plagioclase and more seldom of olivine up to 1 mm in size. Despite the proximity of taking the basalt samples from the opposite rift sides, the basalt differ from each other by the size of the groundmass crystals and the secondary transformation degree. So, on the eastern rift side the plagioclase and pyroxene crystals are greater in size and reach respectively 0.6 mm and 0.15 mm, while on the west side - they are half as much.

In the eastern basalts the pores are intensively filled with chlorite. The small pores are almost completely filled while in the large pores the chlorite covers the inner pore sides and the central pore part is hollow. In the western side rocks there are practically no secondary transformations. The basalts from the eastern rift side have undergone rather great stresses what is indicated by curved pyroxene crystals with undulating extinction, having specific ruptures the rocks are characterized by similar densities (2.64 ton/m^3) and water absorption (1%), but they differ as to velocity of elastic waves, the value of magnetic susceptibility and strength. The largest strength is characteristic for the unchanged fine-crystalline variety from the western rift and it is as much as 238 MPa; on the eastern rift side it is 162 MPa; v_p increases by 0.5 km/s in chloritized varieties of the eastern rift.

Basalts from the eastern surroundings as well as from the rift zone have the same texture but contain a great amount (up to 40%) of large 2-6 mm plagioclase phenocrysts with chlorite also intensively spread and filling the pores. A little bit greater compared to the above rift rocks is the density - up to 2.72 ton/m^3 and v_p - to 5.35 km/s, the strength equalling 220 MPa. The rocks contain a great many often skeleton crystals of titanomagnetite and ilmenite, which are almost completely replaced by sphene and rutile, that is why the magnetic susceptibility of the said basalts is not great, $1.5 \cdot 10^{-5}$ SI units.

Completely different rocks have been sampled in the western neighbourhood of the rift. They are solid andesite - basalt fine-crystalline porphirites with rare 2 mm plagioclase phenocrysts. The groundmass of rocks is formed of plagioclase microlites and 0.15 mm actinolite crystals. Actinolite is prevalent (up to 70-80%) and encountered in two varieties. One is developing over pyroxenes preserving their form; the other is apparently predominant and develops over glass thus taking the "panicular" form.

At the same sampling place there occur mid-crystalline varieties of porphirite, which apart from amphibole contains up to 20% of ferruginous chlorite developing over glass, epidote and prenite in veinlets, many large o.5 mm secretions of are minerals. The latter has caused the highest value χ equal to $35 \cdot 10^5$ SI units. In general, the rocks from the western environs of the rift (crossing I) possess the highest values of longitudinal waves over 6 km/s as compared to all studied samples; the mid-crystalline varieties feature high strength parameters, 265 MPa, the average density being 2.72 ton/m^3

All the samples taken in the northern crossing (I) of the rift zone of the Bouvet Island display transversal anisotropy and high effect of absorption. The acoustopolarigrams close to the theoretical ones at PV have a form of ovals and at CV - that of symmetrical quadripetolous rosettes (Fig. 2b) degraded sometimes. The PV amplitude maximum values countervail to the minimum CV ones. In the directions where on passing of an elastic shear wave the rocks show strong anisotropic properties, the dichroism value reaches 0.35-0.6. The maximum value has been discovered in the samples with deformed crystals. Alterations in all three directions being considered, for the eastern part of the above crossing (including the rift and its surroundings) the average D values appear to be greater and reach as much as 0.3 while for the western part they do not exceed 0.2. An exception is a sample taken on the western rift side. Its rocks are unaltered fine-crystalline can be considered poor in two directions and pronounced in the third one; the dichroism 0.1-0.17 reads that the rock is rather homogeneous.

4.3. The southern crossing (II) of the Bouvet Island area

This crossing passes opposite the Bouvet Island in the northeastern direction. Eastwards, far from the rift samples have been taken of dark-grey basalts with porphiric texture with large 2-4 mm plagioclase and olivine phenocrysts, often forming glomeropophiric aggregations submerged into black noncrystallized glass. The basalts contain a lot of small 1 mm pores, have increased absorption quantities (3.4%) what is indicative of good rock permeability and exhibit a small density - 2.37 ton/m^3 and average v_p and R values equal respectively to 4.75 km/s and 107 MPa. The rock anisotropy is very poor and the great porosity would not allow one to define the direction of the best passing.

In the rift itself black basalts of porphiric texture are widespread; the phenocrysts contain 2-3 mm plagioclase, 0.5 mm olivine and very rarely pyroxene. The groundmass is of hyaline texture in which all structural transformations of rock are present: totally hyalopilitic texture, then incipience of skeleton structurized rather elongated thin crystals of pyroxene and more rarely plagioclase; the letter more and more fills the rock space thus displacing the black glass, which is predominant in the said samples and forms the variolitic-hyaline texture (Polovinkina, 1966). The rock crystallization even throughout one micro section is irregular.

A characteristic feature of the basalts is porosity. The pores are spaced unevenly, forming sometimes accumulations and such a section becomes slaggy (sample 16-45). As a whole, based on the pore size one can single out 2-3 levels coinciding with the size of crystals composing the rock: the first level - mm and the others - one and two orders less. Owing to the porous texture the rocks have a small density 2.15-2.34 ton/m^3, low values equal v_p and R but rather high water absorption (to 3.6%).

The basalt samples taken midway between the rift and Bouvet island when observed with microscope do not practically differ from the said ones, but they contain a greater amount of pores, due to what their density drops down to 1.99 ton/m^3 and the rest physical and mechanical properties are lower as well.

Somewhat aside from the considered crossing in the proximity to the Moshesh fault samples of black porous basalts have been taken. The pores are diverse, from a mm fraction to 9 mm with ragged edges; they are irregularly spaced through the rock volume and less in number than in the rift basalts which affect the density. From the petrographic viewpoint the basalts are similar to the rift rocks. Some samples contain much chlorite, which fills the pores and partially substitutes the glass. Over the glass there developed a thin structurized aggregate of poorly crystallized elongated microlite, pyroxene and plagioclase. The rocks are strong, with average values of density and magnetic susceptibility.

The peculiarity of all studied samples taken from the crossing II of the island area beyond the rift is that they belong to poorly anisotropic rocks. The anisotropy type is probably transversal. To ascertain this fact is very difficult since there is no agreement between the direction of faces and orientation of set-up anisotropy axes. A characteristic of them are the diagrams close to a circle at the parallel vectors they are small with weakly outlined amplitude minimum values (Fig. 2). The acoustic dichroism does not exceed 0.15. The samples taken from the rift zone and not far from the Moshesh fault show marked anisotropy, which is recorded at passing of a shear wave in three directions. The acoustopolarigrams (PV) removed about the centre, multipetalous rosettes (CV) with distinct minimum and maximum amplitude values and increasing of the acoustic dichroism to 0.33 in separate directions betoken a great heterogeneity of basalts what is associated with irregular distribution of pores and their filling.

5. Discussion and conclusion

The preliminary results on the petrophysical properties of basalts, which have been formed in the areas with various tectonic structures, differ greatly. In doing so the most tangible differences are revealed when one is considering the properties of rocks dredged out from the rift or its environs.

By and large the basalts are young formations having either holocrystalling or hyalopilitic texture and in that very case they contain much glass. The last peculiarity is met, apart from the rift zone, also in the areas at some distance away at small depths. The said fact may be indicative of separate volcanic edifices not connected directly with the rifts but where intensive volcanic processes take place causing the formation of like basalts. The basalts of the triple junction (point) are more dense and stronger as compared to those of the Bouvet Island area. The intensive secondary transformations even in the closely located rocks, high chloritization, saussuritization, filling of pore space with secondary minerals etc. brings about the fact that effusive rocks acquire other petrophysical properties that points to the existence of increased temperature zones in the rift valleys. An example of that are changes in the samples from the rift of the northern crossing in the Bouvet Island area. The ocean depth in the area of melt chilling has a perceptible effect on the basalt porosity. Especially it is noticeable on the example of the Bouvet Island rift zone. The less the ocean depth, the greater the porosity (the less the density).

The magnetic susceptibility of the basalts in the rift zones appear to exceed greatly the χ of the volcanites occurring outside the said zones, what is primarily related to secondary transformations of titanomagnetite and ilmenite. In this connection we believe that when making different scientific hypotheses based on the magnetic susceptibility quantities one should be very careful and give due consideration for the secondary transformations of ore minerals.

The impossibility of obtaining oriented samples greatly lessens the body of information of the anisotropy study. The general tendency to the anisotropy change is as follows. The poorly anisotropic rocks are young basalts of the rifts and outside them, what has been recorded in the triple junction area and away from the rift in the Bouvet island crossing II area, where there exist separate volcanic edifices as mentioned before. In that case the anisotropy has not probably got formed yet. In all other cases rocks are anisotropic and the said property shows up even in rocks with considerable secondary transformations. Any small displacement aside from the rift or the transform fault brings about the appearance of anisotropy with low acoustic dichroism. Strong anisotropy has been revealed in the samples taken in the triple junction area outside the rifts what is likely associated with stresses the rocks have endured in the spreading zone and with fissures, which have appeared therewith. An illustration for that may by the formation of the transversal anisotropy with high acoustic dichroism in one of the directions.

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