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# Deep-sea basins of the Atlantic ocean: The structure, time and mechanisms of their formation

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**Abstract.** The aim of this project was to study the deep-sea basins of the Atlantic Ocean. Described in this paper are the morphology and deep crustal structure of the Argentine, Brazil, Cape, Angola, North American, Newfoundland, Canary, Sierra Leone, Iberia, and West-European basins. It is shown that they differ substantially in geological history. Also different are their internal structures. The subsidence of the respective segments of the Earth's crust took place not only following the spreading model, but also as a result of crustal extension between the spreading ridge and the continental margin, caused by the pulling apart of the continental blocks.

## Introduction

The deep-sea basins occupy huge spaces in the oceans. In the Atlantic Ocean they are developed on both sides of the Mid-Atlantic Ridge producing a kind of symmetry in the general structure of the ocean floor. In reality, however, as will be demonstrated below, each of the basins is individual in terms of its morphology, geology, and deep crustal structure, even though they may have some features in common. The subjects of this study were the Argentine, Brazil, Cape, and Angola basins in the South Atlantic Ocean and the North American, Newfoundland, Canary, Sierra Leone, and Iberian basins in the Central Atlantic Ocean.

Four tectonic regions of the first order have been mapped in the Atlantic Ocean, namely, the North, Central, South, and Antarctic ones. These regions are separated by fracture zones. The former two are separated by the Charlie Gibbs fracture zone, the Central and South regions, by the Romanche fracture zone, and the South and Antarctic regions, by the Agulhas-Falkland fracture zone. The main bases of this subdivision were the morphostructural features and geological histories. The Central and Southern regions occupy the largest part of the ocean. Their structural differences are clearly seen in any bathymetric chart. These regions are also different in terms of their geologic histories.



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The ocean began to form in the Central region somewhat earlier than in the Southern one. The oceanic crust began to form, in both regions, in the south , and propagated later to the north [*Pushcharovskii,* 1994]. The Southern and Northern oceans were connected only in the Albian, that is, 100 million years ago, their isolated development lasting more than 50 million years.

One more important fact need be mentioned. The opening of the ocean in the South Atlantic region followed the desintegration of Gondwana. The Central Atlantic Ocean had a more complicated geological prehistory: the Tethys Ocean wedged into this region from the east, the northern areas being occupied by the structural units that had formed in the place of the Yapetus paleoocean. This factor was bound to be imprinted in the peculiar modern structural styles of the Central and South Atlantic Oceans and, consequently, in the forms of their deep-sea basins.

## Characteristics of the Basins

In this section I discuss the evidence available for the morphology, faults, rock sequences, and crustal structure of the basins in the South and Central Atlantic Oceans. The rock sequences are described using deep-sea drilling data. The data available for the deep crustal structure were collected, analyzed, and published by Yu. P. Neprochnov [*Neprochnov and Pushcharovskii,* 2000; *Pushcharovskii and Neprochnov,* 2003]. These papers are provided with extensive references. Of particular value for these studies were two maps of the World Ocean: *General...* [1984] and a gravity map [*Sandwell and Smith,* 2003]. The sequence of the basins' descriptions is controlled by their attitudes toward the Western and Eastern thalassogenes.

## South Atlantic Ocean

**Argentine Basin.** This basin is one of the largest basins in the South Atlantic Ocean (Figure 1). It is bounded by the South American continental slope in the west, its eastern limitation being the slope of the Mid-Atlantic Ridge. In the north it is bounded by the São Paulo continental protrusion (see the text below) and by the Rio Grande Plateau which may also be of continental origin. Its southern boundary is the Agulhas-Falkland fracture zone. Bordering the latter in the south is the Falkland block of the continental crust, broken off by a huge normal fault, where the ocean floor is lowered to a depth of 6200 m. The basin is outlined here using a 4500-meter isobath. The basin is as long as 2250 km in the latitudinal direction and 1500 km in the meridional. The basin has the greatest depths in its sides, its central part being somewhat elevated.

Satellite altimetry data revealed sublatitudinal faults in the ocean floor [*Sandwell and Smith,* 2003]. Most of them fit in the system of the transverse faults crossing the Mid-Atlantic Ridge (Figure 2). Merely single faults cross the entire basin. One of them extend into this area from the area of the southern termination of the Walvis Ridge. Many faults show interruptions where the basin floor is elevated. The specific manifestations of the ocean-floor fault tectonics, the concentration of faults mainly outside of the elevated areas, and the general tectonic situation in this oceanic region suggest that some single continental blocks are buried in the basement of this basin.

The Argentine Basin has an asymmetric structure with the gently dipping northern slope and the very steep southern slope. Deep holes were drilled only in the north and in the extreme southeast of the basin (Figure 3). No acoustic basement has been reached in both areas. The northern hole (358) exposed a rock sequence 830 m thick, with Campanian beds in the bottom hole. All rocks are deep-sea sediments. The southern hole exposed deep-sea deposits, the deepest of them being dated Oligocene. The dating of this basin origin called for some indirect data.

Assuming that the synrifting evolution of the continental margin ended in the Late Jurassic [*Pushcharovskii,* 2002a, 2002b], the onset of the formation of the Argentine basin can also be dated the Late Jurassic. This conclusion is supported by the rock sequence in the Moris Ewing Bank (Hole 330), where the Late Jurassic interval consists of marine sediments about 250 m thick. The seismic profiles across this bank and the Falkland Plateau, bordering the Argentine Basin, show that the thickness of the upper crust under this plateau can be as great as a few kilometers. It follows that the onset of the geological evolution of the Argentine Basin can be dated the Late Jurassic.

Extremely significant period in the structural evolution of this basin was the end of the Cretaceous (∼84 million years ago), when, as follows from the regional geological data, its southern segment was lowered deeply along the Falkland normal fault.

There is evidence of the differentiated structural evolution of the floor of this basin, one being the presence of positive topographic forms in its floor, especially in its central area, recorded also by gravity data, which are believed to be of continental origin [*Pushcharovskii,* 2002a].

As to the crustal structure of this basin, a fairly detailed study using deep seismic sounding was performed in the western part of the basin along a profile consisting of ten recording sites.

The northeastern segment of the profile recorded a comparatively simple structure of the crust consisting of a sedimentary layer (1.7–2.0 km $s^{-1}$), a second layer (4.5–5.0 km $s^{-1}$), and a third layer (6.4–6.6 km $s^{-1}$). The thickness of the sedimentary layer varies form 0.4 to 1.4 km, growing in the southwestern direction. The thickness of the second layer is 0.5–1.5 km, that of the third layer being 3–4 km. The Moho surface with seismic velocities varying around 8 km $s^{-1}$ was found to be located at depths varying from 5 to 7 km below the ocean floor surface.

The southwestern segment of the profile showed the crustal structure similar to that of the northeastern segment, except for the recording site, which was most close to the continental slope rise, which showed the considerably greater thickness of the second layer (about 3.5 km) and, accordingly, the greater depth of the Moho discontinuity (about 9 km below the ocean floor). Worthy of mention is the higher value of seismic velocity in the third layer (7.0 km $s^{-1}$), compared to the other segments of the profile. As mentioned above, the particular tectonic structure of this region suggests the presence of continental fragments in the central and southern areas of the basin.

**Brasil Basin.** This basin extends in the meridional direction between the continental margin of South America and the slope of the Mid-Atlantic Ridge. It is bounded in the south by the São Paulo and Rio Grande seamounts. In the north the basin terminates in the equatorial zone, south of the Romanche fracture zone. The basin has a length of 2500 km, its width being half as large. It has a maximum depth of 6000 m in the north. In the middle of its western half the basin is complicated by the transverse rise of the ocean floor, obviously of continental origin (Abrolhos Bank), in the south of which a chain of volcanic sea-floor mounts and islands (Trindade, Martin Vaz, and others) extends along the 20°S latitude.

The analysis of the gravity maps [*Sandwell and Smith,* 2003] shows that the floor of the Brazil Basin is dissected by a great number of fracture zones (Ascension, Martin Vaz, Rio de Janeiro, and Rio Grande). However, some of them do not extend into the deep-sea part of the basin (Cardno, Tetyaev, and some others).

The above mentioned rise in the western part of the basin precludes the extension of fracture zones, which proves, in addition to other arguments [*Pushcharovskii,* 2002a], its continental origin.

In general, one can see a substantial difference in the tectonic and geodynamic situations in the Brazil and Argentine Basins.

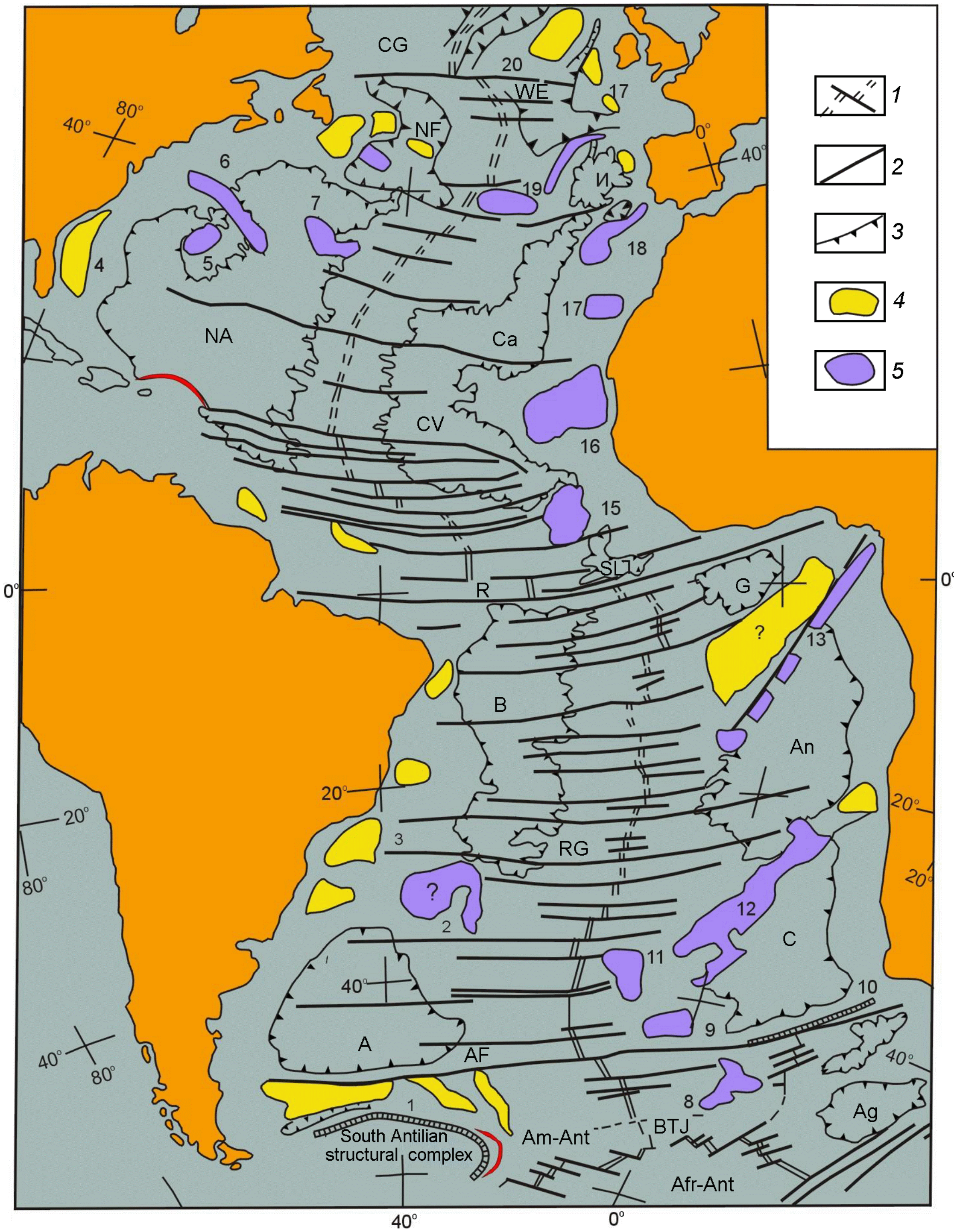


**Figure 1.** Deep-sea basins and adjacent seamounts in the Central and South Atlantic region. (1) Rift zone of the Mid-Atlantic Ridge, (2) transverse fracture zone, (3) deep-sea basin, (4) continental crust fragment, (5) tectonovolcanic seamount. Basins: (A) Argentine, (B) Brazil, (NA) North American, (NF) Newfoundland, (Ag) Agulhas, (C) Cape, (An) Angola, (G) Guinea, (SL) Sierra-Leone, (CV) Cape Verde, (Ca) Canary, (T) Tagus, (I) Iberian, (WE) West European. Demarcation fracture zones: (AF) Agulhas-Falkland, (RG) Rio-Grande, (RO) Romanche, (CG) Charlie Gibbs. Spreading ridges: (Am-Ant) American-Antarctic, (Afr-Ant) African-Antarctic; (BTJ) Bouvet tripple junction. Rises: (1) Falkland Banks, (2) Rio Grande Plateau, (3) Saint Paul Smt, (4) Blake knolls, (5) Bermuda Rise, (6) New England Smts., (7) Corner Rise, (8) Meteor Rise, (9) Discovery Ridge, (10) Heezen Rise, (11) Tristan da Cunha Rise, (12) Walvis Ridge, (13) Cameron Line, (14) Guinea Plateau, (15) Sierra-Leone Rise, (16) Cape Verde Plateau, (17) Canary Ridge, (18) Madeira Tore Rise, (19) Azores-Biscay Rise, (20) Rockall Bank.

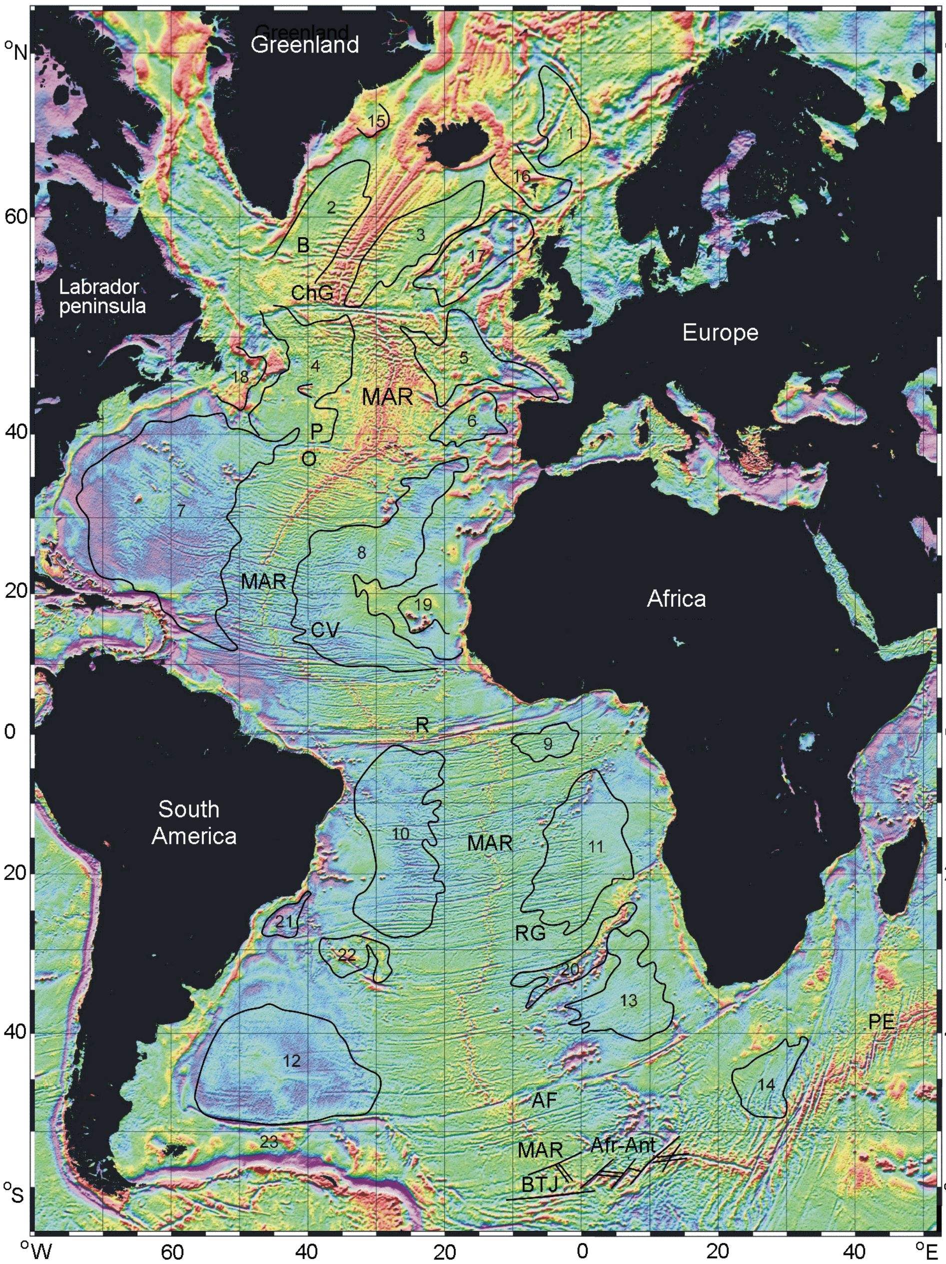


**Figure 2.** Spatial correlation of the Atlantic deep-sea basins with other structural features (given after [*General...*, 1984] and seafloor gravity anomalies [*Sandwell and Smith,* 2003]. Demarcation fracture zones: (ChG) Charlie Gibbs, (CV) Cape Verde, (RO) Romanche, (RG) Rio-Grande, (AF) Agulhas-Falkland, (PE) Prince Edward; second-order fracture zones: (B) Bight F.Z., (P) Picu F.Z., (O) Oceanographer F.Z., (EA) East Azores F.Z. The other notations are: (MAR) Mid-Atlantic Ridge, (Afr-Ant R) African-Antarctic Ridge, (BTJ) Bouvet tripple junction. The numbers denote the major structural units after *General...* [1984]. Deep-sea basins (1–14): (1) Norwegian Trough, (2) Irminger Basin, (3) Iceland basin, (4) Newfoundland Basin, (5) West European Basin, (6) Iberian Basin, (7) North American Basin, (8) Canary Basin, (9) Guinea Basin, (10) Brazil Basin, (11) Angola Basin, (12) Argentine Basin, (13) Cape Basin, and (14) Agulhas Basin. Deep-sea rises (15–23): (15) Greenland-Iceland Rise, (16) Iceland-Faeroe Rise, (17) Rockall Bank, (18) Newfoundland Seamounts, (19) Cape Verde Rise, (20) Walvis Ridge, (21) San Pablo Seamount, (22) Rio-Grande Plateau, (23) Folkland Ridge.

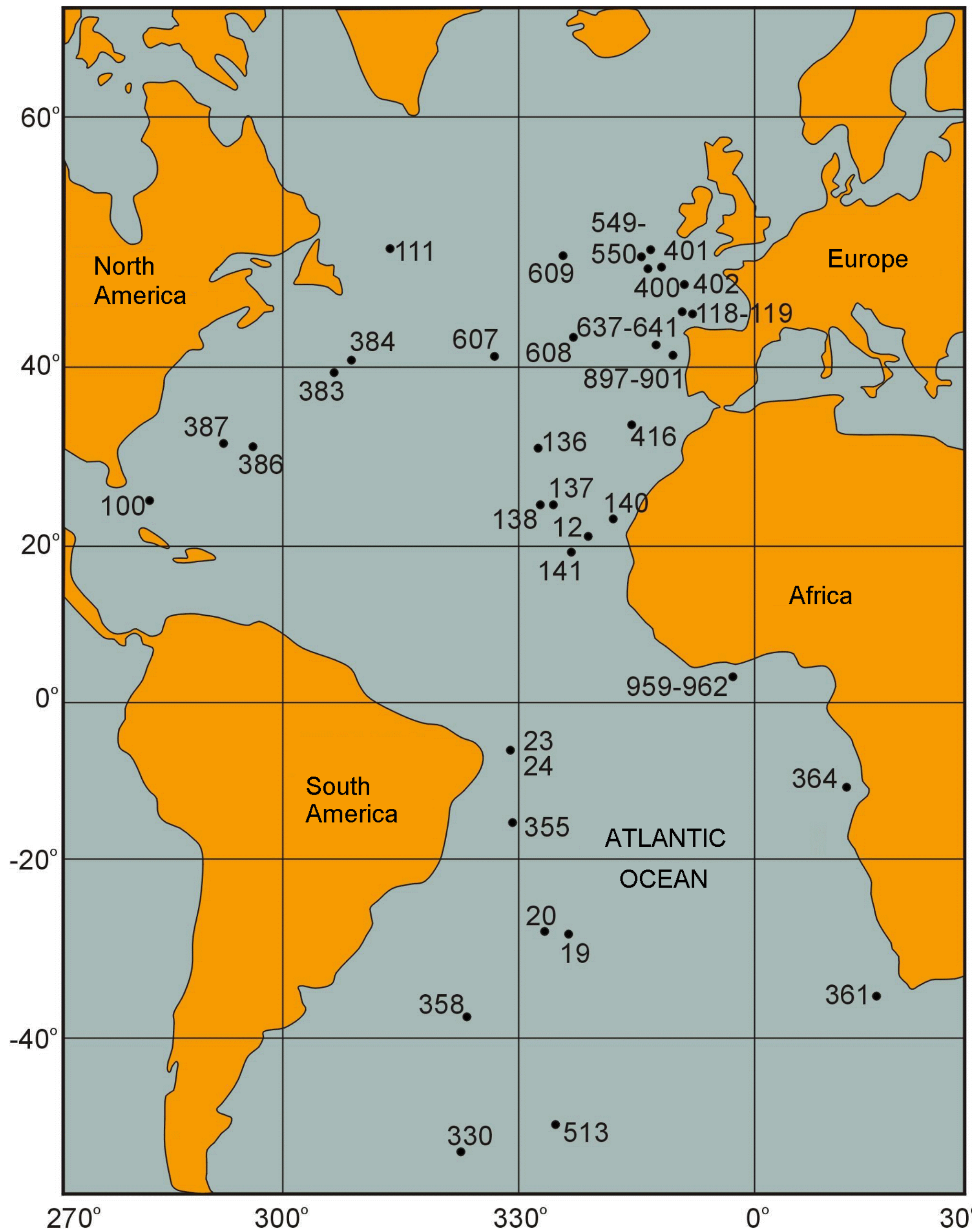


**Figure 3.** Location of the DSDP and ODP holes discussed in this paper.

The research work during cruise 31 of the RV "Dmitrii Mendeleev" in 1984 resulted in the discovery of low (300–800 m) and not very long (10–20 to 50 km) ridges in the northern part of the Brazil Basin, south of the Ascension Fracture Zone. Dredging revealed that they were composed of the rocks of the lower oceanic crust, including mylonitized gabbro and serpentinite [*Neprochnov,* 1985]. We compared these data [*Pushcharovskii et al.,* 1985] with the results of studying the Mid-Atlantic Ridge at the latitude of 20°S in 1982 during Cruise 7 of RV "Professor Shtokman" and with the other data collected by that time for the tectonics of the oceanic crust. Our comparison resulted in the conclusion that overthrust nappes might have developed in the basement of the Brazil Basin. This conclusion was developed by *Raznitsin and Chinakaev* [1989] in their paper based on the results of multichannel reflection CDP profiling along the Angola-Brazil geotraverse, along 12°S. The seismic reflectors dividing the Earth crust from the surface of layer 2 to the M discontinuity, as long as 80 km, were found to be dipping gently eastward, toward the Mid-Atlantic Ridge. The interpretation of the data available suggested them to be overthrust surfaces, and the structural feature as a whole was interpreted as an imbricate structure (see below) [*Raznitsin and Chinakaev,* 1989].

The next step in this direction was supported by the data for the overthrusts [*Pilipenko,* 1993] discovered in two sites of the Brazil Basin, also located along the Angola-Brazil transect west and east of 30°W. The western site shows a series of lithologic sheets separated by low-angle overthrusts which seem to be bounded at depth by the surface of a subhorizontal break. The rock mass movement is directed here toward the mid-oceanic ridge. The eastern observation site shows a change in the ocean-floor topography, where a difference in the geometry between the overlapping sheets can be as great as 1 km. The sheet under the overthrust plane is interpreted most probably as an overthrust sheet-and-block structure. *Pilipenko* [1993, p. 484] believes that "the areas of the tectonic "hummocking" and piling of the oceanic basement occupy about 70% of the Brazil Basin area." The other plain areas are believed to be marked by the undisturbed bedding of the rocks forming a sequence normal for the oceanic crust.

The Brazil Basin differs from the Argentine deep-sea basin not only by its topography but also by its specific geological structure proved by deep-sea drilling. Six holes were drilled in its area: 3 in the south and 3 in the west and northwest. All of the southern holes were drilled in areas where the ocean floor was >4000 m deep, and the northern ones, at the ocean depths >5000 m.

Hole 20, the southernmost one, penetrated the sediments merely 72 m thick. Yet, the pillow basalts and marble fragments discovered at the bottom hole were found to be overlain by deep-sea sediments (nannofossil chalk and the like), which include Maestrichtian, Eocene, Oligocene, and Pliocene–Pleistocene beds. Further westward, Hole 19 showed Quaternary deposits lying on the basalt. This hole was drilled to a depth of 145 m.

One can see that the southern area of the Brazil Basin is distinguished by the substantial instability of its tectonic conditions. Its basalts seem to be of sill origin. Marble fragments from Hole 20 can be associated with the contact metamorphism of the sea-floor carbonate deposits.

The western and northwestern holes exposed basalts at the base too, though the rocks above them varied greatly. In Hole 355 the base of the sedimentary sequence included deep-sea Campanian deposits overlain by Paleocene-Pleistocene open-ocean sediments. The total thickness of the sediments there is 460 m. Two holes, 23 and 24, were drilled in the northwest. The former had a depth of 208 m and exposed Middle Cretaceous to Pleistocene rocks. The basalt under them is highly altered. Hole 24, located nearby, showed a similar situation. Therefore here, too, the geologic structure is highly variable.

In the south, holes were drilled relatively close to the Rio Grande Rise, and in the northwest (Holes 23 and 24), not far from the continental slope, both affecting the accumulation of the rocks in the basin.

The same applies to the Brazil continental margin where the perioceanic basins [*Zabanbark,* 2001] show continental alluvial-lacustrine and deltaic sediments of Jurassic–Neocomian age at the base, followed, in places, by Aptian salts, and still higher, by the limestones of a so called "carbonate platform" (Middle-Late Cretaceous), overlain by Late Cretaceous–Cenozoic turbidites. The latter can serve as a starting point for marking the main stage in the formation of the Brazil Basin. Judging by these data and drilling results, the early stages were not older than Aptian-Albian.

In contrast to the other basins, the floor of the Brazil Basin is dissected by numerous fracture zones (see Figure 2). Of particular tectonic significance is the Rio-Grande fracture zone intersecting the basin in the extreme south. This fracture zone separates the northern and southern regions of the South Atlantic Ocean, which differ greatly in their structural patterns [*Khain,* 2001; *Pushcharovskii,* 2002a]. South of this fracture zone the Brazil Basin becomes more narrow and soon closes. This fracture zone also separates the São Paulo and Rio Grande seamounts and also serves as a structural divide between the Angola Basin and the Walvis Ridge. It extends across the ocean from one continent to the other over a distance of 4700 km.

The western segment of the Angola-Brazil lithospheric geotraverse extends in the Brazil Basin along the 12°S direction [*Pushcharovskii and Neprochnov,* 2002]. Information for the crustal structure there was derived from CDP reflection data. The seismic section obtained for the Brazil Basin showed a sedimentary layer, 100 m to 1 km thick, with a layer velocity of 4.7 to 6.2 km $s^{-1}$ and a thickness of 2–4 km, which is underlain by a layer 2–4 km thick with velocities of 6.7–7.0 km $s^{-1}$. The Moho-discontinuity, marked by a seismic velocity of 8.0 km $s^{-1}$, declines eastward from 4 to 7 km below the ocean floor. Under the Brazil Basin, the CDP data recorded several crustal blocks with different velocities in the second and third layers. These blocks are separated by fracture zones which extend into the upper mantle, as follows from the results of deep seismic sounding.

**Cape Basin.** This basin is situated west of South Africa. It extends from the Walvis Ridge in the north to the Agulhas-Falkland demarcation fracture zone in the south. In the west this basin is bordered by the Mid-Atlantic Ridge. In map view this basin has the form similar to that of a triangle elongated in the NNE direction, the western and eastern sides of which are roughly identical, measuring about 2000 km, its southern side is slightly shorter. The ocean-floor topography is complicated by significant seamounts, especially in its central part. The greatest depths are outlined by an isobath of 5000 m, and the seamounts, by that of 3000 m. The Vema Seamount, situated in the central part, has a depth of 11 m. The seamounts have blurred outlines. In the southwestern corner the Cape Basin is separated from the mid-oceanic ridge by a submarine mountain massif. Its highest peak is the Discovery Seamount with an ocean depth of 389 m. The other seamounts reside at the sea depths of 444, 586, 635, and 737 m.

As follows from gravity data, the basin floor is cut by fracture zones. They extend in the NE direction, parallel to the eastern segment of the Agulhas-Folkland fracture zone. The area also shows the continuations of the Tristan da Cunha and Gough fracture zones, intersected by the Walvis Ridge. Most of these fracture zones do not extend beyond the area of central seamounts, only some of them extending as far as the continental slope of Africa. The general pattern of the fracture zones here suggests that some local spreading zone had existed there in the past.

The deep-sea holes drilled at the eastern margin of the basin showed the following results. The rock sequence penetrated by Hole 361 is represented in the lower part by Aptian "black shales," interbedded with siltstones and sandstones. These deposits contain occasional terrestrial plant remains. The basement was not reached by these holes, yet, judging from their lithology, the black shales mark the early development of the basin. The pelagic deposits (clays) were dated confidently Campanian. The depth of the ocean floor was found to be 4549 m there, and the thickness of the exposed rocks, to be 1335 m, about 1000 m of which being Middle and Late Cretaceous rocks. The post-Eocene deposits had been eroded, yet, they were found in Hole 360 ($P_3 - N_1$). In the east the ocean-continent transition zone includes basalt sheets that had been emplaced during the Late Jurassic-Early Cretaceous time [*Udintsev,* 1987]. Seismic data traced them to a sea depth of 4000 m. These data suggest that the Cape Basin began to form between the end of the Early and the beginning of the Middle Cretaceous.

Only one area in the west of the Cape Basin was investigated in sufficient detail, where the second sedimentary layer, 1.2 km thick, with a seismic velocity of 5.5 km s$^{-1}$ was discovered under a layer of sediments 0.5 km thick. A third crustal layer showed a velocity of 6.8 km/s and a thickness of 3.5 km. The Moho discontinuity with a velocity of 8.2 km s$^{-1}$ was found to be at a depth of 5 km below the ocean floor.

**Angola Basin.** The structural limitation of this basin in the north is the Cameron line of sea-floor volcanic mounts, and one of the largest Atlantic ocean-floor elevations, namely, the Walvis Ridge, in the south. In the east the basin is replaced gradually by the continental slope of Africa. In the west this basin borders the slope of the Mid-Atlantic Ridge. Several parallel, NNW striking fracture zones were mapped there [*Mazarovich and Sokolov,* 1999]. This basin is elongated in the submeridional direction. Its central segment is an abyssal plain roughly 800 km long and some 450 km wide with the ocean depths varying from 5500 to 5700 m.

The periphery of the basin is marked by three systems of fracture zones. One of them has been mentioned above. The second system is represented by fracture zones intersecting the Mid-Atlantic Ridge. As a rule, they terminate at the western margin of the basin (Cardno, Tetjaev, St. Helen, and Hotspur). In the north and south, however, fracture zones have been traced in the basin (Martin Vaz and others). The ends of these fracture zones can be used to trace the lithospheric block residing at the base of the deepest segment of the basin. The third system of fracture zones is situated at the eastern side of the basin. These fracture zones strike WNW and along the latitude and are drastically discordant relative to the system of the transform faults of the Mid-Atlantic Ridge, representing a special generation of faults. Apparently, they can be associated with the destruction of the African continental margin.

As regards the deep-sea part of the Angola Basin, an important fact is the absence of seamounts over a significant area. The exception is the extreme northern area where there are single volcanic cones, mainly restricted to the Cameron volcanic line. The morphostructural specifics of the basin and its relations with the continental margin of Africa suggest that continental crust was present in its limits in the geological past.

The deep-sea hole (364) drilled in the eastern margin of the basin exposed a 1086-meter sequence of almost wholly deep-sea deposits ranging from Aptian to Pleistocene in age, their total thickness being 1086 m. The reconstruction of the geological history of these rocks calls for the knowledge of the specific features of the lower deposits. *Krasheninnikov* [1978, p. 124] wrote in this connection: "The Aptian rocks are gray and greenish-gray argillaceous limestones with black sapropelic clay including planktonic foraminifers and nannoplankton. The base of this member usually contains interlayers of dolomitized limestone and dolomite, its clay being highly bituminous." Drilling operations were suspended at a depth of a few tens of meters above the top of the underlying salt member which was estimated from geophysical data to be as thick as a few kilometers. It follows from the above description that the Angola Basin began to form in Aptian time. Yet, it was proved above that the Cape Basin had been formed at about the same time. Consequently, the propagation of the ocean from the south to the north proceeded very rapidly. Since the origin of the Walvis Ridge was dated Late Cretaceous [*Pushcharovskii,* 2002a], the structural shaping of both basins could be the same.

The eastern boundary of the Angola basin can be traced along the 3000-meter isobath. The continental margin was studied in this region better than elsewhere in the band bordering Africa. The seismic profiles and drilling data available show that the Middle and Late Aptian time witnessed the regional accumulation of salt which covered the earlier continental and lagoonal deposits. The salt is overlain everywhere by Albian platform-type carbonate deposits, including deep-sea sediments in some areas. It follows that the thick zone of salt accumulation at the continental margin was replaced westward by a zone of sedimentation in an oceanic basin during the early period of its evolution, the salt-bearing rocks being highly deformed.

The structure of the basement under this basin was studied during the work along the Angola-Brazil geotraverse in 1979–1986. Brief information on this basin was given by *Neprochnov* [1985].

The surface of the acoustic basement in the Angola Basin is distinguished by its poor ruggedness and comparatively leveled topography. An upthrust and imbricate structure with relatively small blocks and overthrust elements measuring 2–5 km was discovered in the top of the basement under the sediments. The depth of this deformation penetration is also not large. The fault surfaces are inclined to the west, that is, toward the Mid-Atlantic Ridge. The fact that the sediments had not been involved into the deformation process suggests that the latter developed during the early stage of the ocean formation.

The Angola-Brazil Geotraverse crossed the Angola Basin in its northern half along a distance of 1000 km. Here, the CDP reflection data showed that in the eastern part of the basin the sediments are underlain by a second crustal layer with velocities of 5.6–6.0 km s$^{-1}$ and a thickness of 2–4 km and by a third crustal layer, 3–4 km thick, with velocities of 6.8–7.4 km $s^{-1}$ (the boundary velocity measured by deep seismic sounding was found to be 7.1 km $s^{-1}$). The Moho discontinuity (the boundary velocity being 7.9 to 8.2 km $s^{-1}$) was found to plunge eastward from 5 to 10 km below the ocean floor. In the Angola Basin, CDP reflection data revealed, like in the Brazil basin, a few crustal blocks with different layer velocities, which are separated by deep fracture zones. The DSS results showed the substantial lateral structural variation of the lithosphere in the Angola Basin to a depth of 80 km.

## Central Atlantic

**North American Basin.** This basin occupies a very large area in the west of the Central Atlantic Ocean. It is bounded by the Newfoundland Banks in the north, by the North American continental margin in the west, and by the marginal swell extending along the Puerto Rico deep-sea trench in the south. The basin is delineated by a 5000-meter depth contour. It has an irregular shape in map view. It measures 2000 km from the north to the south and has its greatest width >2000 km at 30°N.

This basin consists of several large structural units: second-order basins and the Bermuda Rise. Three central parts of the small basins are represented by abyssal plains. These basins are Sohm in the north, Hatteras in the west, and Nares in the south. In the Sohm Basin the abyssal plain resides at depths of 5136–5396 m, in the Hatteras Basin at depths of 5390–5570 m, and in the Nares Basin at the greatest depths of 5700–5900 m [*Udintsev,* 1987]. The sediments filling these basins vary greatly in thickness. For instance, their thicknesses in the perioceanic regions are 4000 m in the north of the Sohm Basin, 1000 m in its south; 5000 m in the Hatteras Basin, yet decreasing to 2000 m slightly eastward. In the central regions of the basins the sediments are not more than a few hundred meters thick.

The Bermuda Rise is situated east of the Hatteras Basin. Its size is 1500 km from north to south and 1000 km from west to east. It is of oceanic origin, its crust being about 8 km thick. It is bounded in the northeast by the New England young volcanic chain restricting the northern area of the basin (Figure 4). In the east this area is restricted by the New England young volcanic chain separating the northern area of the basin (Figure 4). This area is restricted in the east by the Corner volcanic ridge. Volcanic seamounts are also widespread on the Bermuda Rise itself, and also on the ocean floor east of it. *General...* [1984] shows that the fracture zones crossing the Mid-Atlantic Ridge are not traceable in the North American basin. However, the Hatteras abyssal plain, situated southwest of the Bermuda Islands, is dissected by a number of NW-trending fracture zones (the best known is Blake Spur fracture zone), where seismic data recorded extensive (15–20 km long) subhorizontal or gently E-dipping reflecting horizons, both in the upper and in the lower crust [*McCarthy et al.,* 1988], which can be interpreted as thrust faults (see Figure 7). Hole 383 was drilled in the Sohm abyssal plain at a depth of 5267 m. It penetrated only Quaternary deposits.

Hole 387 was drilled at the eastern slope of the Hatteras Basin, where the ocean floor is 5118 m deep; the drilling depth was 794.5 m. The bottom hole was drilled in 2.9 m of basalt. The basalt is overlain by Upper Berriasian-Lower Valanginian limestones. Above follow Barrhemian-Cenomanian deposits, including black argillite, which are overlain by Turonian-Maestrichtian variegated argillite. The rest of the sequence, beginning from the Upper Maestrichtian, is composed of deep-sea oceanic deposits.

The rocks composing the Bermuda Rise are important for understanding the geological history of the Hatteras Basin. They were penetrated by Hole 386 drilled in the central part of the rise to a depth of 973.8 m below the ocean floor which is 4783 m deep there. The hole entered the basalt and was drilled about 10 m in it. The basalt is overlain by green and black argillites of Albian-Cenomanian age, which are replaced upward by Cenomanian-Late Maestrichtian variegated argillite (resembling the rocks penetrated by Hole 387). The depth interval of 490–613 m is composed of Paleocene to Middle Eocene radiolarian and siliceous siltstones, reflecting the early development of deep-sea oceanic conditions. The higher intervals contain large volumes of turbidite and volcanoclastic rocks. They mark the time when the Bermuda Rise was formed as an intraoceanic tectonic feature.

Worthy of discussion are the rock sequences bordering the western segment of the North American Basin, where a fairly large number of holes were drilled. In the southwestern area bordering the Bahama Islands some holes penetrated Upper Jurassic deposits, dated Oxfordian-Kimmeridgian, or possibly Callovian. Hole 100, drilled in the area where the sea floor is as deep as 5336 m, exposed a rock sequence of 531 m, underlain by 14 m of basalt replaced upward by a member of interbedded basalts and greenish-gray limestones, dated Oxfordian-Callovian(?). This member is overlain by thin (9 m) Tithonian-Valanginian nannoplanktonic deposits. Drilling data prove that oceanic conditions had existed in the southwest of the North American Basin as far back as the Late Jurassic-Early Cretaceous time.

Basalts were also found in the more northern area of the western segment of the North American Basin, between New York and the Bermuda Islands, where Hole 105 was drilled to a depth of 633 m, the depth of the ocean floor being as deep as 5251 m. The basalt is overlain by Oxfordian-Kimmeridgian red argillaceous limestone. This rock sequence is overlain by Tithonian-Neocomian white and gray limestones, Aptian-Barremian-Cenomanian black clays, variegated clays, possibly of Late Cretaceous to Eocene age, and hemipelagic ooze. This rock sequence is typical of the lower continental slope and rise of the Atlantic Ocean.

The above data suggest the progressive development of the North American Basin from south to north in the Late Jurassic–Late Cretaceous period of time. The recently published book by *Byakov et al.* [2001], describing the structure of the sediments in the central sector of the western Atlantic margin, allows me to confine myself to the short information given above.

It was proved earlier [*Neprochnov and Pushcharovskii,*

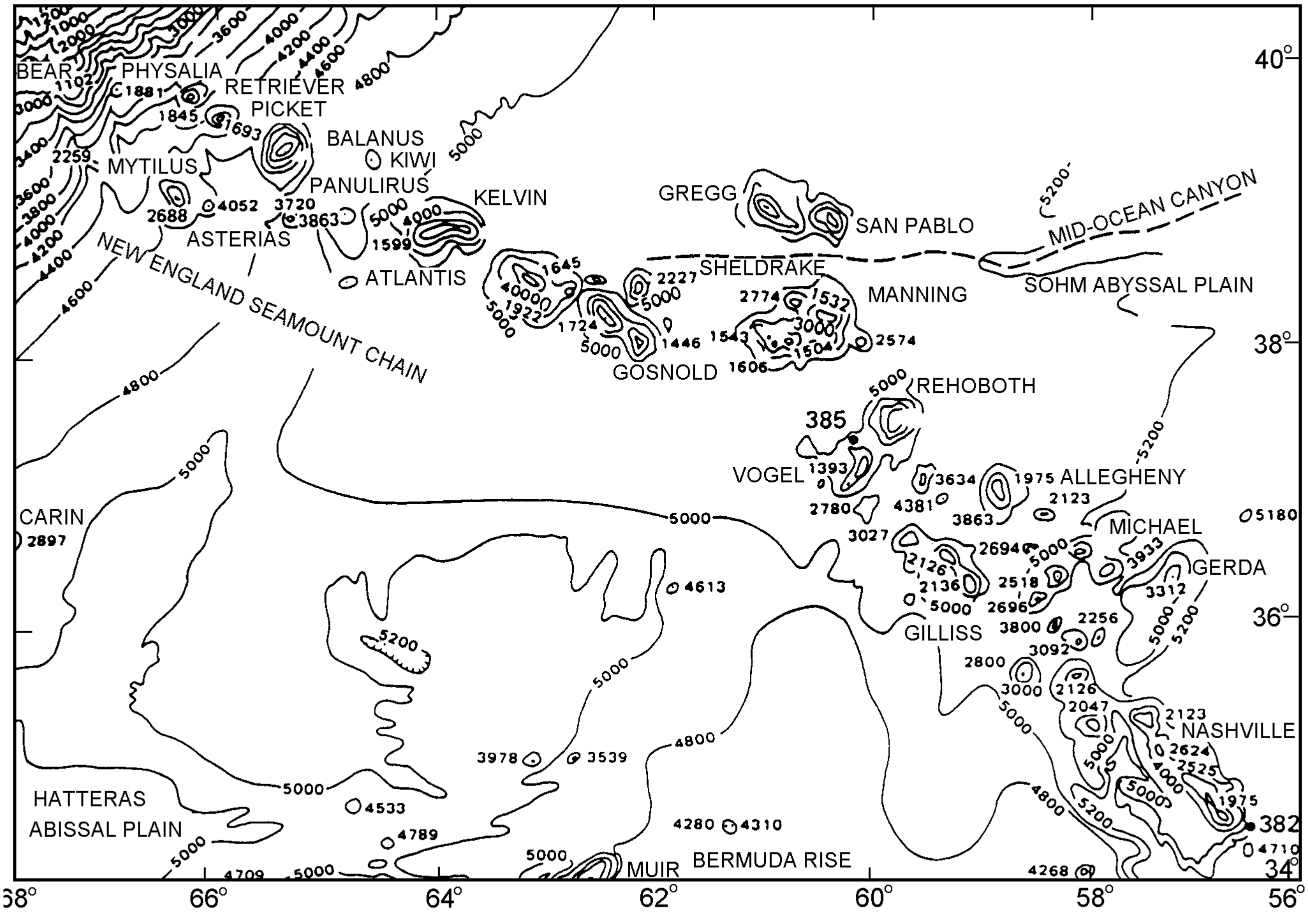


**Figure 4.** Chain of New England Seamounts separating the active part of the North American Basin [*Initial...,* 1972]. One can see a great accumulation of seamounts in this sector of the basin and the location of two DSDP holes: 382 and 385.

2000] that the crust in the North American Basin showed a distinct vertical layering. Discussed below are its most characteristic features.

The 3B layer, which is generally associated with serpentinite or serpentinized peridotite has been recorded in the northwestern and southern areas of the basin. In the former area, the sites with this layer tend to be located in two narrow zones of a NW–SE strike. One of them is the Blake Spur fracture zone located along the deeply lowered extension of the Blake Spur fracture zone located near the deeply lowered continuation of the Blake marginal continental plateau. The other zone continues the line of the southwestern limitation of the Bermuda Rise, being generally a fracture zone as well. In the southern segment of the basin the 3B layer is restricted to the oceanic periphery (marginal swell) of the Puerto-Rico trench. The predominant longitudinal wave velocity in the 3B layer is 7.2 km s$^{-1}$, which suggests comparatively low serpentinization. The thickness of this layer is 3–5 km. The comparison of the total thickness of the crust in the areas with and without this layer showed that the predominant thickness of the crust in the former case is 9 km, and 6 km in the latter, that is, the crust grows 1.5 times thicker in the case of serpentinization.

The layer 2 showed a fairly large range of seismic velocities: from 3.4 to 3.8 km s$^{-1}$ in layer 2A to 5.8–6.2 km s$^{-1}$ in layer 2C. The most common for the seismic models of the North American Basin is layer 2B with the main velocity peak of 5.0 km s$^{-1}$ and two additional peaks (4.6 and 5.4 km s$^{-1}$). The predominant thicknesses of the layers are 0.5–1.0 km for layer 2A, 1–2 km for layer 2B, and 1.5 to 2 km for layer 2C. The distribution pattern of these layers in the basin is highly complicated. The lowest of them (2C) is recorded occasionally, mainly in the Northwestern part of the basin and only in places in its southern margin. The middle layer (2B) is usually recorded everywhere, yet, it was not found in a fairly large area, extending as a broad band of a NW–SE strike and also in some more local areas. The above mentioned band is restricted to the area between the Blake Plateau and the Bermuda Rise.

The upper layer (2A) of the oceanic crust is usually associated with fresh basalt lavas. The areas where this layer is present are restricted to fracture zones or to local ocean-floor elevations, supposedly of volcanic origin. To conclude, the discovery of layer 2A can be used as an indicator of a comparatively recent tectonic activity accompanied by basalt lava flows.

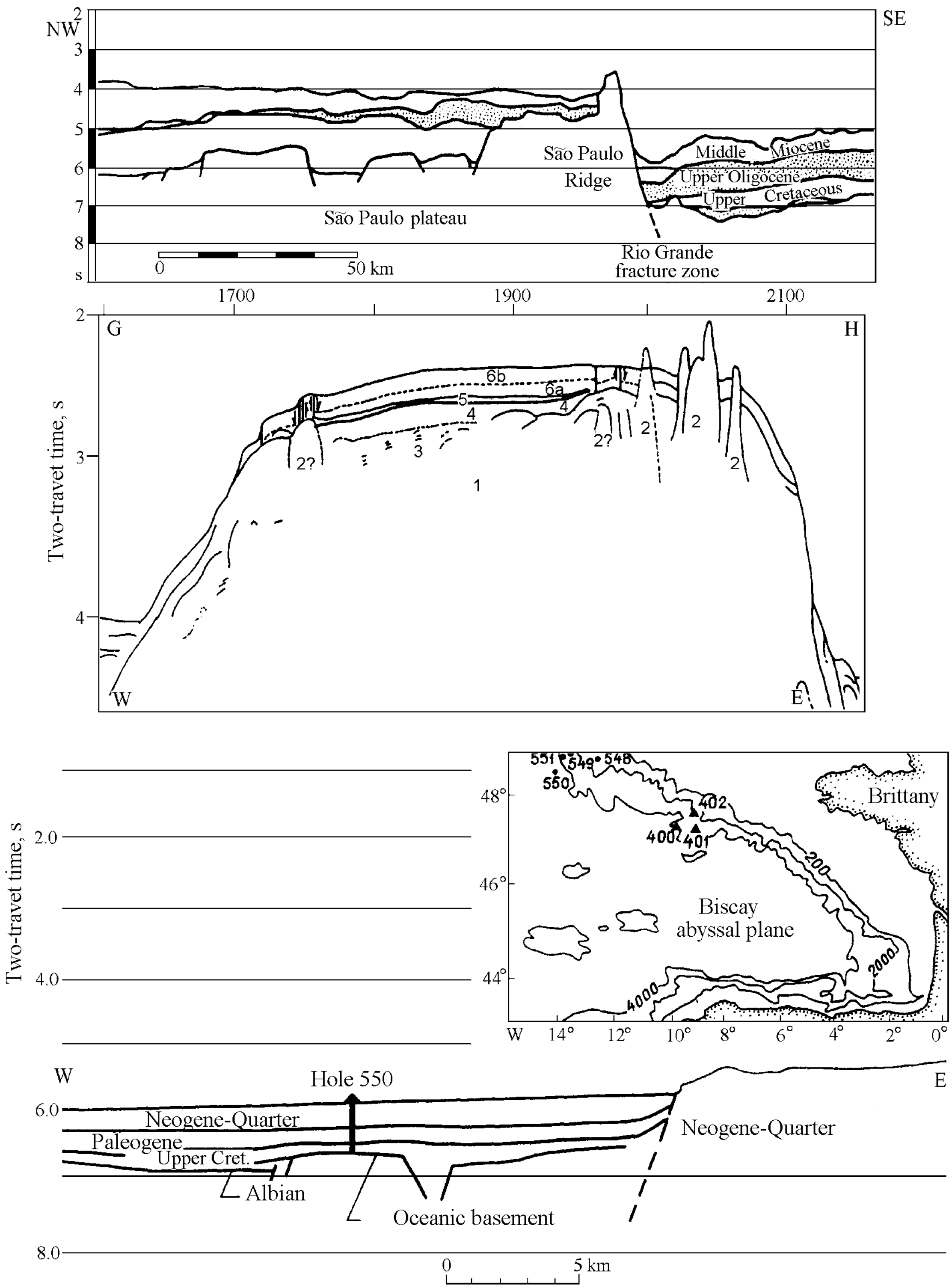


**Figure 5.** Examples of tectonic relations between the deep-sea basins and adjacent uplifts: (a) seismic profile crossing the San Pablo Seamount and deep basin [*Bassetto et al.,* 2000]; (b) seismic profile crossing the Orphan Knoll and Newfoundland Basin (NF) [*Initial...,* 1972]; and (c) seismic profile crossing the West-Europe continental margin and the West Europe Basin [*Noltimier,* 1974]. The inset map shows the locations of the deep-sea holes drilled in this region.

**Newfoundland Basin.** This basin is situated between the Newfoundland Plateau and the Mid-Atlantic Ridge and extends for a distance of 1300 km from 40°N to the Charlie Gibbs Fracture Zone, its width being about 500 km. It is most shallow compared to the other Central Atlantic basins: 4500–4600 m. It has an irregular form outlined by a 4000-meter isobath. Its main gravity background is represented by positive anomalies [*Sandwell and Smith,* 2003]. Three continental blocks border this basin in the west: the Newfoundland Plateau, the Flemish Cap high, and the Orphan Knoll block detached from the continent (see below and Figure 5), the latter measuring about 100 km across. Its top was recorded at ocean depths of 1800–2000 m. The sediments covering it are very thin [*Initial...,* 1972]. Its deepest rocks (150 m thick in Hole 111) are Middle Jurassic (Bajocian) sandstones and shales of continental origin. Their thickness is a few meters. They are overlain by a member of shallow-sea calcareous sandstones and shelly limestones of Albian-Cenomanian age. The overlying rocks (Maestrichtian-Miocene) are pelagic sediments. These highly variable changes in their sedimentation were caused by the periodic tectonic subsidences of the block involved in the process of ocean formation. No deep-sea holes were drilled in the central parts of the Newfoundland Basin, yet deep-sea holes were drilled in the south, in the area where this basin is separated from the North American basin. Hole 384 was drilled to a depth of 330 m at an ocean depth of 3910 m. This hole entered the basalts that flowed under subaerial or shallow-sea conditions. This hole entered the basalts that had flowed in subaerial or shallow-sea conditions. These basalts are overlain by Late Barremian to Early Albian shallow-sea organic limestones overlain by Maestrichtian and Cenozoic deep-sea deposits. It follows that during the last 105 million years this area had experienced a 4000-meter subsidence. The latter began in Maestrichtian time, similar to the area of the Orphan Block. The hole drilled in a strip between the basin and the Mid-Atlantic Ridge (Hole 607, depth of the ocean floor was 3427 m, the interval drilled was 284.4 m) exposed the rocks of a very limited stratigraphic interval: Late Miocene-Quaternary. The rock material was represented by open-ocean deposits. The middle segment of the Newfoundland Basin includes the Milne subvolcanic seamount, and its southwestern region, the Newfoundland Seamount chain. So, this volcanic activity seems to have correlated with the magmatism of the Azores Islands and, hence, was fairly young.

The evolution type of the western margin of the basin suggests that it began to form at the end of the Cretaceous time. The deep seismic sounding (DSS) profiles are scarce and are concentrated mainly in its southeastern segment. The seismic models available suggest that the crust under the Newfoundland basin is vertically layered. The best proved crustal layers are 1A, 2A, 2B, 2C, and 3B, and also the top of the mantle (M1).

The 3B layer (with 7.2 km s$^{-1}$ velocity) was recorded along two DSS profiles in the west of the basin and along three closely spaced profiles in the east. This layer is 2–3 km thick. Layer 2 showed a fairly wide range of velocities ranging from 3.5 to 6.2 km s$^{-1}$, the peak values being 3.5, 4.6, and 6.2 km s$^{-1}$. Its thickness is 1.5–2.0 km. The upper layer of the crust (2A) is usually associated with fresh basalt lavas. This layer was mapped mainly in the southern and southwestern margins of the Newfoundland Basin. The analysis of the detailed bathymetric chart and schematic tectonic map shows that the areas underlain by this layer are restricted to the fracture zones or to local ocean-floor elevations of volcanic origin. The crustal thickness in the Newfoundland basin is 5–7 km, being as great as 9–10 km in areas where the crust includes the 3B layer.

**Canary Basin.** Taking the outlines North-American Basin as a universally accepted fact, the situation is different with

the Canary Basin. In this paper it is interpreted as a deep-sea structural feature extending east of the Mid-Atlantic Ridge between 36°N and 10°N. The Canary Basin is usually outlined following the 5000-m depth contour (like in the case of the North American Basin). The Canary Basin has an irregular form. It is as long as 2600 km and is about 600 km wide in the north, and about 1300 km wide in the south. Arranged along the eastern and southern surroundings of the basin are the following large ocean-floor mounts: Madeira Rise in the north, Canary Ridge further southward, Cape Verde Rise still further south, and Sierra Leone Rise in the south. The northern boundary of this basin is the Azores group of fracture zones.

*General...* [1984] shows three abyssal plains following one another in the following order: Madeira Plain, Cape Verde Plain, and Gambia abyssal plain. The ocean floor is as deep as 5.4–5.3 km there. These three geomorphologic elements are curved around the zone of sea mounts located eastward.

The Map of Marine Gravity Anomalies from Satellite Altimetry [*Sandwell and Smith,* 2003] shows that the transform and other faults crossing the larger area of the Canary Basin have a much more poor expression compared to those in the Mid-Atlantic Ridge. Yet, south of the Cape Verde Seamount its floor is dissected by large fracture zone (Cape Verde and others). Yet, in general, this basin has a much more poor expression in this map in contrast to the bathymetric map. The basin floor does not show any large accumulations of seamounts, the latter being extremely rare. No similitude can be found in the outlines of Canary and North American basins.

Two holes were drilled in the central part of the basin south of 30°N. Hole 137 was drilled a thousand kilometers west of Africa at a depth of 5361 m, the hole penetrated 401 m of the rocks. The sea-floor topography is hilly there. Highly altered and fractured basalt flows were recorded in the lower interval of the hole at a depth of 397 m below the ocean floor. Above follow nannoplankton marl, chert, calcareous mud, and black shale of 120 m thickness and dated Late Albian and lower Late Cretaceous. These rocks are overlain by Turonian claystones and cherts with Senonian-Tertiary beds that had deposited in deep-sea conditions.

Hole 138 was located 30 km east at the ocean depth of 5288 m, its drilling interval was 442 m. It was shut in altered basalt overlain by oceanic sediments including Campanian clay. Since the rock sequence did not include Albian rocks, it was believed that the basalt was present in the form of sills. Anyway, both holes suggest that this oceanic basin had been formed in this area at the end of the Albian to the beginning of the Late Cretaceous.

Hole 136, which is also of great interest, was drilled slightly east of the northern termination of the basin, 160 km north of the Madeira I. The ocean floor depth was 4169 m there. The hole was drilled to a depth of 313 m. Tholeiite diabase cores were raised from a depth of 308 m. The oldest sediments are represented by variegated clay beds which are overlain at the depth of 290 m by Albian nannoplankton marl. It is mentioned in the description of this rock sequence that the oldest rocks are variegated clays which are overlain at a depth of 290 m by Albian nannoplankton marl. The authors [*Initial...,* 1972] who described this rock sequence mentioned that the age of the oldest rocks was 105–110 Ma, and that they were younger than they should be according to narrow magnetic anomalies and than the age of the respective deposits in the west of the North American Basin. This rock sequence shows a time gap of 60 million years: the Albian rocks are overlain by Senonian red clay. In general, this does not contradict the data obtained from the previous two holes.

Holes 140 and 141 were drilled in a more southern area as compared to that of Holes 137 and 138. The depths of the ocean floor and the depths of the holes were 4483 m, 590 m and 4148 m, 298 m, respectively. In Hole 140, the Miocene rocks are underlain by Upper Cretaceous-Middle Eocene shale and chert. Also found there were silt and sand, as well as dolomite. The total thickness of these deposits was found to be 400 m. The base of layer 1 was not exposed. It seems to have been exposed at the bottom of Hole 141, where it was found to be composed of highly altered serpentinized basalt. Above follow reduced oceanic deposits, among which only the Late Cenozoic ones were dated.

The crustal structure in the Canary Basin was studied in less detail than in the North American Basin. The data available suggest the following results. The crustal thickness varies from 5 to 8 km in the area of the Madeira Abyssal Plain and in the nearby southern areas with the oceanic depth varying from 4000 to 5200 m, growing thicker toward the African Continent. The crust has a thickness of about 5 km in the deepest part of the Cape Verde Basin (>5500 m). Here and in the north, the crust consists of its three main layers. In the Cape Verde Basin in the eastern direction where the ocean floor depth is 5200 m seismic velocities grow in the second and third layers, the crustal thickness growing by not more than 1 km.

As mentioned above, the Canary Basin borders the tectonovolcanic rise of the Canary Islands. The latest data on their geology prove the presence of oceanic crust at the base of this archipelago [*Schmincke et al.,* 1998]. The reason for this was the discovery of young volcanic rocks in xenoliths, as well as the finding of xenoliths composed of young volcanic rocks, Miocene clastic rocks, as well as gabbro and MORB-type basalts. The petrology and mineralogy of the gabbroids and metabasalts allowed the conclusion that these rocks were identical to the rocks of layers 2 and 3 of the oceanic crust. The rock samples were dated 156–175 Ma. These figures suggest the initial phase of ocean formation in this region.

The above data hold true for the Gran Canaria, La Palma, and Lanzarote islands. I would add Fuerteventura Island, where N-MORB basalts were discovered under Callovian-Oxfordian red clay [*Steiner et al.,* 1998]. Based on the finding of Bositra buchi remains (179–184 million years), these authors suggest the presence of Toarchian-Early Aalenian post-rifting deposits there.

**Sierra Leone Basin.** This basin is situated directly south and southeast of the Sierra Leone Rise. It has the form resembling a triangle with the sides of roughly 1000 km The depth of the ocean floor in its central part may be as great as 5000 m. Its southern limitation is the Romanche Fracture Zone. In the east the basin is limited by the morphostructural features of the continental margin. Four holes (959 to 962) were drilled at the oceanic depths of 2000 to 4500 m. The oldest rocks penetrated by them were Aptian–Lower Albian in Hole 960 and Albian in Hole 959 (their depths being 450 and 1150 m, respectively). The holes were drilled in the clastic, siliceous, and carbonate deposits that had deposited during the Cretaceous time at depths of 500–1500 m during the time interval of 65–43 million years, at depths of 1000–2000 m during 40–22 million years, and at depths of 1500–2000 m during 18–3 million years [*Clift and Lorenzo,* 1999]. The rock sequences show the progressive accumulation of the bottom sediments depicting the geological history of the continental margin and, hence, of the respective region of the ocean. Merely some individual fracture zones, typical of a mid-oceanic ridge, can be traced at the floor of the basin.

Deep seismic sounding was carried out in this basin along a NE-trending profile at ocean depths of 4500–5000 m. The crust was found to vary in structure, its thickness varying from 4 to 9 km. Crustal layer 2 was found to be thicker than normal.

**Iberian Basin** is outlined by a 5000-meter isobath. It has an irregular round form, elongated in the NE direction to measure roughly 600 km, its width being 400 km. Its central part is occupied by an abyssal plain with a maximum depth of 5390 m. Hilly topography is developed in the other areas.

This basin is separated from the Pyrenean mountain range by a transitional zone, broken by fracture zones, with a continental outlier known as the Galicia Bank. This zone was surveyed by numerous seismic studies and deep-sea drilling, which revealed relationships between the continental and oceanic crust. West of the Galicia Bank [*Whitmarsh et al.,* 1996] the continental crust grows drastically thinner, from 17 to 2 km, in the area of the Peridotite Rise elongated parallel to the continental margin. Directly west of this rise the crustal thickness is 2.5–3.5 km, yet it becomes as thick as 7 km farther westward. A lenticular body of serpentinized peridotite, about 60 km wide, has been recorded under the Peridotite Rise, where it underlies the thin continental and oceanic crust.

South of the Galicia Bank the continental crust (with velocities of 5.0–6.6 km $s^{-1}$) becomes as thin as 2–5 km [*Chian et al.,* 1999]. Like in the west, it is underlain by serpentinized peridotite (velocities of 7.3 to 7.9 km $s^{-1}$). Its serpentinization varies both vertically and laterally, which suggests changes in the geodynamic environment.

The Iberian Basin is restricted in the west by the Azores-Biscay Rise having a block structure and extending in the NE direction. The King Trench of a NW strike approaches the middle segment of this rise from the side of the Mid-Atlantic Ridge. The Iberian Basin is separated from the more northern West-European Basin by the group of the Charcot Seamounts and ends in the south at the latitude of the Azores Islands.

The rocks underlying the abyssal plain of this basin were exposed by deep-sea holes. Hole 897 was drilled in the south at the ocean floor depth of 5320 m to a depth 838 m. The hole entered serpentinized peridotite including Early Cretaceous limestones. The latter are overlain by a member of Aptian black shale overlain by a small member of sandy and clayey rocks of unknown age. From a depth of about 620 m the rock sequence includes Eocene-Pleistocene fine-clastic rocks with some nannosilt developed as facies in the Pliocene and Pleistocene rocks. Of interest is the rocks sequence penetrated by Hole 899 drilled in a more southeastern area from an ocean depth of 5291 m, its drilling interval was 563 m. The bottom of this rock sequence is composed of serpentinized peridotite, argillite, and siltstone composing a drilling interval of 75 m. The lowermost rocks were dated Late Hauterivian. Above follows a breccia with peridotite and argillite blocks (∼110 m) ranging from Early Aptian to Maastrichtian in age. The Campanian, Maestrichtian, and Eocene rocks are reduced to a few meters with Paleocene rocks being missing. The upper part of the rock sequence (from Campanian and higher) resembles the sequence of Hole 897. Yet, the oldest rocks were found in Hole 901 which was drilled in the extreme east (the ocean floor was found to be at a depth of 4718 m, the interval drilled being 248 m). The hole exposed Middle Tithonian and Late Tithonian–Early Berriasian turbidites at its bottom. Proceeding from the regional geological data available, the continent began to be destroyed during the late Triassic, where a zone transitional to the ocean was formed later. This is indicated by the continental clastic rocks which rest unconformably on the Hercynian basement in the Luisitana and Porto Basins extending in the ocean in the vicinity of the continent's edge. Both basins were formed during the early half of the Jurassic at the rifting period of the geological history. Accordingly, the Iberian Basin began to form during the late Jurassic. This is proved by the rock sequences from the southern part of this basin, from the western margin of the Galicia Bank, and from the eastern part of the basin (Holes 637–641). As regards the above mentioned peridotites, they seem to be in the secondary mode of their occurrence, having been transported along the faults. This is proved by the surrounding geological situation: they are associated both with sedimentary rocks and with serpentinite breccias.

The DSS profiles are concentrated mainly in the west of the region. The crust has a considerably simple structure in the middle of the basin. The crustal thickness is 4.5 km there. In the eastern part of the basin the crust has a more complex structure, its thickness being 4.5 km. The crustal structure is more complex, and its thickness is larger. All basic layers of the oceanic crust and upper mantle have been clearly distinguished in the Iberian Basin.

**West European Basin.** This basin is located at the periphery of West Europe which has a large shelf zone there. The base of the latter includes Hercynian folded rocks. The northern boundary of the basin is the Rockall Plateau, its southeastern end being the Biscay Basin. Its boundary is conventional south of the Charlie Gibbs fracture zone because of the complex seafloor topography. It extends for about 1000 km from south to north with a width of ∼600 km. The Porcupine abyssal plain, having an oval form and oriented in the northwestern direction, extends in the east. The depth of its floor is not greater than 4700 m. This plain does not have a clear expression in the gravity map [*Sandwell and Smith,* 2003]. A linear negative anomaly was recorded along its western margin, which records a NW-striking oblique fracture zone (see below and Figure 6). One more similar gravity anomaly was recorded at the latitude of the Bay of Biscay. It records the boundary between the basin and the mid-oceanic ridge. Extending in a more southern area is the King Trough described by *Dobretsov et al.* [1991]. The above evidence proves the existence of a significant system of oblique fracture zones complicating the structure of this oceanic region. Note that striking in the same direction is also the rift-zone fragment of the Mid-Atlantic Ridge, located south of the Charlie Gibbs Fracture Zone, and also two linear gravity anomalies bordering the western end of this fracture zone.

As mentioned above, the southwestern end of the West European Basin is the Biscay Basin which is as long as 400 km. This basin is separated from the structural features of the Pyrenees by a large overthrust fracture zone. The floor of this basin is an abyssal plain residing at depths of 4870-4650 m [*Udintsev,* 1987]. No deep-sea holes were drilled in the central part of the West-European Basin. There are some holes drilled in its margins. Hole 609, drilled near the northwestern end of the basin, at the eastern end of the Mid-Atlantic Ridge (sea depth of 3884 m; the hole depth of 339.4 m), exposed merely Upper Miocene–Quaternary deposits. Also insufficiently informative was Hole 610 drilled at the southern end of the Rockall Rise (sea depth of 2417 m, the hole length of 723 m). The hole did not leave the deep-sea Miocene interval, yet, judging by the seismic profiling data, a depth interval 1.5 times larger than the drilled one, remained to reach the acoustic basement. However, Hole 608 drilled to a depth of 530.9 m south of the King Trough, where the sea floor was 3526 m deep, exposed 15 m of basalts not far from the southwestern corner of the basin, covered by Middle Eocene deposits.

More information is available for the continental margin. Several holes were drilled in the area south of 49°N. The most western of them was Hole 550 drilled to a depth of 720 m from the ocean floor as deep as 4432 m (Figure 5). The hole penetrated a rock sequence from the Albian to the recent. The Albian-Cenomanian rocks are calcareous argillites containing planktonic foraminifers. Their thickness is small (70 m). The remaining sequence ($K_2$ to Kz) is composed of deep-sea deposits, mainly nannoplankton ooze and chalk. The basal sediments rest on basalts enclosing limestone interbeds with Early Aptian organic remains. The basalts penetrated by this hole were 33 m thick.

The other holes of this profile were drilled on the continen-

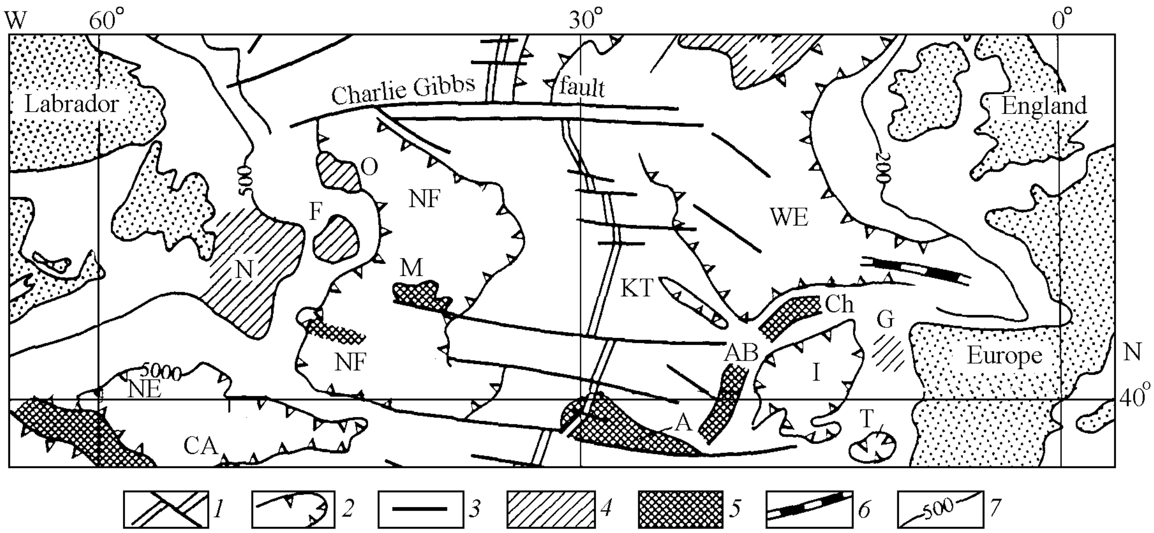


**Figure 6.** The main tectonic features of the northern area of the Central Atlantic region: (1) Mid-Atlantic Ridge rift zone; (2) deep-sea basins; (3) fracture zones; (4–5): continental (4) and oceanic (5) rises; (6) extinct rift; (7) isobath, m. Basins: (NA) North American Basin, (NF) Newfoundland Basin, (WE) West-European Basin, (I) Iberian Basin, (T) Tagus Basin, (KT) Kings Trough; elevations of continental origin (underwater continental rises, intraoceanic fragments): (N) Newfoundland Banks, (F) Flemish Cap, (O) Orphan Knoll, (R) Rockall Bank, (G) Galicia Bank; oceanic elevations: (NE) New England Seamounts, (A) Azores Bank, (NF) Newfoundland Chain, (M) Milne Bank, (AB) Azores-Biskay Rise, (Ch) Charcot Seamounts.

tal margin consisting of a series of half-grabens. Hole 549 was most close to the ocean, which is 2539 m deep there. The drilling interval was 1001.5 m. The hole reached the Hercynean basement overlain by Barremian deposits a few hundred meters thick. They are usually interpreted as synrifting formations of a transgressive cycle. The post-rifting Albian deposits are separated by an unconformity. Yet, the upper Albian and some Cenomanian deposits are absent, and the sequence is continued by pelagic deposits of Late Cenomanian to Maestrichtian age. These data suggest that the West European Basin began to form in the Albian time, that is, earlier than the opposite Newfoundland Basin.

As to the Biscay Basin, two holes were drilled in its southern side where the Biscay Gulf opens to the ocean. Hole 118 was drilled to a depth of ~760 m where the sea floor had a depth of 4901 m. It entered a basalt sill overlain by Upper Paleocene–Lower Eocene altered red clays. Above follow Middle Eocene nannofossil clays. A break was recorded in the Late Eocene–Oligocene interval. Hole 119, drilled nearby, showed a break in the Late Eocene–Oligocene interval.

Holes were also drilled at the opposite side of the Biscay Gulf (where it opens into the ocean). One of them (Hole 402) was drilled in the upper part of the continental slope, where the sea was 2339.5 m deep. Its drilling depth was 469.5 m. The lowest rocks included a sequence of Aptian and Albian shallow-sea (shelf) marly limestone, calcareous siltstone, and chalk, totaling 237 m in thickness, some of them being deltaic deposits. According to seismic data, this rock sequence is underlain by thick faulted supposedly Lower Cretaceous (pre-Aptian) deposits which had accumulated in half grabens. Rifting activity ceased in Aptian time, and the Aptian-Albian sediments, including Lower Aptian pelagic limestone beds, began to accumulate. The lower Cretaceous rocks are underlain by Jurassic platform-type carbonate deposits of the pre-rifting time. The above data suggest that the Biscay Basin had been formed in the Aptian-Albian period of time.

Hole 401, located not far from Hole 402 at the sea floor as deep as 2495 m, its drilling interval being 341 m, ended in the Upper Jurassic (Kimmmeridgian-Portlandian) platform-type shallow-sea carbonate rocks. The rifting period had lasted from the end of the Jurassic to the Neocomian. The subsidence had began in Aptian time. Located nearby is Hole 400 drilled to a depth of 777.5 m where the sea floor is 4399 m deep. The drill section terminates in the Late Aptian rocks represented by carbonaceous siltstone, marly nannofossil chalk, and calcareous siltstone which began the post-rifting rock sequence. The rock sequences of all three holes a significant number of breaks.

Twelve DSS profiles were surveyed in the West European Basin, only seven of them providing information down to the Moho discontinuity. The age of the lithosphere, determined from linear magnetic anomalies, grows from 50 to 85 Ma from the west to the east. As follows from the seismic data, the crust of this region varies greatly in structure, its thickness ranging from 4 to 8 km, the most common values being 7–8 km. Both the seismic velocities and thicknesses of the basic layers vary widely.

Layer 3D with seismic velocities of 7.4–7.6 km $s^{-1}$ was

**Table 1.** Sizes of Atlantic deep-sea basins

| South Atlantic | | Central Atlantic | |
|---|---|---|---|
| Basins | Size, km | Basins | Size, km |
| Argentine | 2250×1500 | North American | 2000×2200 |
| Brazil | 2500×1300 | Newfoundland | 1300×500 |
| Cape | 1400×1300 | Canary | 2600×1000 |
| Angola | 1800×1000 | Sierra Leone | 800×1000 |
| | | Iberian | 600×400 |
| | | West European | 1000×600 |

discovered in this basin only along two profiles in the south of the region. Yet, its thickness was not estimated because the Moho discontinuity had not been reached. Layer 2A with a velocity of 3.5 km $s^{-1}$ was recorded along Profiles 142 and 143 located near the northeastern slope of the basin. Its thickness was found to be 1.3–1.5 km.

## General Comments

The data reported in this paper suggest important differences in the geological histories of the basins studied in the South and Central Atlantic oceans. This concerns the morphology, rock sequences, and crustal structure of the region.

Figure 1 shows great differences in the configurations of the basins in map view. The basins also vary greatly in size (Table 1).

The western thalassic regions include four deep-sea basins. Three of them, namely, the Argentine, Brazil, and North American ones, are the largest basins in the Atlantic Ocean. Six basins have been described in the eastern thalassic regions, yet, adding the Agulhas, Guinea, and Tagus basins to this list makes up nine basins (the small basins, known in the east and west were not included). Only one of them, namely, the Canary Basin, has the size comparable with the sizes of the basins from the western thalassic regions. It is located in the southern latitudes of the thalassic regions like the North American and Argentine deep-sea basins.

The deep-sea basins are separated from one another by seamounts or fracture zones, the seamounts being of tectonovolcanic origin (Figure 1). One can see that seamounts of this kind are developed mainly in the eastern thalassic regions. Those in the western ones are mainly separated by the systems of fracture zones.

Tectonic ruggedness is common also for the internal structure of the basins. It is especially obvious in the North American and Canary basins, each of which includes three isolated rises in the floors of abyssal depressions with extensive abyssal plains in their central parts.

The greatest tectonic ruggedness in this oceanic region is characteristic of the area between the latitude of the Azores islands (37°N) and the Charlie Gibbs Fracture Zone (52°N). The tectonic style of this region is controlled to a great extent by its comparatively small deep-sea basins (Figure 6). The basins are separated from the continents by structurally complex continental margins. The western margin is represented by the Newfoundland Plateau and the Flemish-Cap Bank both having a continental crust at the base. Residing close to the margin is the Orphan Knoll microcontinent. In the east the marginal part of the ocean manifests itself as the British extensive shelf with its block structure, and in the south, as a transitional horst-and-graben zone with significant basins, which separates the Pyrenean Peninsula from the Iberian Basin. The southern part of this area includes a group of young tectonovolcanic massifs. The largest of them is the Azores Bank which extends into the Newfoundland Basin as the Milne Bank. Also of tectonovolcanic origin may be the Azores-Biscay Rise and the Charkot Seamounts, both separating the West European and Iberian basins. In addition to the transverse fracture zones, the structure of this segment is complicated by oblique fracture zones extending in the northwestern direction.

In the southern part of the Central Atlantic Ocean it is only the North-American Basin alone that that includes large intrabasin volcanotectonic elevations: Bermuda Rise, New England Seamounts, and Corner Seamounts. All other seamounts belong to the surroundings of the basins.

As to the South Atlantic Ocean it is correct to assume continental blocks at the base of the elevated sea floor blocks of the Argentine Basin. The same applies, though more confidently, to an uplift west of the Brazil Basin, which is within the continental rise. We cannot exclude the presence of a continental structural feature (though, certainly, altered) at the base of the deeper part of the Angola Basin. As to the uplift in the Cape Basin, the traces of a local spreading zone can be expected judging by the abundance of fracture zones and by the structural pattern of the ocean floor [*Pushcharovskii,* 1998].

Tectonic layering of the oceanic crust was discovered in the oceanic crust in the 80s of the last century (Figure 7) [*Pilipenko,* 1993, 1994; *Pushcharovskii et al.,* 1985; *Raznitsyn and Chinakaev,* 1989; *Raznitsyn and Pilipenko,* 1997]. One of the tectonic features, where this phenomenon has been proved definitely, was the Brazil Basin. Almost at the same time tectonic layering was discovered in the North American Basin [*Collier et al.,* 1998], and later in the Canary Basin [*McCarthy et al.,* 1988].

The Brazil Basin differs in terms of its igneous rocks. The basalts penetrated by drill holes are overlain in this basin by sediments of different ages up to very young ones ($N_1^2$), The highly broken floor of the basin suggests the presence of basalt sills there. The high igneous activity in the Brazil basin, especially in its northern half, is proved also by the abundance of seamounts in the South Atlantic Ocean (Most of them being of volcanic origin.) [*Marova and Alekhina,* 1997].

In addition to the Brazil Basin, significant accumulations of seamounts are concentrated in the northern half of the North American Basin, however, here merely scarce volcanic edifices are found. In the South Atlantic area, their main accumulations, apart from the Brazil Basin, are confined to the structural separations between the basins (Cameron Fracture Zone, Whale Ridge, etc.). Apart from the regions

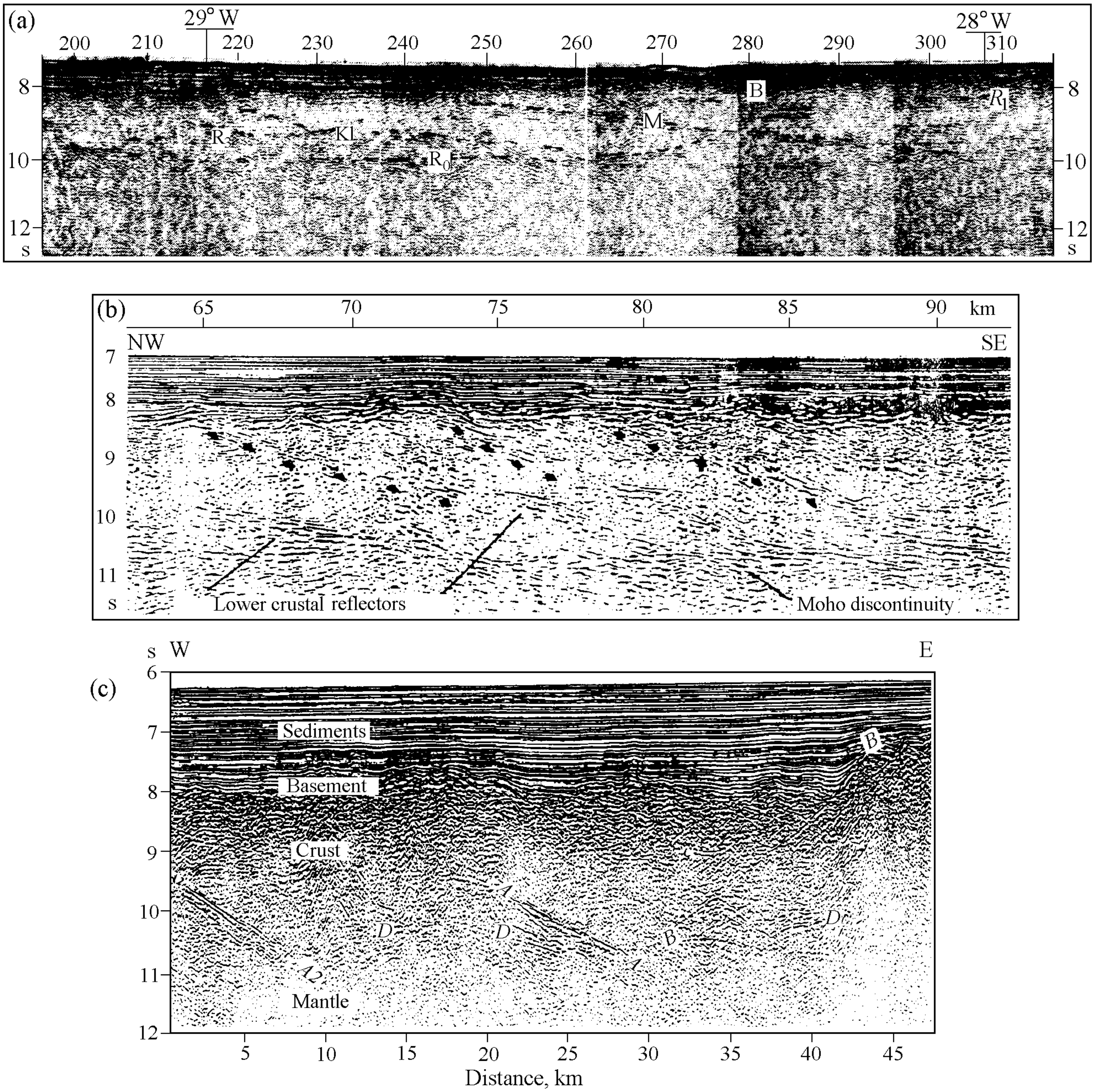


**Figure 7.** Deep seismic profiles showing inclined reflecting horizons depicting the tectonic layering of the crust in deep-sea basins; (a) Brazil Basin, 12°S [*Raznitsyn and Chinakaev,* 1989]. B, R1, R0, R2, and M (Moho) are CDP reflectors; (b) North American Basin, Blake Spur area [*McCarthy et al.,* 1988]. One can see inclined reflecting horizons; (c) Canary Basin west of the Canary Islands: 28°N, 338°50′–339°20′ W [*Collier et al.,* 1998]. One can see inclined CDP reflectors.

mentioned above, the Central Atlantic region includes abundant seamounts sitting of the Mid-Atlantic Ridge and also in some areas of the eastern strip of the ocean. This selective distribution of the seamounts is the subject calling for a special study and is beyond the scope of this paper. Here, I would mere state that most of the volcanic seamounts are younger than the ocean floor.

The rock sequences penetrated by the deep-sea holes and the data available for the geology of continental margins can be used to date the formation of the basins (Table 2). One can see that these dates vary greatly. In the South Atlantic region the oceanic phase of the Argentine Basin formation was Late Jurassic, whereas in the case of the opposite Cape Basin, it was Early Cretaceous (Figure 8). The Angola Basin, located north of the Cape Basin, has roughly the same age as the latter. At the same time the Brazil Basin had been formed in Aptian-Albian time, that is, later than the opposite Angola Basin.

A similar picture is observed in the Central Atlantic Region. The oceanic evolution phase of the North American basin began about 170 million years ago, whereas that of the opposite Canary Basin began to develop, as follows from the above dating, as far back as the Early Jurassic.

A not less complicated pattern follows from the analysis of the depths of the ocean floor and the basement under the basins. The results of this analysis are listed in Table 3.

Small depths of the basement under the abyssal plains were found in the Central Atlantic region and at the peripheries of the ocean. The western periphery includes three basins: Hatteras, Sohm, and Newfoundland. The basement depth in the former two is about 10 km, the ocean floor being as deep as 5.1–5.6 km. In the Newfoundland Basin the basement has a depth of about 10 km, the ocean floor having depths of 5.1 to 5.6 km. In the Newfoundland the basement is as deep as 9 km, the depth of the ocean floor being 4.5–4.6 km, that is, slightly smaller than in the former two basins. At the eastern periphery there are only two basins with a deep basement: the Biscay and Guinea basins with the basement depths of 8 and 7 km, respectively. They are similar to the Newfoundland basin in this respect.

The basement under the abyssal plains varies highly in age both in the South and Central Atlantic regions. In the South Atlantic region it varies from Late Jurassic (Argentine Basin) to Albian (Brazil Basin), the difference being 50–60 million years. At the same time, the depths of the basement under the abyssal plains in the South Atlantic Ocean are comparable.

The following data are available for the Central Atlantic region. The ocean has the oldest age, 170 million years, in the west and is even older in the east. This applies to the southern parts of the North American and Canary basins. The basement in the north is the youngest (80–85 million years; Late Cretaceous), the difference being 90 million years. The depth of the basement is about 6 km under the Nares Abyssal Plain situated in the tropic area in the south of the North American Basin, with a basement depth of about 6 km. It has a roughly similar depth under the opposite Cape Verde Abyssal Plain (5.4–5.7 km). Yet, under the Iberian Basin, located 1800 km farther north, the basement grows in depth up to 6.1–6.4 km, instead of decreasing in accordance with the spreading theory. The basement has a similar depth, 6 km, under the Tagus Basin. It follows that there is no correlation, both in the Central and South Atlantic Oceans, between the time of the basement formation under the deep-sea basins and the basement depth. Yet, the basement is more shallow (5 km) under the Porcupine Abyssal Plain located in the extreme north of the Central Atlantic Ocean (50°N). This segment of the Atlantic ocean is known for its peculiar tectonic pattern (extensive shelf areas, banks, continental outliers, and highly dissected topography). To sum up, no correlation is observed between the formation time of the basement in the deep-sea (abyssal) basins and its depth.

Let us discuss their spatial relationships. The width of the ocean floor varies substantially and repeatedly from the south to the north. In the south of the South Atlantic Ocean

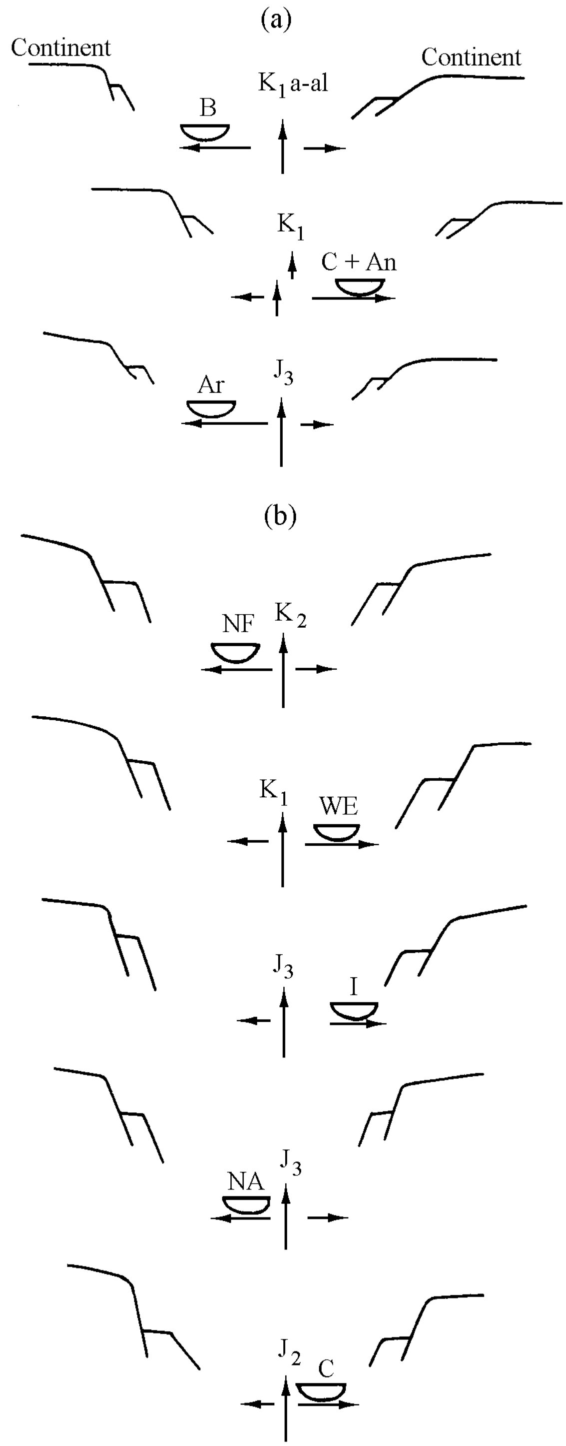


**Figure 8.** Asymmetric spreading during the initial formation of deep-sea basins in the South (a) and Central (b) Atlantic regions. The vertical arrows show the spreading center, the horizontal ones, the asymmetric spreading. The lenses show the locations of deep-sea basins: (Ar) Argentine, (C+An) Cape and Angola, (B) Brazil, (C) Canary, (NA) North American, (I) Iberian, (WE) West European, and (NF) Newfoundland.

**Table 2.** Origin times of Atlantic deep-sea basins

| Basins | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Time | South Atlantic | | | | Central Atlantic | | | | |
| | | Argentine | Cape | Angola | Brazil | North American | Canary | Newfoundland | West European | Iberian |
| Onset of formation | $J_1$ | | | | | | + | | | |
| | $J_2$ | | | | | + | | | | |
| | $J_3$ | + | | | | | | | | |
| | $K_1$ | | + | + | | | | | | + |
| | $K_1$a-al | | | | + | | | | + | |
| | $K_2$ | | | | | | | + | | |

it is 5700 km, being 4700 km in the equatorial region. North of the latter, the width grows larger amounting to 6200 km at the latitudes of the Bermuda Islands. It decreases to 4700 km at the latitude of the Azores Islands measuring merely 2400 km northward at the latitude of the Charlie Gibbs fracture zone. The meridional lengths of the respective oceanic segments are 6000 km of the South Atlantic segment, 4070 km of the southern segment of the South Atlantic, and 1650 km of the northern segment.

The question is whether the basement depth in the deep-sea basins varies with their spatial positions relative to the axis of the Mid-Atlantic Ridge. Judging by the data available for the depths of the abyssal basins in the South Atlantic Ocean, no significant changes have been recorded in their depths (see Table 3). No regular diminishing of the depths of the basins were found in the Central Atlantic re-

**Table 3.** Depths of the sea floor and basement in the abyssal plains of the oceanic basins

| Basins | | Depth, km | |
|---|---|---|---|
| | | ocean floor | basement |
| | South Atlantic | | |
| | Argentine | 4.8–6.2 | |
| | Brazil | 5.5–5.8 | 5.7–6.0 |
| | Cape | 5.0–5.2 | 5.6–5.7 |
| | Angola | 5.5–5.7 | up to 6.0 |
| | Guinea | 5.1 | up to 7.0 |
| | Southern segment of Central Atlantic Ocean (up to 37°N) | | |
| | North American Basin | | |
| Abyssal plains: | Nares | 5.7–5.9 | up to 6.0 |
| | Hatteras | 5.4–5.6 | up to 10.0 |
| | Sohm | 5.1–5.4 | 9.1–6.4 |
| | Canary Basin | | |
| Abyssal plains: | Sierra-Leone | 5.0 | 6.0 |
| | Cape Verde Plateau | 5.3 | 5.4–5,7 |
| | Madeira | 5.4 | 5.6–5.7 |
| | Central Atlantic northern segment (37°–52°N) | | |
| | Newfoundland basin | 4.5–4.6 | 9.0 |
| | Tagus Basin | 5.0 | 6.0 |
| | Iberian basin | 5.1–5.4 | 6.1–6.4 |
| | Biscay Abyssal Plain | 4.6–4.8 | 8.0 |
| | West European (Porcupine) Abyssal Plain | 4.7 | 5.0 |

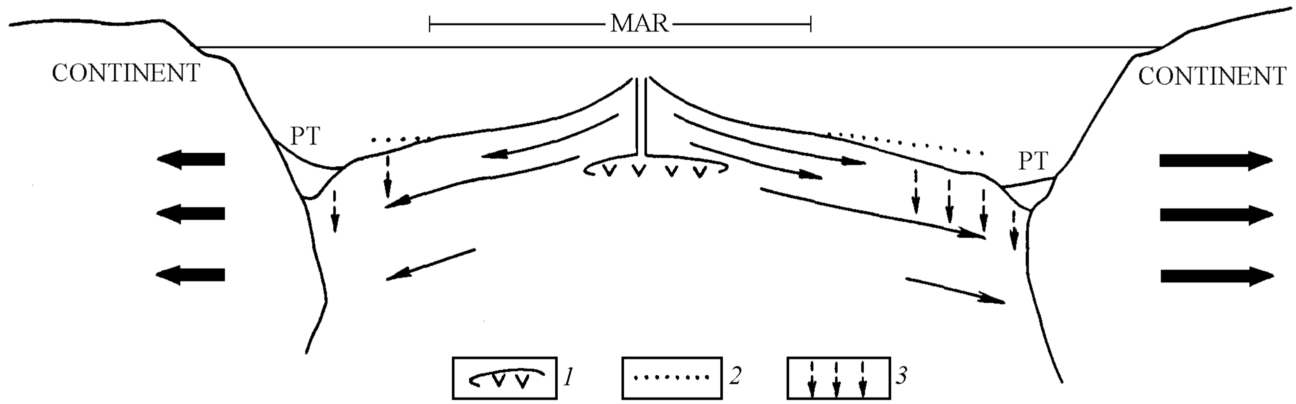


**Figure 9.** Mechanism of the formation of deep-sea basins in the Atlantic Ocean: (1) magma chamber, (2) calculated depth of the ocean-floor subsidence as a result of spreading, (3) ocean-floor subsidence in the extension zone. Thin arrows show irregular spreading, thick arrows show the continents moving at different spreading rates. MAR stands for Mid-Atlantic Ridge, PT, for perioceanic trough.

gion where the ocean floor narrows northward from 6200 km to 2400 km. The exceptions are the particular basins mentioned above where the depths are fairly similar, that is, where no correlation exists between the spatial positions and the depths of the basement in the basins.

It can thus be concluded that, in addition to any other factors, some local tectonic subsidence of the crust had taken place in some local areas. This subsidence might have been sudden enough, as indicated by the presence of large normal faults from the side of the continent. The normal faults have been recorded in the south of the Argentine Basin, in the east of the West-European Basin, in the west of the Newfoundland Basin, and in some other areas. The same mechanism might have been responsible for the formation of the Atlantic continental slopes, at least of the steeply inclined ones. The fact that the basins are separated by the tectonovolcanic ridges suggests that these basins subsided displacing lithospheric igneous rock masses toward the periphery. These are the Walvis, Cameroon, Discovery-Heezen, Canary, Azores-Biscay-Shona, and other ridges.

This comparative study of the crustal structure of the Atlantic basins revealed differences between them. The comparison of the DSS data obtained for the South Atlantic basins and for those located between the equator and the latitude of the Azores Islands yielded the following results. In terms of the structure of the upper Earth Crust (crustal layer 2), the Angola and Cape basins are similar to the middle segment of the Canary Basin. A layer (2B) with seismic velocities of about 4 km $s^{-1}$ has been recorded in these basins. At the same time the Brazil and Argentine basins are similar in the crustal structure to the northern part of the Canary Basin and to the Sierra-Leone Basin. They differ only in layer-2 seismic velocities (5.8 and 5.0 km $s^{-1}$). The comparison of the crustal structure of the basins in the southern area of the Central Atlantic region and in the region north of 37°N also reveals a difference between them. In the southern region layer 1B has a lower velocity (2.7 km $s^{-1}$) than that in the northern region (3.0 km $s^{-1}$). In the southern region layer 2A has an extra velocity peak about 3.6 km $s^{-1}$. Layer 2C has a better expression in the northern region (a distinct peak of 6 km $s^{-1}$). The dominant velocities of layer 3A in the southern region are lower (6.8 km $s^{-1}$) than those in the northern region.

The results of this study taken together prove that the conventional averaging approach to the estimation of the crustal structure in oceanic regions masks their regional and local heterogeneities. At the same time these heterogeneities provide valuable data for reconstructing the real mechanisms of oceanic structure formation.

## Conclusion

1. The deep-sea basins are highly variable in geology, geologic history, and in the deep structure of the crust. These variations in geology and crustal structure exist not only between the basins, but also inside them. Local fragments of the continental crust can be found at the base of some basins as has been proved by their structural features and gravity data [*Sandwell and Smith,* 2003]. This should be taken into consideration in the reconstructions of the spatial relationships between the continents for some period of geologic time.

2. The specific geology of the South and Central Atlantic regions reflects not only the peculiarities of the deep crustal geodynamics, but also the geological characteristics of old continental blocks where the structural features of the initial phase of oceanic evolution originated.

3. The popular view of the symmetrical evolution of the tectonic structure of the Atlantic Ocean stems from the extreme adherence to schematism in geodynamic reconstructions.

4. The deep-sea basins of the Atlantic Ocean are the large ocean-floor tectonic forms with long evolution histories. The nonuniform process of their formation is still in progress at the present time.

5. The subsidence of the respective fragments of the crust operates not only by way of spreading but also as a result of crustal extension between the spreading ridge and the continental margin caused by the spreading of the continental blocks (Figure 9). The spreading process operated in a complex manner during the geological history, as evidenced by the asymmetry in the formation time of the opposite basins. The rates and scales of the movements of the continents varied greatly on both sides of the spreading axes.

6. The geodynamic environments differed greatly in various regions of the Atlantic Ocean. This was imprinted in the general structural patterns and internal structure of individual deep-sea basins. The structural complexity and heterogeneity of the deep crustal structure suggest the selective mechanism of dynamic and kinematic processes that operated in the Earth's geospheres, namely, their different scales and irregular operations. This suggests the effects of nonlinear geodynamic factors on the tectogenesis.

7. Similar to ocean-floor rises [*Pushcharovskii,* 2002a], oceanic basins are tectonic elements that call for the special study of their structure and structural evolution.

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