ISSN 0869-5938, Stratigraphy and Geological Correlation, 2018, Vol. 26, No. 1, pp. 109–120. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © T.A. Khusid, N.S. Os'kina, N.P. Lukashina, I.F. Gablina, N.V. Libina, A.G. Matul, 2018, published in Stratigrafiya, Geologicheskaya Korrelyatsiya, 2018, Vol. 26, No. 1, pp. 115–126.

Benthic and Plankton Foraminifers in Hydrothermally Active Zones of the Mid-Atlantic Ridge (MAR)

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Received September 4, 2016; in final form, September 26, 2016

Abstract—Comparison of benthic foraminiferal assemblages from the core obtained within the Peterburgskoe ore field (Mid-Atlantic Ridge) and from the core taken five kilometers away from the ore field revealed evident differences in their composition, in the appearance of their shells, and also in the benthic–plankton species ratio. It was noted that the foraminiferal assemblage from the ore-bearing sediments of the Petersburg field was characterized by a higher relative content of benthic species and a large number of chemically altered and broken shells. The first occurrence of the species *Osangularia umbonifera*, which is able to exist in low-oxygen and $CaCO_3$-undersaturated bottom waters at the boundary of biogenic sediments surrounding the ore field and in the ore-bearing sediments, was established. In the core section sampled beyond the ore field, the composition of foraminiferal assemblages differs insignificantly from typical oceanic ones.

Keywords: Benthic and planktonic foraminifers, hydrothermal processes, Peterburgskoe ore field, Mid-Atlantic Ridge

DOI: 10.1134/S0869593817060041

INTRODUCTION

Benthic foraminifers are widely distributed in bottom sediments on the ocean floor. They are diverse, are well preserved in bottom sediments, and live in different climatic zones at different depths. The study of foraminiferal assemblages makes it possible to determine changes in the level of the World Ocean, the circulation of water masses, the areas of their distribution, and properties. Benthic foraminifers are more diverse than planktonic, but their amount is much less in deep-water sediments. According to calculations, the ratio of benthic and planktonic foraminifers in sediments is 1 : 4, which is determined by the different biological productivity and the preservation of their shells (Murray, 1976). The distribution of benthic foraminifers in the Atlantic Ocean has been described in a large number of articles, beginning with the works of Kushman et al. (Cushman and Parker, 1931; Cushman and Henbest, 1940).

However, the first detailed studies in the hydrothermally active regions of the Mid-Atlantic Ridge were carried out only in the 1990s (Lukashina and Lisitsyn, 1990; Lukashina, 1991; Gablina et al., 2010, 2015; Os'kina et al., 2013). As a result of these studies, a significant influence of hydrothermal processes on the species composition of benthic foraminifers and on the preservation of calcareous planktonic organisms was revealed. It was found that, during the burial of calcareous organisms in the ore-bearing sediments during the Holocene and the Upper Pleistocene, acid solutions had a negative effect on the preservation of these organisms, especially on the shells of planktonic foraminifers. Under the influence of hydrothermal fluids, foraminiferal shells accumulate heavy metals, which results in the formation of Fe–Mg crusts on shells, dissolution, and metasomatic replacement of biogenic calcite with various hydrothermal minerals, including ore ones. Moreover, changes in the composition and structure of foraminiferal skeletons occur up to their complete alteration and disappearance.

There is no doubt that the study of modern microfauna inhabiting hydrothermally active regions of mid-oceanic ridges under extreme chemical and thermal conditions is an important task. This work continues research in this direction and aims to study the distribution of benthic foraminifers and their preservation in modern and Pleistocene biogenic sediments in the core sampled within the Peterburgskoe hydrothermal ore field and in biogenic sediments of the same age in the core sampled at a distance of five kilometers from the field and compare the data obtained with those from other areas of the Atlantic Ocean.

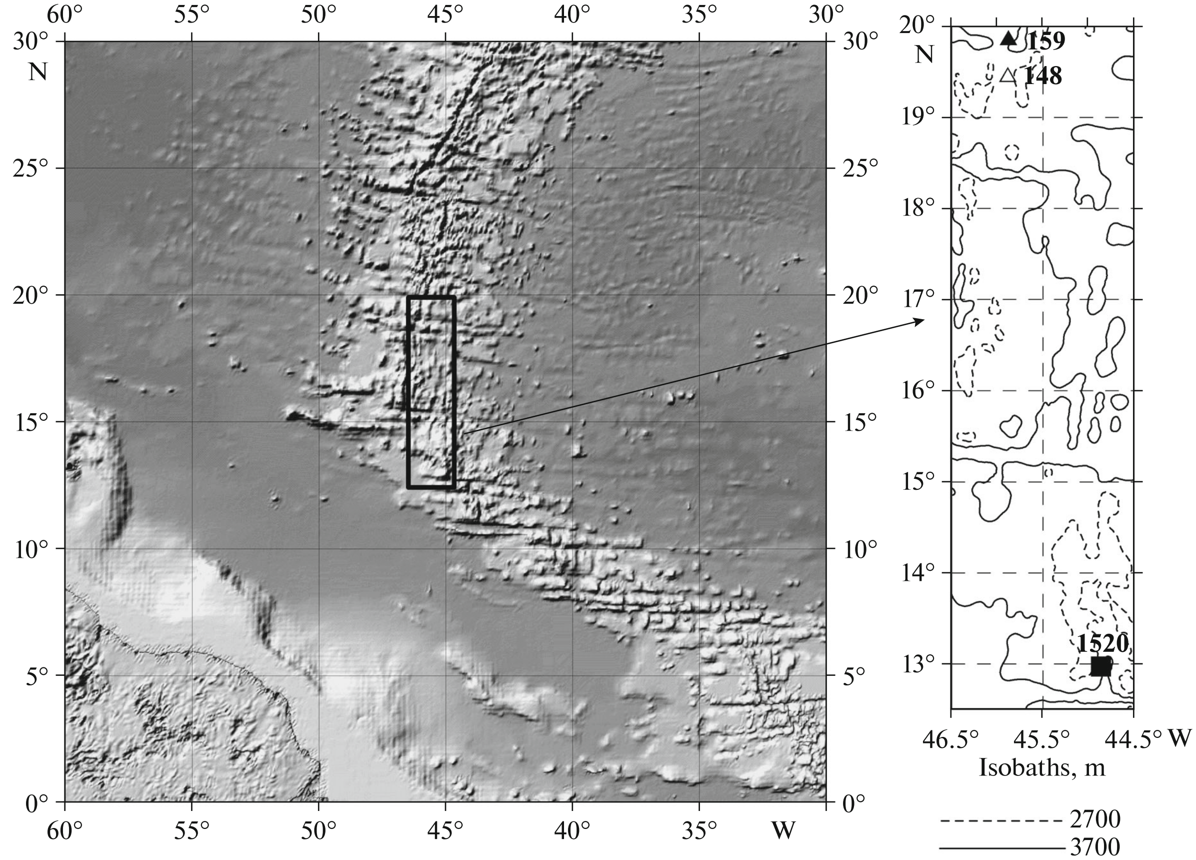

Fig. 1. Location of the Peterburgskoe ore field (station 33L159), station 33L148, and the Ashadze ore field within the studied area of the Mid-Atlantic Ridge. Legend: black triangle—Peterburgskoe hydrothermal ore field (station 33L159), white triangle—station 33L148, black square—Ashadze hydrothermal ore field.

MATERIAL AND METHODS

Complexes of benthic foraminifers and lithological and mineral composition of sediments have been studied in two cores sampled during the 33rd cruise of the R/V *Professor Logachev* in the North Atlantic in 2010 (Fig. 1). The study area is located in the tropical area of the Mid-Atlantic Ridge between 19° and 20° N. This area is located in an oligotrophic, nutrient-poor region of the Atlantic Ocean within the anticyclonic circulation, where an extremely low level of bioproductivity in surface waters is noted (Dubravin, 2001). The core sampling sites are washed by North Atlantic cold and salty deep water with a large amount of dissolved oxygen (Stepanov, 1983; Neshiba, 1991).

The 34-cm core 33L159 was sampled by a TV grab sampler at a depth of 2960 m. The sampling site (19°52′ N, 45°52′ W) is located in the rift valley of the Mid-Atlantic Ridge within the Peterburgskoe hydrothermal field, composed of iron-copper sulfide ores and ore-bearing metalliferous and carbonate biogenic sediments. The field is located at the flattened foot of the western slope of the rift valley at the border with a large not transform fault. The ore field is surrounded by carbonate sediments with a visible thickness of up to 150 cm, consisting of pteropodic, foraminifer, coccolith–foraminifer, and foraminifer–coccolith oozes and sands, with edaphogenic material at the base. Sediments overlie hydrothermally altered basalts.

The second core 33L148 was sampled at a depth of 2623 m beyond the Peterburgskoe field, 5 km to the south (19°28′ N, 45°53′ W). It was sampled by a box corer from unaltered (background) biogenic carbonate sediments. The thickness of this core (150 cm) is five times larger than the core sampled within the Peterburgskoe ore field.

Granulometric fractions of sediments were selected with the wet mechanical analysis and subsequent sieving (Geological Institute, Russian Academy of Sciences, Moscow). Mineralogical investigations were performed using optical and electron microscopes (CamScan MV2300 equipped with INCA Energy 200 energy-dispersion analytical system) at the Geological Institute.

Benthic foraminifers in fractions of 0.1–0.25 and 0.25–0.5 mm were studied under a Leica light microscope with 40× magnification. In all samples, the species composition of benthic foraminifers was determined (at least 150 specimens were examined), as well as the relative abundance of all identified species, the number of species, and the total number of tests.

Planktonic foraminifers were studied to make the stratigraphic subdivision of columns and to estimate the sedimentation rates, the paleotemperatures, and the productivity. Paleotemperature and biostratigraphic methods developed by Erickson et al. (Ericson et al., 1964; Ericson and Wollin, 1968) and Barash et al. (1987) for the Atlantic Ocean were used for stratigraphic subdivision of sediments. On the basis of the ratio of benthic to planktonic foraminifers and by the degree of preservation of their tests, the influence of hydrothermal fluids on these foraminifers was estimated.

RESULTS

Core 33L159

Lithology. Sediments in the 0–14 cm interval of core 33L159 are represented by carbonate foraminifer-coccolith and coccolith oozes and beige-colored sands with rare black inclusions. The upper part (up to 10 cm) contains fragments of pteropods. Below 14 cm, biogenic deposits are replaced by metal-bearing reddish brown carbonate sediments. At a depth of 22 cm, ore-bearing carbonate-free dark brown sediments appear, which are replaced by black sediments below 28 cm (Fig. 2). The calcium carbonate content in the upper interval (0–22 cm) is quite high (60–70%). Below, it decreases sharply to 3% in ore-bearing sediments; below 28 cm, sediments are calcium carbonate-free. Concurrently, the contents of ore elements sharply increase from top to bottom of the section: Fe (from 4.04 to 35.6 wt % Fe_2O_3), Cu (from 0.25 to 18% carbonate-free compound), as well as S_{total} (from 0.02 to ≈36%) and SiO_2 (to >30%) (Os'kina et al., 2013; Gablina et al., 2015).

Metal-bearing and ore-bearing sediments are predominantly (85–90%) composed of rounded, spherical, irregularly isometric foraminifer-sized grains (0.1–0.5 mm), composed of hydrothermal minerals, which sometimes preserve the form of altered foraminiferal tests (Figs. 2b, 2c). In the bottom of the column (28–34 cm) are basalts, altered to clayey state and enriched in sulfides. At the top of the column, ore minerals are rare and are represented by iron hydroxides and atacamite; in the lower part, pyrite and copper sulfides, along with goethite and paratakamite, occur in significant amounts.

Hydrothermal changes in sediments are observable in the zone 39–59 cm wide surrounding the ore structure.

Sediments are replaced by iron hydroxides (goethite) and chlorite. Because of this, they have bright spotted color (red-brown and green spots). During TV profiling of the bottom surface, these zones are distinguished by brown spots against the background of unaltered beige sediments (Gablina et al., 2015).

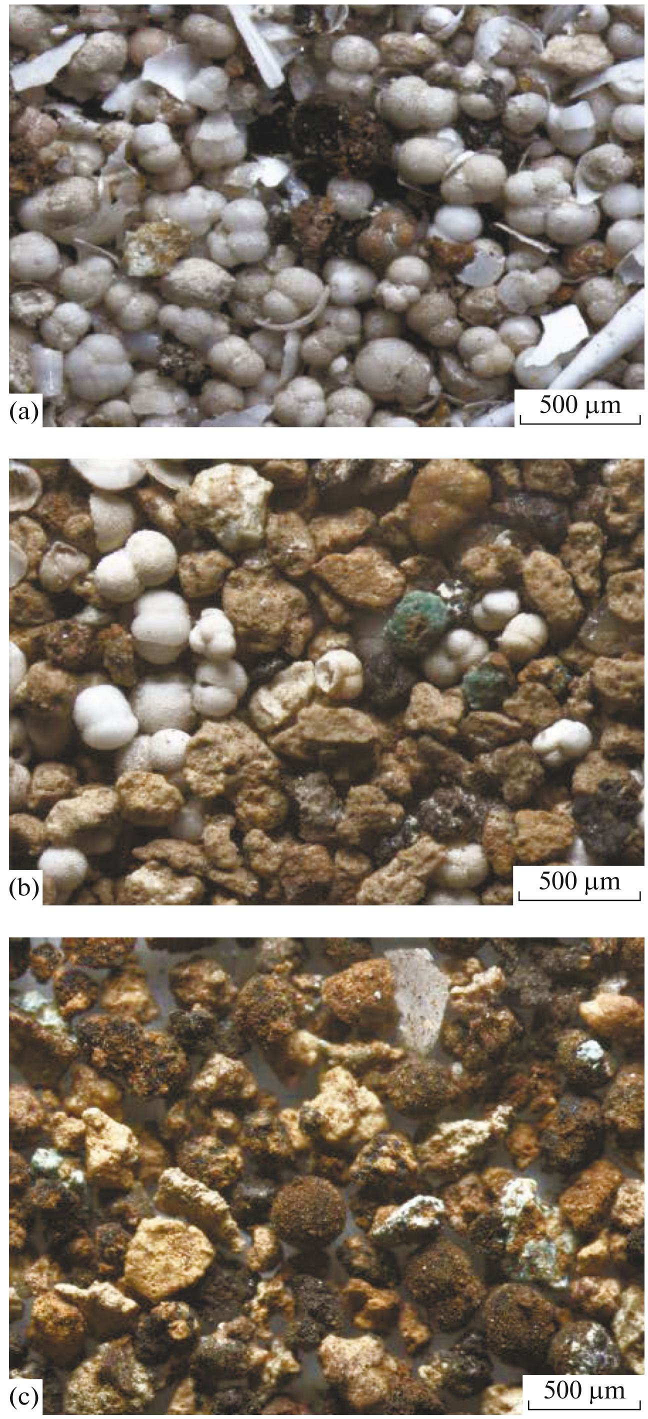

Fig. 2. Change in the lithology of sediments with depth along the column 33L159. Microphotographs of the 0.25–0.5 mm fraction. (a) Int. 2–5 cm, carbonate sediment with single grains of iron hydroxides, the fraction is represented mainly by foraminiferal shells and, to a lesser extent, by fragments of pteropods; (b) int. 19–22 cm, the same, with grains of atacamite, iron hydroxides, single pseudomorphs of hydrothermal minerals after foraminiferal shells; (c) int. 26–28 cm, an ore-bearing sediment composed of grains of hydrothermal minerals, some of which preserved the shape of altered planktonic foraminifers.

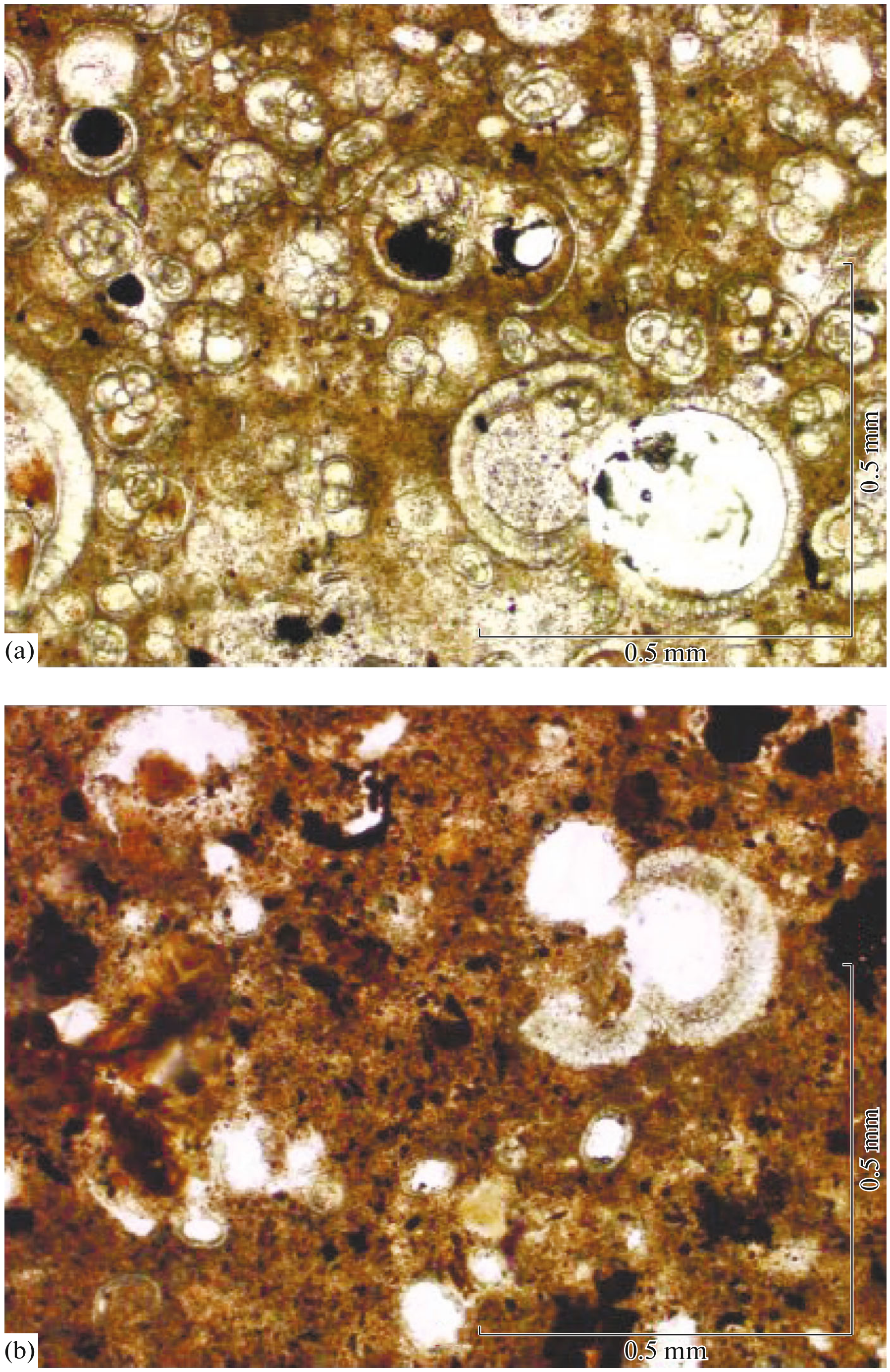

Fig. 3. Degree of preservation of shells of microorganisms in different horizons of sediments at the Peterburgskoe hydrothermal field, st. 33L159, transparent sections. (a) Int. 14–18 cm; (b) int. 22–24 cm; black spots are ore minerals.

Planktonic foraminifers. The planktonic foraminifers from the upper part of the column 33L159 are well preserved (Figs. 2a, 3a). The shell surfaces are covered by small Fe–Mn crusts, crystals of atacamite and aragonite, and Fe opal (Figs. 4a, 4b). The species composition of their assemblages is common for these latitudes. There are no signs of redeposition. There were more than 30 species belonging to the equatorial–tropical, tropical, subtropical, and temperate groups. In one sample, a shell of *Neogloboquadrina pachyderma* sin., belonging to the subpolar group, was also found. In total, 20–25 species of planktonic foraminifers were identified in each sample, taking into account both fractions. Among them are *Globoquadrina hexagona* and *Globorotalia menardii flexuosa*, which were used for stratigraphic dating using Erickson's scale (Ericson et al., 1964; Ericson and Wollin, 1968). They became extinct during the peak of the last glaciation (Barash et al., 1987). Thus, the age of the core is determined from planktonic foraminifers as Holocene–Late Pleistocene. The Holocene boundary was established at a level of 20 cm; i.e., the column is composed almost entirely of Holocene sediments. The thickness of the Pleistocene sediments is only a few centimeters and they are confined to the Holocene–Pleistocene boundary. Consequently, ore-bearing sediments, lying at a depth interval of 22–34 cm, deposited in the Late Pleistocene.

Paleotemperature analysis of assemblages of planktonic foraminifers showed that, during the deposition of sediments of core 33L159, the average annual temperature of surface water at the sampling site changed slightly: the minimum temperature was 24.5°C and the maximum temperature was 26.5°C, at the current average annual surface water temperature in this area of 25°C. Thus, in the area of core 33L159, there were tropical conditions. An absence of sharp temperature fluctuations is undoubtedly due to the small stratigraphic volume of this core.

At the bottom of the core, calcareous tests of planktonic foraminifers are represented by single specimens or they are absent (Fig. 3b). Since the depth where the core was sampled is much higher than the lysocline, an absence of tests cannot be related to dissolution of carbonates, which is a common process at depths of more than 5 km. It is most likely that an absence of tests in the lower part of core 33L159 is associated with hydrothermal activity, which was resulted in dissolution of calcareous tests and in their replacement with hydrothermal minerals (Figs. 2c, 4e, 4f).

The productivity of planktonic foraminifera (the number of specimens per one gram of dry sediment) in core 33L159 varied from 3500 to 18 200 specimens per one gram of dry sediment. Compared to benthic foraminifera, their content is almost 100%; the amount of benthic foraminifers are usually tenths of a percent.

Benthic foraminifers. The benthic foraminiferal assemblage in the Holocene sediments of core 33L159 is represented by a rather homogeneous complex (Fig. 5) with *Epistominella exigua* (Brady) being dominant (up to 50%). The subdominant species (up to 25%) is *Globocassidulina subglobosa* (Brady). There are miliolids (*Triloculina* sp., *Quinqueloculina venusta* Karrer, *Q. pigmaea* Reuss, *Q. seminula* (Linnaeus), *Pyrgo murrhina* (Schwager), *P. williamsoni* (Silvestri), *Q. weaveri* Rau, about 17% in total) and *Planulina wuellerstorfi* (Schwager) (up to 10%).

The foraminiferal complex dominated by *Globocassidulina subglobosa*, miliolids, and *Planulina wuellerstorfi* is typical of modern sediments lying at depths above 3500 m in the tropical latitudes of the North Atlantic. *Planulina wuellerstorfi* is an epifaunal species (Fontanier et al., 2002; Schnitker, 1980; Mackensen et al., 1993), which is widespread in the area where the inflow of organic matter to the bottom is very low, and the oxygen concentration in the bottom water, on the contrary, is high (Lutze and Coulbourn, 1984). It is believed that miliolids in the North Atlantic also prefer well-aerated waters with a high oxygen content (Gudmundsson, 1998). *Planulina wuellerstorfi* and miliolids dominate at depths of 2000 to 3500 m in oxygen-rich and nutrient-poor North Atlantic deep waters (NADW) (Miller and Lohman, 1982; Streeter and Laveri, 1982; Murray, 1991; Lukashina, 1991, 1992; Hughes et al., 2000).

The first occurrence of *Globocassidulina subglobosa* in the *Planulina wuellerstorfi*/miliolid complex is recorded in the lower latitudes of the Atlantic Ocean. It is distributed mainly at the continental margins of Europe and North Africa and on the Mid-Atlantic Ridge (Schnitker, 1980; Pujos-Lamy, 1984; Lutze and Coulbourn, 1984; Lukashina, 2008). This species also prefers a higher concentraion of dissolved oxygen and does not need an excess of organic material (Loubere et al., 1988; Murgese and De Deckker, 2005). Here, a high content (about 50% of the assemblage) of *Epistominella exigua* in the Holocene sediments of core 33L159 seems very strange. As our studies show (Lukashina, 2008), the fact is that this species in the tropical Atlantic (Canary Basin) dominates only on the North African continental slope between about 2500 and 4500 m and is very rare on the Mid-Atlantic Ridge.

In general, the species *Epistominella exigua* is widely distributed in the North Atlantic below a depth of 3500 m, being dominant in the Irminger, Iceland, Labrador, and West European basins filled with North Atlantic bottom water (NABW), where the content of this species often exceeds 50% (Lukashina, 2008). It is assumed that *Epistominella exigua* occurs in those areas where seasonal flowering of phytoplankton takes place and the sea bottom is periodically supplied with fresh organic matter (Smart and Gooday, 1997; Fontanier et al., 2003; etc.). The development of this species in the zone of hydrothermal activity under consideration (core 33L159) could have been stimulated by pulsation inflow of methane-rich fluids.

At the same time, the hydrothermal activity had an adverse effect on the concentration of tests and the species diversity of benthic foraminifers in the Holocene sediments observed in the core 33L159 section. The content of benthic foraminiferal tests in these sediments is very low (no more than 50 specimens per one gram of sediment) and they are represented by ~15 species. This situation is typical for the sediments of the rift valleys of the Mid-Atlantic Ridge, especially near hydrothermal sources (Lukashina, 1991; Gablina et al., 2011, 2015).

In the interval of 20–22 cm (near the zone where carbonate sediments are replaced with carbonate-free ore-bearing ones), miliolids disappear and the amounts of *Epistominella exigua* and *Planulina wuellerstorfi* sharply decrease. There is no doubt that

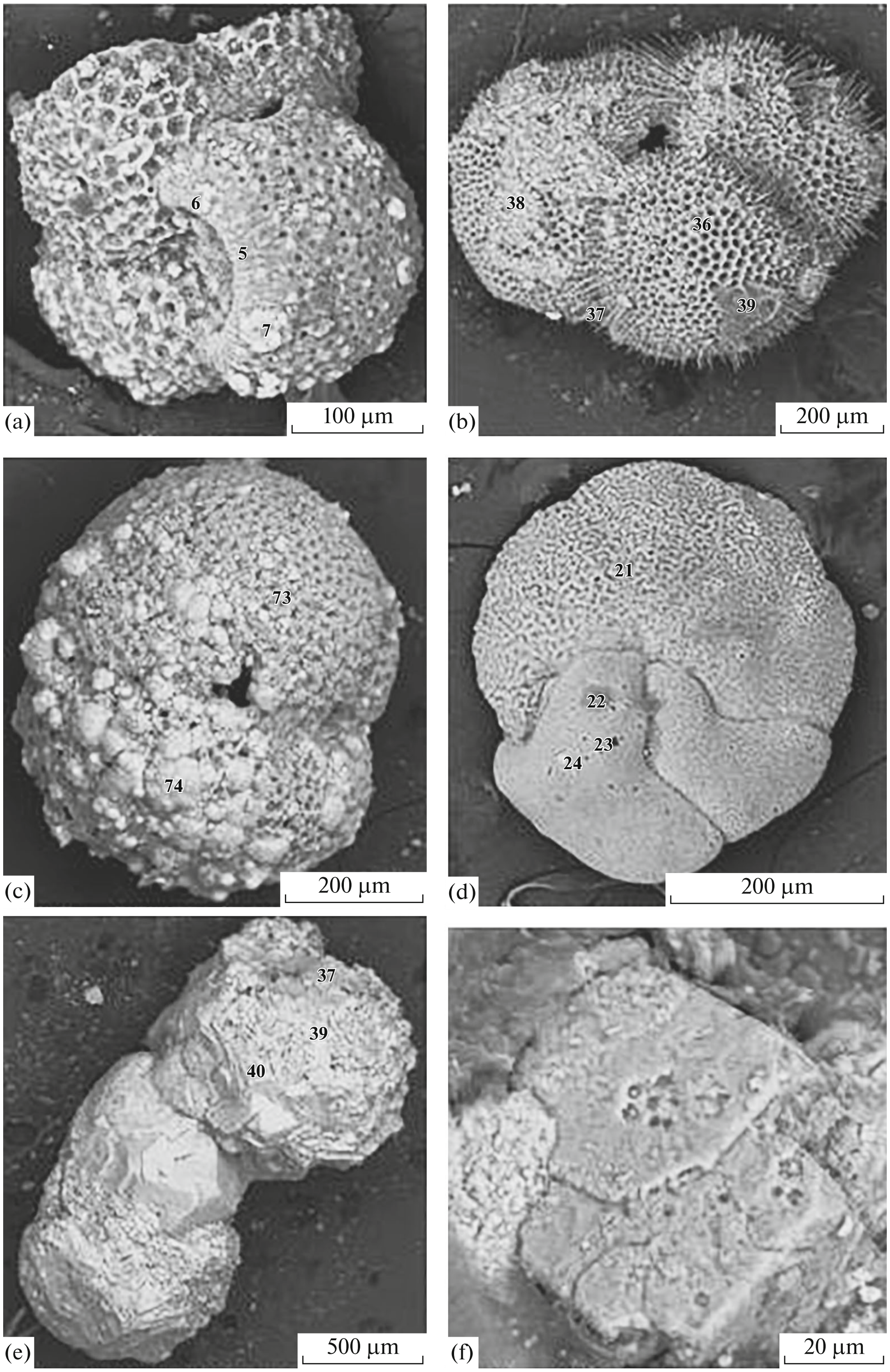

Fig. 4. Transformation of biogenic material of sediments along the core 33L159 section. Microimages; numbers in images are analytical points of electron microprobe analysis. (a) Int. 5–10 cm, calcite (point 5) shell of the planktonic foraminifera *Globigerinoides* cf. *ruber* with fine Fe-Mn crusts containing an admixture of atacamite and clay minerals (points 6–7); (b) int. 10–14 cm, calcite shell of the planktonic foraminifera *Globigerinoides* cf. *sacculifer* (point 36) with newly formed aragonite (point 37), Fe–Mg clay minerals (point 38), and a bacterial film (point 39) on the surface; (c) int. 19–22 cm, a more intense development of Fe–Mn crusts and atacamite (point 74) on the surface of dissolving calcite shells *Globigerinoides* cf. *conglobatus* (point 73); (d) int. 22–24 cm, slightly altered calcite (point 21) shell of planktonic foraminifera *Globorotalia* sp. with bacterial (point 22) and fine copper and iron sulfide crystals (points 23, 24); (e) int. 24–26 cm, atacamite pseudomorphs (points 37, 39, 40) after foraminifers; (f) near-ore altered sediments 30 cm from sulfide structure: pyrite crystals with relics of foraminifers.

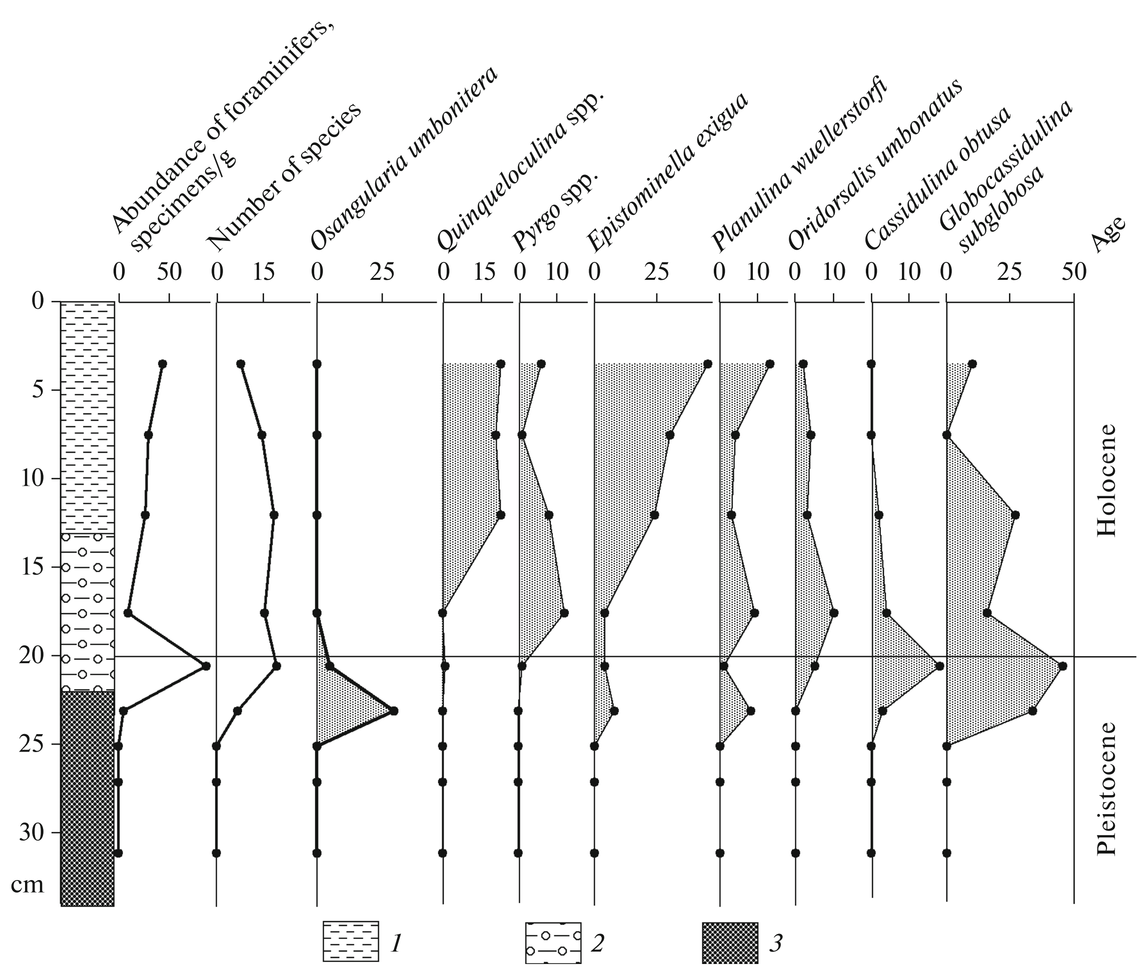

Fig. 5. Distribution of the main benthic foraminiferal species in the section of column 33L159 (Peterburgskoe hydrothermal ore field). (*1*) Sediment biogenic, carbonate, beige; (*2*) sediment carbonate, reddish brown; (*3*) sediment carbonate-free, ore-bearing.

Globocassidulina subglobosa dominates in the foraminiferal complex (almost 50%), and the proportion of *Cassidulina obtusa* increases, reaching approximately 20%. At this boundary, the abundance and diversity of benthic foraminifers in metal-bearing carbonate ooze increase to 86 specimens per gram of sediment and 18 species, respectively.

The occurrence of *Osakularia umbonifera* (up to 25%) was established among single tests of benthic foraminifera in one of samples of the Late Pleistocene carbonate-free ore-bearing sediments (int. 22–24 cm). It is known that this species was adapted to living under conditions of undersaturation of the bottom waters with calcium carbonate, characteristic of the Antarctic bottom water mass (ABW) (Corliss, 1979; Bremer and Lohman, 1982; Murray, 1991). In this case, the undersaturation of waters with calcium carbonate could have been associated with hydrothermal activity.

In ore-bearing sediments below 25 cm, there are no calcareous tests (Fig. 2c).

The share of benthic forms in the total number of foraminifers (benthic and planctonic) varies along the core section. In the biogenic sediments of the upper part of the core, the relative content of benthic forms is tenths of a percent. In ore-bearing brown oozes (int. 22–24 cm), the share of benthic foraminifers increases to 1–2% or more. In ore-bearing black sediments below 24 cm, where only single specimens of benthic and planktonic foraminifers were found, the share of benthic foraminifers increases to 50%. The apparent increase in the relative share of benthic species in foraminiferal assemblages of ore-bearing horizons is associated with more active destruction of tests of planktonic species under the influence of acid hydrothermal solutions entering sediments.

It should be noted that the appearance of foraminiferal shells differs greatly in beige carbonate muds (0–14 cm bed) and metal-bearing brown oozes (14–22 cm bed). Most of shells of both benthic and planktonic forms are well preserved in biogenic carbonate sediments, although ferruginous tests occur occasionally

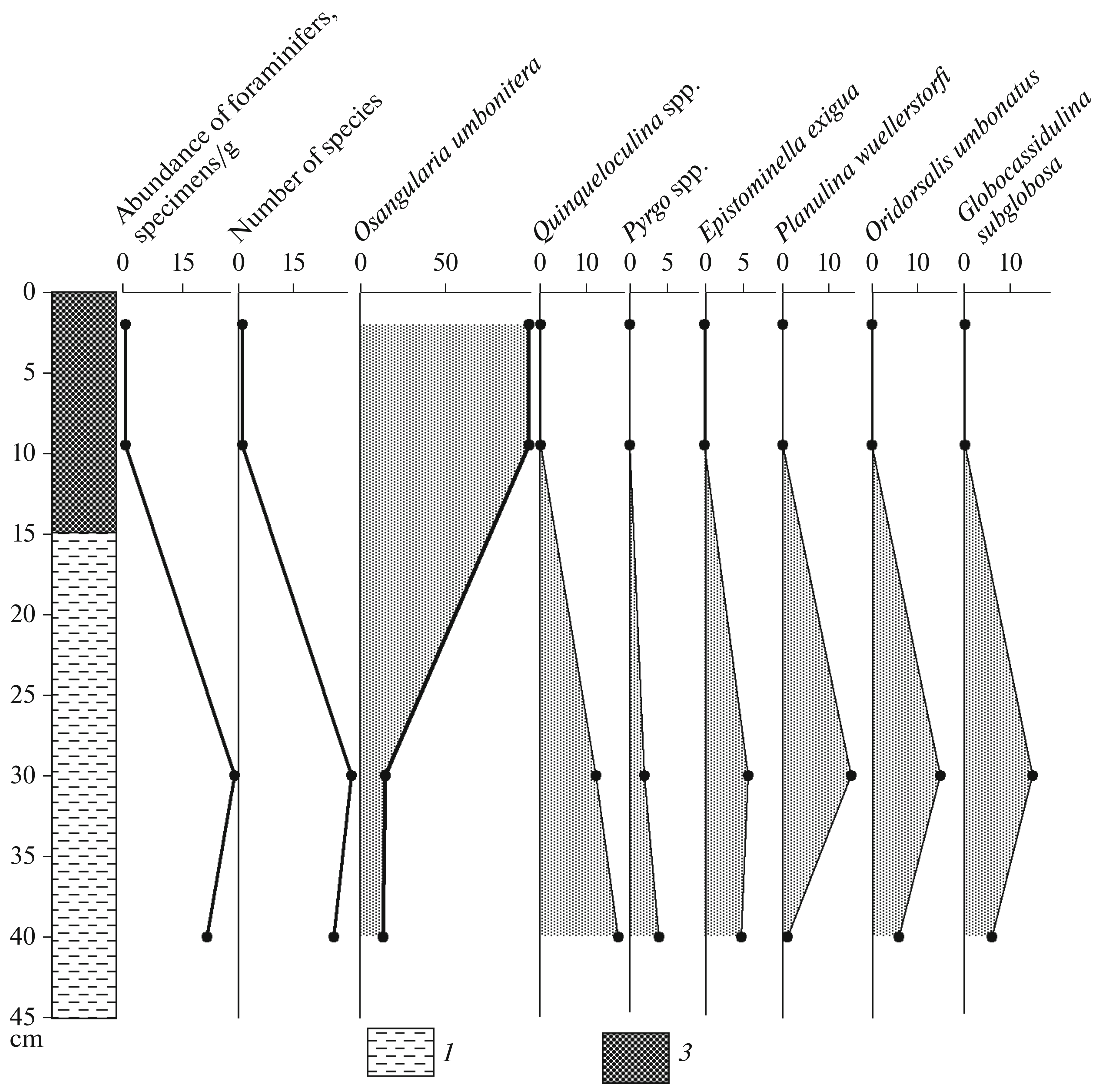

Fig. 6. Distribution of the main benthic foraminiferal species in the section of column 26L1520 (Ashadze-1 hydrothermal ore field). See legend in Fig. 5.

(Fig. 4). Below 14 cm, the sediments contain abundant foraminiferal tests enveloped by Fe–Mn crusts and impregnated with atacamite. Intense ferrugination can be traced along sutures. Many tests, especially of planktonic species, are covered with small Fe–Mn crusts and atacamite crystals (Fig. 4c). In ore-bearing sediments below 24 cm, almost all foraminiferal tests are completely altered by iron hydroxides, atacamite, and sometimes pyrite as a result of hydrothermal processes (Figs. 2c, 4e, 4f). More intense changes in the tests of planktonic foraminifers can be explained by their greater porosity and, accordingly, greater solubility and sorption capacity (Fisher et al., 2003). Recent studies of bottom sediments of the deep-water hydrothermal fields of the Mid-Atlantic Ridge showed that such metals as Fe, Mn, Cu, Ni, Pb, and Cd have an ability to adsorb on the surface and in pores of tests of planktonic foraminifers (Demina et al., 2016). This happens not as much during their life cycle as after their death during secondary transformations of bottom sediments.

A similar situation is observed at the deepest Ashadze-1 hydrothermal field (4100–4200 m; 12°58′ N, 44°51′ W) on the Mid-Atlantic Ridge (core 1520, sampled during the 26th cruise of the R/V *Professor Logachev*) (Gablina et al., 2011). This hydrothermal field was formed at the end of the Holocene, a little later than the Peterburgskoe field. The foraminiferal assemblage in ore sediments contains small and approximately equal amounts of tests of benthic and planktonic species. Benthic foraminifers are represented by only one species *Osangularia umbonifera* (Fig. 6), which was able to exist in low-oxygen and $CaCO_3$-undersaturated bottom waters. Planktonic foraminifers are represented by common tropical species, mainly *Globigerinoides* *sacculifer* and *G. ruber*. Some shells are entirely covered with ferromanganese crust; there are many fragments of shells and small not rounded lumps of rusty color.

Within the Ashadze-1 hydrothermal field, ore-bearing sediments are overlain by biogenic carbonate and clay-carbonate foraminiferal-coccolith and coccolith-foraminiferal oozes with a high content of tests of planktonic foraminifers (hundreds or thousands of specimens per gram of dry sediment), which is higher than the number of benthic forms by three or even four orders of magnitude. Benthos in biogenic carbonate sediments is represented by the following species: *Globocassidulina subglobosa*, *Planulina wuellerstorfi*, and miliolides.

The metalliferous interbeds in the core sampled at the test area of the Transatlantic Geotraverse from a depth below 4000 m contain tests of modern species *Osangularia umbonifera*, 30–60% of which are of brown color and of ugly shape (ventral or dorsal sides of the chamber are strongly convex; the last whorl is curved). It was suggested that these morphological changes may also be related to the activity of underwater hydrothermal sources (Lukashina, 1991).

Core 33L148

Lithology. The sediments of core 33L148 are represented, as a whole, by beige carbonate coccolith-foraminiferal silt, in which the calcium carbonate content varies in a range of 70–80%. Below 38 cm, the sediments are of brownish beige color.

In the upper part of the core (intervals of 9–15 cm, 24–27 cm, 75–76 cm) are pteropod-bearing interbeds. Below 50 cm, the column contains black microinclusions; at its bottom (depth of 143–150 cm) is a layer of edaphogenic material. The contents of ore elements are common for carbonate biogenic sediments and they vary slightly along the core section ($Fe_{bcm} \leq$ 10%, $(Cu + Zn)_{bcm} \leq 0.25\%$; bcm is the content of elements per carbonate-free matter) (Os'kina et al, 2013; Gablina et al., 2015).

Planktonic foraminifers. The shells of planktonic foraminifers in the 150-cm 33L148 sample core are well preserved. It was revealed that the core section includes horizons of sediments formed during the Holocene, the last glaciation, and the last interglacial. The Holocene–Pleistocene boundary is at the same level (20 cm) at that in the 33L159 sample core. The paleotemperature analysis of planktonic foraminiferal assemblages has shown that during the formation time of sediments under consideration, the average annual temperature of the surface water at station 33L148 ranged from 21 to 24.5°C, at the modern average annual temperature of 24.5°C. According to the temperature conditions in the area of station 33L148, the Pleistocene was characterized by climatic conditions typical of the southern part of the subtropical zone, in contrast to modern tropical climatic conditions (Gablina et al., 2015). Sediments sampled at station 33L148 show no signs of superimposed hydrothermal processes. There are only slightly developed spots of ferrugination on single tests.

Benthic foraminifers. The Holocene–Upper Late Pleistocene interval of the core (0–40 cm) is characterized by an exceptionally low concentration of benthic foraminifers (less than 1 specimen per one gram of sediment) (Fig. 7). It is noteworthy that the sediment here consists predominantly of planktonic foraminifers, as well as subordinate amounts of pteropods, gastropods, and ostracods. The share of benthic foraminifers is no more than a thousandth of a percent of the total number of foraminifers. Therefore, only 10–14 specimens belonging to 4–5 foraminiferal species were identified in the sample. In this core interval, benthic types are mainly represented by different miliolids (*Spiroculina asperula* Karrer, *S. antillarium* d'Orbigny, *Quinqueloculina auberiana* d'Orbigny, *Q. culter* (Parker et Jones), *Pyrgo murrhina* (Schwager), *P. lucernula* Schwager), lagenides (*Lagena favosa* (Brady), *Nodosaria inflexa* Reuss), and one rotaliid species—*Planulina wuellerstorfi* (Schwager). All tests are well preserved.

Below 40 cm, the role of benthic foraminifers becomes more significant. Here, they constitute hundredths or tenths of a percent of the total amount of foraminifers. The concentration of tests reaches 20 and sometimes 50 specimens per gram of dry sediment; the species diversity increases, reaching 10–20. Thus, the abundance of tests and the number of species of benthic foraminifers in this core interval are nearly the same as in carbonate sediments of core 33L159. In general, the same species occur here: *Planulina wuellerstorfi* (7%), *Pyrgo* spp. (up to 17%), and *Cassidulina obtusa* (up to 10%) with *Globocassidulina subglobosa* being dominant (averaging about 20%). Unlike core 33L159 sampled within the ore field, the foraminiferal assemblage of the core 33L148 does not contain *Epistominella exigua*, and the *Osangularia umbonifera* tests occur in single specimens in the lowermost horizon. In this horizon, spots of ferrugination are observed on foraminiferal tests, especially planktonic species, but most of the tests are well preserved. The occurrence of the species *Osangularia umbonifera* and spots of ferrugination can be signs of weak hydrothermal activity. At present, ABW fills the Canary Basin below 4700 m, whereas during the last glaciation period, as shown by our study, ABW, mixed substantially with the lower NADW, was upwelling above 3000 m and washing the top of the Mid-Atlantic Ridge (Lukashina, 1992, 2008). This is confirmed by the presence of ABW in the Late Pleistocene sediments of core 33L159.

CONCLUSIONS

(1) The Holocene–Late Pleistocene age of the hydrothermal Peterburgskoe ore field was established on the basis of studying the foraminiferal assemblage.

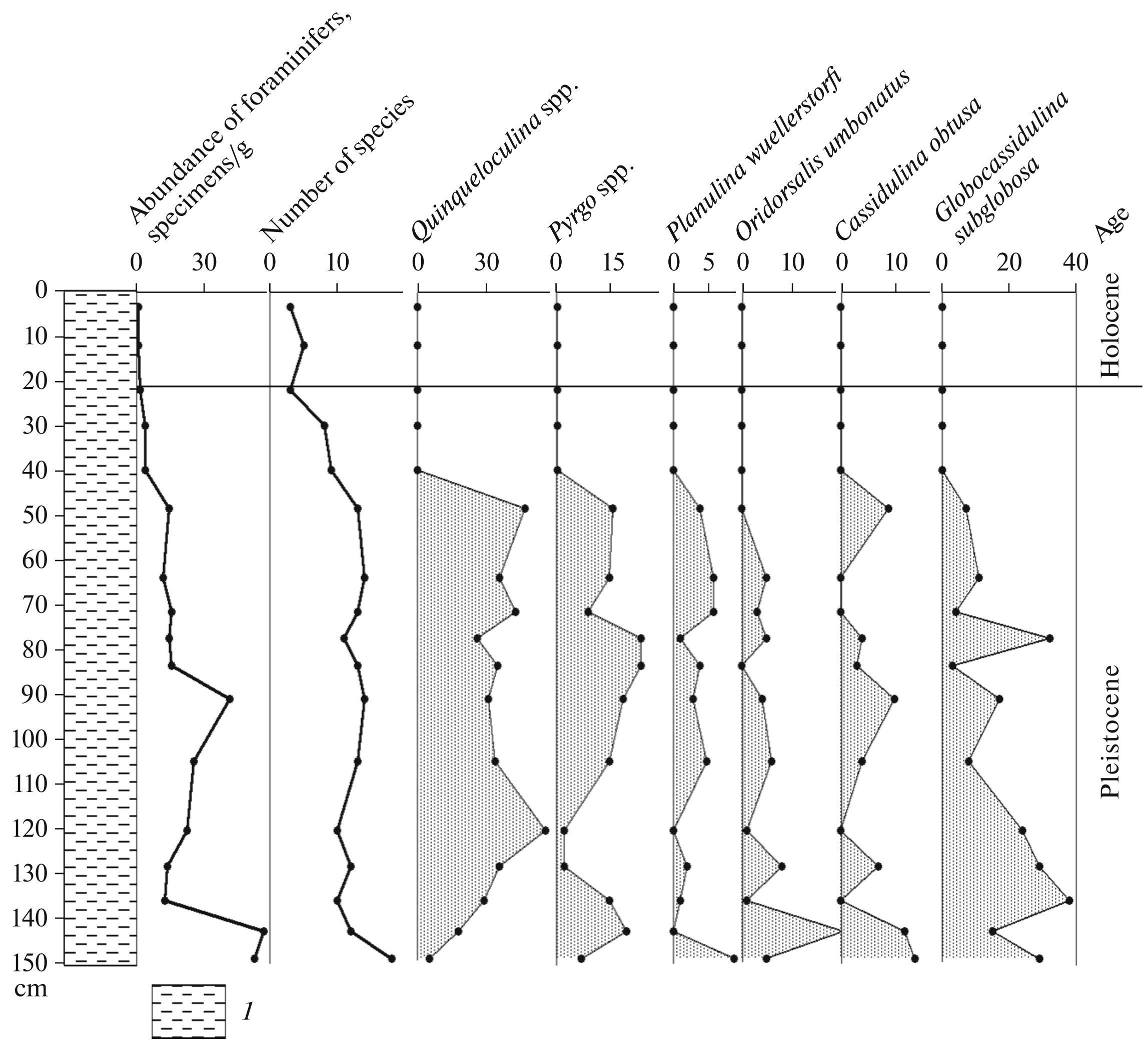

Fig. 7. Distribution of the main benthic foraminiferal species in the section of column 33L148 (Peterburgskoe hydrothermal ore field). See legend in Fig. 5.

The hydrothermal activity in the lower, Late Pleistocene, interval of the section of biogenic carbonate sediments resulted in dissolution of carbonate foraminiferal shells and their replacement by hydrothermal minerals.

(2) The comparison of foraminiferal assemblages from biogenic carbonate sediments surrounding the Peterburgskoe ore field (core 33L159) and from sediments beyond the ore field (core 33L148) allowed us to reveal evident differences in the composition of assemblages of benthic foraminifers, in the shape of their shells, and in the relative content of benthic foraminiferal species. There is an evident increase in the share of benthic species in foraminiferal assemblages of biogenic sediments in the area of the Peterburgskoe ore field, as well as an increase in abundance of chemically altered and defragmented shells. The first occurrence of *Osangularia umbonifera*, able to exist in low-oxygen and $CaCO_3$-undersaturated near-bottom waters, was established. At a distance of 5 km from the ore field, the composition of benthic foraminiferal assemblages in biogenic sediments is slightly different from common oceanic assemblages.

The minimal amount of foraminifers in the assemblage from the ore-bearing layer of core 33L159 and the predominance of *Osangularia umbonifera* and the rapid destruction of foraminiferal tests, mainly of planktonic forms, indicate unfavorable conditions for the habitat of benthic species and the preservation of biogenic carbonate material, which was due to hydrothermal activity. The prolonged effect of hydrothermal solutions on sediments of the lower, Late Pleistocene, interval of the section of bottom sediments in the area of the Peterburgskoe field led to complete dissolution of calcareous tests of microorganisms and their alteration to hydrothermal minerals.

(3) The more intense transformation of planktonic foraminifers in comparison with benthic ones can be

explained by much greater porosity of their tests and, accordingly, by greater sorption capacity and solubility.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 14-05-00480), the Institute of Oceanology of the Russian Academy of Sciences (project no. 0149-2014-0027), and the Basic Research Program of the Presidium of the Russian Academy of Sciences 1.43P.

Reviewers V.S. Vishnevskaya and M.A. Bylinskaya

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Translated by Dm. Voroshchuk