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Transport of Bottom Waters through the Vema Fracture Zone in the Mid-Atlantic Ridge*

A. N. Demidov[a], **Corresponding member of the RAS S. A. Dobrolyubov**[a],
E. G. Morozov[b], **and R. Yu. Tarakanov**[b]

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This paper is dedicated to the study of structure and transport of deep and bottom waters through the Vema Fracture Zone (11° N) in the Mid-Atlantic Ridge. In 2006, during an expedition onboard R/V *Akademik Ioffe*, a survey of 25 CTD-stations was carried out in the study region with a size of 15 × 15 km over the main saddle of the Vema Fracture Zone at 41° W. Strong spatial variability of water mass characteristics was found in the study region. A strong easterly flow was found in the main part of the channel with velocities up to 30 cm/s. This flow includes Antarctic Bottom Water (AABW) and lower part of the North Atlantic Deep Waters (NADW). It was found that the transport of AABW is within 0.11–0.64 Sv (1 Sv = 10^6 m^3/s). A decrease in the potential temperature of bottom waters by 0.027°C was found compared to 1994.

Recently, deep-water fractures, troughs, and channels between large oceanic basins became interesting objects of research. These investigations allow us to characterize water exchange in the deep water parts of the ocean through narrow channels. This cannot be obtained in the modern global circulation models even at high resolution. At the same time, observations indicate that strong velocities reaching a few tens of cm/s are observed in deep layers of the ocean [1].

Antarctic Bottom Waters occupy the bottom position over the major part of the Atlantic Ocean. The bottom topography has a special determining influence on their propagation and properties. The core of AABW is located at the bottom. Therefore, only the upper part of the waters overflows each topographic obstacle. The characteristics of the core of this watermass change strongly due to mixing with overlying waters. Everywhere in the Atlantic Ocean, AABW is characterized by low temperature, low salinity, and high content of nutrients compared to the overlying waters [1].

In the Atlantic Ocean, AABWs are formed over the continental slope of Antarctica in the Weddell Sea as a result of mixing between Antarctic Shelf Water and Circumpolar Deep Water [9]. Not more than 5.0–6.8 Sv of AABW spreads to the Atlantic Ocean north of the Antarctic Circumpolar Current, and only 1–2 Sv reach the Equatorial Channel [10].

The Vema Fracture Zone (11° N) and Romanche Fracture Zone at the equator are the main channels for bottom water transport from the western to the eastern part of the Atlantic Ocean. Previous investigations [7, 8] showed that the waters transported through the Romanche Fracture Zone influence only the equatorial and southeastern parts of the Atlantic, whereas the Vema Fracture Zone is the main pathway for the bottom waters to the northeastern part of the Atlantic. It is commonly accepted that AABW does not exist in pure form in the East Atlantic. Instead, the eastern area of the Mid-Atlantic Ridge (MAR) incorporates the Bottom Water of the Eastern Basin, which is a mixing product of the Antarctic Bottom Water transformation [12]. In many places, the MAR also serves as an obstacle for the propagation of the lower part of North Atlantic Deep Waters (LNADW), which can propagate only through some of the transform fractures. The LNADW is located within the layer from 3700 to 4100 m. A deep maximum of oxygen and freon concentration is found in the core of this water.

The Vema Fracture Zone was found only in 1956. It is located along 11° N from 45 to 40° W. Its width is 8–20 km, and the maximal depth is approximately 5200 m. According to the survey carried out by the Geological Institute of the Russian Academy of Sciences used in our expedition as a guideline, three approximately equal saddles exist in the fracture zone located at 41.02°, 40.92°, and 40.88° W at depths of

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* This article was translated by the authors.

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[a] *Geographical Faculty, Moscow State University, Leninskie gory, Moscow, 119991 Russia*
[b] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Nakhimovskii pr. 36, Moscow, 117997 Russia*
e-mail: egmorozov@mail.ru

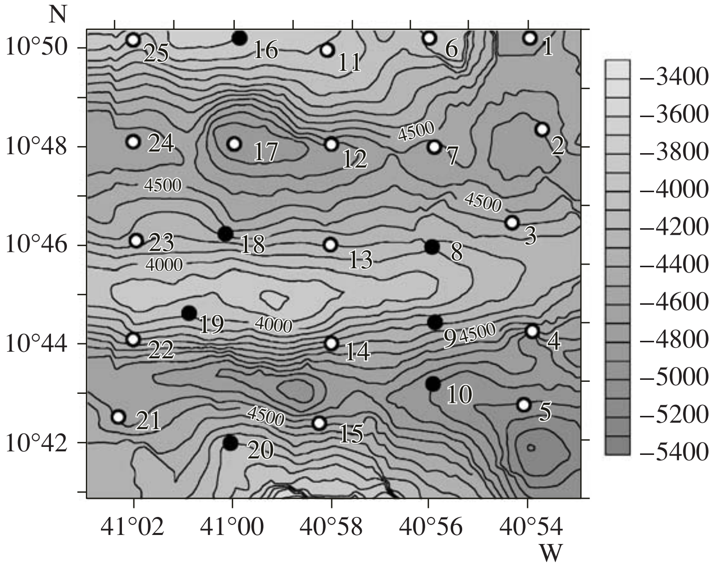

Fig. 1. Bathymetric chart in the region of the Vema Fracture Zone based on the measurements in Cruise 22 of R/V *Akademik Ioffe*. Dots indicate the locations of stations when the instrument was at the bottom. Points with LADCP measurements are highlighted.

4690, 4650, and 4660 m, respectively. Depth measurements using an ELAC LAZ 4700 echo sounder during the investigations in cruise 22 of R/V *Akademik Ioffe* in 2006 allowed the introduction of corrections to the previous surveys and compilation of a chart (Fig. 1). During the expedition of R/V *Akademik Ioffe* in October 2006, the study region was surveyed at 25 CTD stations using a Sealogger SBE-25 probe in the region of three saddles of the Vema Fracture Zone (40.5–41° W). One additional station located west of the study region (41.94° W) repeated the station in 1994 occupied by R/V *Meteor*. The study region was located in the main part of the fracture zone. Only two southern stations on each of the sections were located in an isolated basin separated by an elevation from the main part of the fracture zone. At 18 stations of the survey, the measurements were carried out using an RDI Workhorse Sentinel lowered acoustic Doppler current profiler (LADCP). Thus, the total numbers of CTD stations (21) and direct LADCP measurements (3 stations) made in the cruise described here exceeded the respective numbers during the previous history of research in the fracture zone.

The Antarctic Bottom Water in the deep-water part of the Vema Fracture Zone is a well-mixed (due to bottom and lateral friction) jet in the bottom layer up to 700 m thick [4]. The authors of [4] distinguish thermocline (benthal [4]) and transition gradient zones at the boundary with the NADW. These zones differ in the vertical temperature gradients, which are equal to 0.0012°C/m and 0.0004°C/m, respectively. The maximal thickness of the transition zone reaches 300 m in the eastern part of the fracture zone. The benthic thermocline is located 1200 m above the bottom with temperature $\theta = 1.55–1.99°C$. In the paper cited above, its origin is related to the waters of a two-degree interface distinguished by Broker et al. in [2]. They are located at a significant distance south of the study region. These waters are formed in the region of the Rio Grande Rise due to diffuse interaction between AABW and NADW or due to intensification (or weakening) of the inflow of NADW (or AABW).

The problem of limits of the spreading of bottom waters and their structure is closely related to the choice of their upper boundary and structure of the AABW layer. The estimate of AABW transport and the region of AABW spreading in the Northeast Atlantic changes strongly due to the differences in the choice of this boundary. Based on different estimates of the location of boundaries, which are within the range of $\theta = 1.5–2°C$ and σ_4 45.895–45.920 for the fracture zone, the transition zone is assigned or not assigned to the AABW layer. In rare cases, the zone is divided into parts.

A quasi-homogeneous AABW layer (thickness 400–500 m, $\theta = 1.34°C$) at the bottom was recorded at the distant western station. While propagating to the east, the flow reaches the main saddle region (station 22 area) after passing the western saddle and the relatively smooth bottom topography. At station 22, the flow is approximately 100 m thick and its temperature is $\theta = 1.36°C$. Near station 19, its thickness increases to 200 m and θ increases to 1.395°C, which probably indicates strong mixing in the bottom layer. The temperature at point 9 (the second saddle area) is higher than at point 12, indicating the spatial inhomogeneity of the flow. Finally, a temperature jump in the mixed layer is recorded at point 2 following the second saddle. Based on the bottom temperature distribution at the station in the depression (point 5) located south of the elevation, which separates the depression from the main

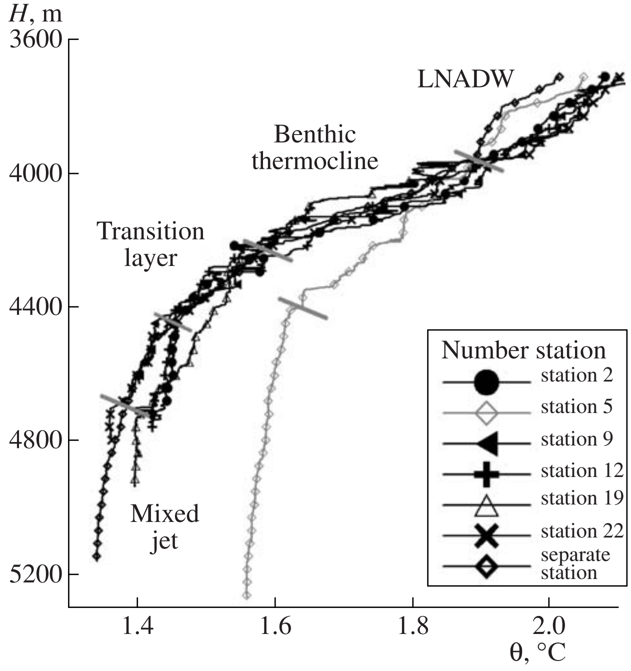

Fig. 2. Depth variation of potential temperature at several stations in the Vema Fracture Zone.

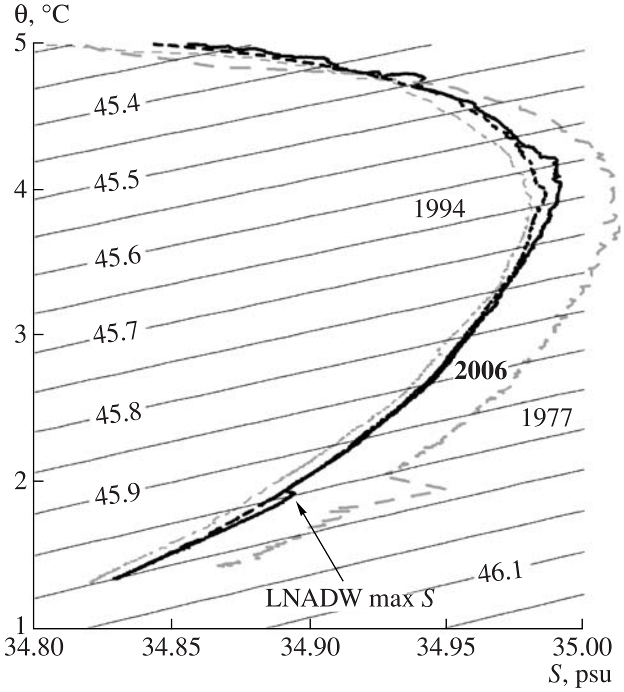

Fig. 3. θS-diagram for the bottom layer waters in the Vema Fracture Zone based on the data of 1977 and 1994 with nearest stations in 2006 (shown in black; station 2 of the study region is shown with a dashed line, and the remote station is shown with a solid line). Isopycnals of σ_4 are shown.

channel (Fig. 2), we can conclude that the AABW jet part mentioned above, which is characterized by the lowest temperatures, does not get into the depression basin. The temperature at the depression bottom corresponds only to the upper part of the transition zone in the main channel.

Since the determination of the upper AABW boundary is ambiguous and the total transport depends strongly on this fact, we used in this work different versions of the location of the upper AABW boundary coinciding with isotherms $\theta = 1.5$, 1.8, 1.9, and 2.0°C. A local salinity maximum (Fig. 3) was found at a depth of 3850 m at the station west of the study region. This maximum indirectly confirms the opinion in [6] about the existence of recirculation flow of LNADW in the western basin of the Atlantic. Based on the difference in the LNADW layer structure, which is manifested as a salinity increase in the southern part of the study region, one can suppose that this water flows to the east along the southern slope of the fracture after penetration of the fracture zone. In previous studies, the existence of the above-mentioned local maximum of salinity in the LNADW layer was not mentioned.

At the stations located in the saddle area, no notable long-term temperature variations were found between the measurements in 1977 and 2006. Temperature variations exceeding 0.06°C were found near the 4000-m isobath, which possibly evidences the variation in the location of the upper AABW boundary. The salinity differences reaching 0.05 psu are explained by insufficient accuracy of old measurements in 1977. An increase in θ by 0.027°C and salinity by 0.009 psu was found between measurements at the distant station in 2006 and the measurements from the R/V *Meteor* in 1994 in the AABW core. Comparison of the depth distribution of velocity during direct measurements of currents in 1994 and 2006 showed a decrease in the transport in the bottom part of the channel in 2006 (Fig. 3).

The first estimate of AABW transport through the Vema Fracture Zone was obtained in [13] based on the data of two current meters at depths of approximately 5040 m. These data showed that the mean velocities were approximately equal to 2.9–3.7 cm/s, while the maximal observed velocity reached 33 cm/s. The authors of [4] recorded an easterly current at a depth of 4790 m with the maximal velocity equal to 3 cm/s (mean velocity 0.07 cm/s) observed for 11 days. The calculation of geostrophic velocities allowed the authors of [8] to estimate the velocities in the bottom layer as 20 cm/s. Velocity measurements using LADCP from R/V *Meteor* [5] indicated the presence of maximal velocities equal to 20 cm/s at a depth of 4200 m in the middle of the channel. It should be noted that the authors reported some malfunctions of the instrument. Table 1 presents results of the determination of the AABW transport.

The measurements carried out in Cruise 22 of R/V *Akademik Ioffe* in 2006 allowed us to estimate the absolute values of velocities and calculate the total trans-

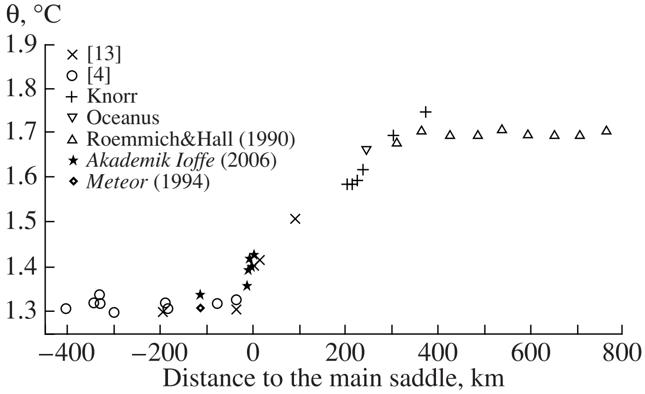

Fig. 4. Potential temperature at the bottom as a function of the distance from the main saddle of the Vema Fracture Zone. Combined data from [8] and the data of the new expeditions are presented.

ports of deep and bottom waters in the study region on the basis of LADCP measurements. The main transport of AABW and LNADW in the main part of the Vema Fracture Zone was observed not at the bottom but in the layer between 3700 and 4000 m (maximal LADCP velocities), i.e., near the upper AABW boundary. A strong flow of AABW confined to the southern slope is observed in the velocity distribution on the sections based on LADCP measurements. At the same time, the depth of the flow decreases in the course of its flow to the east. The maximal velocities (30 cm/s) recorded on the eastern section practically coincided with the zones of decrease in temperature and salinity of vertical gradients. The main AABW transport over the secondary saddle is concentrated at some distance from the bottom, while the velocities appear close to zero below this layer. This fact also explains its notable layering.

Table 2 presents values of the transport of bottom waters recorded in the Vema Fracture Zone. The estimates of AABW transport differ significantly depending on the method of determination of the fracture section area in the section plane and the method of extrapolation of the current velocities in the section area, where the bottom waters exist but measurements are lacking. We also performed separate calculations, which do not take into account the transport beyond the main channel within the study region lacking direct flow of AABW. One should keep in mind that current velocities measured with the LADCP also include the influence of tides and other periodical motions. Finally, the values of transports over the meridional sections differ by a factor greater than 1.5. Therefore, the final estimates are presented in this paper only in the form of the interval.

Values of the AABW transport through the Romanche Fracture Zone at the equator in the eastern saddle region during the expedition of R/V *Akademik Ioffe* in 2005 were calculated similarly based on current measurements using the same LADCP instrument. In general, the estimates of transports appeared to be significantly smaller than those reported in the literature with the upper AABW boundary based isotherm $\theta = 2°C$ isotherm. The maximal estimate of transport reached only 0.64 Sv. A smaller amount of cold waters (with $\theta < 1.5°C$) is transported through the Vema Fracture Zone than through the Romanche Fracture Zone because these waters almost do not reach the Vema Fracture Zone along the longer pathway in the western part of the Atlantic.

The representativeness of calculations in this work is confirmed by close values of transports over three sections (Table 2).

The analysis of measurements allows us to make the following conclusions:

(1) A strong easterly flow of bottom waters with velocities up to 30 cm/s was distinguished. The easterly flow is displaced to the southern slope of the main channel, and the depth of the flow decreases.

(2) The estimate of transport of Antarctic Bottom Waters is within 0.11–0.64 Sv, which is significantly smaller than the value given in previous publications.

(3) An increase in the potential temperature by 0.027°C as compared to 1994 was recorded in the bottom water layer in the Vema Fracture Zone. Compari-

Table 1. Transport of Antarctic bottom waters in the Vema Fracture Zone in the eastern direction based on literature data

Source	AABW boundary, θ (°C)	Transport, Sv	Comments
[12]	1.5	0.05–0.46	Moored current meter
[11]		0.0–0.7	Box model
[8]	2	2.08–2.24	Geostrophic transport. Reference surface $\theta = 2.17–2.43°C$
[8]	1.5	0.46	
[5]	2	1.8–2.0	Combination of geostrophic transport and LADCP data at 42° W
[5]	$\sigma_4 = 45.9$	2.1–2.4	
[10]		1.1	Correction of the results of Fischer et al. related to the inclusion of the LNADW part into the AABW layer
[12]	1.8	2	

Table 2. Transport of bottom waters (Sv) at different versions of the upper AABW boundary in the Vema and Romanche fracture zones

Boundary, θ, °C	Western section, stations 21–25	Central section, stations 11–15	Eastern section, stations 1–5	Romanche Fracture Zone
2.0	0.15–0.64	0.13–0.21	0.23–0.46	0.28–0.78
1.9	0.14–0.51	0.13–0.21	0.19–0.40	0.15–0.48
1.8	0.12–0.37	0.11–0.18	0.13–0.32	0.15–0.44
1.5	0.01	0.04	0.02	0.13–0.38

son of potential temperatures with the data of 1977 did not reveal any significant variability.

(4) We recorded a local salinity maximum in the lower component of North Atlantic Deep Water and an increase in its values in the southern area of the study region. Probably, these waters propagate to the east (mainly near the southern slope of the fracture). This result refines the scheme presented in [6].

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