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Physical and chemical properties of seawater over the slopes of the northern part of the Mid-Atlantic Ridge

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Abstract. We analyze physical and chemical properties of seawater east and west of the Mid-Atlantic Ridge in the tropical North Atlantic based on the historical data and our measurements in 2014. Concentration of nutrients in the bottom layer east of the ridge is smaller than west of the ridge because Antarctic Bottom Water propagated to the East Atlantic through abyssal fractures in the ridge and mixes with the overlying waters in the course of its propagations. We found a local temperature increase near the bottom in the rift zone of the Mid-Atlantic Ridge along 16°39' N, which can be related to hydrothermal activity in the region.

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Introduction

In the next decade, intense studies of the physical and chemical properties of deep and bottom waters are planned in the region of deposits of sulfide ores in the Mid-Atlantic Ridge. A wide set of ecological and oceanographic research is planned within this project. The region, in which Russia is planning long-term research on deep polymetallic sulfides in the Mid-Atlantic Ridge (MAR) region, is located between 12°and 20° N. In October 2015, the R/V "Akademik Sergey Vavilov" conducted prospecting research works in this region, which included hydrological and hydrochemical measurements.

The major part of the abyssal waters in the Atlantic has an Antarctic origin. These waters are formed in the Weddell Sea as a result of descending of cold and dense shelf waters down the Antarctic continental slope and mixing with the warmer and more saline Circumpolar Deep Water. The layer of abyssal Antarctic waters of low salinity with potential temperature $\theta < 2.0$°C is called Antarctic Bottom Water (AABW) [*Wüst*, 1936]. These waters propagate to the Argentine Basin through a number of fractures and then propagate further to the Brazil Basin [*Morozov et al.*, 2010; *Sandoval and*

Weatherly, 2001]. After passing the Brazil Basin, part of these waters flows to the north into the basins of the Northwest Atlantic and reaches the Newfoundland Bank; the other part propagates to the East Atlantic through the fractures in the Mid-Atlantic Ridge.

The Mid-Atlantic Ridge is cut by many transform faults. The ridge that separates the deep Atlantic Ocean into the western and eastern parts plays an important role in the structural transformation of deep and bottom waters. The fractures over the entire length of the Mid-Atlantic Ridge determine the water exchange between the deep layers of the eastern and western parts of the ocean.

High concentration of dissolved silicates, which is in abundance in the Antarctic waters, is a good tracer of Antarctic Bottom Water in the Atlantic Ocean. As AABW propagates to the north its temperature and salinity increase, while the concentrations of nutrients decrease because it mixes with the overlying waters. The bottom waters of the eastern basins of the North Atlantic are much more transformed than the western waters, and their renewal time is much longer [*Morozov et al.*, 2010].

Region of Measurements

A chart of the region is shown in Figure 1. The dots indicate the stations, in which CTD/LADCP measurements were made to the ocean bottom. The data about all stations are given in Table 1. Usually the profilings were terminated at a distance of 5 m from the bottom. The CTD-profiles were accompanied by LADCP (Lowered Acoustic Doppler Current Profiler) measurements (using an RDI 300 kHz instrument). The hydrochemical measurements included determinations of the concentration of silicates, phosphates, nitrates, and alkalinity.

The locations of stations in cruise 39 of the R/V "Akademik Sergey Vavilov" were planned in the fractures of the ridge. In addition, five stations of the sulfide section along 16°39' N were located so that the western and eastern stations were on the MAR slopes, the central station was in the rift zone and the remaining two were over the crests of the ridges divided by the rift zone. The bottom topography section along 16°39' N and locations of the stations are shown in Figure 2.

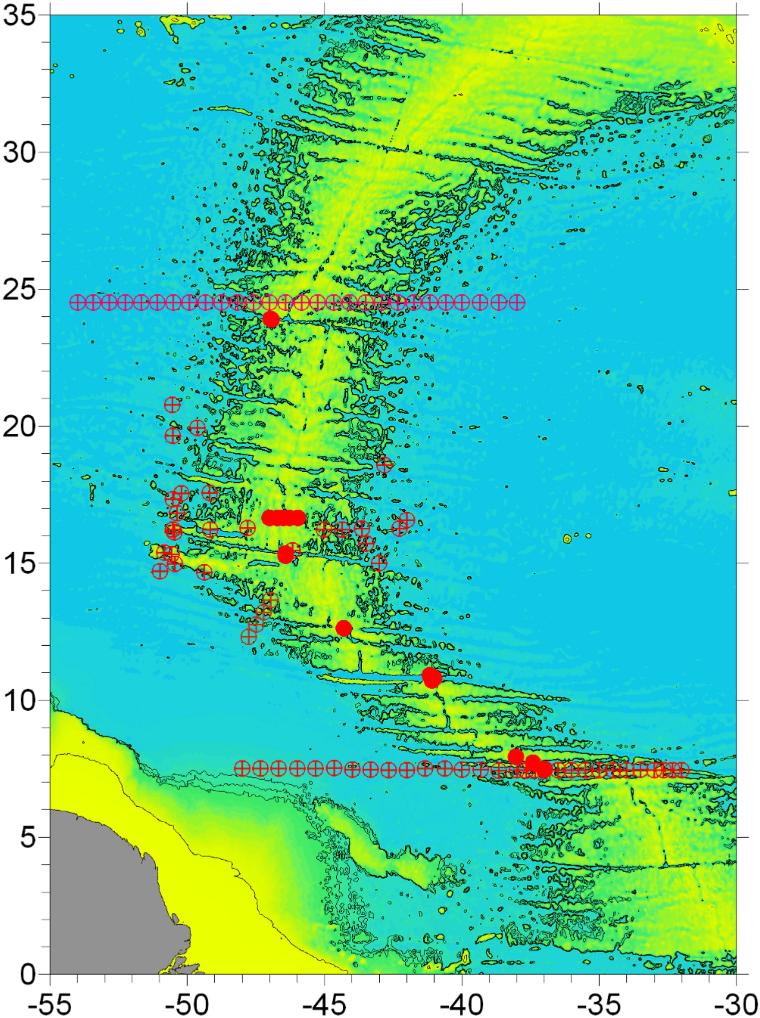

Figure 1. A chart of the North-Atlantic Ridge with the points of historical stations (with crosses) and stations in 2014 (red dots).

Table 1. Information About the Stations

Regions of CTD profiles	Ship time; Begin–end (GMT-2)	Station	Coordinates	Lower measurements/ sea bottom, m
Kane FZ	03.10 12:23 15:17	2540	23°54.6 N, 46°58.0 W	4349/4354
Sulfide section	05.10 10:15 11:50	2543	16°38.9 N, 46°42.7 W	2439/2445
Sulfide section	05.10 13:55 17:10	2544	16°39.0 N, 46°29.4 W	4193/4198
Sulfide section	05.10 18:45 20:35	2545	16°39.0 N, 46°16.8 W	2934/2939
Sulfide section	05.10 23:05 06.10 01:27	2546	16°39.0 N, 45°58.0 W	2991/2997
Cabo Verde FZ	06.10 13:17 16:10	2547	15°16.3 N, 46°25.0 W	4499/4505
Cabo Verde FZ	06.10 17:10 19:50	2548	15°20.5 N, 46°25.0 W	4166/4171
Marathon FZ	07.10 12:46 15:30	2549	12°37.4 N, 44°18.0 W	4215/4220
Vema FZ	08.10 11:15 14:09	2550	10°52.6 N, 41°07.3 W	4309/4315

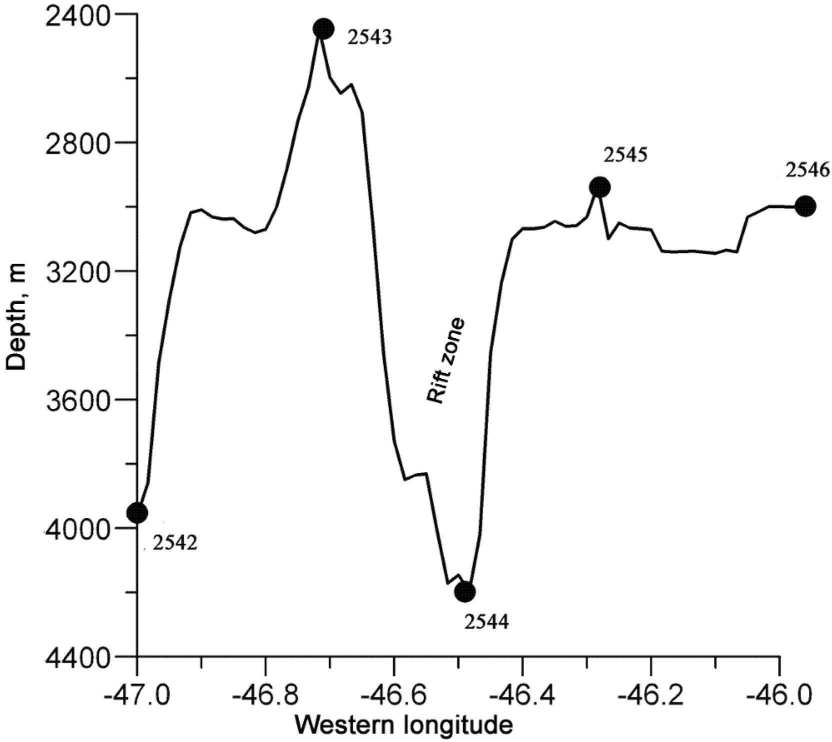

Figure 2. Scheme of the bottom topography along the sulfide section (16°39' N) and locations of the stations.

Instruments for Research

The CTD-casts were performed using profiler SBE 19 plus SEACAT with a carousel of bottles SBE 32 (Carousel Water Sampler) and deck unit SBE 33 (Carousel

Deck Unit). The instrument is in operation since 2004, it was calibrated in 2013.

The measurements of currents were carried out using an Acoustic Doppler Profiler Workhorse Sentinel 300 kHz LADCP version 8.19.

Location of the profiler at the bottom was controlled by the Benthos altimeter (model PSA-916) and Benthos pinger.

In the sulfide study region we determined the concentrations of: silicates, phosphates, nitrites, nitrates, pH, and alkalinity. The concentrations of: silicates, phosphates, and nitrates were determined on the basis of optical density using the Leki SS2107UV spectrophotometer. Alkalinity was determined by titration using titrator-dosimeter "Digitrat" (Jencons) with visual search for the point of the titration end.

Analysis of Historical Data

We used the historical data from different databases including the data of international expeditions and database WOD09 (http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html). In particular, we used the data of the World Ocean Circulation experiment database (WOCE lines A05 along 24°N in 1992, A06 along

7.5°N in 2010, and quasi-meridional line A17 in 1993).

The distinguishing properties of the lower layer of North Atlantic Deep Water (NADW): high salinity and low concentration of silicates were vanishing east of the MAR due to the mixing with AABW. The North Atlantic Deep Water west of the MAR was least transformed compared to the same water east of the MAR.

The data of the WOCE A06 section in 2010 demonstrate the variations in the water properties. Figure 3 shows comparative properties of the relations between potential temperature and dissolved silicates west and east of the MAR based on the data of the WOCE A06 section along 7.5°N (2010).

The distributions of nitrates and silicates versus potential temperature were similar (Figure 3 and Figure 4). The concentrations of nutrients increased as the temperature decreased to 6°C. At lower temperatures they had synchronous extrema in the same temperature range. However, the maximum concentrations of nitrates were found in the Antarctic Intermediate Water (40 μMol/kg), and the maximum of silicates up to 77 μMol/kg was found in AABW. The concentration of silicates in the core of North Atlantic Deep Water was 15 μMol/kg and the concentration of nitrates was even greater 20 μMol/kg.

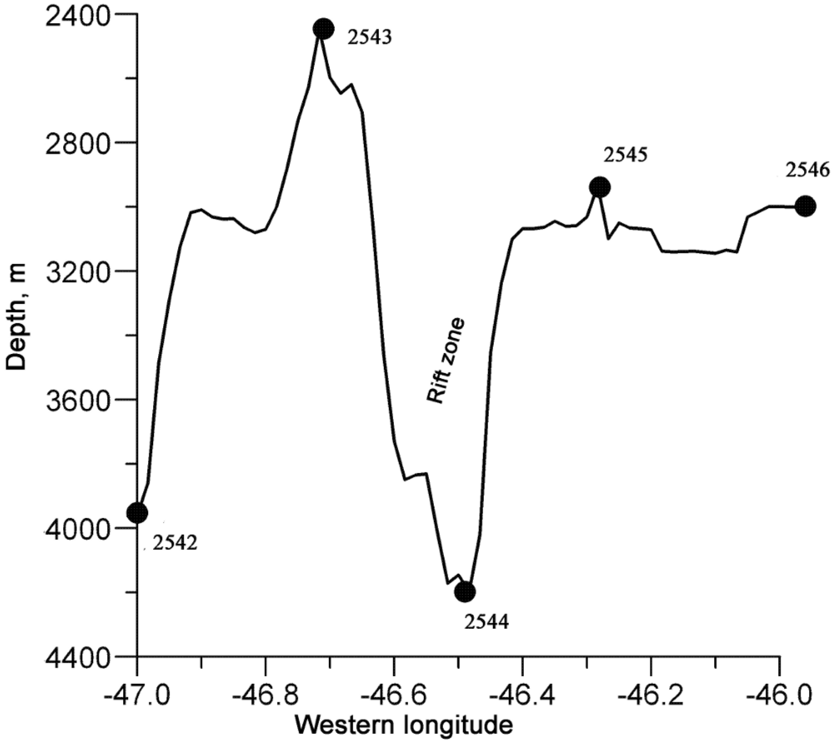

Figure 3. Relation between potential temperature and dissolved silicates over WOCE section A06 in 2010. Red dots indicate measurements east of the MAR and blue dots are related to the measurements west of the MAR.

The figures also show that bottom waters propagating from the south along the western MAR slope have greater silicate concentration (approximately by 25 μMol/kg), and nitrate concentration (Figure 4) than the waters flowing to the north but on the eastern side

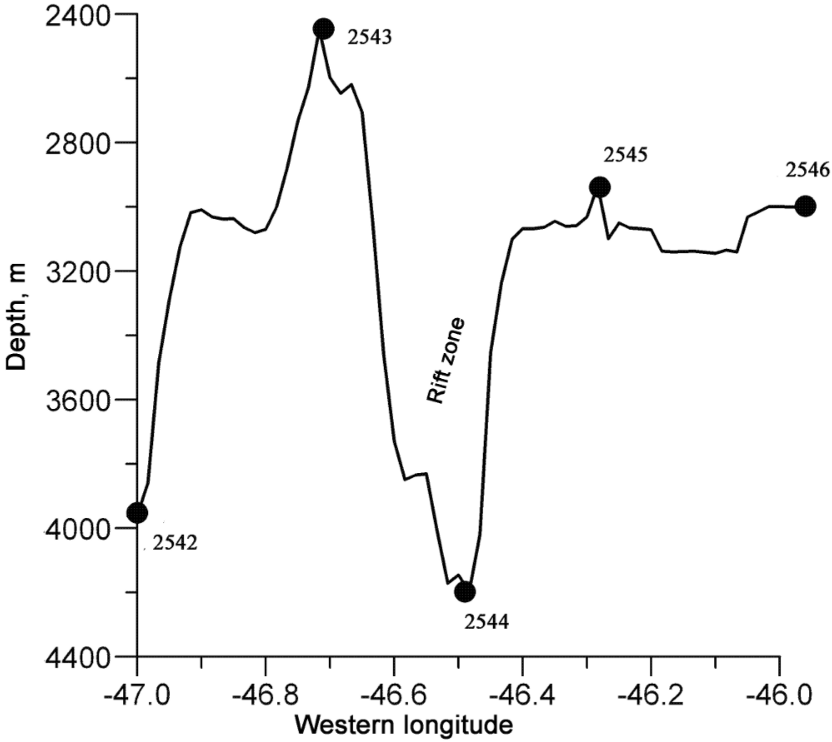

Figure 4. Relation between potential temperature and dissolved nitrates over WOCE section A06 in 2010. Red dots indicate measurements east of the MAR and blue dots are related to the measurements west of the MAR.

of the MAR that passes the abyssal channels.

Vertical distributions of alkalinity, phosphates, nitrates, and silicates based on the historical data for this region, which are not numerous here, are shown in Figure 5. The historical data are shown with colors.

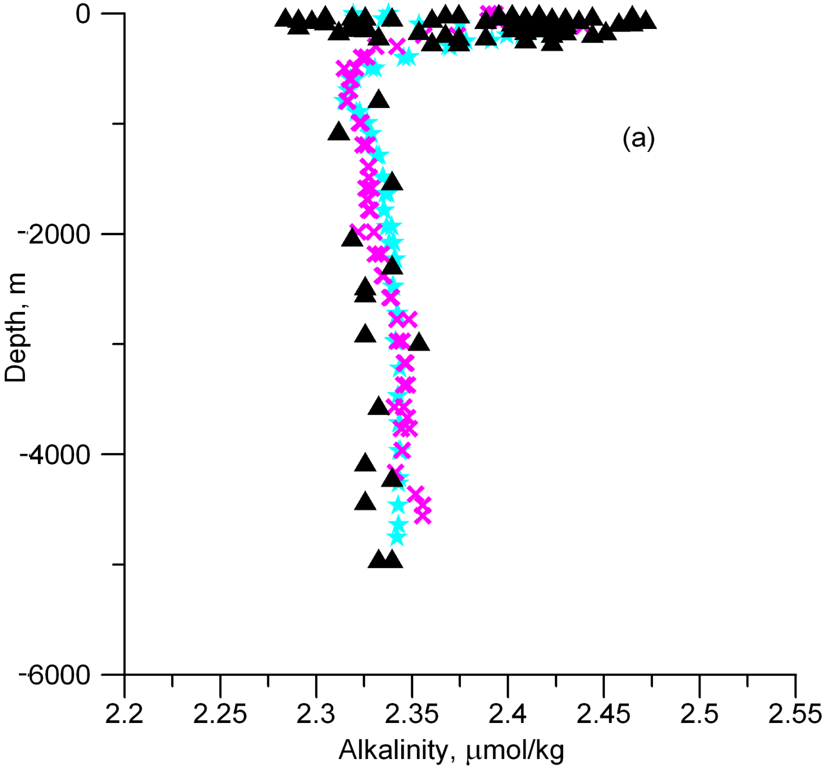

Figure 5a. Vertical profiles of chemical parameters based on the historical stations and data in 2014: **a** – alkalinity. The differences between the measurements east and west of the ridge are most clearly seen on the phosphate concentration. Light green stars show the measurements west of the ridge; pink color shows the measurements east of the ridge. Our data are shown with black triangles.

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Comparison of three chemical parameters west and

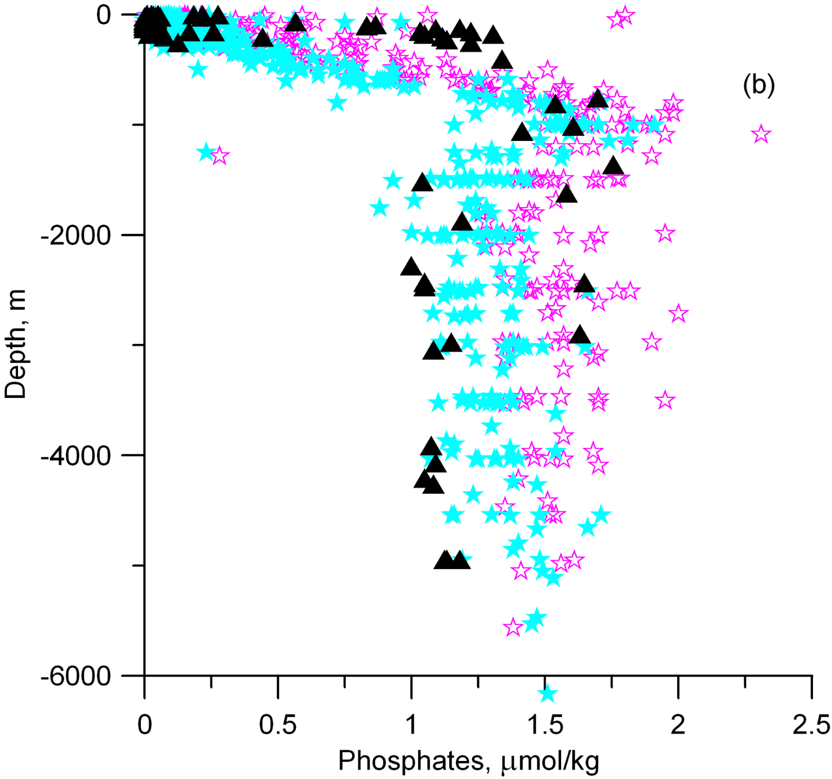

Figure 5b. Vertical profiles of chemical parameters based on the historical stations and data in 2014: **b** – phosphates. The differences between the measurements east and west of the ridge are most clearly seen on the phosphate concentration. Light green stars show the measurements west of the ridge; pink color shows the measurements east of the ridge. Our data are shown with black triangles.

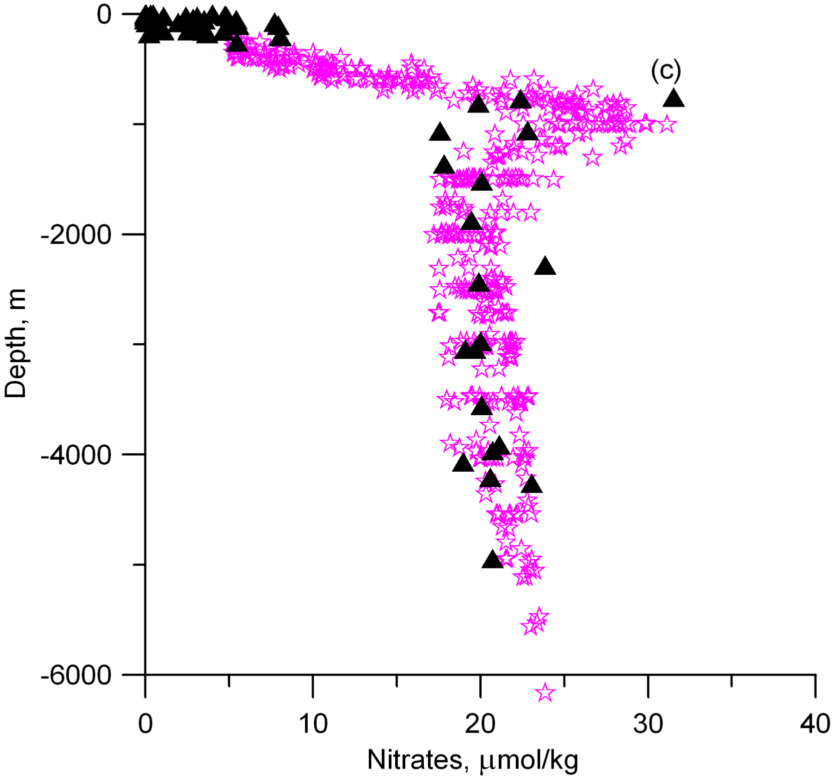

Figure 5c. Vertical profiles of chemical parameters based on the historical stations and data in 2014: **c** – nitrates. The differences between the measurements east and west of the ridge are most clearly seen on the phosphate concentration. Light green stars show the measurements west of the ridge; pink color shows the measurements east of the ridge. Our data are shown with black triangles.

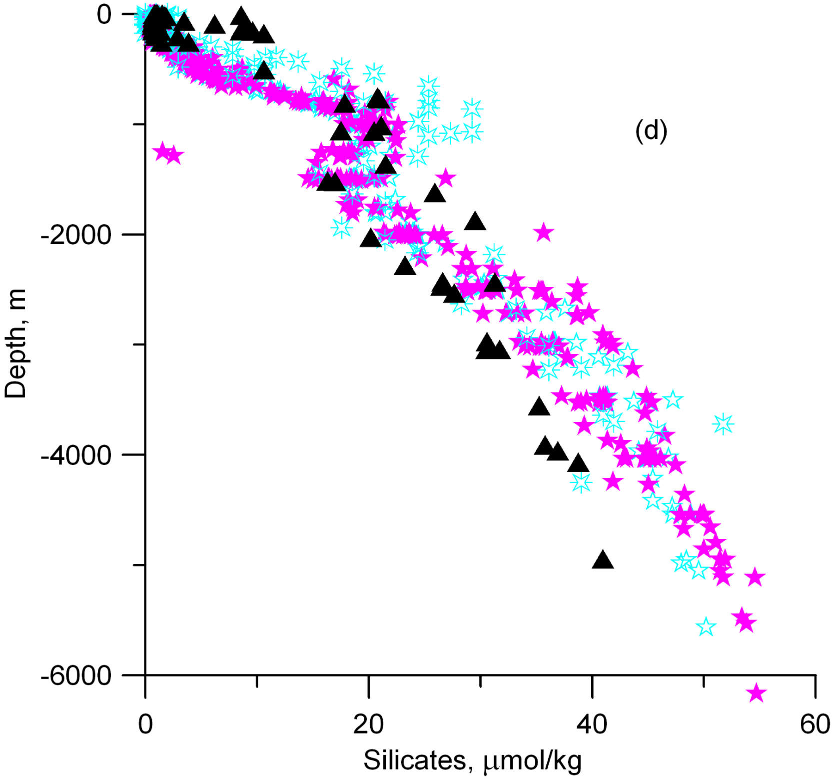

Figure 5d. Vertical profiles of chemical parameters based on the historical stations and data in 2014: **d** – silicates. The differences between the measurements east and west of the ridge are most clearly seen on the phosphate concentration. Light green stars show the measurements west of the ridge; pink color shows the measurements east of the ridge. Our data are shown with black triangles.

east of the ridge was performed on the basis of the WOCE A05 section along 24°N (Figure 6). Data in the east (38°W) are shown with red stars and the data in the west (54°W) are shown with blue stars. A short length of our study region from 46°to 47°W does not allow us to reveal notable differences in the nutrients. Concentration of nutrients in the layer of North Atlantic Deep Water is greater in the east. In the bottom layer of Antarctic Bottom Water the concentration of nitrates, silicates, and phosphates is greater in the west because Antarctic Bottom Water propagates to the East Atlantic thorough the Vema and Doldrums fracture zones located south of 11°N.

Analysis of the Measurements in 2014

Figure 7 shows the CTD-data of two stations in 2014 located along 16°39' N west and east of the MAR together with the data in 1992 and 2010. Since the slopes of the ridge were approximately 4000 m deep the data presented here do not characterize the deeper layers. The westernmost station is 2542 (western slope of the MAR) and the easternmost station is 2546. It is obvious that the θ,S-curve that characterizes the waters along 16°39' N latitude is located between the curves

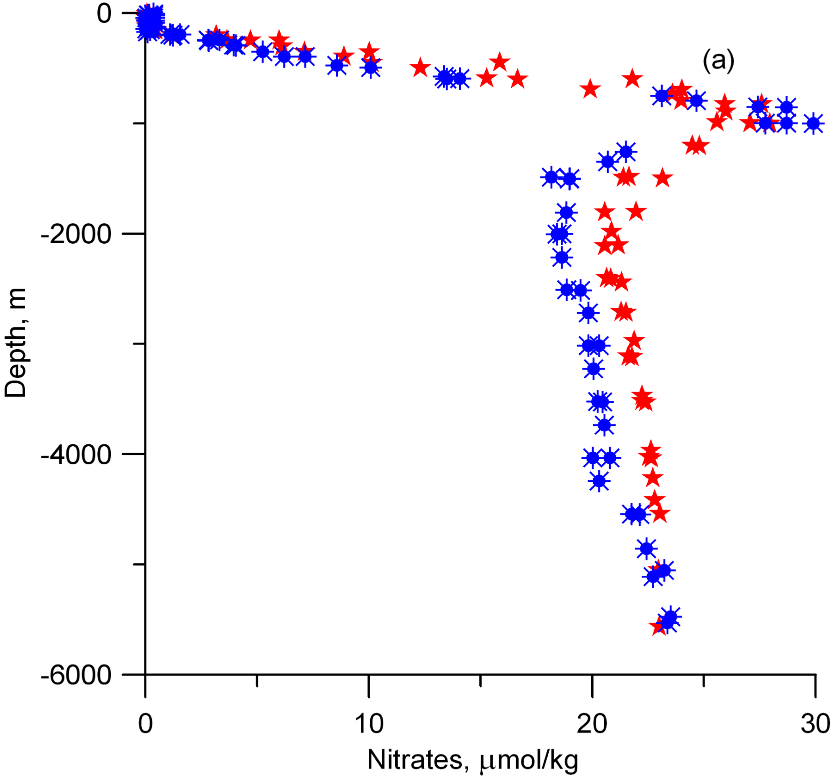

Figure 6a. Comparison of chemical parameters: **a** – nitrates east and west of the ridge along 24°N based on the WOCE section A05. Chemical parameters east of the ridge are denoted with red symbols and west of the ridge with blue symbols.

related to 7.5°N and 24°N.

According to the data of 2014, AABW over the slopes of the MAR were characterized by high con-

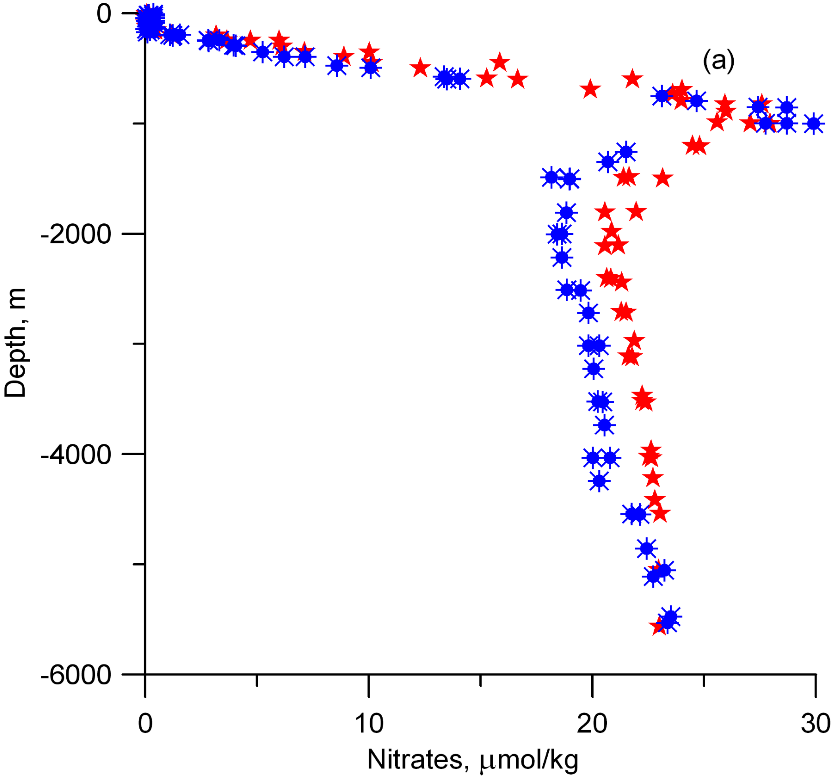

Figure 6b. Comparison of chemical parameters: **b** – phosphates east and west of the ridge along 24°N based on the WOCE section A05. Chemical parameters east of the ridge are denoted with red symbols and west of the ridge with blue symbols.

centrations of dissolved silicates (Figure 8). The bottom potential temperature at the westernmost station 2542 was cooler approximately by 0.3°C and fresher

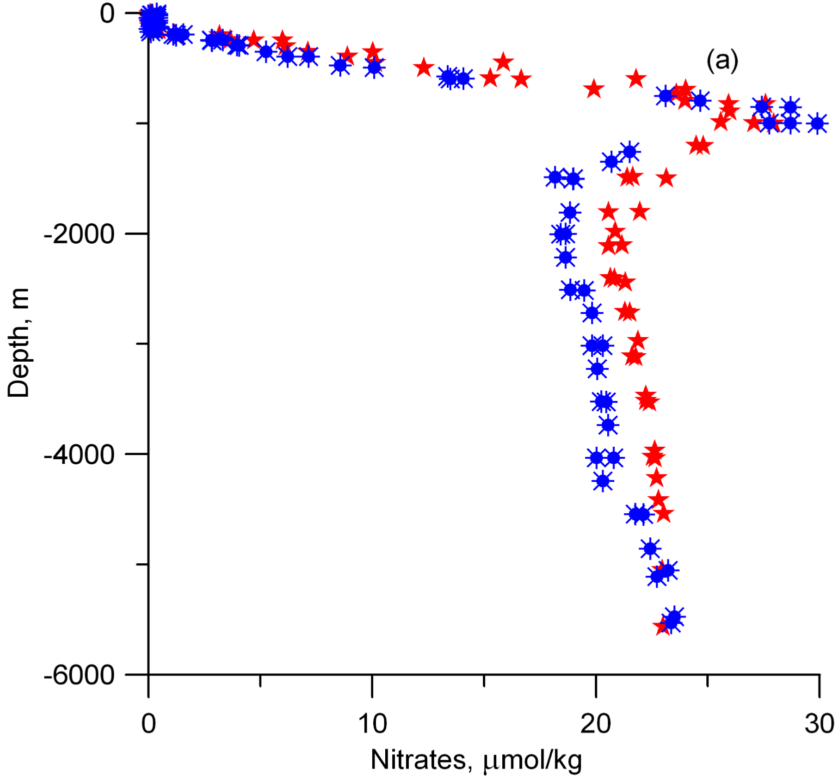

Figure 6c. Comparison of chemical parameters: **c** – silicates east and west of the ridge along 24°N based on the WOCE section A05. Chemical parameters east of the ridge are denoted with red symbols and west of the ridge with blue symbols.

by 0.05 psu than the water at the easternmost station 2546. However at equal depths the difference almost diminishes.

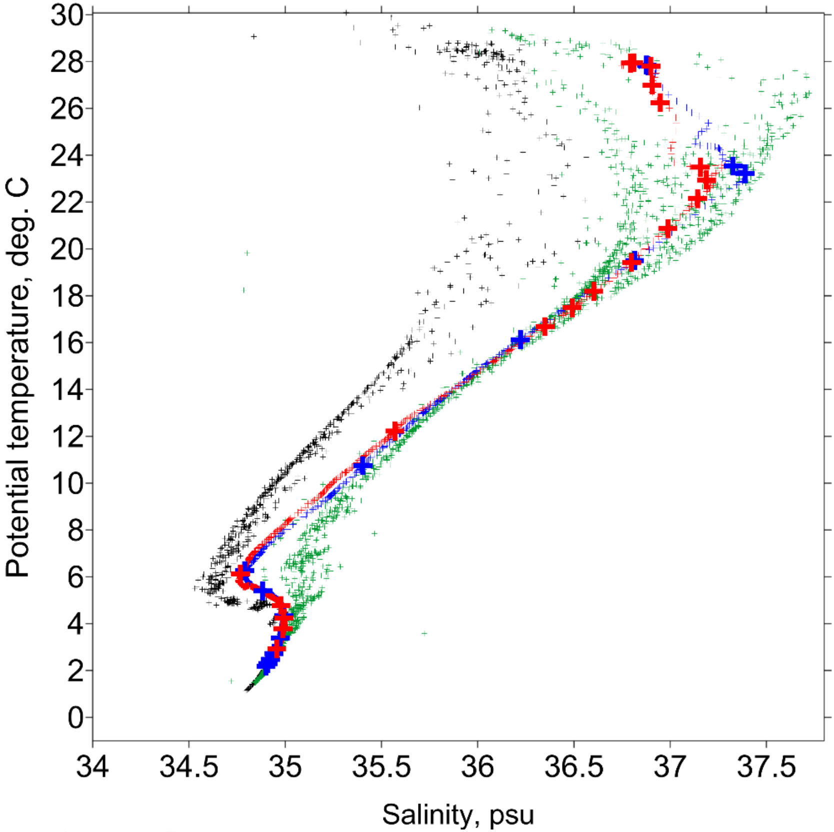

Figure 7. Relation between potential temperature and salinity. Black dots indicate the data from the WOCE A05 section in 1992; the green dots are related to the data of A06 section in 2010. Red dots and crosses correspond to the data of easternmost station 2546 in 2014. Blue dots and crosses indicate the data from the westernmost station 2542 west of the MAR. Large crosses denote the hydrochemical samples.

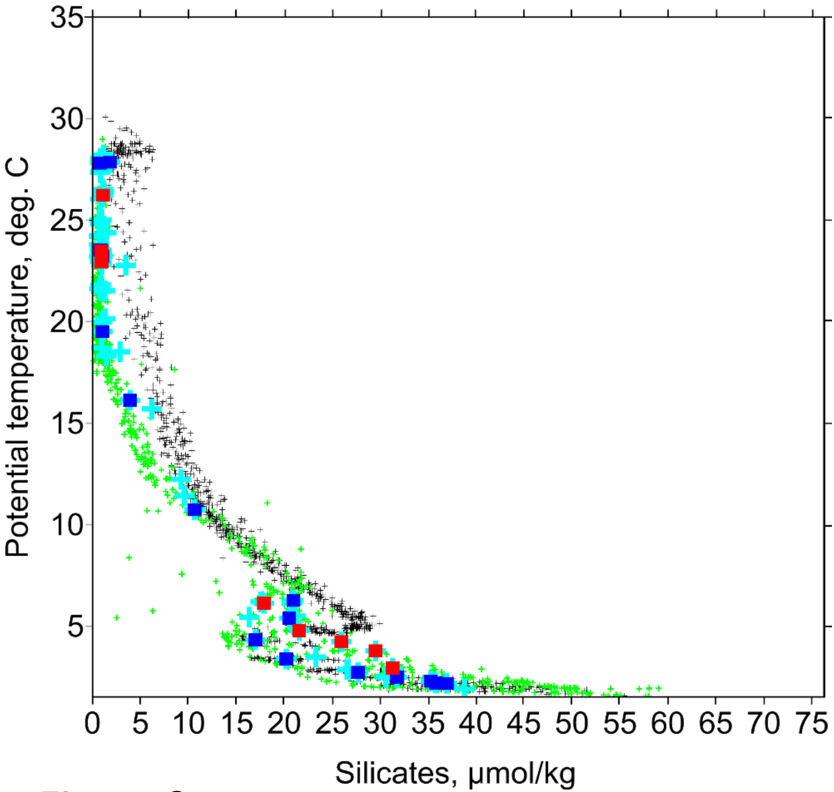

Figure 8. Comparison of the potential temperature–silicates relations over sections: in 2010 (green dots); in 1992 (black dots); in 2014 (red squares east of the MAR and blue squares west of the MAR).

North Atlantic Deep Water at these two stations had almost the same θ,S-properties. The maximum salinity (35.2 psu) was found at intermediate depths of NADW at temperatures of 3–5°C.

Comparison of potential temperature-silicates relations over three sections is shown in Figure 8. The distributions of silicates over three sections have similar features; the data in 2014 and in 2010 fall on the same curve (green, blue, and red dots). The data do not confirm the existence of an intermediate maximum of silicates at $T = 5^{\circ}$C, as it was found in 1992 over the 24°N latitude. In 2014, the concentration of dissolved silicates over the section along 16°39' N was at a level of 31–37 μMol/kg. However, we did not reach the depths of the maximum concentration of silicates in AABW.

Concentration of silicates over the sulfide section in 2014 was much smaller in the bottom layer than was found in the previous measurements. Concentration of silicates over the western MAR slope (37 μMol/kg) was greater than over the eastern slope (31 μMol/kg). Such small values can be explained by the fact that we did not reach the core of AABW over the sulfide section.

The graphs on Figure 7, Figure 8, and Figure 9 indicate that the properties of waters over the section along 16°39' N in 2014 are closer to the waters at 24°N (measured in 1992) than to the waters along section A06 at 7.5°N (measured in 2010).

We note that we found higher temperatures at station 2544 in the bottom part of the rift zone than over the MAR slopes (Figure 10). A temperature maximum was found at a distance of 400 m over the bottom. Three "yo-yo" profilings were made through this peculiarity. We lowered and raised the instrument three times in the range of the depths with this phenomenon. The profile is not conserved here during a time interval of half-hour when the "yo-yo" measurements were made. This makes us think that the temperature increase at the bottom is related to hydrothermal activity.

The measurements of currents along 16°39' N demonstrated that at the westernmost station (2542) the velocities are directed to the north. The velocities are close to 12–13 cm/s. The eastern component dominates at the station over the crest of the western ridge (2543) with a velocity of 9–10 cm/s. Velocities in the rift zone do not exceed 5 cm/s. At a distance of 200–300 m over the bottom we recorded a temperature increase by 0.05°C, which is possibly related to a warm plume. Velocities over the eastern crest of the ridge

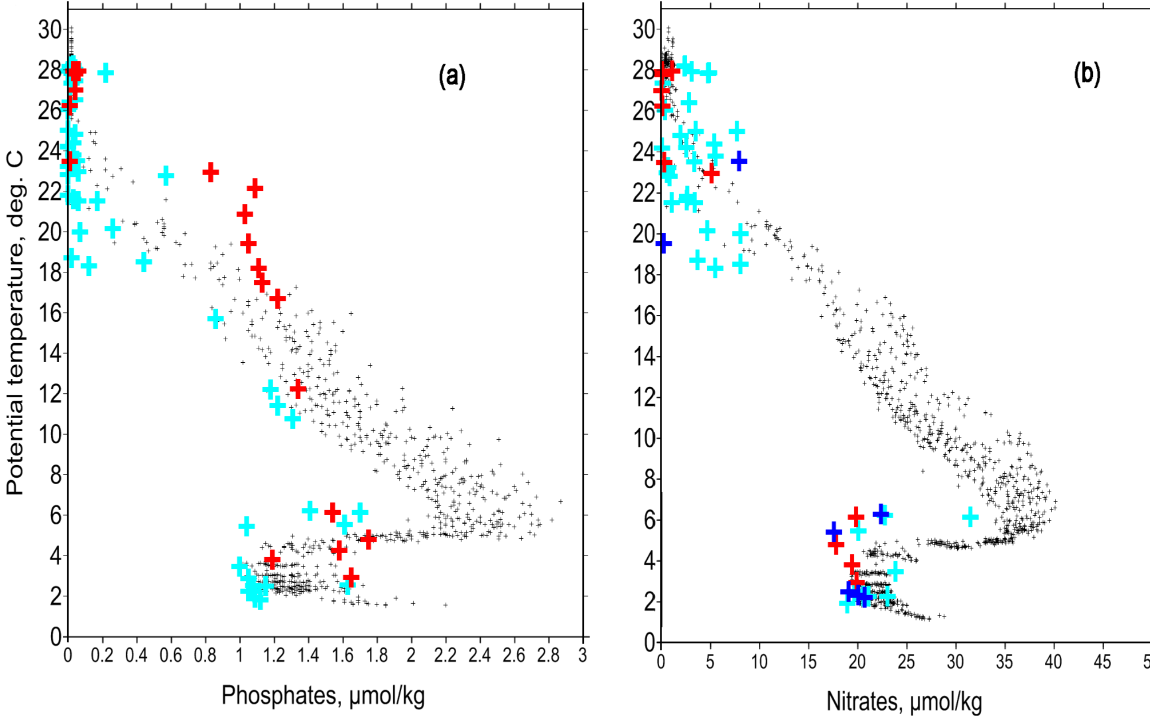

Figure 9. Relation between potential temperature and concentration of phosphates (a); potential temperature and concentration of nitrates (b) over the WOCE A06 section along 7.5°N in 2010 (black dots). Red crosses indicate the easternmost station of the sulfide section in 2014 (station 2546); blue crosses indicate the westernmost station (2542). Light blue crosses indicate all other measurements in 2014.

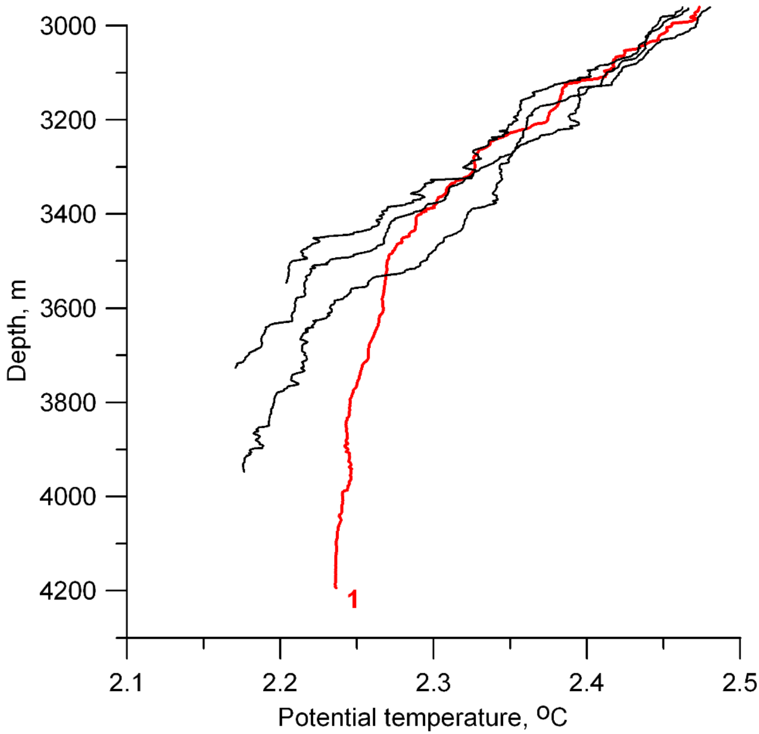

Figure 10. Vertical temperature profiles at stations to the west and east of the ridge (gray lines) and at station 2544 in the rift zone (red) (1). A temperature maximum exists at a distance of 400 m from the bottom. Three "yo-yo" profiles were made through this temperature anomaly. The profile was not stable during half-an-hour of this repeated profiling. This makes us think that the temperature increase over the bottom is caused by the hydrothermal activity.

(depth 2930 m) are low: 4–5 cm/s, however at the depths from 2040 to 2360 m a strong southerly flow is observed with velocities 38–40 cm/s. The velocities are directed to the south over the eastern slope, the velocities are within 12–15 cm/s.

Conclusions

Chemical properties of seawater west and east of the Mid-Atlantic ridge are different. The concentration of dissolved nutrients in the bottom layer east of the ridge is smaller than west of the ridge because Antarctic Bottom Water propagated to the east through abyssal fractures in the ridge and mixes with the overlying waters during its propagation.

We found a local temperature rise in the rift zone located at 16°39' N, which can be related to hydrothermal activity.

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