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# SPREADING OF ANTARCTIC BOTTOM WATER IN THE ATLANTIC OCEAN

ABSTRACT. This paper describes the transport of bottom water from its source region in the Weddell Sea through the abyssal channels of the Atlantic Ocean. The research brings together the recent observations and historical data. A strong flow of Antarctic Bottom Water through the Vema Channel is analyzed. The mean speed of the flow is 30 cm/s. A temperature increase was found in the deep Vema Channel, which has been observed for 30 years already. The flow of bottom water in the northern part of the Brazil Basin splits. Part of the water flows through the Romanche and Chain fracture zones. The other part flows to the North American Basin. Part of the latter flow propagates through the Vema Fracture Zone into the Northeast Atlantic. The properties of bottom water in the Kane Gap and Discovery Gap are also analyzed.

KEY WORDS: Abyssal channels, Vema, Romanche, Chain, Kane, bottom water

## INTRODUCTION

Antarctic Bottom Water (AABW) is formed over the Antarctic slope as a result of mixing of the cold and heavy Antarctic Shelf Water with the lighter, warmer, and more saline Circumpolar Deep Water [Orsi et al., 1999]. In the region of origin, Antarctic Shelf Water is formed in the autumn-winter season over the Antarctic shelf due to cooling of the relatively fresh Antarctic Surface Water to nearly freezing point temperature and increased salinity caused by ice formation. The resulting water mass with increased density descends and reaches the ocean floor. In the Atlantic Ocean the regions of dominating Antarctic Bottom Water formation are in the southern and western parts of the Weddell Sea.

Antarctic Bottom Water represents the coldest and deepest layer of the South Atlantic. A commonly accepted definition describes AABW as water with potential temperature cooler than 2°C [Wüst, 1936]. This layer can occupy a layer 1000 m thick and even more at the bottom of the Atlantic Ocean. The thickness decreases in the northern direction up to complete wedging-out at the bottom in the North Atlantic.

Generally, propagation of Antarctic waters in the bottom layer of the Atlantic Ocean is confined to depressions in the bottom topography. The pathways of AABW in the Atlantic Ocean are shown in Fig. 1. The general flow of these waters can be presented as follows [Morozov et al., 2010].

There are several channels for the flow of Antarctic Bottom Water from the Weddell Sea. It propagates to the north through the passages in the South Scotia Ridge, through the South Sandwich Trench, and South Sandwich Abyssal Plain. Part of Antarctic Bottom Water flows to the west to the Drake Passage. The other part of Antarctic Bottom

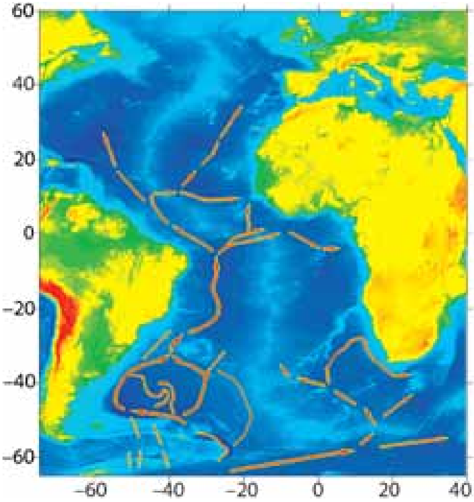

Fig. 1. Scheme of Antarctic Bottom Water propagation in the Atlantic Ocean

Water propagates through the Georgia and Northeast Georgia passages to the Georgia Basin. Then, Antarctic Bottom Water flows to the Argentine Basin through the Falkland Gap in the Falkland Ridge.

It is commonly accepted that AABW propagates from the Argentine Basin to the Brazil Basin in three places: through the Vema Channel, Hunter Channel, and over the Santos Plateau. In the northern part of the Brazil Basin, the flow of AABW splits. A part of the flow is transported to the eastern basin through the Romanche and Chain fracture zones, influencing the waters of the bottom layer in the Southeast Atlantic. The other part flows through the Equatorial Channel, propagating further to the Northeast Atlantic through the Vema Fracture Zone and to the North American Basin in the west, where it is entrained into the cyclonic gyre within its northward spreading zone, reaching the Newfoundland Bank.

## VEMA CHANNEL

The depth in the Vema Channel exceeds 4600 m as compared to the background depths of 4200 m. Based on moored current-meter observations in combination with

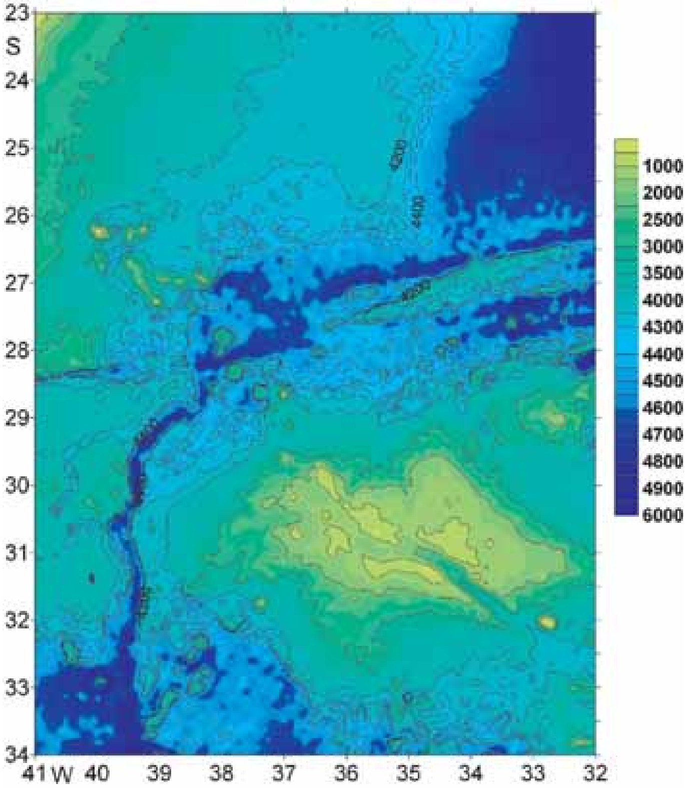

Fig. 2. Bottom topography of the Vema Channel

geostrophic velocity computations from hydrographic stations, the total Antarctic Bottom Water transport across the Rio Grande Rise and Santos Plateau is estimated at 6.9 Sv [Hogg et al., 1999]. On the average, two thirds of this volume passes through the Vema Channel. The rest part flows over the Santos Plateau and through the Hunter Channel.

The bottom topography around the Vema Channel is shown in Fig. 2. The Vema Channel is the deepest one among the passages existing for Antarctic Bottom Water. Therefore, the coldest water (Weddell Sea Deep Water) can exit the Argentine Basin in the equatorward direction only through this channel [Zenk et al., 1993].

According to the moored measurements (two moorings), the mean transport of Antarctic Bottom Water (layer below 2°C isotherm) through the Vema Channel is estimated at 3.5 Sv. The mean velocities are 30 cm $s^{-1}$ and the highest reach 60 cm $s^{-1}$. (Fig. 3).

However, the instantaneous transport measured by LADCP instruments (five sections across the channel in the middle part of the channel) appears lower and fluctuates between 2.5 and 3.5 Sv. Usually, the jet core is vertically mixed in a layer approximately 150 m thick. Owing to the Ekman friction the coldest core of the flow in the Vema Channel is usually displaced to the eastern slope of the channel.

In 2010, we carried out the measurements of currents in the region where Antarctic Bottom Water outflows from the Vema Channel to the Brazil Basin at latitude of 26°40′ S. Let us compare the sections at the standard section (31°12′ S) and in the northern part of the channel. The sections are presented in Fig. 4. The red line shows the location of the zero isotherm of potential temperature. In the narrow passage in the northern part of the channel (the Vema Extension), where the channel becomes deeper and narrower, the isotherms of the potential temperature greater than 0°C do not reach the slopes of the channel as in the south. This means that the flow with a temperature of $\theta$ = 2°C and even with a temperature of $\theta$ = 0.2°C becomes wider. Using the available data we can compare only the

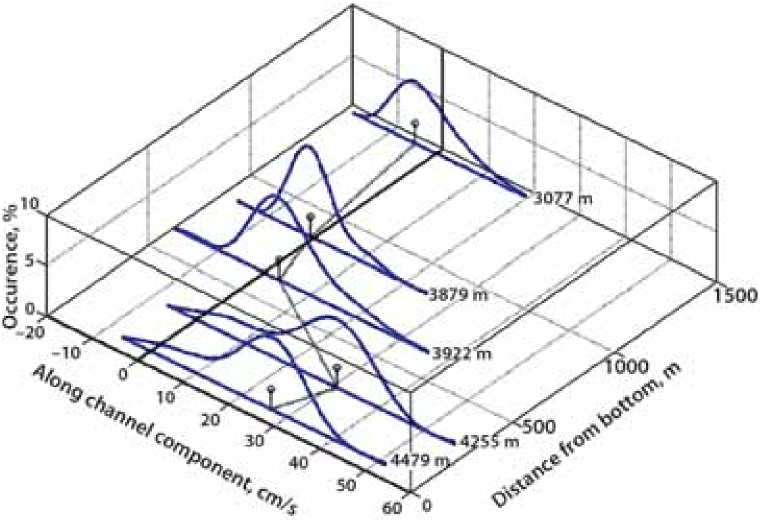

**Fig. 3. Three-dimensional frequency distributions of mean speeds above the abyssal Vema Channel. Results from five moored current meters close to our standard section (31°12′ S) on the eastern flank are shown. In the x-y plain a year-long averaged speed profile is displayed as a stippled line with hair needles (means) as a function of the distance from the sea bed. Positive speed values point northwards. Collateral numbers indicate instrument depths (for details see [Zenk & Visbeck, 2012]).**

*Note the high speed core of AABW in the lowest 250 m and some rare current reversals caused by highly energetic eddies*

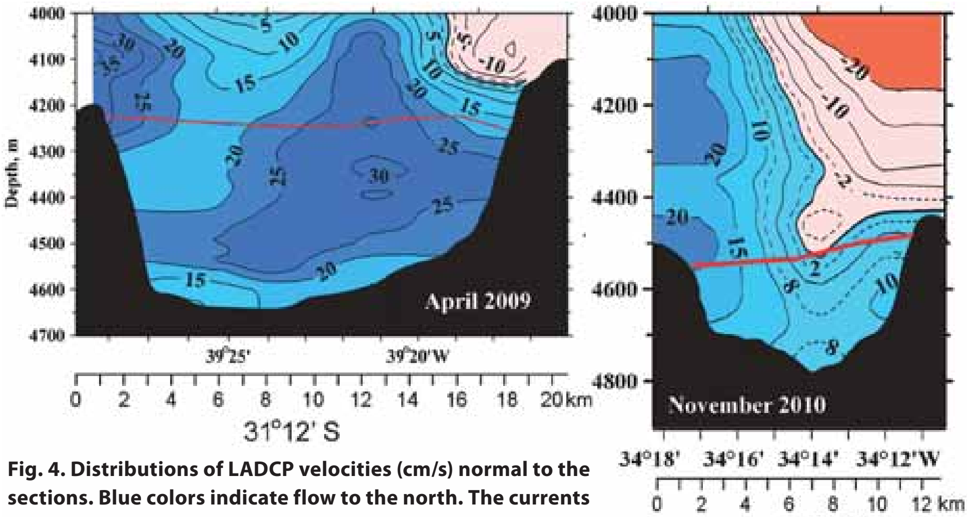

**Fig. 4. Distributions of LADCP velocities (cm/s) normal to the sections. Blue colors indicate flow to the north. The currents across the standard section are shown on the left (31°12′ S), the currents in the northern part of the channel are shown on the right (26°40′ S). The red line shows isotherm 0°C**

water flows with potential temperatures θ m 0°C. The mean velocities of the flow with such temperatures at the standard section are 23 cm/s, while at the northern section they decrease to 11 cm/s. Antarctic Bottom Water with higher temperatures flows above the western slope of the channel with velocities exceeding 20 cm/s. Unfortunately we could not extend the section farther to the west in the expedition in 2010 for a more precise calculation of the transport.

The square of the standard section for the water below 0°C is $6 \cdot 10^6$ $m^2$, while in the north the similar square is almost four times smaller ($1.4 \cdot 10^6$ $m^2$). The transport of this water across the standard section is 1.4 Sv, while the transport across the northern section is 0.16 Sv, which is almost 10 times smaller. Despite the fact that these sections were made not simultaneously, we relate this variability to the spatial variation of the flow. Thus a large amount of the coldest water does not reach the northern section remaining beyond the topographic obstacles and mixes with the overlying waters.

The decadal variability of the AABW flow in the Vema Channel is seen from the time series of 22 visits to the standard section of the Vema Channel from 1979 to 2009. During the period from 1979 to 2003, a temperature increase of the coldest temperature of the flow was observed. The temperature increased from –0.18°C to –0.12°C. In the end of 2004, this warming changed to temperature fluctuations with an amplitude of 0.02°C. Thus, we observed a general trend of warming of Weddell Sea Deep Water in the Vema Channel with slight fluctuations over a period greater than 30 years [Zenk & Morozov, 2007].

## ROMANCHE AND CHAIN FRACTURE ZONES

Only three channels in the Mid-Atlantic Ridge exist that allow the propagation of Antarctic Bottom Water to the northern latitudes of the East Atlantic. These channels are: the Romanche and Chain fracture zones (at the equator) and the Vema Fracture Zone (11° N) [Messias et al., 1999; McCartney et al., 1991]. Other small and shallower passages are less significant and do not allow the propagation of the coldest bottom waters.

The Romanche Fracture Zone is a deep passage in the Mid-Atlantic Ridge 800 km long and 10 to 40 km wide. Together with the Chain Fracture Zone they form an equatorial pathway for Antarctic Bottom Water to the East Atlantic. The Chain Fracture Zone is located south of the equator, 200 km south of the Romanche

Fracture Zone. Both fracture zones allow the water flow from the Brazil and Guinea basins.

The Antarctic Bottom Water (θ < 2°C) flow through the Romanche and Chain fracture zones is estimated at 0.5 Sv in each channel [Messias et al., 1999]. The mean velocities are 10–20 cm $s^{-1}$. Velocities measured by current meters on moorings in 1991–1992 and on the same section across the fracture zone using LADCP in 2005 and 2009 are very close. The bottom water passing through the Romanche and Chain fracture zones spreads only to the southeastern and equatorial parts of the Atlantic. Its further propagation to the north is almost limited by the Kane Gap at 9° N.

## VEMA FRACTURE ZONE

The Vema Fracture Zone is located at 11°N between 43.5° and 41° W. It connects the Demerara and Gambia abyssal plains. The width of the fracture zone is 8–10 km and the maximum depth is approximately 5200 m, while three sills of the fracture zone have depths 4690, 4650, and 4710 m.

In 2006, an expedition with CTD and LADCP measurements onboard R/V *Akademik Ioffe* visited the region of the main sills. The Antarctic Bottom Water flow through the Vema Fracture Zone (11° N) based on the measurements with a lowered velocity profiler was estimated at 0.5 Sv. The mean velocity is 10 cm $s^{-1}$, while the greatest velocity reaches 30 cm $s^{-1}$. The Vema Fracture Zone is the main pathway for Antarctic Bottom Water to the Northeast Atlantic.

## PROPAGATION OF ANTARCTIC BOTTOM WATER TO THE NORTHEAST ATLANTIC

In this section we consider the flow of bottom waters to the Northeast Atlantic from the Vema, Romanche, and Chain fracture zones and their further propagation in the Northeast Atlantic basins. The present-day concept was for the first time suggested in [Mantyla and Reid, 1983]. They wrote that bottom waters propagating through the Romanche Fracture Zone influence only the equatorial and southeastern part of the Atlantic Ocean. The bottom water from

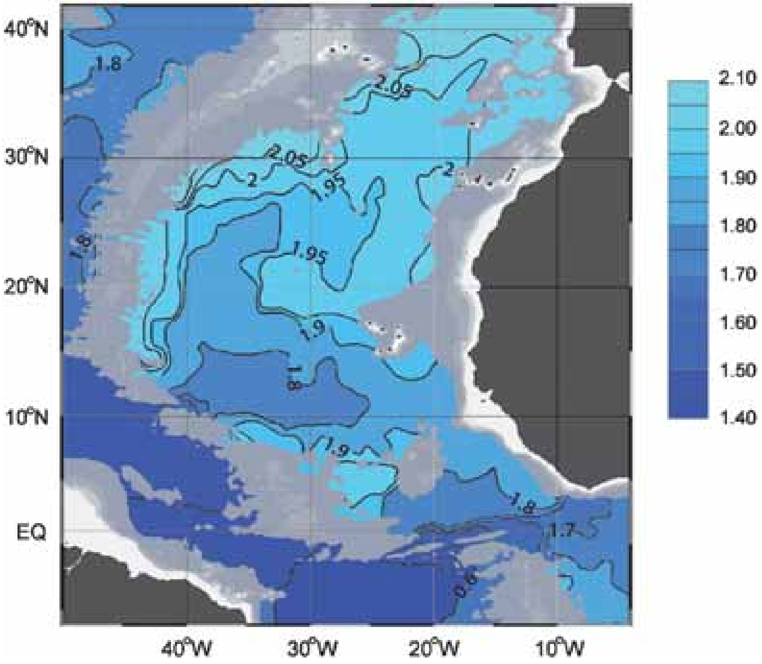

**Fig. 5. Distribution of potential temperature (°C) at the bottom in the eastern part of the North Atlantic based on the WODB-2009 data. The data below 4000 m is presented. Gray shade shows the bottom topography above 4 km**

these channels does not spread to the north through the Kane Gap, whereas the Vema Fracture Zone is the main pathway for bottom waters into the northeastern Atlantic.

The potential temperature of bottom waters in the Northeast Atlantic based on the recent and historical measurements is shown in Fig. 5.

One branch of the bottom water flow from the Vema Fracture Zone in the Gambia Abyssal Plane is directed to the north and waters of the Antarctic origin fill the deepest parts of the Northeast Atlantic basins including the Canary Basin. The flow reaches the Discovery Gap at 37°N. The second branch is directed from the Vema Fracture Zone to the southeast. This branch reaches the Kane Gap near the coast of Guinea.

The waters with θ = 1.80°C are located north and south of the Kane Gap. At the same time, isothermal surfaces θ = 2.00°C are not separated over the Kane Gap, which indicates that the exchange of Antarctic Bottom Water through this passage is possible. The large basin of the Northeast Atlantic including the Gambia Abyssal Plain and the Canary Basin is filled with bottom water that propagated through the Vema Fracture Zone. The bottom water that propagated through the Romanche Fracture Zone is localized in relatively small basins east of the fracture: the Sierra Leone and Guinea basins with a possible insignificant outflow to the Angola Basin.

Such localization seems surprising because Antarctic Bottom Water transports through the Romanche and Chain fracture zones are of the order of 1 Sv, which is almost the same as the water transport through the Vema Fracture Zone. We believe that this phenomenon may be explained by stronger mixing in the Romanche and Chain Fracture Zones compared to the Vema Fracture Zone caused by internal tidal waves.

## KANE GAP

The Kane Gap is located between the Grimaldi Mountains, which are a part of the Sierra Leone Rise and the Guinea Plateau near the African Continent (Fig. 6). The gap connects Gambia Abyssal Plain (Cape Verde Basin) and Sierra Leone Basin. The sill depth in the gap is 4502 m.

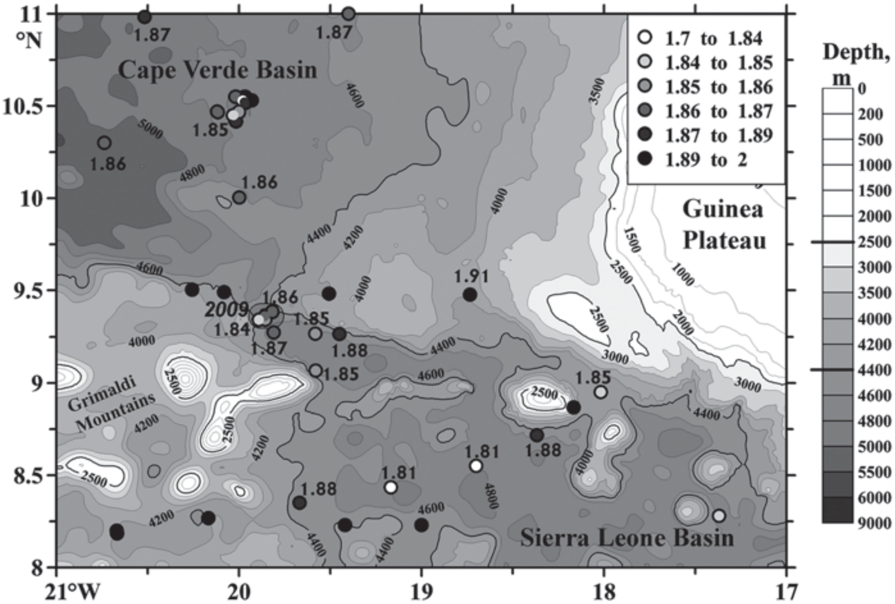

Fig. 6. Bottom topography (m) in the Kane Gap region showing locations of historical and recent stations near the main sill of the gap. Bottom potential temperatures (°C) are indicated at deepest stations

There are very few historical measurements in the Kane Gap. The scientists from the Shirshov Institute of Oceanology carried out CTD and currents measurements in this region in 2009–2011. In May 2009, the currents measured with LADCP were directed to the south at all depths below 2500 m. Thus, the bottom transport was directed from the Gambia Abyssal Plain to the Sierra Leone Basin. In October 2009, the measurements with a LADCP profiler demonstrated that the flow was directed to the northwest. Thus, the flow was opposite to the one recorded in May 2009.

The temperature stratification of the flow is similar to the flow in the Vema Channel. The coolest and densest water of the flow is displaced to the western wall of the gap due to the Ekman friction. Lower salinities are also recorded here at the foot of the western slope. Since the Kane Gap is located in the Northern Hemisphere, Ekman friction displaces the densest water to the left wall of the channel (southwestern slope in our case) (Fig. 7).

The total transport below 1.9°C potential temperature isotherm based on LADCP measurements fluctuates between zero and 0.2 Sv based on our measurements in different years. Thus, the bottom water from the Vema Fracture Zone influences at least the northern part of the Sierra Leone Basin, while the bottom water from the Romanche Fracture Zone can spread to the north through the Kane Gap and influence the adjacent southern region of Cape Verde Basin. However, the bottom water transport does not exceed 0.2 Sv and can be influenced by tides.

## DISCOVERY GAP

The northward propagation of bottom waters from the Canary Basin to the northeastern Atlantic occurs through the Discovery Gap. This region is the boundary for the further northward transport of bottom water with potential temperatures below 2°C. This passage is considered the terminal point of AABW spreading to the north in the sense that this is the water with a potential temperature less than 2°C. This is a narrow passage in the East Azores Fracture Zone at 37°N between the Madeira and Iberian abyssal basins [Saunders, 1987]. The passage is 150 km long. Its narrowest place is located at 37°20′ N, 15°40′ W. The width of the narrowest gap is 10 km and the depth of the sill is 4800 m. The measured mean velocities were 5 cm $s^{-1}$. The flux of bottom water colder than potential temperature $\theta = 2.05$°C was estimated at 0.2 Sv. Numerous CTD measurements around the Discovery Gap indicate that water with potential temperature below 2°C does not propagate through this passage.

During the last 29 years since the previous measurements in 1982 the temperature at the bottom of the Discovery Gap decreased by 0.023°C from 2.025°C in 1982 to 2.002°C that we measured in 2011. Unlike the current measurements in 1982, the measurements in 2011 did not demonstrate clearly

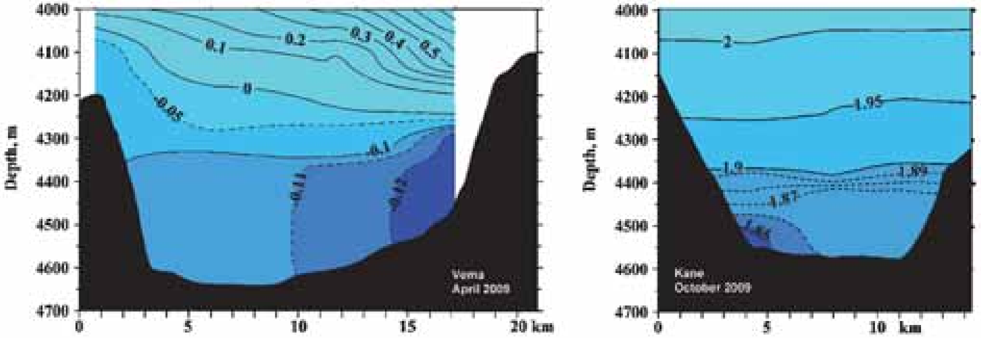

**Fig. 7. Distribution of potential temperature (°C) across the Vema Channel and Kane Gap**

manifested northerly flow of the bottom water. A fluctuating flow was observed in 2011. One core displaced to the eastern slope was directed to the northeast with velocities of approximately 5 cm/s and the second core with slightly greater velocities was directed to the southwest and displaced to the western slope.

## CONCLUSIONS

We summarized the characteristics of the transport of bottom water from its source region in the Weddell Sea through the main abyssal channels of the Atlantic Ocean. The analysis is based on the recent CTD-sections and moored current meters as well as on the historical data. The main properties of the bottom flow in the Vema Channel include a flow with a mean speed of 30 cm/s. The measurements in the Vema Channel that have been continuing for 30 years already revealed a temperature increase and recent fluctuations in the temperature of the coldest water. After the flow of Antarctic Bottom Water passes the Brazil Basin it splits into two flows. Part of the water flows through the Romanche and Chain fracture zones to the east. The other part flows to the northwest to the North American Basin. Part of the latter flow propagates through the Vema Fracture Zone into the Northeast Atlantic. We analyze an unsteady flow of bottom water in the Kane Gap. The terminal point for the Antarctic Bottom Water flow is the Discovery Gap.

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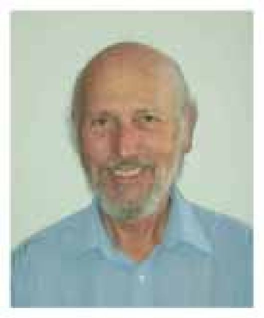

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