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GEOLOGY

Relationships between Basalts and Carbonate Sediments in the Mid-Atlantic Ridge (13°–20° N)

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The marine geological investigations conducted in cruises of the R/V *Professor Logachev* operated by the Polar Marine Geological Research Expedition (St. Petersburg) in 2008–2012 in the Mid-Atlantic Ridge area (13°–20° N) culminated in the discovery of new ore fields: Semenov 1–Semenov 5, Irinovskoe, Peterburgskoe, Zenit-Viktoriya, Yubileinoe, and Syurpriz. They are mostly confined to walls of the rift valley or less commonly localized beyond its limits: for example, the Peterburgskoe ore field is located in the second rift ridge. The ore fields are associated with basalts (Peterburgskoe, Zenit-Viktoriya, Yubileinoe, Syurpriz) or peridotites (Semenov 1–Semenov 5, Irinovskoe). Basalts and peridotites are overlain by Late Pleistocene–Holocene biogenic carbonate sediments. They are represented by foraminiferal and nannofossil–foraminiferal oozes with the $CaCO_3$ content exceeding 50% and from several centimeters to 2 to (locally) 3 m thick. According to [1, 2], in the present-day Atlantic Ocean, carbonate sediments cover 67% of the oceanic bottom.

Our observation revealed that all the above-mentioned ore fields are characterized by the presence of basalts, which demonstrate "hot" contact with unconsolidated biogenic carbonate sediments. In addition, it is established that the ore bodies in these ore fields were formed both at the bottom surface and within the sedimentary sequence [3–6].

The presence of young basalts in rift valleys filled with unconsolidated carbonate sediments was also documented by previous investigations [7–9]. At the same time the contact between basalts and sediments was never described in these works. The "hot" contact between basalts and carbonate sediments in the Mid-Atlantic Ridge (MAR) was first recorded in samples from the Semenov ore cluster and Peterburgskoe field [4, 10, 11].

The samples obtained by dredges and a TV-grab sampler in the above-mentioned hydrothermal fields of the Mid-Atlantic Ridge during cruises of the R/V *Professor Logachev* served as material for this investigation. In these samples, the structural and textural features of exo- and endocontact zones were studied with analysis of their chemical and mineral compositions.

The textural relationships between basalts and carbonate sediments were analyzed immediately onboard in samples both visually and under the microscope. The detailed examination of newly formed minerals and their diagnostics were conducted under optical and electron microscopes. The following equipment was used: BS-350, VIMS; Cam Scan MV 2300 with the energy dispersion microanalyzer INCA Energy 300, VSEGEI; Vega-3 with the analyzer INCA, IO RAN; X-ray spectral microanalyzer JXA-8100 with the energy dispersion device INCA, VIMS; diffractometric system D/max-RC, Closed Joint-Stock Company *Mikrozond*.

Three types of contacts between basalts and carbonate sediments are definable.

The contact of the first type is characteristic of basalts cooled within unconsolidated carbonate sediments. The rock fragments taken from the contact zone are usually inappropriate for estimating both the sizes and shapes of bodies. Only some of them characterized intact basaltic bodies (laccoliths) shaped like a flower bud approximately 70 cm high (Station 33-l-173) or a pancake approximately 60 cm across (Station 33-l-124).

Basalts from the contact zone of the first type (basalt I) demonstrate two peculiar features. First, they are characterized by development of a crust composed of lithified sediments from a few millimeters to a few centimeters thick at their surfaces. The lithified sediments demonstrate baking and a decrease in porosity immediately near the contact but increase in porosity away from the latter. Second, they have a transitional zone of hybrid rocks from a few millime-

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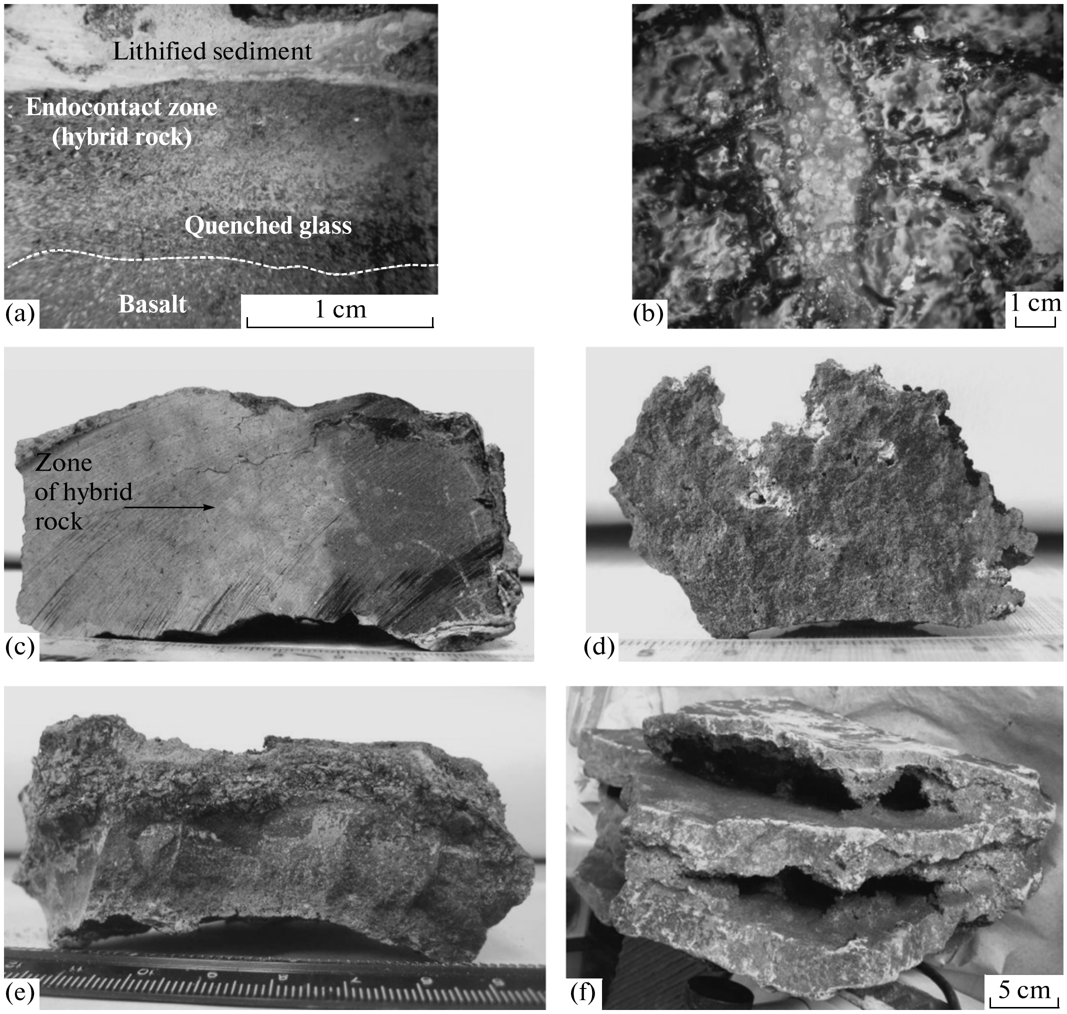

Fig. 1. Basalts characterizing different types of contacts. (a) Tonality in basalts of the first type (basalt I); (b) enlarged fragment of hybrid rock with the reticular texture and relicts of planktonic foraminiferal tests (microimage); (c) basalt I with the zone of hybrid rocks resulting from the metasomatic replacement of the sediment xenoliths; (d) basalt II with "corroded" edges, thin crust of lithified sediments, and sediment xenoliths; (e) basalt III representing microsill with two hot endocontacts with sediments; (f) three-layer microsill.

ters to a few centimeters thick and characterized by a peculiar reticular texture. This zone and basalts are separated by a thin (up to 0.5 cm) crust of quenched glass. Thus, all the samples demonstrate well-developed tonality reflected in the following succession: basalt–glass–hybrid rocks with a reticular texture–lithified carbonate sediment (Fig. 1a). In addition, one of the pancake-shaped laccoliths encloses two xenoliths of lithified carbonate sediments, which are connected by a fissure tenths of a millimeter thick filled with crystalline–granular calcite.

According to electron microscopy, lithificates in the exocontact zone contain up to 60% of SiO_2 and 30% of Al_2O_3 in addition to CaO, which may be explained by the metasomatic replacement of carbonates by the alumosilicate material. The exozcontact zone contains also single euhedral and skeletal plagioclase and olivine phenocrysts.

The remains of some microorganisms constituting sediments are replaced by aluminosilicates (54% of SiO_2, 31% of Al_2O_3, and only 7% of CaO). At the same time, the sediments contain preserved foraminiferal tests with a fine (bacterial?) disseminated native iron. The content of the calcite component and the total share of microfossils increase in lithified sediments away from the contact, while the content of Si and Al decreases in the same direction.

The exocontact zone also includes different lithificates in addition to their carbonate varieties. They are represented by more intensely altered sediments barren of foraminiferal tests and replaced by beige and bluish thin-platy crystals up to 0.1 mm in size. According to the X-ray phase analysis, these newly formed minerals are represented by forsterite, kyanite, phillipsite, aegirine, and hauyne. They include also cryptocrystalline glassy veinlets of goethite (confirmed by X-ray

The petrochemical composition of clay material filling cells in hybrid rocks from the transitional zone

Al_2O_3	SiO_2	SO_3	ClO_2	K_2O	CaO	TiO_2	MnO	Fe_2O_3	NiO	CuO	P_2O_5	Cr_2O_3	MgO
22	29.3	2.06	2.61	1.65	2.37	2.90	1.21	28.88	1.68	1.35	4		
20.1	19.9	1.52	1.87	1.94	3.13	3.27	1.98	34.09	3.66	6.07	2.43		
36	34	1.85	2.18	1.30	1.90	2.01	0.70	15.56				0.52	3.91

analysis) with the Al_2O_3 content reaching 40%. Such a high concentration of Al is probably explained by kyante microinclusions in goethite veinlets. In many analyzed points, noncarbonate lithificates are characterized by the elevated P and K contents amounting to several percent. These lithificates are also characterized by microadmixtures of Cu and Ni with concentrations up to a few percent, which likely indicate the contribution of pneumatolithic–hydrothermal processes to their formation.

The transitional zone is represented by a hybrid rock consisting of quenched glass, which forms a fine (tenths of a millimeter) network, and clayey material filling cells. Locally, the rock retains relicts of foraminiferal tests (Fig. 1b). According to the electron microprobe analysis, the hybrid rocks of the exocontact zone demonstrate an elevated content of Cl amounting to 2%. It was shown that elevated concentrations of this element are characteristic of melts that were crystallized at the shallowest depths [12]. The electron microprobe analysis of quenched glass constituting the walls of the cells revealed its heterogeneous composition. In the SiO_2–(Na_2O+K_2O) diagram [13], some data points correspond to ultramafic picrite basalts with elevated CaO contents amounting to 16%; others belong to alkaline picrites. Moreover, glass retains the biogenic microtexture inherited from the replaced sediments. It encloses small titanomagnetite inclusions and chrome spinel octahedrons. The clayey material that fills the cells demonstrates a specific petrochemical composition (table). The main elements constituting this clay are represented by Fe, Al, and Si.

Thus, it may be stated that the petrochemical composition of hybrid rocks developed at the contact between carbonate rocks and basalts does not correspond to particular igneous or sedimentary rocks. Their formation is most likely explained by the interaction between a hot magmatic melt with cold watered carbonate sediments. In the exocontact zone, quenched glass is subjected to fracturing with the formation of fissures, which become filled by liquid sediments subsequently transformed into hybrid rocks.

According to electron microscopic investigations, quenched glass in the contact zone is highly variable in its composition. In the SiO_2–(Na_2O+K_2O) diagram, data points located only 500 μm away from each other fall into fields of alkaline picrites, basic picrite basalts, or ultramafic picrite basalts. In the transmitted light, this glass is recognized as rounded and oval dark brown spots up to 0.1 mm across. They are characterized by an elevated CaO concentration (up to 16%), which could result from the capture of carbonate sediment by glass.

Some basalt samples demonstrate the presence of light areas several centimeters away from the contact zone that are close in coloration to carbonate sediments (Fig. 1c). These areas are characterized by a variolitic texture and heterogeneous compositions, which correspond in the SiO_2–(Na_2O + K_2O) diagram to ultramafic picrite basalts and alkaline picrites. In addition, one of the points analyzed yielded a composition that appeared to be beyond the field of igneous rocks in this diagram. Thus, it may be assumed that these areas represent metasomatically transformed xenoliths of carbonate sediments.

Approximately 5 cm away from the contact of ordinarily colored basalts with sediments, they exhibit fissures filled with zeolite containing relicts of foraminifers with preserved calcite tests (Figs. 2a, 2b). The electron microprobe analysis at some points of samples revealed a composition corresponding to ultramafic picrite basalts and even located beyond the field of igneous rocks in the SiO_2–(Na_2O + K_2O) diagram. In addition, basalts of this type are characterized by an elevated Ti concentration owing to titanomagnetite aggregates that developed along contacts between pyroxene and plagioclase grains.

The contact of the second types are observed between basalts intruded into sediments or erupted onto unconsolidated biogenic carbonate sediments on the walls of volcanic edifices.

The volcano edifices with magma flows on their walls are readily recognizable in bottom photographs obtained by the side scanner (Fig. 3). The fragments of such basalts (basalt II) are characterized by uneven "corroded" edges, abundant xenoliths of sediments, and partly preserved thin (up to 1 cm) crusts of lithified sediments (Figs. 1d, 2c). Moreover, at their contact with sediments, basalts frequently exhibit a bleached zone up to a few millimeters to a few centimeters thick particularly well observable in thin sections and, less commonly, visually in samples. The xenoliths contain well-preserved foraminiferal tests frequently with their calcite envelope (Fig. 2d). At the same time, the electron microscope investigation revealed that calcite of foraminiferal shells may contain Si, Fe, and Al microadmixtures indicating their metosomatic replacement. The inner part of foraminiferal tests is usually filled with clay minerals and zeolites.

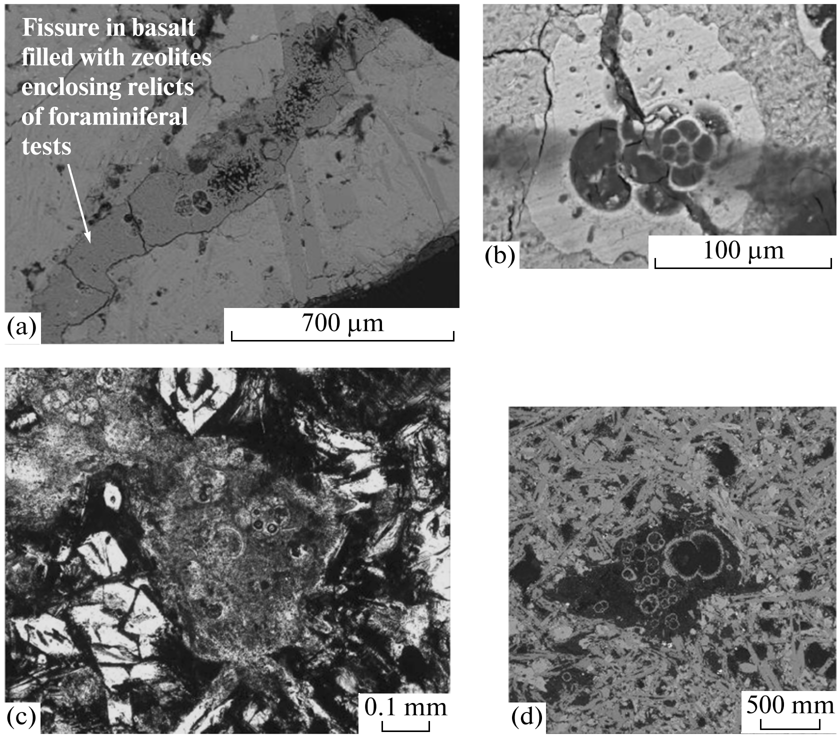

Fig. 2. Photographs of transparent polished thin sections with relicts of foraminiferal tests. (a) electron microscope image of the sample area powdered with coal. Fissure in basalt I filled with zeolites enclosing relicts of foraminiferal tests; (b) enlarged fragment illustrating a well-preserved planktonic foraminiferal test presumably belonging to the genus *Globorotalia*; (c) fragment of lithified sediments filling a pocket in basalt II (petrographic microscope), parallel nicols; (d) electron image of the sample area powdered with coal. Xenolith of sediment in basalt II.

The lithificates from the exocontact zone that are retained at external edges of basalt II fragments are represented by carbonate material that practically avoided metasomatosis and contains relicts of calcite foraminiferal tests. This provides grounds for the assumption that the sediments were overlain by cooled magma.

The exocontact zone of basalts contains relicts of foraminiferal tests as well, although they are partly replaced by silicate material. There are also foraminiferal tests replaced by magnetite and tests with partly preserved calcite composition.

Like basalts of the first type, basalts II are characterized by elevated Ti concentrations due to development of titanomagnetite aggregates along the contacts between pyroxene and plagioclase grains. Titanomagnetite is usually represented by skeletal cruciform crystals hundredths of a millimeter in size disseminated in fact around all the plagioclase and pyroxene grains.

Basalts II also contain phlogopite, which represents a typical contact metasomatic mineral alien to oceanic basalts.

The contact of the third type is characteristic of microsills, which intruded sediments in the form of thin flows and demonstrate two hot contacts with sediments (basalt III). Like in basalt I, hot contacts are

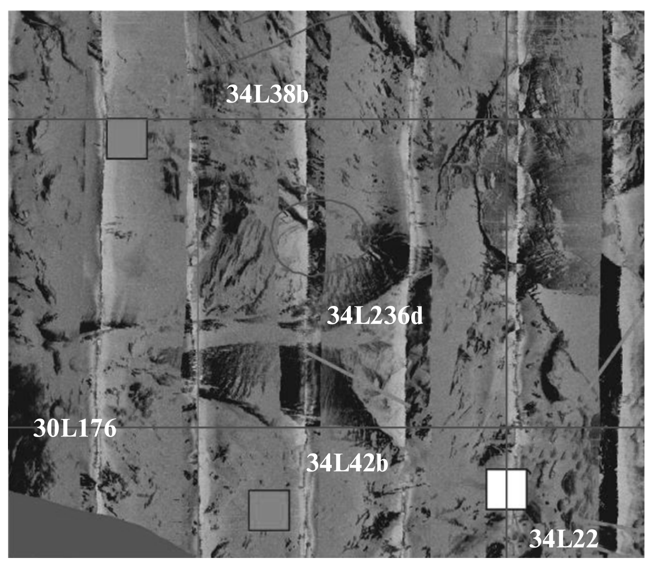

Fig. 3. Image of the bottom obtained by the side-scanner equipment in Cruise 34 of the R/V *Professor Logachev*. The central part of the image is occupied by the volcanic cone with cooled magma flows. Squares designate stations of sediments sampling by the box corer; bars show dredging intervals. Numerals designate numbers of cruises and stations. Letter designations: (l) R/V *Professor Logachev* (placed between cruise and sampling station numbers), (b) box corer; (d) dredge.

represented by a zone with a reticular texture. Some sills demonstrate two- or three-layer structures with lithified sediments and a zone enriched with captured and metasomatically altered carbonate sediments between individual flows (Figs. 1e, 1f). Similar to basalts I and II, these rocks are characterized by elevated Ti concentrations.

Basalts intruded immediately into sediments are recorded both within ore fields and beyond their limits. In areas where they are documented beyond ore fields, host sediments contain minerals indicating hydrothermal activity such as pyrite and chalcopyrite, which implies relations between young volcanism and hydrothermal mineralization. The formation of a specific hydrothermal ore-forming system related to intrusion of the basaltic melt into bottom sediments was assumed in [14], the authors of which investigated modern hydrothermal activity in the Gulf of California.

Basalts of all the above-mentioned types are formed away from the spreading axis in the rift valley and beyond its limits. They are always characterized by elevated Ti concentrations.

Thus, the presented data on exo- and endocontact alterations of rocks and on xenoliths of carbonate sediments in basalts allow the conclusion that they represent young flows, which have broken through the older oceanic basaltic crust and intruded into Upper Pleistocene–Holocene carbonate biogenic sediments.

It has been established that the alkalinity of basalts in exocontact zones increases in response to their contamination with carbonate sediments.

The wide distribution of such basalts in ore fields and the presence of minerals indicating hydrothermal activity in host sediments beyond ore fields confirm the ideas in [14] that young volcanism triggers ore formation and, thus, may serve as an indirect diagnostic feature for discovery of additional ore fields.

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