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# The Morphostructure of the Atlantic Ocean Floor

## Its Development in the Meso-Cenozoic

*Translated from the Russian by*

V. M. DIVID, N. N. PROTSENKO and YU. U. RODZHABOV

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# Introduction

The study of the topography and structure of the ocean floor is one of the most important stages in ascertaining the geological structure and history of development of the Earth's oceanic crust. This, in its turn, provides a means for purposeful, scientifically-substantiated prospecting, exploration and development of the mineral resources of the ocean.

The Atlantic Ocean has been geologically and geophysically studied to a great extent and many years of investigating its floor have revealed the laws governing the structure of the major forms of its submarine relief (e.g., the continental shelf, the continental slope, the transition zones, the ocean bed, and the Mid-Oceanic Ridge). The basic features of the Earth's oceanic crust structure, anomalous geophysical fields, and the thickness and structure of its sedimentary cover have also been studied. Based on the investigations of the Atlantic Ocean floor and its surrounding continents, the presently prevalent concept of new global tectonics has appeared. A great number of works devoted to the results of geomorphological, geological, and geophysical studies of the Atlantic Ocean floor have appeared. In the U.S.S.R., such summarizing works as *The Geomorphology of the Atlantic Ocean Floor* [34], *Types of Bottom Sediments of the Atlantic Ocean* [24], *The Geology of the Atlantic Ocean* [38], and, somewhat earlier, *Geophysical Studies of the Earth's Crust Structure in the Atlantic Ocean* [13], have been published.

It should be stressed, however, that each of the above-mentioned publications follows a specific trend and deals mainly with one particular aspect of ocean-floor studies. In these works, morphostructural anslysis aimed at ascertaining the interrelations between the submarine relief and the geological structure of the oceanic crust, determining the role of tectonic movements, volcanism, and sedimentation in the formation of structural elements of the ocean floor relief and verifying the history of its development, is either not considered at all or used to a very small extent. It is well known that the methods of morphostructural analysis and the morphostructural approach in land studies were developed long ago and have now found extensive application [15]. In ocean-floor studies, however, this method, up to now, has been used only occasionally. The main objective of our work in studying the Atlantic Ocean floor was, therefore, to develop the morphostructural approach in submarine geomorphological, geological and geophysical investigations. This work was carried out over a period of several years in the Laboratory of Atlantic Geology at the Atlantic division of the P. P. Shirshov Institute of Oceanology, U.S.S.R. Academy of Sciences, and was done within the framework of the International Geodynamics Project.

The specific objectives of the work were: (1) to reveal the interrelations between the submarine relief and the geological structure of the Atlantic Ocean floor, between the structural forms of the relief and anomalous geophysical fields, between the structure of the sedimentary sequence and the relief of the oceanic basement; (2) to determine the role of horizontal and vertical tectonic movements, faults, volcanism and sedimentation in the formation of ocean-floor morphostructure; (3) to ascertain the laws governing the spatial and temporal development of the morphostructural and morphotectonic zones of the ocean in the Meso-Cenozoic; to clarify the history of ocean-floor development in terms of the concept of global plate tectonics.

The methodological basis of research was laid down by morphostructural analysis, known to include the use, comparison and integrated interpretation of geomorphological, geological and geophysical data. The concept of global-plate tectonics and its application to the development of the ocean-floor morphostructure in the Meso-Cenozoic served as the theoretical basis of the work. At the same time, the possibility was considered of applying the concept of large-scale subsidences of the continental crust and its reworking into the crust of an intermediate or sub-oceanic type ('oceanization') to explain the origin of the continental margins and the adjoining parts of the Atlantic Ocean floor.

The morphostructure (and in a more general concept, the morphotectonics) of the ocean floor was chosen by the author as the main object of study. Morphostructure is understood as the manifestation of the ocean floor's geological structure in a submarine relief. The same meaning, but in a more general sense, is given to the concept of morphotectonics. Large and medium-size forms of submarine relief, whose formation is caused by tectonic movements and geological structure, are regarded as specific morphostructures. In the present work, while analysing the data on the structure and genesis of the relief and structural characteristics of the ocean floor, the primary emphasis is placed on the influence of endogenous factors, with sedimentation being the only exogenous factor considered.

The work done was based on the data of geomorphological, geological and geophysical studies conducted on board the research vessels of the Institute of Oceanology, *Akademik Kurchatov* and *Dmitri Mendeleev*, as well as on other Soviet research vessels, such as *Mikhail Lomonosov, Akademik Vernadsky, The Pole, Sevastopol, Akademik Knipovich, Petr Lebedev* and others. Over the period of 1967–1977 *Akademik Kurchatov* made 17 voyages in the Atlantic (including five specialized geological and geophysical voyages) during which geomorphological, geological and geophysical studies were made. Altogether during these voyages, 250 000 miles of continuous echo-soundings, more than 100 000 miles of magnetic survey and 30 000 miles of continuous seismic profiling (CSP) were performed. Twenty-four polygons, 16 of them geophysical, were run with comprehensive geological and geophysical studies and echo-sounding and some geological or geophysical work was performed on the others (Figure 1).

We have also used the echo-sounding data of other Soviet expeditions and the data of other expeditions have been resorted to. By the beginning of 1976, numerous expeditions, mainly American, had performed more than 400 000 miles of continuous seismic profiling. Regional magnetometric, gravimetric, and seismic investigations have been carried out and a large number of bedrock and bottom sediment samples have been studied. Of great importance for the understanding of ocean-floor structure are the deep-sea drilling data obtained on board R/V *Glomar Challenger*. Over the period of 1968–1976 more than 160 boreholes were drilled in the Atlantic Ocean and the Norwegian-Greenland Basin, and the data thus obtained have been extensively used in this work.

Based on the analysis of the above data, the author has described the general scheme of the ocean-floor relief and the geomorphological features of individual morphostrcutures. The data of seismic profiling and deep-sea drilling pertaining to the structure of sedimentary cover have been summarized. The geophysical data on the Earth's crust structure and anomalous geophysical fields have been correlated with the morphostructure of the ocean floor. Seismotectonics, volcanism and ocean-floor faults have been studied, and their role in submarine relief formation ascertained. The role of horizontal and vertical tectonic movements in the formation of ocean-floor morphostructure has also been assessed, and this served as the basis for the elaboration of a new scheme of its development in the Meso-Cenozoic.

The author has compiled a number of new maps of the Atlantic Ocean – physiographic, geomorphological, sedimentary cover thickness, seismotectonic, morphotectonic, horizontal and vertical tectonic movements, as well as the paleomorphostructural schemes for different stages of ocean development in the Meso-Cenozoic.

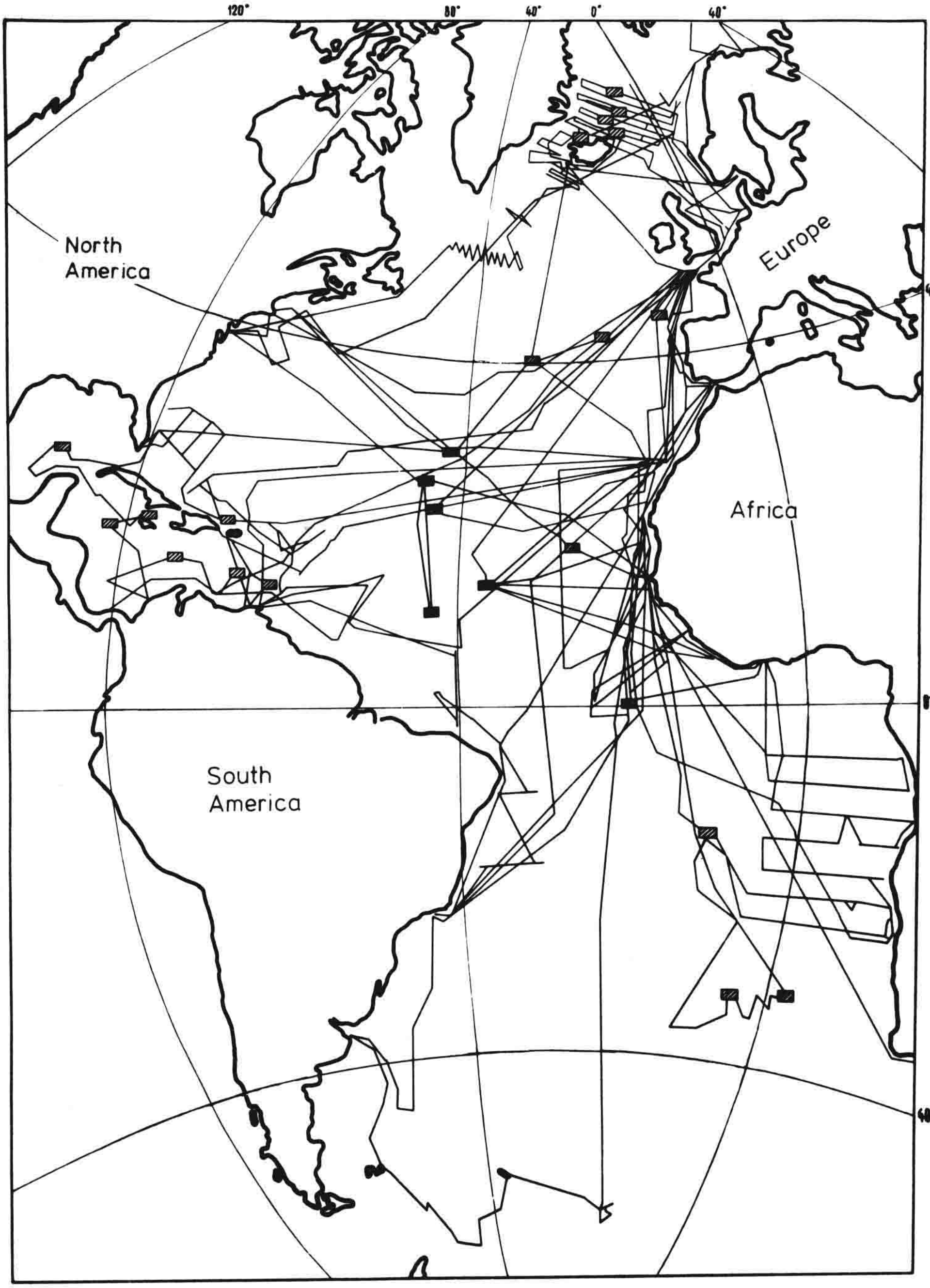


Fig. 1. Map of the expeditions undertaken by the Institute of Oceanology, U.S.S.R. Academy of Sciences, in 1967–1976.

# Contents

# Abstract

This monograph summarizes the results of geomorphological, geological and geophysical studies that have been conducted in the Atlantic Ocean over a period of many years on board the R/V '*Akademik Kurchatov*' and by other expeditions, the results of deep-sea drilling, and numerous published data on the ocean floor structure. The present work has been carried out in accordance with the programme of the International Geodynamic Project. Morphostructural analysis served as its methodological basis, and the concept of global plate tectonics as its theoretical basis. At the same time, the development of continental margins and the adjacent parts of the ocean was examined in its association with large-scale submersions of the Earth's crust and possible 'oceanization'. A number of new maps of the ocean floor have been compiled, reflecting its structure, the role of various factors in its formation, and the ocean floor morphostructure development in the Meso-Cenozoic.

The general scheme of the structure of ocean floor relief and the geomorphological peculiarities of individual morphostructures are described. The features of symmetry and circumcontinental zonality in the submarine relief, explained by ocean floor spreading, are revealed. Sedimentary cover thickness and age are observed to increase on both sides of the Mid-Atlantic Ridge axis in the direction towards the continental margins. The interrelations of the oceanic basement relief and that of the ocean floor are shown. The role of sedimentation in relief formation, consisting in the shaping of morphostructures created by endogenous processes, is estimated. The influence of sedimentation, up to complete smoothing-out of the primary relief of the basement, is seen to manifest itself to the greatest extent on continental margins, in foredeeps and the peripheral areas of oceanic basins.

The Earth's crust structure, anomalous geophysical fields (magnetic, gravitational, thermal) and their relationship with the ocean floor morphostructure are described. A marked difference is noted between the structure of the Earth's crust on continental margins and on the ocean floor, indicating that they were formed by different processes. Special attention is

given to banded magnetic anomalies characteristic of the oceanic crust and indicative of ocean floor spreading.

The data on ocean floor seismicity, volcanism and fractures are presented. Seismological data indicate tension in the rift zone and compression in the zone of deep-sea trenches. Volcanic processes play the decisive role in forming the oceanic basement and volcano-tectonic morphostructures of the ocean floor, and also participate directly in creating seamounts and volcanic islands. Faults on the ocean floor, the latitudinal ones being decisive, are indicative of a layered-block structure of the Earth's crust in the ocean.

The role of tectonic movements in the formation of ocean floor morphostructure is assessed. Horizontal movements, of which the most significant are the processes of lithospheric plates spreading away from the axial rift fault on both sides of it, determine the relative positions of individual ocean floor morphostructures and the overall morphostructural plan. An important role is also played by the regional movements of individual blocks, e.g., in the Caribbean and the South Antillean Transition Zones. Vertical movements, taking place simultaneously with the horizontal ones and interconnected with them, determine the formation of the morphostructures themselves, their height and disjunction. In the course of spreading the lithospheric plates gradually subsided, and as a result the Mid-Atlantic Ridge and the oceanic basins on both sides of it appeared. During the Meso-Cenozoic the subsidence was practically uninterrupted on continental margins, leading to sedimentary cover accumulation and the creation of epicontinental platforms. Transition zones are characterized by a complicated combination of the rising ridges of island arcs and the submerging basins of marginal seas.

Three main stages are distinguished in the development of the Atlantic Ocean floor morphostructure: (a) the stage of the opening of the ocean (Late Jurassic–Early Cretaceous), (b) the stage of the formation of basic morphostructures (Late Cretaceous–Early Paleogene), (c) the neotectonic stage (Late Paleogene–present-day period). At the first stage, as a result of the break-up of the primeval continent, a narrow basin (or a series of basins) appeared, from which the Atlantic Ocean was later created. At the second stage all the basic morphostructures were formed, such as the Mid-Oceanic Ridge, oceanic basins, dome-and-block uplifts, transition zones, continental foredeeps and epicontinental platforms. At the neotectonic stage the formation of these morphostructures and their shaping by exogenous processes, the most powerful of which was sedimentation, were completed. Formation of new morphostructures in the rift zone of the Mid-Oceanic Ridge and in the areas of the island arcs of transition zones continued.

CHAPTER 1

# Bathyography of the Atlantic Ocean Floor

## 1. PRINCIPAL FORMS OF RELIEF AND GEOMORPHOLOGICAL ZONING OF THE OCEAN FLOOR

In the present work, the Norwegian-Greenland Basin is considered together with the Atlantic Ocean. Inland seas, such as the Baltic, Mediterranean and Black seas are not dealt with as their structure is not directly associated with the ocean.

A characteristic feature of the Atlantic Ocean floor relief is the Mid-Oceanic Ridge stretching from north to south approximately midway between the coasts of Europe and North America and Africa and South America. The ridge axis bends following the general conformation of the ocean and the coastlines. In the south the ridge bends round Africa and continues in the Indian Ocean. In the north it passes through Iceland and the Norwegian-Greenland Basin continuing in the Arctic Basin. The Mid-Atlantic Ridge is part of the global system of mid-oceanic ridges encircling the Earth's ocean floor.

On both sides of this grandiose structure are located the abyssal basins of the Atlantic Ocean separated either by transverse (relative to the Mid-Oceanic Ridge strike) rises and ridges or by elevated zones of hilly relief. The depth of these depressions reaches 3–6 km. The floor is comprised of flat and hilly plains with elevations, plateaus, hills and seamounts. Along the coasts of its surrounding continents stretch the shelf zones ending on their seaward side in escarpments of the continental slopes. The structure and geomorphology of the underwater marginal parts of the continents are retained in the shelves. The bordering continental slopes are, in essence, the flanks of continental blocks and represent the zones of transition between the shelf and the ocean bed. In places, the continental slopes are complicated by banks located at different depths and usually called marginal plateaus.

A special place in the ocean-floor relief is occupied by complex transition zones comprising island arcs, deep-sea trenches conjugated with them, and the depressions of marginal seas separated by them from the ocean.

Such a type is known to be widespread in the western part of the Pacific Ocean, but in the Atlantic Ocean it is only found in two regions: the Caribbean and the Scotia Seas.

Almost everywhere at the foot of the continental slopes are located inclined plains, formed by accumulated sediments, which are called continental rises. Although morphologically they form the lower parts of the continental slopes, structurally they should be regarded as forms superimposed on the marginal parts of the ocean floor.

The following major forms (provinces) of the submarine relief on the Atlantic Ocean floor can thus be identified: (a) the continental shelf, (b) the continental slope, (c) complex transition zones, (d) the ocean bed or the floor of abyssal basins, (e) the Mid-Oceanic Ridge (Figure 2). These forms of the relief, as will be shown later, are clearly differentiated by the structure of the Earth's crust and by geophysical anomalies, which were undoubtedly caused by global effects.

Within the above-mentioned physiographic provinces there are numerous regional and local forms of submarine relief. They form the observed diversity of the floor structure when one looks at the bathymetric chart or ocean-floor profiles. Their origin is determined by a combined action of endogenous and exogenous factors that form the morphostructures and the morpho*sculptures* on the ocean floor. Everywhere both these groups of factors act jointly and simultaneously; only in some cases the first one prevails and in others, the second. As already noted, in this work the endogenous factors and their effects are primarily dealt with.

To estimate the significance of certain physiographic provinces in the ocean-floor morphostructure, we have measured their areas [59]. The results are shown in Table I. Table II lists the data characterizing the areas, volumes

TABLE I
Areas of the Atlantic Ocean geomorphological provinces

| Geomorphological provinces | Area | |
|---|---|---|
| | $\times 10^3$ km$^2$ | % |
| Shelf | 7900 | 9.0 |
| Continental slope | 7282 | 8.3 |
| Continental rise | 9345 | 10.6 |
| Transition zones | 5233 | 6.0 |
| Mid-Atlantic Ridge | 24023 | 27.3 |
| Ocean bed | 34102 | 38.8 |

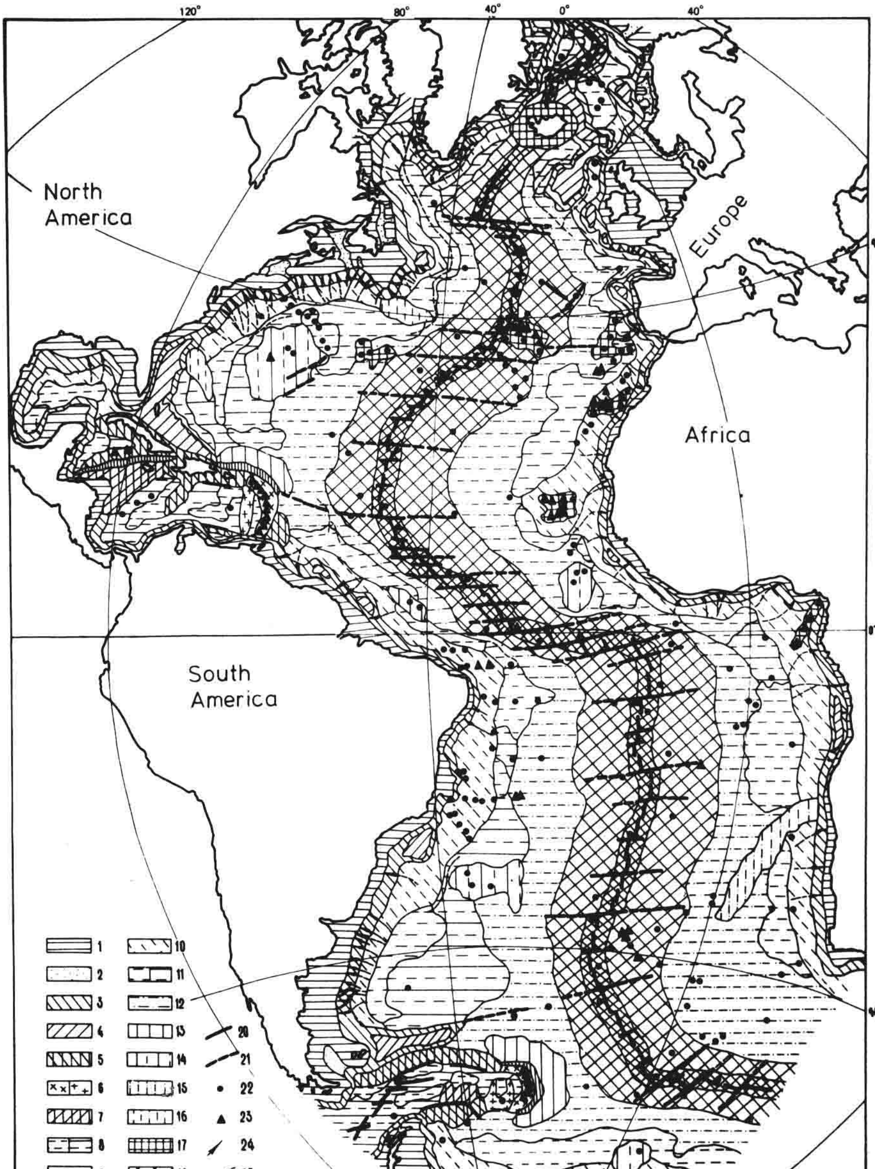


Fig. 2. Geomorphological map of the Atlantic Ocean. (1) abrasive-accumulative shelf plains; (2) shelf basins and trenches; (3) continental slope scarps; (4) marginal plateaus; (5) submarine island arc ridges; (6) modern and ancient volcanic arcs; (7) submarine rises; (8) flat (a) and hilly (b) plains of the floor of marginal seas; (9) deep-water trenches; (10) sloping plains of continental rises; (11) flat (a) and rolling (b) abyssal plains; (12) zones of abyssal hills; (13) marginal outer swells; (14) elevations and plateaus; (15) block ridges; (16) accumulative ridges; (17) volcanic massifs; (18) the Mid-Oceanic Ridge flanks; (19) rift zone; (20) trenches-faults; (21) zones of submarine relief disjunction; (22) volcanic seamounts; (23) volcanic islands; (24) submarine canyons; (25) turbidity flow channels.

TABLE II
Areas, volumes and depths of the Atlantic Ocean and the Norwegian-Greenland Basin

| | Atlantic Ocean (without seas) | | Atlantic Ocean (with marginal seas) | | Norwegian-Greenland Basin | |
|---|---|---|---|---|---|---|
| | $km^2 \times 10^3$ | % | $km^2 \times 10^3$ | % | $km^2 \times 10^3$ | % |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1. Areas of bathymetric sections, km: | | | | | | |
| 1. 0–0.2 | 5689 | 7.0 | 7256 | 8.2 | 247 | 9.9 |
| 2. 0.2–0.5 | 1948 | 2.4 | 2219 | 2.5 | 477 | 19.4 |
| 3. 0.5–1.0 | 1136 | 1.4 | 1443 | 1.6 | 173 | 7.0 |
| 4. 1.0–2.0 | 2626 | 3.2 | 3353 | 3.8 | 511 | 20.5 |
| 5. 2.0–3.0 | 6237 | 7.6 | 7189 | 8.2 | 586 | 23.5 |
| 6. 3.0–4.0 | 15723 | 19.4 | 17618 | 20.0 | 501 | 20.0 |
| 7. 4.0–5.0 | 28473 | 35.0 | 29462 | 33.4 | – | – |
| 8. 5.0–6.0 | 18937 | 23.3 | 19005 | 21.6 | – | – |
| 9. 6.0–7.0 | 512 | 0.6 | 542 | 0.6 | – | – |
| 10. > 7.0 | 155 | 0.1 | 57 | 0.1 | – | – |
| Total | 81309 | 100.0 | 88144 | 100.0 | 2495 | 100.0 |
| 2. Volume, $km^3 \times 10^3$ | 312576 | | 328315 | | 4261 | |
| 3. Max. depth, m | 8428 | | 8428 | | 3970 | |
| 4. Mean depth, m | 3844 | | 3725 | | 1708 | |

and mean depths of the Atlantic Ocean and the Norwegian–Greenland Basin. It is seen from these tables that the continental margins and transition zones occupy, all in all, less than a quarter, the Mid-Atlantic Ridge occupies slightly more than a quarter, and the abyssal basins together with the continental rises occupy about a half, of the total area of the Atlantic Ocean

There are many islands in the Atlantic Ocean and they can be subdivided into two general types: epicontinental and oceanic. Physiographically and tectonically those of the first type are either directly connected with the adjoining parts of continents or situated on the extensions of continental structures. Among these are such shelf islands as the British Isles, Newfoundland, Greenland, the Falkland Islands, and others, as well as the island arcs:

the Antilles, the South Sandwich and South Orkney Islands and South Georgia. Oceanic islands do not have any direct connection with continents and are exclusively volcanic formations. They are situated either within the Mid-Oceanic Ridge (Iceland, Jan Mayen, the Azores, St Paul Rocks, Ascension, St Helena, Tristan da Cunha, Gough and Bouvet islands) or on the floor of abyssal basins (the Bermudas, Madeira, the Canary Islands, the Cape Verde Islands, and a number of others).

## 2. CONTINENTAL SHELF

In the structural-tectonic respect, the continental shelf represents a direct extension of the coastal parts of land, mainly of coastal plains. The basement of the shelf is evidently composed of continental structures, with an overlying sedimentary cover of varying thickness almost everywhere, which masks the original bed causing the observed considerable smoothness of the submarine relief. Moreover, the surface of the shelf in a comparatively recent geological past was epicontinental land and has, therefore, passed through the subaerial stage of development. A subsequent rise of the ocean level and the neotectonic subsidence of the continental margins caused the abrasive-accumulative levelling of the shelf surface.

The shelves of glacial regions, such as those in the northern part of the Atlantic Ocean, in the Norwegian-Greenland Basin and in Antarctica, differ most sharply from those in other areas. Their characteristic features are: the dissection of the floor surface by systems of longitudinal and transverse trenches into a number of elevated areas – banks – littoral shoals with a hillocky relief, the widespread occurrence of minor forms of relief on the shelf – hillocks and small ridges on the slopes of banks and trenches (Figure 3). The dissection of glacial shelves is, on the one hand, caused by neotectonic dislocations, as a rule of an inherited character, and on the other hand, by the effect of Quaternary and recent glaciers, that penetrated within the shelf, performed the glacial scouring along the trenches and, after melting, left morainic material on the shelf [25, 53, 163].

With the exception of the zones of coral activity, the rest of the shelf regions may be defined as normal. Their surface has been mainly levelled by abrasive-accumulative processes occurring with changes of sea-level in the Quaternary time [34, 57]. Three principal zones are, as a rule, identified in the relief of the normal shelves: (a) littoral shoal coinciding with the underwater coastal slope and exposed to present-day wave abrasion; (b) median zone with a very even and almost horizontal surface, in some places with sand ridges, submarine valleys and terraces; (c) outer zone with gradually increasing gradients up to the outer edge of the shelf, characterized by submarine terraces. These zones are most distinctly manifested and sufficiently

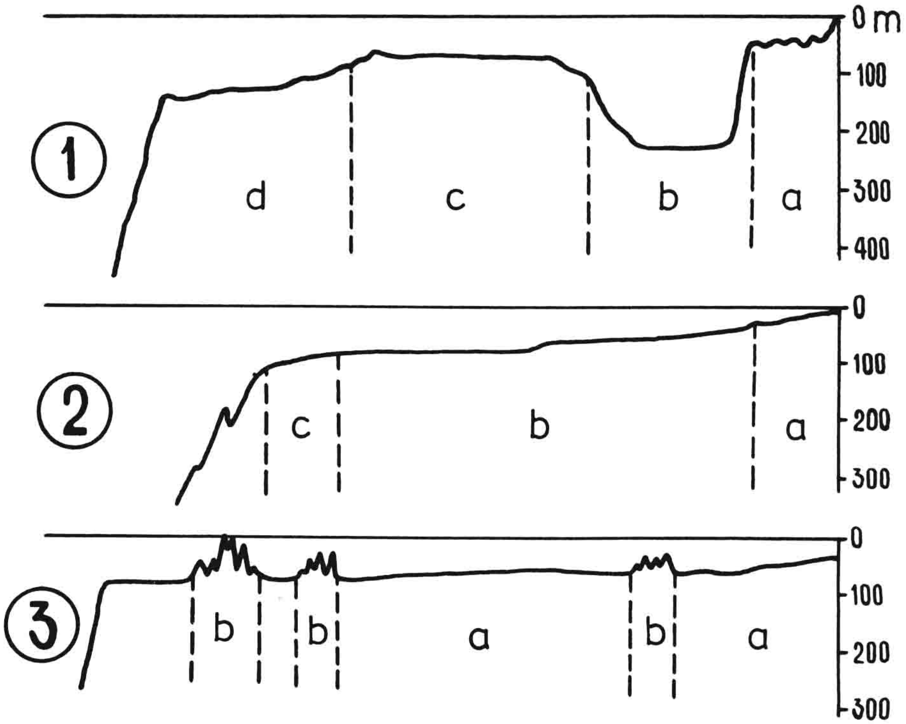


Fig. 3. Typical profiles of the continental shelf relief. (1) glacial shelf: (a) littoral shoal (strandflat), (b) longitudinal trench, (c) the outer shelf bank, (d) outer part of the shelf; (2) normal shelf: (a) coastal zone, (b) median zone, (c) outer zone; (3) shelf with coral structures: (a) shelf surface, (b) coral reefs.

well studied on the shelves of the eastern coast of the U.S.A. and the western coast of Central Africa [81, 223].

Shelf regions with coral structures are mainly constructed in the same way as normal shelves. Their surface, however, is complicated by hills, odd forms of knolls and ridges made by reef-building organisms and their detritus. This type of relief is common in the coastal areas of Central America (the Gulf of Mexico and the Caribbean) and in the north-eastern part of South America.

## The Greenland Shelf

The width of the shelf differs along the eastern and the south-eastern coasts of Greenland. In the north it is more than 170 miles wide and in the south it contracts to 30–40 miles. The shelf surface is everywhere dissected by transverse trenches, most of them on the extension of large coastal fiords. Banks of the outer shelf are separated from the littoral shoal by series of longitudinal trenches. Depths in the trenches reach 350–400 m, sometimes more than 500 m, and on the banks are not greater than 200–250 m [54]. A level relief prevails on the banks, whereas a hill-and-ridge relief is predominant