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Structure and Variability of Deep Waters in the Romanche Fracture Zone[1]

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Hydrophysical measurements in the Romanche Fracture Zone carried out in October 2005 were compared to the data of measurements in 1991. As a result, warming by 0.01°C was found in the core of North Atlantic Deep Water (NADW), and warming by 0.034°C was recorded in the layer of Antarctic Bottom Water (AABW). Our results confirmed the conclusions of Mantyla and Reid [7], according to which the major part of AABW passes to the Northeast Atlantic not through the Romanche Fracture Zone but through the Vema Fracture Zone at 11° N (Fig. 1).

The heat and salt balance of the deep part of the Word Ocean is significantly determined by the temperature and velocity of the global AABW transport. The pathways of AABW spreading from the Antarctic coast to mid-latitudes of the Northern Hemisphere in each of the three oceans are related to their geomorphological peculiarities.

It is likely that, in the bottom topography of the Atlantic Ocean, the AABW can spread to the northern latitudes only via two deep channels: the Romanche Fracture Zone (at the equator) and the Vema Fracture Zone (11° N). The Romanche Fracture Zone is a deep passage in the Mid-Atlantic Ridge 800 km long and 10 to 40 km wide (Fig. 2). The main sill across the fracture is located at a depth of 4350 m. The Vema Deep (7850 m) is the deepest place in the Vema Fracture Zone. Direct measurements of velocities in the Romanche Fracture Zone presented in [10] revealed easterly transport of the AABW at a rate of 1.2 Sv. According to the calculations of Schlitzer (see review in [10]), the transport of bottom water through the Romanche Fracture Zone varies from 2.6 to 5.1 Sv. According to the estimate given by Warren and Speer, the transport in zones deeper than 4000 m is equal to 2 Sv ([10]).

The history of hydrophysical studies in the Romanche Fracture Zone is longer than a century. The first measurements in this region were made in 1901. Later, the fracture zone was studied during the International Geophysical Year (1958) and during Soviet expeditions in the 1960s and 1970s, in particular, in 1967 onboard R/V *Akademik Kurchatov*. In 1991, onboard the French vessel *L'Atalante* within the Romanche-I project, a series of measurements using a thermohaline profiler was carried out and a wide range of hydrochemical parameters was determined in the fracture zone region. The data on this section (AR15, according to the WOCE classification) were taken from the WODB-2001 database. The data of deep-water stations from the same source were used to characterize the spreading of AABW in the eastern basin. Finally, a section was made with the participation of the authors in October 2005 (Cruise 19 of the R/V *Akademik Ioffe*). The section crossed the local sill of the fracture along 16° W (the shallowest depth is 4750 m) and coincided with the section in 1991. The measurements were made from the surface to the bottom using a SeaBird 911plus thermohaline profiler with 24 bottles for determining the concentration of oxygen, silicates, and phosphates.

In order to describe the structure and variability of water masses, the location of their core was determined using the core method [13], while the horizontal boundaries of water masses were determined on the basis of maximal vertical gradients of temperature and salinity [1, 2]. The structure of water masses is shown in Fig. 3. The characteristics of the main water masses in the Romanche Fracture Zone are given in the text on the basis of the expedition in 2005. Let us consider in more detail some parameters of two water masses occupying the lower part of the ocean hydrosphere.

The *North Atlantic Deep Water (NADW)* differs from the overlying and underlying Antarctic waters by greater salinity, temperature, and oxygen content, as well as low content of nutrients [6, 12]. It is considered

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[1] The article was translated by the authors.

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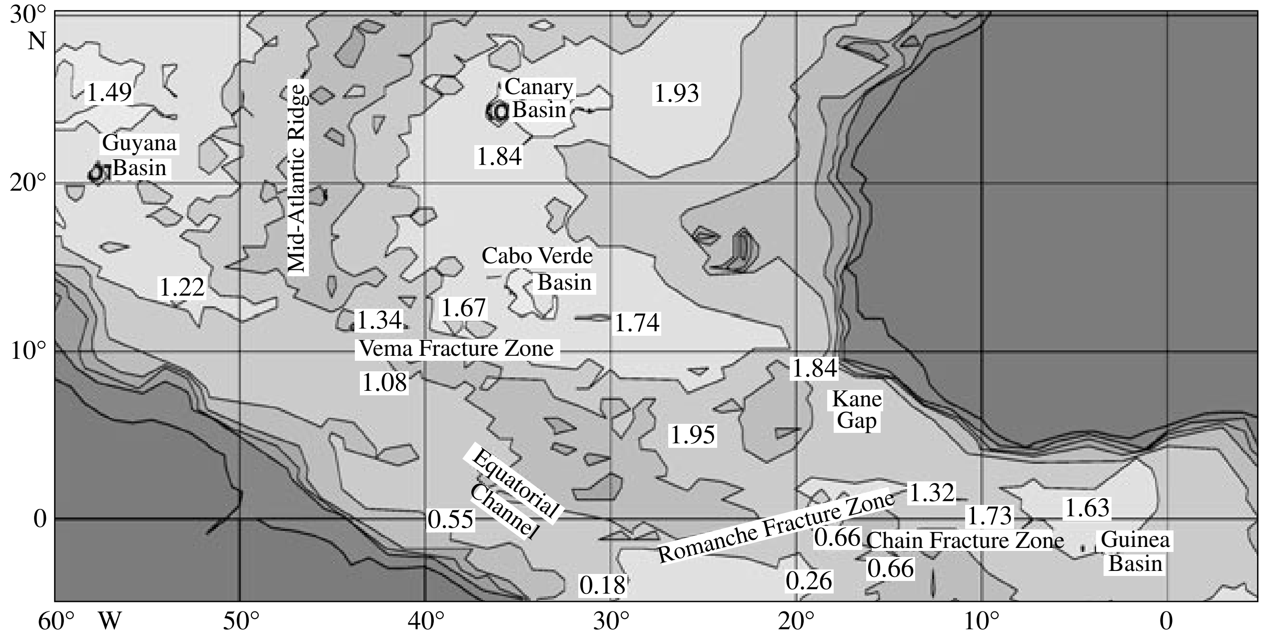

Fig. 1. Main forms of bottom topography in the tropical Atlantic. Values of potential temperature at the bottom are indicated.

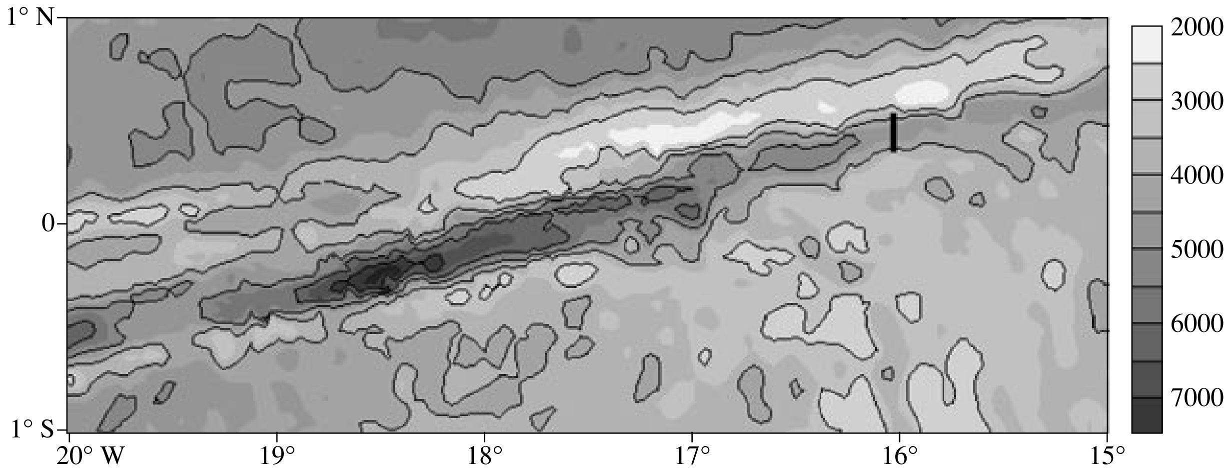

Fig. 2. Bathymetry in the region of the Romanche Fracture Zone. Vertical line indicates the location of section occupied by R/V *Akademik Ioffe* along 16° W.

that NADW consists of a few sublayers. According to the most popular concept [1, 3, 4], the NADW consists of upper, middle, and lower components (UNADW, MNADW, and LNADW).

The UNADW occupies the layer between 1100 and 2250 dbar, which corresponds to the isopycnal interval $\sigma_2 = 36.60$–37.00. The vertical boundaries of this layer differ from the interval 1300–1900 m indicated in [10] published on the basis of the results of the expedition in 1991. The salinity maximum (34.975 psu) corresponding to the main core of the entire NADW is located within the UNADW at a depth of 1700–1800 dbar ($\sigma_2 = 36.88$). Minimal concentrations of phosphates (1.4 μM/kg) and silicates (less than 20 μM/kg) are also located in this core. A local maximum of oxygen concentration (5.76 ml/l) is located in the UNADW layer at a depth of 2000 dbar, although this peculiarity was associated with the MNADW core in the earlier period [10].

The MNADW layer reaches depths of 3400–3500 dbar ($\sigma_2 = 37.00$–37.06), where its characteristic minimum of oxygen concentration (5.66 ml/l) is located (approximately at a depth of 3000 dbar). In some papers, MNADW is associated with the maxi-

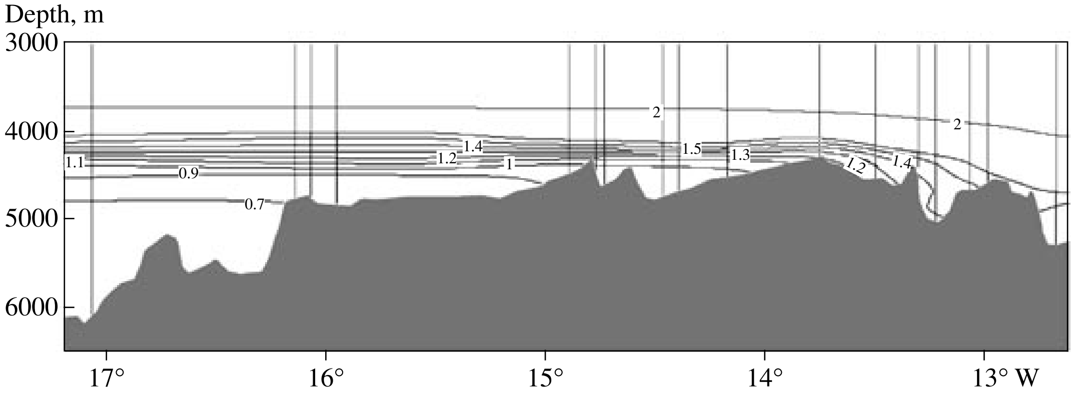

Fig. 3. Potential temperature section (°C) along the Romanche Fracture Zone based on the data in 1991. Vertical lines show location of stations.

mum of oxygen concentration [10], while other authors [3] associate it with the minimum of freon concentration. The position of the boundaries found between water masses suggests that the latter concept seems to be more correct. The estimate of the lower MNADW boundary is close to the value of $\sigma_2 = 37.07$, which is close to the corresponding value indicated in the papers of Fu and Macdonald (see review in [1]). The location of the upper MNADW boundary is not given in these papers.

The LNADW layer is located within the depths from 3500 to 4200 dbar, which correspond to the density interval $\sigma_2 = 37.06$–37.11. The upper LNADW boundary coincides with the local phosphate maximum (up to 1.5 μM/kg), which changes to the local minimum in the LNADW core (less than 1.35 μM/kg) at a depth of 3800 dbar ($\sigma_2 = 37.08$), where a deep oxygen maximum (5.93 ml/l) is also found. According to the data of the French expedition, the deep maximum of freon concentration was also found at 3800 dbar.

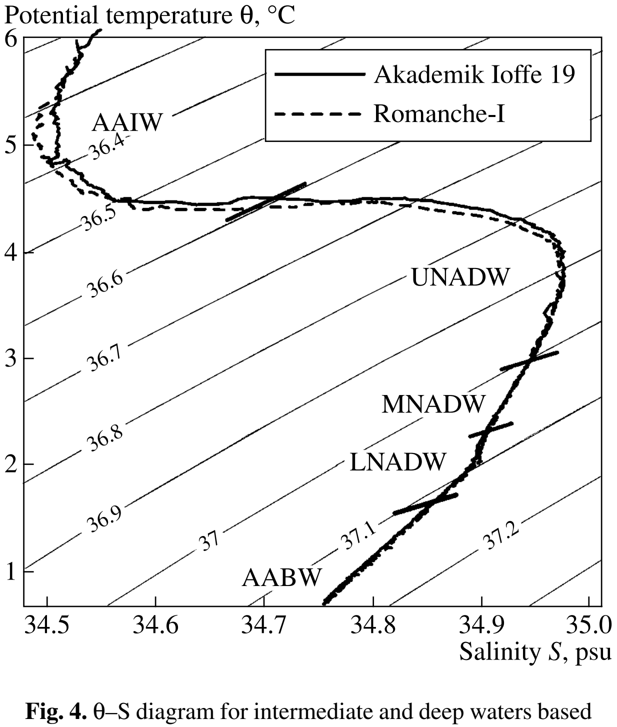

Fig. 4. θ–S diagram for intermediate and deep waters based on the data of the deepest stations in the expeditions of 1991 and 2005. Boundaries of water masses are shown and their names are indicated. Designation of abbreviations is given in the text.

The *Antarctic Bottom Water (AABW)* has the greatest density in the studied section. It is characterized by the absolute maximum of potential temperature (0.72°C), bottom minima of salinity (34.755 psu), and dissolved oxygen concentration (5.3 ml/l) and the maxima of phosphate concentration (up to 2 μM/kg) and silicates (95 μM/kg). No significant inhomogeneities in the vertical distribution of the characteristics under study were found in the AABW layer. Therefore, we did not divide this quasi-homogeneous water mass into individual sublayers.

It was mentioned above that the Romanche Fracture Zone is interesting from the point of view of studying the AABW transport from the southwestern basin of the Atlantic Ocean to its northeastern basin. One can see in Fig. 4 that sills crossing the fracture zone are located east of the Vema Deep. These sills are orographic obstacles for the AABW propagation. Only the upper part of the AABW layer, which changed its threshold density under the influence of LNADW, can overflow these barriers. Consequently, the AABW potential temperature changes from 0.7°C to 1.4°C; salinity, from 34.75 to 34.82 psu; density, from $\sigma_2 = 37.15$ to 37.10 (or σ_4 from 46.00 to 45.91); oxygen concentration, from 5.4 to 5.8 ml/l; and silicate concentration, from ~100 to ~70 μM/kg.

The study of further propagation of AABW requires determination of its upper boundary. Judging from the location of the maximal vertical gradients of temperature and salinity, this boundary is located at a depth of $\sigma_2 = 37.11$ (or $\sigma_4 = 45.94$), which is close to independent estimates made in the papers by Fu, Macdonald, Temperature (°C) of deep and bottom waters in the Romanche Fracture Zone

Level	Expedition and year						
	Albatross, 1948	*Crawford*, 1958	*Chain*, 1965	*Meteor*, 1965	*Akademik Kurchatov*, 1967	*Akademik Vernadskii*, 1969	*Mikhail Lomonosov*, 1972
4000 m	1.75	1.66	1.61	1.64	1.77	1.57	1.54
7000 m	0.63	0.64	0.62	0.60	0.65	0.66	0.67

and Roemmich (see review in [1]). Let us note that estimates of the location of this boundary based on the isotherms of potential temperature 2°C [4] and 2.07°C [3] differ by 400–500 m, which makes the previous choice of the UAABW boundary ambiguous. This strongly influences the interpretation of properties of the UAABW and the determination of its spreading region.

Abyssal waters with the lowest potential temperature at the bottom in this region (1.74°C) were first found in 1927 in the Cabo Verde Basin by Wust [13] on the basis of the *Meteor* expedition. The presence of these waters in the region was explained in the paper by Worthington and Wright (see review in [9]) by their propagation through the Romanche Fracture Zone and further through the Kane Gap. Heezen et al. (see review in [9]) write about penetration of AABW to the northeastern part of the ocean through the Vema Fracture Zone (11° N). They note that the low intensity of this transport results in a weaker influence on the abyssal region of the Eastern Atlantic relative to the waters that pass through the Romanche Fracture Zone. According to [7], these waters influence only the equatorial and southeastern Atlantic, whereas the bottom waters are transported to the northeastern part of the ocean through the Vema Fracture Zone. According to the results of Worthington and Wright (see review in [9]), waters with $\theta < 1.8$°C do not pass through the Kane Gap, while the authors of [9] consider that there are no AABW at all.

The depths of the Kane Gap and the channel between the Sierra Leone Rise and Mid-Atlantic Ridge do not allow the AABW to flow along the mentioned depressions of the bottom bypassing the Romanche Fracture Zone. This fact is consistent with the supposition put forward in [7, 9]. The near-bottom potential temperature 1.84°C and density $\sigma_4 = 45.88$ in the Kane Gap region are similar to the characteristics in the passage between the Cabo Verde Basin and Canary Basin. In the region between the Sierra Leone Rise and Mid-Atlantic Ridge, the density is even lower ($\sigma_4 = 45.86$) and potential temperature is higher than 1.95°C. All these facts indicate that the Vema Fracture Zone, rather than the Romanche Fracture Zone and Kane Gap, is the main pathway for the bottom waters to the northeastern part of the Atlantic. These facts also confirm the concept proposed in [7].

The size of the AABW spreading region strongly depends on the method of determining its upper boundary. If it is determined on the basis of isopycnals $\sigma_4 = 45.92$ ($\sigma_4 = 45.94$) or $\sigma_2 = 37.1$, the AABW spreading region in the eastern basin is limited to a small space near the Romanche and Vema fracture zones. If we take the $\theta = 2$°C isotherm as the boundary, the AABW occupies the major part of the eastern basin (Fig. 1). It is clear that a part of AABW is present in the NADW layer due to transformation. However, it is generally accepted that AABW is not present in the eastern basin in the pure form.

The eastern side of the Mid-Atlantic Ridge incorporates the Eastern Basin Bottom (or Abyssal) Water, a transformation product of the Antarctic Bottom Water, which is characterized by low salinity, low concentration of dissolved oxygen, and high content of silicates and nitrates [11].

If we compare the changes in the deep layer from 1991 to 2005, we can note the following regularity: a temperature increase of 0.01°C and salinity increase of 0.004 psu was found in the NADW core (this corresponds to a maximum of salinity), while a temperature increase of 0.034°C and salinity increase of 0.001–0.002 psu were observed in the bottom layer. However, one should keep in mind that high horizontal gradients along the fracture zone can introduce errors in the results of determining the temporal variability of waters due to the lack of coordinate coincidence of repeated stations measured at a fixed point.

Since the initial formation of characteristics of deep and bottom ocean waters occurs in the upper layer, there are grounds to think that they can conserve climatic signal in their temperature field for a long time during their gradual sinking to the depths. Hence, the observed warming of NADW in the Romanche Fracture Zone is related to the warming of these waters in the tropical North Atlantic [14]. In particular, this can be related to the temperature increase in the initial NADW in their source (Labrador Basin), which has actually been observed from the beginning of the 1970s [5]. The travel time of such a climatic signal from the source to the equator is estimated at 25–40 yr [5, 8, 12].

In this relation, it is useful to analyze additional materials of earlier observations. Although these observations had a lower accuracy as compared with the modern data, they can still be applied to determine the dominating tendency of water temperature change at abyssal depths. Therefore, we present the table with a time series of instrumental measurements of water potential temperature θ in the Romanche Fracture Zone within the layers of NADW (4000 m) and AABW (7000 m) based on the data of several known expeditions [15].

The data presented in the table demonstrate significant fluctuations of temperature in the NADW layer, but no gradual secular climatic trend in NADW can be seen. At the same time, warming of the AABW by 0.0n°C is undoubtedly observed starting approximately from the second half of the 20th century.

Thus, on the basis of the analysis performed in this work, we can make the following conclusions:

(1) After passing through the Romanche Fracture Zone, the Antarctic Bottom Water spreads only to the southeastern and equatorial parts of the Atlantic. Its further propagation to the north is limited by the Kane Gap. Bottom waters transported predominantly through the Vema Fracture Zone (11° N) spread into the Northeastern Atlantic. This fact confirms the conclusions presented in [7].

(2) In 2005, a temperature increase of 0.01°C and salinity increase of 0.004 psu, as compared to 1991, were recorded in the NADW core in the Romanche Fracture Zone.

(3) In the AABW layer, a temperature increase of 0.034°C and salinity increase of 0.001–0.002 psu, as compared to 1991, were found in the Romanche Fracture Zone.

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