Bottom Morphology and Tectonics of the Southern Ocean

ALEXANDER V. ZHIVAGO

Institute of Geography, USSR Academy of Sciences, Moscow, USSR

***Abstract*:** The paper gives the brief characteristics of the main bottom morphostructures, revealed as the result of geomorphological analysis and according to separate geophysical data taken by expeditions of different countries. Differences in the type of the earth's crust under ocean floor serve as the main taxonomic principle. Thus the shelf on the margin of Antarctica is characterized by purely continental features. To the transition continental-oceanic area belong the continental slopes, the zones of island arcs and the basins of marginal seas. Structure areas of the oceanic crust are represented by gigantic depressions of oceanic basins and arched uplifts of oceanic swells, by linear folded-block elevations of median ridges, by oceanic trenches and their marginal swells. Seven bathymetrical, geomorphological and tectonic maps have been compiled for "The Atlas of the Antarctic".

Introduction

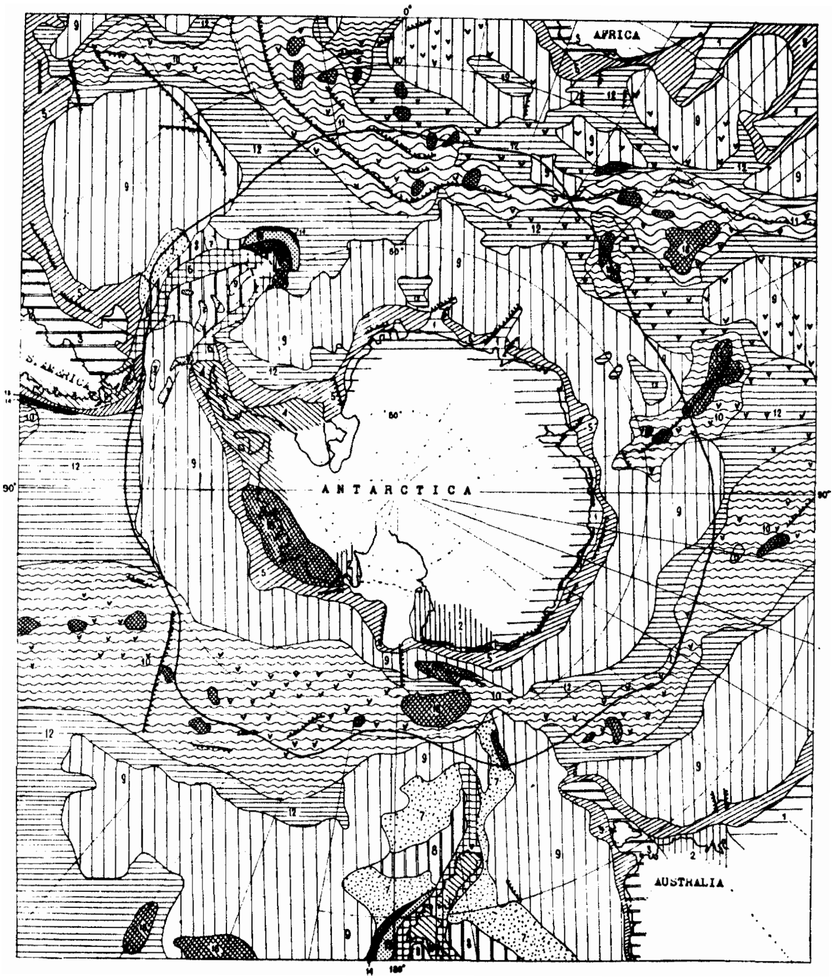
The name Southern Ocean is assigned to the oceanic part of the Antarctic that surrounds the Antarctic continent and is bounded in the north by the front of Antarctic Convergence, *i. e.* a confluence zone of Antarctic waters with warmer waters of the Subantarctic.

At the present stage of researches the structure of the Southern Ocean bottom can be characterized only approximately mostly by geomorphological data accumulated during the expeditions on the research ship OB and according to data of separate seismometric and gravimetric measurements taken by expeditions of different countries. Large morphostructures that can be distinguished in this way differ, first of all, by the character of association with three fundamental types of the crust under the bottom of the Southern Ocean: continental, transition and oceanic (Fig. 1).

Bottom Structures in the Area of a Crust of Continental and Transition Types

Shelf: The Antarctic shelf is located entirely within the area of the crust of a continental type. This area is characterized by a general great thickness of 25–35 km (EVISON *et al.*, 1959; KORIAKIN, 1963; USHAKOV, 1963; MURATA *et al.*, 1963) and the presence of a rock layer with seismic wave velocities of 5.8–6.2 km/sec characteristic for granites.

In the Eastern Antarctic continent the shelf is developed along the margin of the continental platform with a basement of crystalline rocks, mostly schists,



A. Areas of the continental crust morphostructures (inside the limits of continental shelfs)

1. Pre-Cambrian shields and Epi-Proterozoic platforms
2. Caledonian folded belts
3. Hercynian folded belts
4. Alpine folded belts

B. Areas of the transition crust morphostructures

5. Transition area of the continental slopes (sloping plains, regions of block dissection, ridges). (Mz-Kz)
6. Mega-anticlines of the insular arcs, dissected by faults and superstructed by volcanic massifs. (Kz)
7. Fold-clumpy and volcanic structures (submarine ridges and plateau). (Kz)
8. Depressions within the systems of geosynclines, fringed by insular arcs and submarine ridges. (Mz-Kz)

C. Areas of the oceanic crust morphostructures

9. Downwarps of the oceanic bed with great thickness of sediments (plains of the oceanic basins). (Mz-Kz)
10. Arched uplifts of the oceanic bed with small thickness of sediments (oceanic swells). (Mz-Kz)
11. Zones of the fold-clumpy linear structures (mid-oceanic ridges). (Mz-Kz)
12. Areas of rejuvenated Meso-Cenozoic clumpy structures within the regions of mean depths of the bed (surfaces of blocks). (Q)
13. Areas of deep linear sinkings of the bed, conjugated with insular arcs structures (oceanic trenches). (Kz)
14. Compensative elevations of the oceanic crust near the oceanic trenches (marginal swells of the trenches). (Kz)
15. Areas of volcanic cover (block-volcanic relief superstructuring different elements of the ocean floor). (Kz)
16. Great fractures and ruptures.
17. North limit of the Southern Ocean (the middle position of Antarctic convergence).
18. Large volcanic massifs.

Scale 1:110,000,000

Fig. 1 Bottom morphostructures of the Southern Ocean.

gneisses and granites of Preriphean age. In the area of Queen Victoria Land and Oates Coast the continental shelf is located within the Caledonian belt of folding with its characteristic shistose-gray wacke rocks and phyllite-like schists as well as with biotite-muscovite gneisses in a varying degree of granitization (RAVICH, KLIMOV and SOLOVIEV, 1965). Three zones can be distinguished within the shelf that vary structurally (Figs. 2 and 3): 1) coastal zone, where young disjunctive disturbances found their expression in the formation of a hillocky shelf, 2) zone of deep faults oriented en echelons in respect to the coast and determined by changes in the ice load at the edge of the continent during the Quaternary period, and 3) the marginal zone of old shelf plains that experienced a compensatory isostatic uplift during the Holocene and inclined presently towards the continent (ZHIVAGO, 1964). In the western part of the Antarctic continent the shelf passes along the periphery of the folded part of the Antarctic Andes represented mainly by Paleozoic and Mesozoic sedimentary and metamorphic rocks that include volcanogene rock masses and are partly overlain by latest volcanic lavas.

Continental slope : The transition are between the continent and the ocean includes the continental slope of the Antarctic continent and the Scotia Island Arc

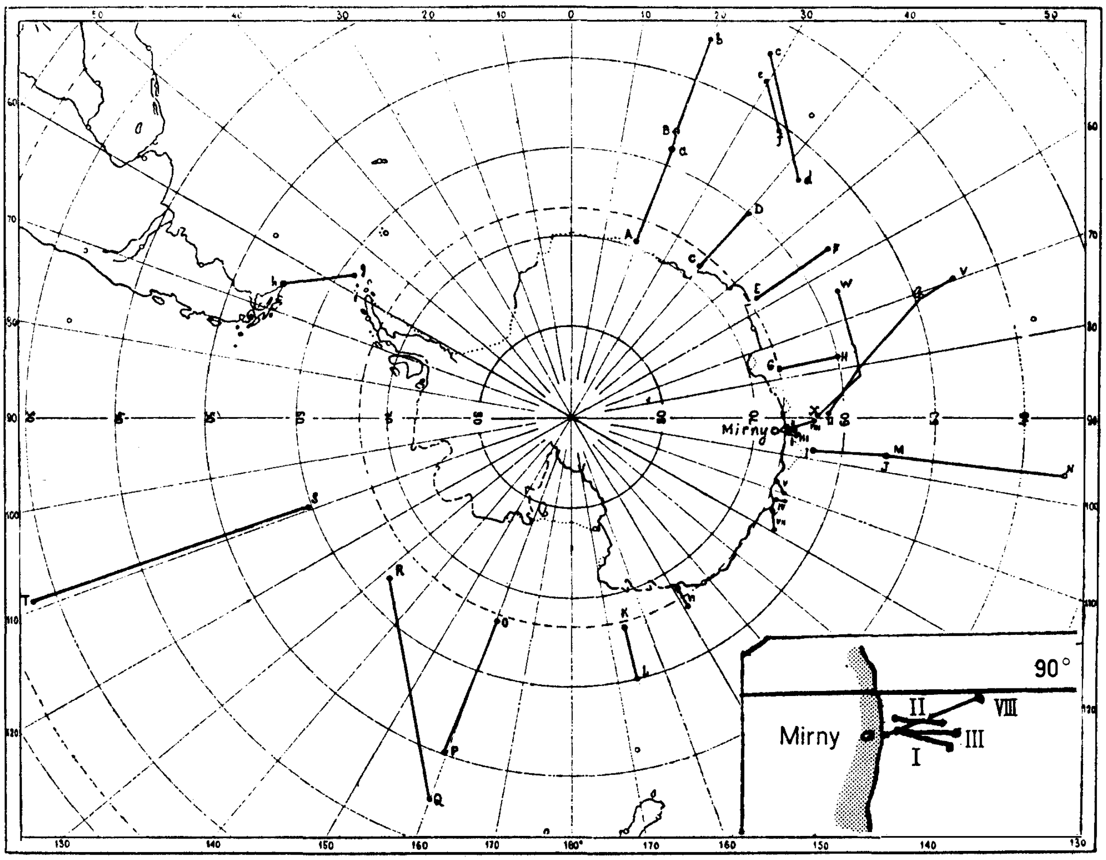


Fig. 2. Locations of sections, shown on Figs. 3–9.

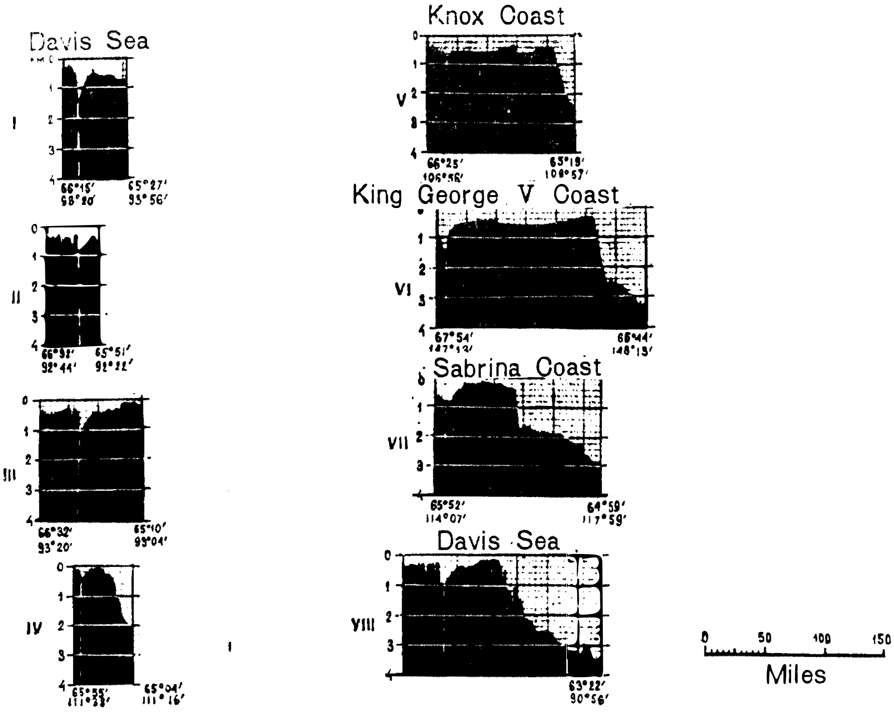


Fig. 3. Morphostructures of the Antarctic shelf and continental slope.

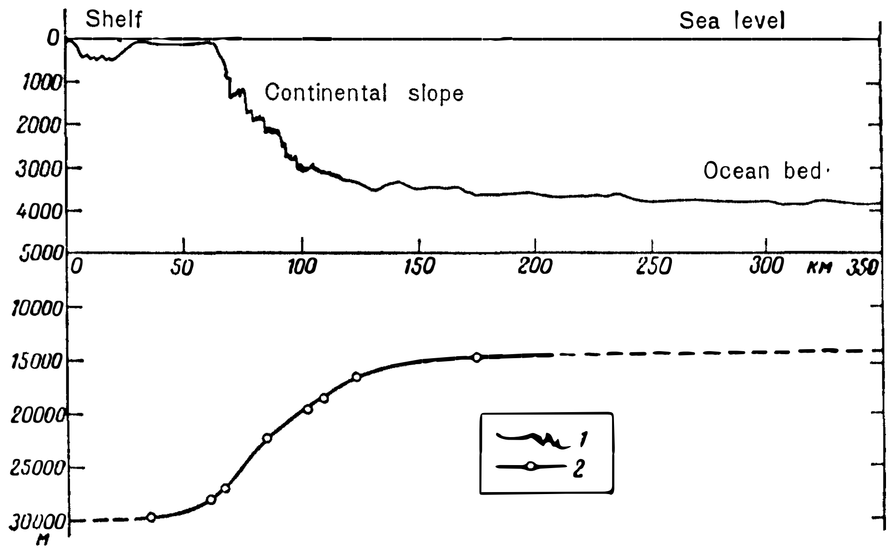


Fig. 4. Location of the Mohorovicic discontinuity under shelf and continental slope of Antarctica (after ZHIVAGO, ISAEV and USHAKOV, 1964).
1. Bottom profile.
2. Mohorovicic discontinuity (points of measurements).

with part of Scotia Sea. The continental slope is characterized by a gradually diminishing thickness of the crust expressed both in a lower bottom surface and a rise of the Mohorovicic discontinuity (Fig. 4). Here also three structural zones are distinguished, the top and lowest of which reflect comparatively quiet tectonic conditions and are expressed in the relief as inclined plains, whereas the middle zone corresponding the greatest gradients in the change of crustal thicknesses, is characterized by an exceptionally complex alternation of ridges, blocks and depressions determined by numerous faults (ZHIVAGO, ISAEV and USHAKOV, 1964). This zone characterized by the greatest strains represents, in a narrow sense, a transition from the continent to the ocean bed. It is interesting that it also serves as an obstacle for the propagation in the direction of the ocean of structural elements of the continent, which are oriented approximately normal to its edge, of the so-called transverse ridges and mountains. This transition zone often is pushed out northwards. An example of such mountain structures is Gunnerus Ridge in the area of Queen Maud Land, several protrusions of the continental slope near Wilkes Land, etc. The thickness of the crust within the transition zone changes from 35 km in the south to 10–14 in the north. A decrease in the thickness of the granitic layer proceeds apparently in the same direction, this layer completely petering out in the area of the bed.

Scotia Arc and Scotia Sea : A peculiar complex of morphostructures is developing in the zone of island arcs. Scotia Arc is usually considered to be a link between the folded chains of South America and Western Antarctic continent, though it is not clear whether all island groups included into the arc system are analogous by their structure to the mountain uplifts of the continents. The majority of the islands is characterized by Paleozoic and Mesozoic schistose and gray wacke-tuff facies of rocks similar to the facies of other peripheral areas of the Pacific Ocean (ADIE, 1964). The southern Orkney Islands contain graptolitic layers, which were subjected to folding during the Cretaceous. And yet both the islands and the Antarctic Peninsula contain thick Mesozoic sedimentary rock masses that have not been subjected to any folding at all. This refers also to the extreme eastern link of Scotia Arc – the Southern Sandwich Islands, where, at least in the emerged part, there are no sedimentary, metamorphic or igneous rocks. The islands consist of basaltic and andesitic lavas exclusively and their structure, as a whole, apparently does not differ at all from the ordinary volcanic ridges fringing the oceanic trenches. In this way, former concepts on the Alpine folding as the main stage for the transformation of a geosyncline, should be revised. If the main orogenesis is referred to the Hercynian time, as suggested by M. G. RAVICH (oral communication), the formation of the so-called Andian intrusions should sooner be regarded as a posterior phenomenon within a already formed folded land that went through a stage of deep dissection. The Andian intrusions were probably associated with displacements of this stage, which occurred during the end of the Mesozoic – the beginning of the Cenozoic and were accompanied by the creation of new big relief elements.

Inasmuch as the Southern Sandwich Islands – the youngest link of Scotia

Arc – greatly differs geologically from other islands, HEEZEN and JOHNSON (1965) suggest not to regard them as a junction element between the southern and northern latitudinal parts of the arc. Such an element, they think, is the badly dissected bottom stretch of Scotia Sea extending between the island South Georgia and the Southern Orkney Islands. In Scotia Sea there are several elevations of the bottom, which with the same right could be regarded as junction links between the southern and northern parts of the arc. Large submarine ridges exist also in Drake Passage (Fig. 5). It is important to stress that the ends of submarine ridges, just as separate links of the island arc are oriented en echelons against each other. It seems that along with the development of the relief there have been an eastward shift by stages of the entire structure of the arc, when the youngest parts of the arc occupied a gradually more and more eastern position. The Southern Sandwich Islands and the Southern Sandwich Trench form apparently an independent morphostructural complex that originated on the margin of a transition zone at the boundary of two oceans during quite recent times. The basaltic layer of the crust 4–6 km thick is appreciably sunk under the floor of the trench and here negative gravity anomalies are recorded. The deep depression of the trench with its steep slopes dissected by faults, steps and a narrow flat floor can be regarded as a recent geosyncline analogous to abyssal peripheral depressions of the Pacific Ocean. The youth of the complex in indicated by a high seismicity and recent character of volcanic phenomena recorded within its limits. It is also possible to assume that the formation of morphostructures in the entire area of Scotia Sea was to a great extent determined by horizontal crustal movements induced, in their turn, by movements in the upper mantle directed from the Pacific Ocean towards the Atlantic Ocean. By these movements crustal blocks became displaced eastward, possibly, already at the moment of their formation.

Seismic sounding in Scotia Sea area (EWING and EWING, 1959) indicates that the crust here is of an transition type and is about 18 km thick. In a western direction it gets thinner changing into a typically oceanic crust (about 8 km thick) approximately on the meridian of South Shetland Islands. In this way, the crust of Scotia Sea by its type stands closer to the crust of oceanic seas than to the seas of the transition zone, to which it is, however brought closer by a great thickness of surface sediments (about 500 m). West of Scotia Sea a typically oceanic crust is developed in Drake Passage. According to E. D. KORIAKIN

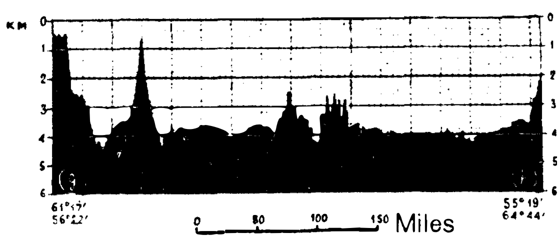


Fig. 5. Cross section of the Drake Passage.

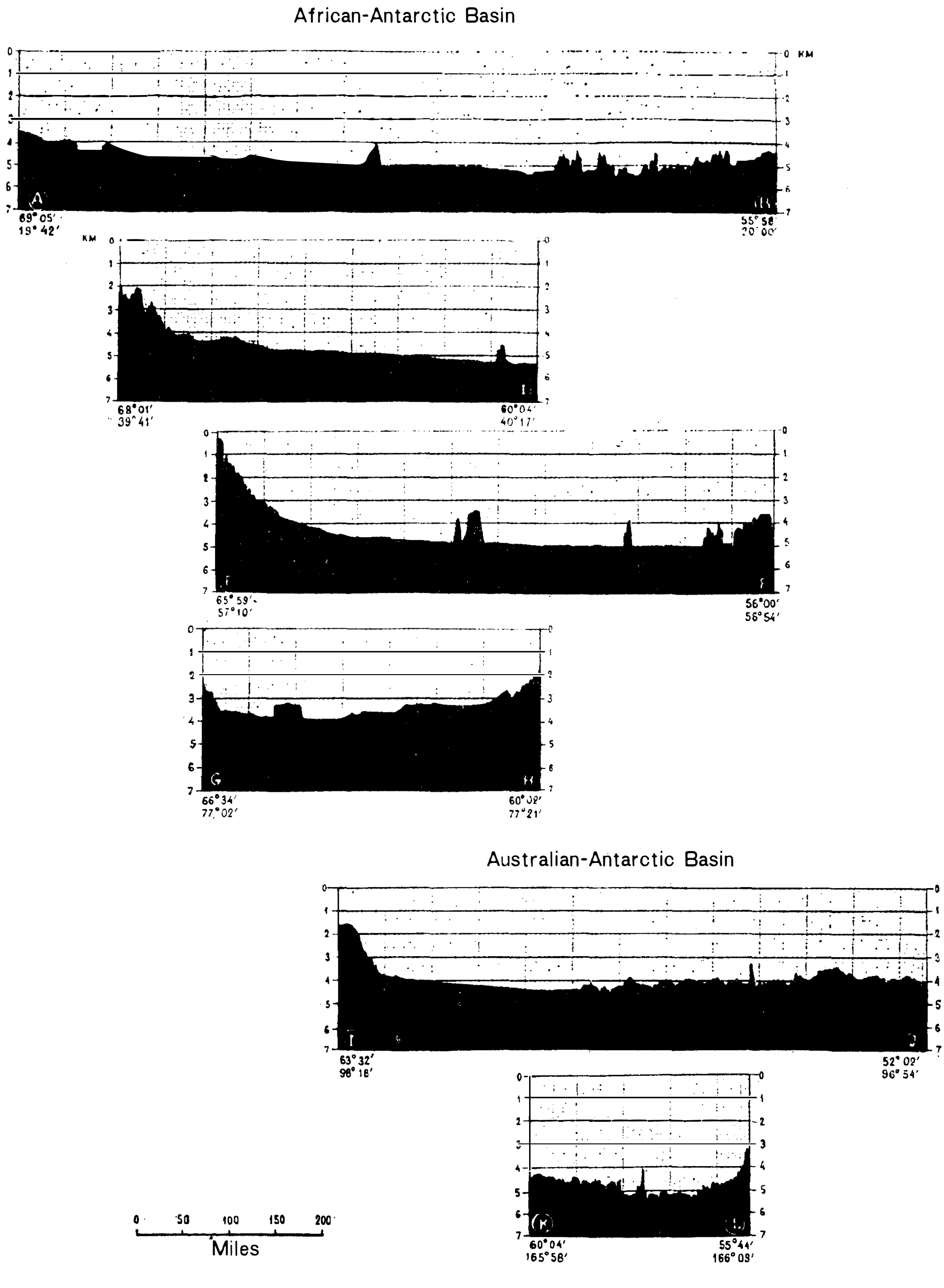


Fig. 6. Morphostructures of the oceanic basins.

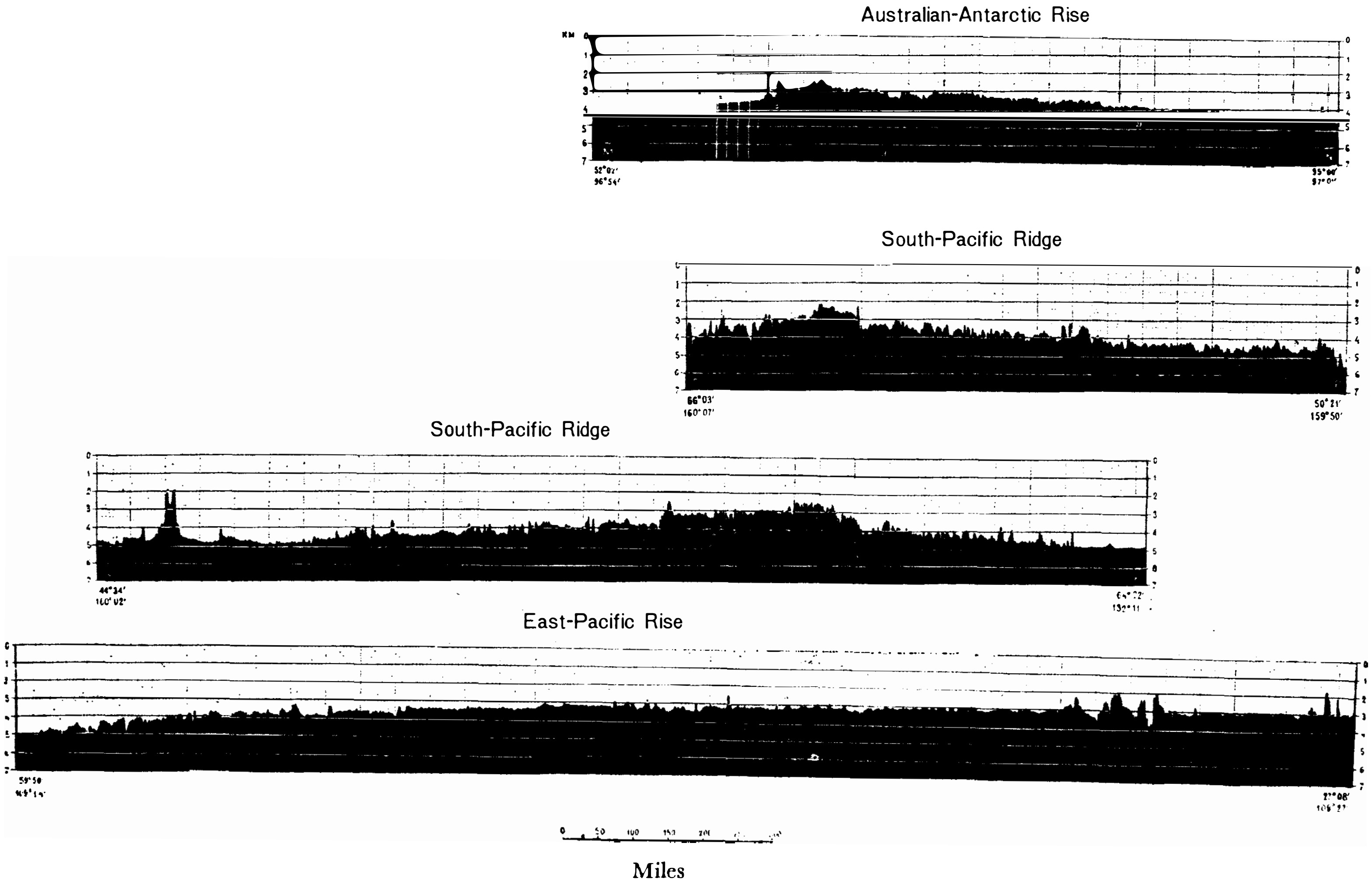


Fig. 7. Morphostructures of the mid-oceanic swells.

(1963) its thickness here under submarine ridges does not increase, as usually, but remains the same, which proves that these ridges are young. As to the western part of Scotia Sea, the presence there of separate "roots" among a typically oceanic crust indicates a submergence of older folded structures.

Bottom Structure in the Area of an Oceanic Crust

A crust of oceanic type is developed over tremendous expanses of the bed of the Pacific Ocean. Its general thickness is 5–8 km (DEMENITZKAIA, 1961) with a pronounced predominance of basalts in its composition and a complete absence of a granitic layer. The basalts are covered by a so-called "second layer" consisting mostly of volcanic rocks and having an extremely uneven surface. Higher up comes a sedimentary layer from 200 to 700 m thick.

The morphostructural elements on the bed of the Southern Ocean are of an enormous size and have very distinct external contours (ZHIVAGO, 1964, 1966). They are of different age. Many of them are associated with the gigantic faults of the crust - lineaments. The disturbances originated at different stages in the development of the oceanic basin and were subsequently repeatedly renewed.

Oceanic basins fringe the Antarctic continent in a continuous stretch, its width varying from 80 to 1200 miles (Fig. 6). This stretch includes the African-Antarctic, Australian-Antarctic Basins, Bellingshausen Basin, etc. From a tectonic point of view the basins are vast isometric depressions of the bed. They are characterized by a small thickness of the crust, which in the central parts does not exceed 5 km (EVISON *et al.*, 1959) and a sheet of sediments 500–700 m thick.

The floor of the basins consists of a crust of oceanic type with a predominance of basalts and a volcanic "second layer". A common structural feature of the basins is a discrepancy between the simply built horizontally bedded surface masses and the complex block-volcanic relief, which they conceal. These areas can be distinguished under the term of oceanic platforms, the development of which takes place on the background of continuous vertical movements, a local dissection of the bottom and volcanicity processes.

Oceanic swells: Oceanic swells are located on the periphery of the Southern Ocean north of the deep basins. Beginning in the Indian Ocean around Amsterdam and Saint Paul Islands a chain of swells extends to the south-east as the Australian-Antarctic Rise that changes south of New Zealand into the South-Pacific Ridge and further into the East-Pacific Rise (Fig. 7). Structurally the swells are meganticlinal uplifts of the crust complicated by numerous faults and by volcanicity. Transverse faults cause horizontal displacements of some parts of the swells against the others (MENARD, 1964). High indices of heat flows are recorded along the axial zones of the swells, which indicate a near-by position of the mantle and a general thin crust (HEEZEN, 1959). This thickness is an average of about 4.5 km. The thickness of the sedimentary cover also does not exceed 200–300 m. The real thickness values are camouflaged by phenomena of volcanicity, which are both of a shield and linear nature. The age of the swells is not exactly established, but in any case, during the Cenozoic these structures already existed, which is indicated by the Tertiary age of volcanic rocks on some islands crowning the peaks of the swells. With the crests of the swells foci of shallow

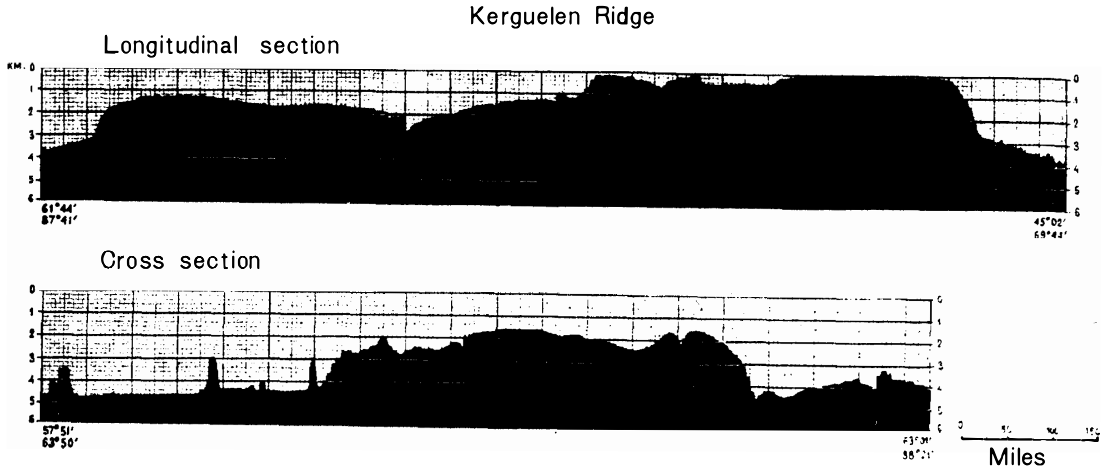


Fig. 8. Morphostructures of the oceanic swells.

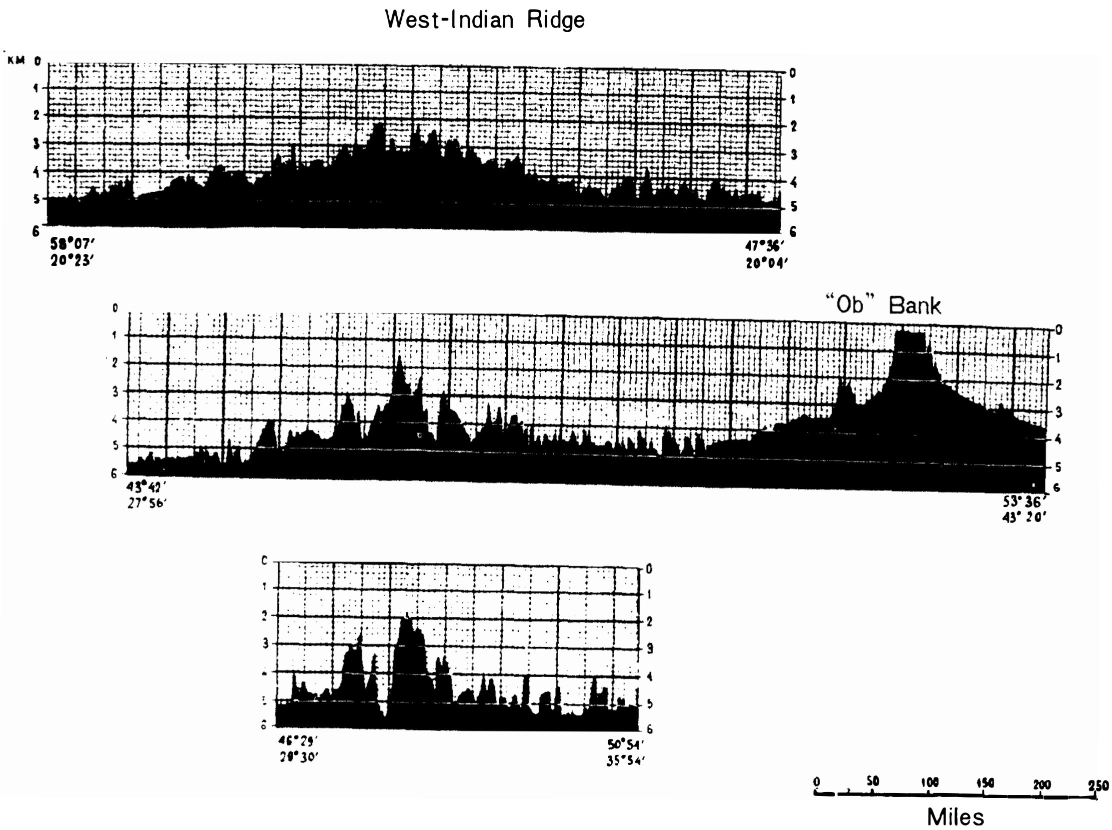


Fig. 9. Morphostructures of the mid-oceanic ridges.

earthquakes are associated. Their intensity is appreciably higher in places where the swell experiences a lateral displacement along the lines of transverse faults.

Kerguelen Ridge separating the African-Antarctic and Australian-Antarctic Basins (Fig. 8) belong apparently to the type of swells. Separate sections of the plateau-like surface of the swell are elevated as banks and islands Heard and Kerguelen. Their rocks give an idea about the structure of the new edifice. These are Tertiary limestones, hidden by a sheet of basaltic lavas. The volcanic activity of Kerguelen Ridge continues with minor intervals probably since the Paleogene and up to the present time and is mainly associated with a gigantic longitudinal fault, along which several volcanoes can be traced. Large submerged banks within the swell are also volcanoes.

Oceanic median ridges : This type of submerged elevations is represented in the Southern Ocean by the African-Antarctic Rise, which serves as a connecting link between the Mid-Atlantic and Mid-Indian Ridges. Recently it has received the name of the West-Indian Ridge (Fig. 9). A high seismicity of the median ridge indicates its present tectonic activity. The amplitude of bottom dissection within the ridge is locally from 3 to 4 km. The highest crests with their volcanoes rise over the surface of the ocean as Bouvet and Prince Edward Islands. In the central stretch of the rise a deep rift valley can be traced framed by high ridges. The flanks of the entire structure are dissected less. From the south it is adjoined by the Crozet Islands plateau also consisting of volcanic rocks.

No measurements were made for the thickness of the crust on the interval of the median ridge in the Indian Ocean. For the more northern parts higher thickness (10–15 km) have been established as compared with the adjacent basins (HEEZEN, THARP and EWING, 1959). Rock fragments raised from the surface of the ridge proved to be serpentinites, peridotites, gabbroes and basalts. Old sedimentary and metamorphic rocks are, apparently, absent. The "roots" of the ridge sink deeply into the material of the mantle.

The genesis of median ridges still remains unclear. Most reliable seems to be HEEZEN's hypothesis (1963), which connects the origin of the ridges with fractures in the crust formed owing to its expansion. New elements of the bottom are formed at the expense of material rising from the mantle. The central parts of the median ridges and their rift valleys are, apparently, the youngest in a series of consecutive fractures in the ridge zone. It is characteristic that rootless structures of median swells, which occupy in the oceans, actually, the same position as median ridges, have no common deep rift valley. Numerous small longitudinal depressions alternate here with block-volcanic ridges and massifs of medium height that are often poorly expressed in the relief owing to a thick mass of lavas that cover them.

A stretch of swells and a part of the median ridge located south of Africa form a chain of peripheral rises of the bottom of the Southern Ocean, in other words a boundary of the Antarctic. The position of submarine elevations nearly coincides with the average position of the Antarctic convergence of oceanic waters accepted as the northern bonndary of the Southern Ocean. In this way, the seggregation of this ocean as an independent basin proves to be legitimate not only by a combination of exogenetic features, which should include also the zonal structure of the sedimentary cover, but also by rather distinct morphostructural data, which might have served as an original basis for a spatial distribution of agents in an oceanic medium.

References

ADIE, R. J.: Geological history. Antarctic Research, London, 1964.

DEMENITZKAIA, R. M.: Main features of crustal structure of the Earth by geophysical data. Trans. Sci. Res. Inst. Geol. Arctic, **115**, 1961.

EVISON, F. F., C. E. INGHAM and R. H. ORR: Thickness of the Earth's crust in Antarctica. Nature, **183** (4657), 1959.

EWING, J. and M. EWING: Seismic Refraction Measurement in the Scotia Sea and South Sandwich Island Arc. Int. Oceanogr. Cong. Preprints of Papers, Washington, 1959.

HEEZEN, B., M. THARP and M. EWING: The Floors of the Oceans. I. The North Atlantic, 1959.

HEEZEN, B. C.: Rift valley at the bottom of ocean. Oceanology, **3** (1), 1963.

HEEZEN, B. C. and G. L. JOHNSON: The South Sandwich Trench. Deep Sea Res., **12** (2), 1965.

KORIAKIN, E. D.: Some specific features in the crustal structure of the transition zone from the Atlantic Ocean to the continents of America and the Antarctic. Morskie gravimetricheskie issledovania. Publ. Moscow State Univ., 1963.

MENARD, H. W.: Marine Geology of the Pacific, N, Y., 1964.

MURATA, I., T. SAITO, Y. FUJII and Y. HARADA: Report of the gravity measurement by the Japanese Antarctic Research Expeditions 1957–1962. Papers presented at the SCAR–IUGS Symposium on Antarctic Geology, Cape Town, 1963.

RAVICH, M. G., L. V. KLIMOV and D. S. SOLOVIEV: Precambrian of Eastern Antarctic continent. Results of the IGY, Gravimetry, No. **4**, 1963.

USHAKOV, S. A.: Geophysical researches on the crustal structure in the east of the Antarctic continent. Results of the IGY, Gravimetry, No. **4**, 1963.

ZHIVAGO, A. V., E. N. ISAEV and S. A. USHAKOV: On the relations between the transition zone geomorphology of the Antarctic continent with the struction and thickness of the crust. C. R. Acad. Sci. USSR, **155** (**3**), 1964.

ZHIVAGO, A. V.: Bottom geomorphology and tectonics of the Southern Ocean. Results of the IGY, Oceanological Researches, No. **13**, 1964.

ZHIVAGO, A. V.: Tectonic and relief maps of the sea floor in the Southern Ocean. Antarctic Geology, Amsterdam, 1964.

ZHIVAGO, A. V.: Tectonic and geomorphological maps of the Antarctic (in part of the Southern Ocean). The Atlas of the Antarctic, 1966.