Abyssal Channels in the Atlantic Ocean
Abyssal Channels in the Atlantic Ocean

Water Structure and Flows

With a contribution by Anatoly Schreider and Vadim Sivkov
Editor: Georges Weatherly
Foreword

This book is dedicated to the study of structure and transport of deep and bottom waters above and through underwater channels of the Atlantic Ocean. The study is based on recent observations, analysis of historical data, and literature reviews. This approach allows us to understand how water transport and water mass properties have changed over the last years and decades. The focus of our study is on the propagation of bottom waters in the Atlantic Ocean based on new field data at key points.

At the end of the 1920s, the first integral study of water masses and bottom topography of the Central and South Atlantic was carried out from the German research vessel Meteor. This German Atlantic Expedition was one of the first cruises equipped with the newly developed echo sounder (fathometer): an obligatory prerequisite for the investigation of bottom morphology in the deep sea on an operational base. The results of the expedition were published by Wüst, Defant, and colleagues in the multivolume METEOR publication series starting with the cruise report by the ship’s commander (Spiess 1928, 1932). Historically, this series of publications, intermittently interrupted by World War II, was the basis for many years of research into the development of modern concepts about Atlantic water masses and their circulation schemes.

Since then, many national and international programs were initiated to study the properties of bottom water in the Atlantic Ocean and their propagation through narrow channels in submarine ridges. The present book summarizes the results of many field experiments and describes our contribution to this research.

Recently, deep-water fractures, troughs, and channels between large oceanic basins became interesting objects of research. These investigations have allowed us to characterize specific features of water exchange in deep-water parts of the ocean through narrow channels. Such features cannot be obtained even at high resolution in modern global circulation models. The peculiar abyssal water exchange through narrow channels is extremely difficult to integrate in numerical global circulation models with a sufficiently high resolution. Long-term observations indicate that strong velocities reaching a few tenths of meters per second are not unusual at selected choke points in the deepest layers of the ocean. It is interesting that such
high velocities are otherwise found primarily beneath the wind-driven surface layer of the ocean.

Intense research into the deep ocean was carried out during the field works that were a part of the World Ocean Circulation Experiment (WOCE) in the 1990s. The deepest fracture zones and channels of different origins in the ocean provide water exchange between deep basins. Since the beginning of the World Ocean Circulation Experiment in early 1991, sustained observations of Antarctic Bottom Water characteristics and transport were conducted at selected sites around the Brazil Basin. One of the WOCE core projects, the Deep Basin Experiment, was focused on the key passages that allow an equatorward interbasin exchange of bottom water. After the WOCE decade, field measurements in the Atlantic abyssal channels continued to broaden our understanding of these phenomena.

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Preface

Our book reviews a number of studies carried out in different abyssal channels, combined with our recent oceanographic research and analysis of observations in the main channels of the Atlantic Ocean. We also analyze properties of water masses involved in flows through the channels and their variability on the decadal time scale.

The following abyssal channels are the most important in bottom water exchange in the Atlantic Ocean: Falkland Gap (Arhan et al. 1999), Vema Channel and Hunter Channel, Vema Fracture Zone, Romanche and Chain fracture zones, nameless Equatorial Channel, Kane Gap, and Charlie Gibbs Fracture Zone. Of course, numerous channels in the Scotia Sea and Drake Passage, as well as passages connecting the Weddell Sea with the Georgia Basin, which provide the initial outflow of Antarctic water from the Weddell Sea to the Atlantic abyssal zone, also play a significant role. Actually, water in the Weddell Sea is the source of the bottom waters in the Atlantic and Southern oceans, while the Scotia Sea is one of the basins responsible for the first appreciable transformation of bottom water. Locations of the main abyssal channels are shown in Fig. 1. Detailed charts of bottom topography in the regions of major channels are shown in individual topographic maps in Figs. 2–8.

Most of the Atlantic abyssal channels provide a unidirectional flow of bottom water. Progressive vector diagrams based on moored measurements of currents in the channels give a clear illustration of the prevailing flow directions, current strength, and steadiness. Figure 9 shows eleven progressive vector diagrams in the major channels around the Argentine and Brazil basins of the South Atlantic.

Images on the left side are inferred from observations across the Rio Grande Rise. Diagram 1 is related to the Deep Western Boundary Current on the continental rise off Santos. The strongest near-bottom flows through the Vema Channel were recorded on the west bank of the Sill (diagrams 2, 3) and on its east bank (diagrams 4, 5). Diagram 6 represents the main vein in the Hunter Channel. Diagram 7 shows examples of inflow for bottom water from the Shag Rocks Passage (Fig. 2) at the northern rim of the Scotia Sea. Diagram 8 shows the outflow of bottom water to the north, the Vema Extension (northern part of the Vema Channel). Diagrams 9 and 10 show outflow across the Mid Atlantic Ridge at the Romanche and Chain fracture
zones. All curves are barely 1.5 years long (527 days) except diagram 7, which is about half this duration time. Ticks are 30 days apart. No filters were applied to the data sets. Sampling interval is 2 h. The topographic steering effect is obvious at all locations.
Moreover, specific similarity can be found between flows in different abyssal channels (Zenk et al. 1999). The authors constructed daily vertical profiles based on measurements in several channels. The vertical axis was normalized by the level, where the velocities decreased to 14% of their maximum (unit depth). The zero
Fig. 5 Bathymetric chart of the Romanche and Chain fracture zones

Fig. 6 Bathymetric chart of the Hunter Channel
Fig. 7 Bathymetric chart of the Kane Gap

Fig. 8 Bathymetric chart of the Charlie Gibbs Fracture Zone
depth was defined as the level of the deepest current meter (15–50 m above the bottom). Mean velocity maxima served as scaling factors on the abscissa axis. Figure 10 shows time-averaged profiles from different abyssal channels: Vema Channel, Hunter Channel, Romanche Fracture Zone (Mercier and Speer 1998), and Vema Fracture Zone at 11°N (Vangriesheim 1980).

The general common property of abyssal flow in deep channels is location of the maximum velocity at a distance above the bottom. Velocities decrease in both upward and downward directions. This property of the flow was later confirmed by measurements with lowered acoustic current profilers (see Sect. 4.2.10). They demonstrated that the core of the flows is located at a distance of approximately 100 m above the bottom in different channels.

The major part of the book is dedicated to the propagation of Antarctic Bottom Water (AABW) and different modifications of this water in the Atlantic abyssal channels. Antarctic Bottom Water occupies a bottom position over the major part of the Atlantic Ocean. The bottom topography plays a crucial role in the propagation and properties of Antarctic Bottom Water. Therefore, only the upper part of this water can overflow each topographic obstacle. The characteristics and specific structure of abyssal waters in these regions may differ strongly due to entrainment and mixing with the overlying waters. Everywhere in the Atlantic Ocean, Antarctic Bottom Water is characterized by low potential temperature, low salinity, and high content of nutrients compared to the overlying deep waters. It is formed in several regions above the continental slope of Antarctica as the result of complex mixing of Antarctic Shelf Water and Circumpolar Deep Water. Formation of Antarctic Bottom Water spreading to the north in the Atlantic Ocean occurs mainly in the Weddell Sea.

**Fig. 9** Progressive diagrams based on 527-days long measurements in different abyssal passages around the Argentine and Brazil basins: (1) Santos Plateau; (2–3) west bank of the Vema Channel; (4–5) east bank of the Vema Channel; (6) Hunter Channel; (7) Shag Rocks Passage (1 year only); (8) Vema extension; (9) Romanche Fracture Zone; (10) Chain Fracture Zone. Tick marks are 30 days apart. See Fig. 1 for the location of passages. The figures are based on archive data of IFM-GEOMAR and WODB 2005.
Abyssal channels in submarine ridges are key points for bottom water advection in the ocean. Locations of abyssal channels are geographically distant from each other. Therefore, the specific structure of waters is different in these regions. In addition, it is determined by complex processes of interaction between the waters of the North Atlantic and Antarctic origin. However, abyssal channels play an exclusive role in the formation of deep circulation, because they are the main pathways for Antarctic Bottom Water spreading to the north.

Although we are aware of a geographically unequal coverage of individual channels in the ocean, we believe that the Vema Channel is a test laboratory and the best example for analysis of the flows in underwater channels. This is the only channel that could be investigated deeply because many other abyssal channels are located very far from the leading oceanographic centers of the World. Our efforts were mainly concentrated on measurements in the Vema Channel, which is probably the best example of strong flow in a channel. Experiments in the Vema Channel constitute the most important part of our research. Our measurements in the Vema Channel provide insights into physical processes that occur in deep narrow channels with high velocities and intense mass transport.

**Fig. 10** Similarity of velocity vs. depth profiles in different channels. Averaged vertical current profiles of the recorded meridional current components in different regions (Modified on the basis of Zenk et al. (1999)): (1) Vema Channel, (2) Hunter Channel, (3) Romanche Fracture Zone, and (4) Vema Fracture Zone. The diagram shows velocities between 2°C potential temperature isotherm and the bottom.
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Abbreviations

AABW Antarctic Bottom Water (Note: AABW = WSBW + WSDW in classification of Orsi et al. (1999); AABW = WSDW + LCPW in classification of Wüst (1936) and Reid et al. (1977))

AAIW Antarctic Intermediate Water

AASW abbreviation used for both Antarctic Surface Water and Antarctic Shelf Water (AASurW and AAShW, respectively, in this book)

ACC Antarctic Circumpolar Current

BF Brazil Front

BFZ Bight Fracture Zone

CBW Circumpolar Bottom Water (term used in this book). Original term introduced in (Orsi et al. 1999) is ACCbw (ACC bottom water)

CFC chlorofluorocarbon

CGFZ Charlie Gibbs Fracture zone

DF Deep Front (in the northern part of the Argentine Basin near the Vema Channel)

DSOW Denmark Strait Overflow Water

FZ Fracture zone

HFU heat flux unit; 1 HFU = 42 m W/m²

IfM Institut für Meereskunde

ISOW Iceland Scotland Overflow Water

LADCP Lowered Acoustic Doppler Current Profiler

LCDW Lower Circumpolar Deep Water (in the ACC zone)

LCPW Lower Circumpolar Water (in the Argentine Basin (Reid et al. 1977)) (Note: LCPW is not the same as LCDW)

LOIW Lower Intermediate Water

LSW Labrador Sea Water

LWSDW Lower Weddell Sea Deep Water

Ma million years (age)

mbsf meters below sea floor

NADW North Atlantic Deep Water

PDW Pacific Deep Water (sometimes SPDSW designates South Pacific Deep Slope Water)
### Abbreviations

<table>
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<tr>
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<th>Definition</th>
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<tbody>
<tr>
<td>psu</td>
<td>practical salinity unit</td>
</tr>
<tr>
<td>PVD</td>
<td>progressive vector (PVD) diagrams</td>
</tr>
<tr>
<td>SACCB</td>
<td>South Boundary of ACC</td>
</tr>
<tr>
<td>SACCF</td>
<td>South ACC Front</td>
</tr>
<tr>
<td>SAF</td>
<td>Subantarctic Front</td>
</tr>
<tr>
<td>SAMW</td>
<td>Subantarctic Mode Water</td>
</tr>
<tr>
<td>SB</td>
<td>South Boundary of ACC in some figures</td>
</tr>
<tr>
<td>SF</td>
<td>South ACC Front in some figures</td>
</tr>
<tr>
<td>SPF</td>
<td>South Polar Front; occasionally also Southern Polar Front</td>
</tr>
<tr>
<td>STF</td>
<td>Subtropic Front</td>
</tr>
<tr>
<td>Sv</td>
<td>Sverdrup (1 Sv = $10^6$ m$^3$/s)</td>
</tr>
<tr>
<td>UCDW</td>
<td>Upper Circumpolar Deep Water (in the Antarctic Circumpolar Current zone)</td>
</tr>
<tr>
<td>UCPW</td>
<td>Upper Circumpolar Water (in the Argentine Basin (Reid et al. 1977))</td>
</tr>
<tr>
<td>UPIW</td>
<td>Upper Intermediate Water</td>
</tr>
<tr>
<td>UWSDW</td>
<td>Upper Weddell Sea Deep Water</td>
</tr>
<tr>
<td>WDW</td>
<td>Warm Deep Water (in the Weddell Gyre) (Note: WDW = LCDW + CBW if we use the approach in (Orsi et al. 1999))</td>
</tr>
<tr>
<td>WOCE</td>
<td>World Ocean Circulation Experiment in the 1990s (Siedler et al. 2001)</td>
</tr>
<tr>
<td>WSBW</td>
<td>Weddell Sea Bottom Water</td>
</tr>
<tr>
<td>WSDW</td>
<td>Weddell Sea Deep Water</td>
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<tr>
<td>WF</td>
<td>Weddell Front</td>
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Chapter 1
Geological and Geophysical Characteristics of the Transform Fault Zones

1.1 General Description

From the point of view of the new concept of global tectonics, oceanic fracture zones consist of one or more transform faults. Their geomorphological descriptions were given for the first time in (Wilson 1965; Menard 1966; Menard and Chase 1970). The authors defined the transform faults as long narrow zones of strongly rugged bottom topography characterized by the existence of linear forms that usually separate topographic provinces with different regional depths. In the transform zones, fault-line ridges are extended parallel to the troughs. It is noteworthy that remains of shallow-water sediments are found on some of the fault-line ridges and bottom terraces. A fracture zone located between contiguous spreading axes is called an active zone. The fracture walls between neighboring spreading axes are characterized by opposite directions of motion. Passive parts of transform faults are located beyond the active zone, but the direction of their motion is the same. Transform faults are distinguished well not only in the ocean bottom topography, but also in anomalous geophysical fields. High fault-line ridges near the walls of faults (mainly between the neighboring parts of spreading axes), deep troughs, faults, and fissures are characteristic of the fracture zones, which represent an assemblage of deep and bottom structures. Anomalies of the magnetic and gravity fields, undulations of the heat flux, and other geophysical data testify to a complex dynamic regime of lithosphere in the fracture zones. Active parts of transform faults are also characterized by the most intense seismicity with clear manifestation of the shear component in earthquake sources.

Transform faults (Charlie Gibbs, Vema, Romanche, and Chain fracture zones) and the Vema Channel analyzed in this work are extremely different in terms of morphological and geological-geophysical characteristics, history of origin, and evolution. All transform faults in the Atlantic Ocean are characterized by their confinement to the slowly spreading Mid-Atlantic Ridge.

The Charlie Gibbs Fracture Zone is the southern boundary of the Reykjanes Ridge, a segment of the Mid-Atlantic Ridge, which extends in an anomalous oblique
direction (at an angle of 30° relative to the spreading direction). The fracture is the northernmost major one, along which the ridge axis is displaced over many hundreds of kilometers. The Vema, Romanche, and Chain fracture zones are related to the equatorial segment of the Atlantic Ocean. This segment occupies a key position in the structure of the Atlantic, because only after its opening in the mid-Cretaceous did the Central and South Atlantic regions unite into a single oceanic basin. Before the final destruction of the continental bridge, which connected South America and Africa, the regions mentioned above were developing separately.

Concentration of large transform faults is a peculiarity of this segment. There are as many as 12 fractures over a distance of about 1,700 km along the spreading axis. The 15°20′ Fracture Zone (sometimes named the Cabo Verde Fracture Zone) is the northernmost one, while the Romanche Fracture Zone is the southernmost one. Owing to such concentration of transform faults, the spreading axis of the Mid-Atlantic Ridge is divided here into a large number of short, approximately 75-km-wide, segments. Total displacement of the spreading axis within this segment is more than 1,500 km to the east relative to its location north of the 15°20′ Fracture Zone (950 km of the total displacement is associated with the Romanche Fracture Zone).

The width of the Mid-Atlantic Ridge in the southern segment of the Charlie Gibbs Fracture Zone is only 500–650 km. The rift zone is represented by an echelon of troughs up to 4,000 m deep. Appearance of multiple (although small-scale) jumps and progradation of the spreading axis is a characteristic feature of this structure.

The transform faults have a quite complex structure mainly owing to variation in the location of rotation poles of the plates during the fracture development. The largest fracture zones (Romanche and Vema) are accompanied by troughs up to 4,500–5,200 m deep. The record depth of the trough (7,856 m) for the Mid-Atlantic Ridge is located in the Romanche Fracture Zone (Vema Deep). It is not surprising that such vertical motions led to exhumation of not only the entire section of the oceanic crust, but also the upper mantle layers. In addition, protrusions of serpentinized peridotites in the topography of these zones play an essential role in the fracture zones.

We shall use the US Geological Service (USGS) data [www.neic.usgs.gov/epic] (as of February 2009) to illustrate the seismological characteristic of the regions. The earthquake magnitudes are given according to the Gutenberg scale (body wave magnitude, mb). Morphology of the bottom topography in this research is based on the International database [www.topex.ucsd.edu/html/mar_topo.html] (as of February 1, 2009). All illustrations are made using the “Global Mapper” programming environment.

1.2 Charlie Gibbs Fracture Zone

The Charlie Gibbs transform fault is one of the well-studied fracture zones of the Atlantic. The rift valley of the Mid-Atlantic Ridge (Fig. 8) is displaced along the left-lateral fault plane over 340 km near 52°30′ N. Passive traces of the fracture zone are extended up to 49° N and 16°30′ W (Cherkis et al. 1973).
The results of geological and geophysical investigations (Cherkis et al. 1973; Searle 1980; Dubinin 1987) allow us to state that a narrow 550-km-long ridge elongated along 52°30′ N, 28°30′–37° W is the main element of the bottom topography here (Fig. 1.1). The width of the ridge at its basement does not exceed 20 km. Individual peaks of the ridge are elevated above the ocean bed by 1,200–2,900 m. The ridge is limited from the north and south by troughs parallel to the ridge (Fig. 1.2). The ocean depth in the troughs is 4,000–4,800 m. The width of the steeper and deeper northern trough (Fig. 1.3) is 10–20 km (2–5 km at the bottom). The width of the southern trough is 20–30 km. The total width of the entire fracture zone reaches 80 km. A supposition was made on the basis of detailed studies in (Searle 1980; Lilwall and Kirk 1985) that the northern and southern trenches are connected in the active part of the fracture zone by a short segment of the spreading axis extending from north to south. This 31°48′ W segment, which is a narrow trench a few tens
of kilometers wide with depths up to 4,500 m or more, can also serve as a channel for deep water exchange. Drilling and dredging in the Charlie Gibbs Fracture Zone revealed that the northern wall is composed of serpentinized peridotites, amphibolites, and basalts. Summits of the central ridge are basalt peaks and bare intrusions of gabbro and serpentinites (Oliver et al. 1974; Dubinin 1987).

It is likely that large ultrabasic mantle bodies intruded through the oceanic crust into the fracture zone. In the passive zones of the fracture zone, the main ridge and troughs become less prominent with increasing distance from the active zone. A sedimentary rock layer was found in the entire fracture zone except its southern valley. The thickness of dominating turbidite sediments in the northern trench is 500–700 m, while the sedimentation rate is 2.5 mm/year (Blazhchishin and Lukashina 1977). Thickness of this bed increases with increasing distance from the active part of the fracture and reaches 1,000 m near 17° W. Morphological structures of the fracture zone are well expressed near the rift, but they are strongly smoothed and buried at a significant distance from the fracture zone (Smoot and Sharman 1985). Anomalies of the gravity force in the free-air reduction are minimal along the fracture zone. The greatest minimum $\Delta g$ (~30 mGal) corresponds to deep depressions of the bottom topography (Oliver et al. 1974).

Anomalously high values of the heat flux were measured in the Charlie Gibbs Fracture Zone (Popova et al. 1984). Based on five measurements of the heat flux in the northern trough in the active zone of the fracture zone, the mean value is $3.8 \pm 1.7$ heat flux units (HFU), while the maximum value 6.5 HFU is confined to the middle part of the active zone of the transform fault.

The heat flux slightly decreases at the continuation of the northern trough to the inactive part of the transform fault west of the Reykjaness Ridge. The mean value of three measurements is 2.2 HFU. The heat flux in inactive parts of the southern trough of the Charlie Gibbs Fracture Zone is (1.3 HFU in the eastern part and 1.7 HFU in the western part). Two high values of heat flux were measured on the ridge dividing two depressions within the active part of the fracture: 1.3 and 1.7 HFU (Popova et al. 1984; Dubinin 1987).
Intense seismicity was recorded between 30° W and 35° W along a 340-km-long segment of the transform fault (Fig. 1.4) (Kanamori and Steward 1976; Lilwall and Kirk 1985; Searle 1980; Dubinin 1987). The main earthquake events have a magnitude of 3–6. Their hypocenters are located at depths exceeding 35 km.

Thus, the active part of the Charlie Gibbs transform fault is characterized by anomalously high values of heat flux, while its values decrease significantly in inactive parts of the fracture zone. We suppose that the Charlie Gibbs Fracture Zone emerged on the continent in the Paleozoic and developed further during the opening of the Atlantic Ocean. The ocean bottom morphology and anomalously high values of the heat flux also suggest that widening occurs in the active part of the fracture.

1.3 Vema Fracture Zone

The active part of the Vema transform fault displaces the segments of the Mid-Atlantic Ridge by 320 km in the nearly latitudinal direction along 10°30′–11° N (Fig. 4). The fault has a prominent valley (up to 5,200 m deep) bounded by steep walls (20°–30°). The distance between walls varies from 10 to 20 km (Fig. 4). The southern wall of the valley is the slope of a narrow (approximately 30 km wide) monolithic ridge located parallel to the transform valley (Fig. 1.5). Some peaks of the ridge are as high as 500 m below surface, while the mean depth of the ridge is 2,000–2,500 m. Peaks of the Mid-Atlantic Ridge adjacent from north and south to the Vema Fracture Zone do not exceed 2,500 m. Steep walls and the general shape of the ridge suggest that this structure is an elevated block of the oceanic crust rather than a product of eruptions of several underwater volcanoes. This explanation is also valid for the northern slope. The ridge on the northern wall of the fracture is
relatively less prominent in its topography (ocean bottom depth 3,000–3,500 m). It smoothly grades into the abyssal plain, the depth of which is consistent with the general age dependence of the usual oceanic lithosphere with increasing distance from the mid-oceanic ridge axis. Thus, one can see a topographic asymmetry across the Vema Fracture Zone (Fig. 1.6). The fracture valley with adjacent ridges is also

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**Fig. 1.5** Active part of the Vema Fracture Zone

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**Fig. 1.6** A perspective view of the active part of the Vema Fracture Zone (view from the east)
prominent (although not so clearly) in the passive zones. The flat bottom of the valley extends west up to 44°30′ W. Then, the valley becomes narrower and its extension turns slightly to the north (van Andel et al. 1971). The transform valley is shallower near the southern segment of the Mid-Atlantic Ridge, while the eastern part of its passive zone extends far to the east into the Gambia Abyssal Plain as a solitary trough (Fig. 1.7).

In the 38° W zone, the trough is 600–900 m deep, while the heights of the southern and northern slopes are 1,900 and 1,000 m, respectively (Syrsky and Greku 1975).

Profiles based on the method of reflected waves (MRW) show that the Vema fracture valley is filled with a thick layer of sediments (1,000–1,200 m) lying on a highly reflective basement surface located at a depth of 6,200–6,500 mbsf (meters below sea floor) (van Andel et al. 1971; Kastens et al. 1998). The troughs of inactive valleys located south of the Vema Fracture Zone are covered with similar sediments up to 900 m thick. Drilling from R/V *Glomar Challenger* (cruise 4, Hole 26; 10°54′ N, 44°03′ W) showed that the sediments are represented mainly by Pleistocene turbidite sediments transported from the Demerara Abyssal Plane under the influence of the Amazon alluvial fan. The mean sedimentation rate is approximately 120 cm/ka (Bader et al. 1970). Sediments of the fracture valley are deposited uniformly as a flat layer. Insufficient overlapping and flat undulation can be related to erosion activity, different degrees of compaction, continuing rise of the fault-line ridges, and relative motion of contacting lithospheric blocks. The character of de-

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**Fig. 1.7** A perspective view of the active part of the Vema Fracture Zone (view from the west)
formation suggests the existence of local (subordinate) contraction and extension zones, which can be indirectly related to the relative motion of contacting parts of plates.

Zones of sediment piling and rises make up a small median ridge. They can be related to local mantle protrusions under the sedimentary cover (Eittreim and Ewing 1978). Such distortions of the top of the sedimentary cover could have occurred during the last 500 ka. Based on the method of reflected wave (MRW) data, the valley bed under the sedimentary cover represents a series of rises and depressions (Eittreim and Ewing 1978; van Andel et al. 1971; Kastens et al. 1998; Bonatti et al. 2005). The deep structure of the oceanic lithosphere in the fracture zone based on the results of seismic investigations at 42°–43° W shows that seismic layer 3 of the oceanic crust (P = 5.9–6.3 km/s) under the fracture valley is significantly thinner (about 2.5 km) (Ludwig and Rabinowitz 1980).

This layer is underlain by rocks of the upper mantle (P = 8.12 km/s). Its roof is located above the expected Moho boundary. All these facts suggest the ascent of high-temperature mantle matter along a fracture in the study area of the fracture zone. It is likely that high-temperature mantle matter reached the hydrothermal circulation zone.

The active part of the Vema Fracture Zone is characterized by seismicity (Fig. 1.8). Earthquake epicenters are generally located along the southern footwall of the fault. Solutions of mechanisms in the sources suggest the predominance of shear dislocations along the transform fault (Sykes 1970).

Usually, the earthquake magnitude does not exceed 5, and the hypocenters are located at a depth of less than 35 km. Passive zones of the fracture are aseismic.

Rocks dredged along the walls of the fracture zone included basalts, mafic basalts, gabbro, and metagabbro of the amphibolite stage of metamorphism, as well as peridotites subjected to different degree of serpentinization (Bonatti and Honnorez 1976; Bonatti et al. 2005). Compositions of rocks between the southern and northern walls are asymmetric. Although basalts dominate at all levels of the section, their chemical compositions are slightly different at the northern and southern

![Fig. 1.8 Sites of recorded seismic activity in the Vema Fracture Zone](image-url)
walls. The composition of basalts at the northern wall is close to that of basalts at the Mid-Atlantic Ridge axis (Bonatti 1976). The northern ridge is dominated by gabbro and serpentinites, while the southern slope is composed of highly metamorphosed amphibolites and mylonites. Serpentinites are found almost at all levels on walls of the fracture valley along both vertical and horizontal directions. Morphological, seismic, and petrological data on the Vema Fracture Zone indicate that the structure of the northern block is similar to the normal oceanic crust formed in the axial Mid-Atlantic Ridge (Bonatti 1976; Dubinin 1987).

The structure of the southern wall was strongly affected by processes in the fracture zone: diapir rise of serpentinized ultrabasic rocks responsible for high fault-line ridges (for example, the southern ridge of the Vema Fracture Zone). During their ascent, serpentinized rocks can capture fragments of surrounding rocks (harzburgites, peridotites, metagabbro, and gabbro) and transport them to higher layers of the Earth’s crust.

The active part of the Vema Fracture Zone is characterized by increased heat flux with a mean value greater than 1 HFU. The maximum values of heat flux are confined to the fracture valley (3.42 ± 1.00 HFU), namely to its middle part located equidistantly from the Mid-Atlantic Ridge axis segments. Heat flux in some areas is as high as 6.2 HFU, although thick sediments decrease the heat flux in the trough through the basement by 20–30% (Langseth and Hobart 1976; Dubinin 1987).

The maximum free-air $\Delta g$ anomalies (100–120 mGal) are confined to the southern ridge of the Vema Fracture Zone. Negative anomalies confined to the central valley reach −80 mGal (Robb and Kane 1975). Robb and Kane interpreted the anomalous gravity field as a two-layer lithospheric model with the following parameters: water density 1.03 g/cm$^3$, crust density 2.60 g/cm$^3$, and mantle density 3.15 g/cm$^3$. Density of the thick sedimentary cover in the local depressions was assumed to be 1.90 g/cm$^3$ (Bader et al. 1970). The lithosphere was bounded at a depth of 40 km by a flat isobaric surface. Anomalies $\Delta g$ calculated within this model agree well with the observed ones. The form of Bouguer anomalies within the two-layer model assumes the existence of mass excess under the southern ridge and lesser excess under the northern ridge. It is likely that a zone of rocks with lesser density exists under the axial part of the Vema Fracture Zone, which can be filled with hot mantle material ascending in the pull-apart setting.

Data on the Vema Fracture Zone discussed above suggest the existence of a high southern ridge mainly composed of the mantle-derived serpentinized peridotites, significant deconsolidation of the mantle under the transform valley, anomalously high values of the heat flux, and specific character of the free-air $\Delta g$ anomalies. All these facts suggest that the Vema Fracture Zone includes an active high-temperature intrusion, which ascended along the fracture up to the level of thermal water penetration. Calculation of the thermal regime of lithospheric blocks contacting along the transform fault during intrusion of the high-temperature mantle matter to a depth of 10,000–11,000 mbsl demonstrates that properties of the studied profile, which makes up 1.5–2.0 km of the total fault-line ridge height, is affected by temperature increases at the edges of blocks owing to processes of intrusion (Dubinin 1987).
Properties of the remaining 2 km of the fault-line ridge height (Dubinin 1987; Dubinin and Ushakov 2001) can be explained by the serpentinite diapirism of the mantle. According to the calculations, the serpentinitization temperature interval (~500–300°C) is located at a depth of 9,500–7,000 mbsl under the fracture valley axis. Low-density fissured material of mylonites, basalt, gabbro, and serpentinites underlies the fracture valley beneath the 1-km-thick sedimentary layer in the zone of intense deformations.

Walls of the valley and the southern fault-line ridge are also composed of these rocks. At a depth of about 8,000–9,000 m, density of rocks and, consequently, seismic wave velocity increase sharply, probably, owing to the presence of gabbro and peridotite rocks with a low degree of serpentinization. Seismic boundary at a depth of 11,000 m can represent the roof of the high-temperature mantle intrusion. The gravity field based on such geodynamic model agrees well with the observed field.

After termination of the active mantle intrusion, the thermal component of the topography and, consequently, the corresponding part of the fault-line ridge height decrease rapidly (during 10–15 Ma). At the same time, intrusions of serpentinized ultrabasic rocks continue during a longer time and can be traced in passive zones of the fracture zone.

Thus, the model of pull-apart transform faults explains the facts related to mantle intrusions, such as high values of the heat flux, manifestation of serpentinites along the slopes of ridges, and existence of a thin deconsolidated crust under the axial zone of transform valleys.

1.4 Romanche Fracture Zone

The Romanche transform fault (Fig. 5) is among the largest tectonic fractures in the Central Atlantic. In the Equatorial Atlantic, it extends from the coast of Africa to South America. The main morphological and tectonic features of the Romanche Fracture Zone were revealed for the first time in (Heezen et al. 1964a) and later supplemented in (Bonatti et al. 1977; Bonatti and Chermak 1981; Belderson et al. 1984). Active segments of the spreading axis of the Mid-Atlantic Ridge are displaced over 930 km along the fracture zone (Pushcharovsky 2005).

Abundance of nearly latitudinal linear troughs both north and south of the modern fracture valley is a specific feature of the Romanche Fracture Zone (Fig. 1.9). The troughs are covered with sediments several hundred meters thick. The modern valley of the Romanche Fracture Zone is not strictly linear. Its extension sharply changes near 19°–20° W.

The fracture zone represents a valley, which is more than 7,000 m deep east of 22° W and is less prominent west of 22° W. The width of the valley bottom is 3–10 km while the depth usually exceeds 6,500 m and reaches 7,856 in the Vema Deep (Metcalf et al. 1964; Belderson et al. 1984) at 18°30′ W. The valley is bounded by steep walls (inclination more than 30° in some places), which grade into slopes of the high fault-line ridges that accompany the valley along its entire extension on
both northern and southern sides (Fig. 1.10). Amplitudes of the topographic gradient in the Romanche transform fault frequently exceed 5,000 m. The total width of the fracture zone exceeds 100 km (Belderson et al. 1984; Bonatti and Fisher 1971). Individual summits of the fault-line ridges reach a depth of 1,000 mbsl (Fig. 5).

The fracture valley bottom accommodates a small median ridge (100–800 m), which is most prominent in the eastern part of the active zone (Bonatti and Fisher 1971; Belderson et al. 1984; Dubinin 1987). In the passive part of the fracture zone, it is partly masked by a large amount of sediments. The southern and northern fault-line ridges in the western passive part of the fracture zone are traced in bathymetry up to 31° W and 33° W, respectively. Further up to 36° W, they are reflected in the basement topography and gravity anomalies (Cochran 1973). Fault-line ridges are distinguished in the bottom topography of the eastern passive zone up to ~7° W. West of 7° W up to the steep continental slope of Ghana, the fracture zone is recognized as a large ridge and basement trough, which are buried under the sedimentary