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by V. D. Rvachev

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Geomorphology of the Continental Shelf in the Northwest Atlantic

23*

By V. D. Rvachev

(Geomorfologiya shel'fa severo-zapadnoy Atlantiki. Trudy Polyarnogo nauchno-issledovatel'skogo i proyektnogo instituta morskogo rybnogo khozyaystva im. N. M. Knipovicha (PINRO), vyp. XXVIII, 1972.)

The development of Soviet ocean fishing, the need to increase the catch and, therefore, the expansion of the fishing area have required the study and exploitation of fishing grounds of the northwest Atlantic belonging to the continental shelf and slope of North America and Greenland. Oceanographic investigations in that region were organized by the Arctic Institute ("PINRO") in 1954, when the Newfoundland area was visited by a study team on the scientific ships Sevastopol and Odessa, a field trip that was in the nature of a reconnaissance. In the following years, investigations

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* Figures in the margin give page numbers in the original. -- TR.

were carried out on the continental shelf and slope along the coasts of Nova Scotia, Newfoundland, Labrador, Baffin Island, and West and East Greenland. The geomorphological investigations involved more than 32,700 miles of echo sounding and 660 bottom samplings. The resulting data make it possible to elucidate certain questions concerning the geomorphology of the bottom of the Northwest Atlantic.

Terrestrial Geology

From the land side, the area of the Northwest Atlantic adjoins a region of heavy glaciation which covered the North American continent during the Quaternary period and which is preserved to this day in Greenland. The continental shelf in this area, geologically speaking, is a part of the North American Platform, with the Canadian and the Greenland shields and the adjacent zone of Paleozoic folding. The North American Platform takes up more than half the North American continent and represents its structural base (17). The morphology of the continent, reflecting its structural characteristics, exhibits the following sequence, from the middle of the continent to the ocean: plateau (shield) -- interior plains -- mountainous relief -- coastal plains -- continental shelf -- continental slope -- bottom of the ocean basin. The largest structural-morphological units that make up the eastern coast of North America and that are bounded by the depression of the Atlantic Ocean, are the Canadian Shield, the mountain system of the

Appalachians and the Atlantic Coastal Plain. The Shield also embraces the southeastern part of the Candian Arctic Archipelago (Baffin Island and others) and Greenland.

The Canadian Shield occupies the entire Labrador Peninsula and extends into the Canadian Arctic Archipelago. The massif of the Shield is rendered complex by large ruptures or fault zones. A large fault extends from north to 24
south along the southwestern part of Baffin Island and the coast of Ungava Bay in northern Labrador and cuts off the northeastern part of the peninsula. Another fault runs at right angles to the former from southwest to northeast and separates the southeastern margin of the Shield. This fault is exposed at the east coast of Labrador and extends into the peninsula's shelf. In the eastern part of the Shield we know of several small faults or fractures, which have given rise to fjords on the Labrador coast (19).

To the Shield corresponds the low Laurentian Plateau, representing an ancient peneplain on the Shield structures and worked over by glaciation. The eastern uplifted margin of the plateau was cut off during pre-glaciation (Upper Tertiary) time by a large fault along which a subsidence took place (28), i.e., the subsidence embraced the area of the modern shelf.

The Canadian Archipelago, in its geological structure and relief, is closely related to the northern part of the continent. Mesozoic-Cenozoic tectonic movements led to a break-up of the northern part of the Shield; this involved not only the ancient features of the Archipelago but in some areas fractures and faults also disturbed Tertiary strata (17, 39).

At the southeastern extremity of Baffin Island we know of basalt which may be of the same age as the basalt in the area of Disko Island, where it breaks through Cretaceous and Tertiary rocks overlying the foundation (28, 38). The shores of many islands in the Archipelago exhibit shore lines at an elevation of up to 200-300 m, evidence of an uplift of the islands during post-glacial time (20).

The Appalachian mountain system extends along the eastern margin of the continent and, preserving its northeastern strike, dips to the northeast of Newfoundland beneath the sea level. The Appalachian relief is characterized by an alternation of ridges, which are narrow and considerably eroded and which extend along the strike of the tectonic structures, and intervening broad valleys. The relief form usually reflects directly the folded structure, but one can often observe an inversion of the relief. Many valleys have the shape of grabens as a result of subsidence along fractures.

The Atlantic Coastal Plain is closely related to the Appalachians, whose buried structures are overlain by the strata of the plain. The coastal plain and its submarine extension are composed on the ocean side of a stratum of sedimentary rocks whose thickness increases at the margin of the continental shelf, where the foundation is buried most deeply (19). The manner in which the sedimentary rocks are bedded indicates repeated fluctuations in the continental margin, with the predominance of a general slight subsidence, disturbed in some places by fractures, and a displacement of the axis of tectonic movements toward the ocean (28). The presence of a series of Pleistocene terraces along the coast indicates considerable fluctuations in the sea level, coinciding with glacio-isostatic movements of the land due to variations in the thickness of Quaternary glaciation.

In Greenland only the margins of the shield are free of ice; beneath the ice the surface of the shield may be depressed 250-400 m below the sea level (42). Mountain massifs and the plateau of the coast show traces of being scoured by the icesheet and are cut up by fjords many of which run along lines of fractures.

A post-glacial uplift of the marginal parts of Greenland is indicated by uplifted shore lines along the western and eastern shores of the island (28).

Relief of the Continental Shelf and Slope in the Northwest Atlantic 25

The largest elements of the relief of the bottom of Northwest Atlantic are the continental shelf, submarine sills, the continental slope, abyssal plains in the ocean basin, and the Mid-Atlantic Ridge, represented by the North Atlantic and the Reykjanes ranges.

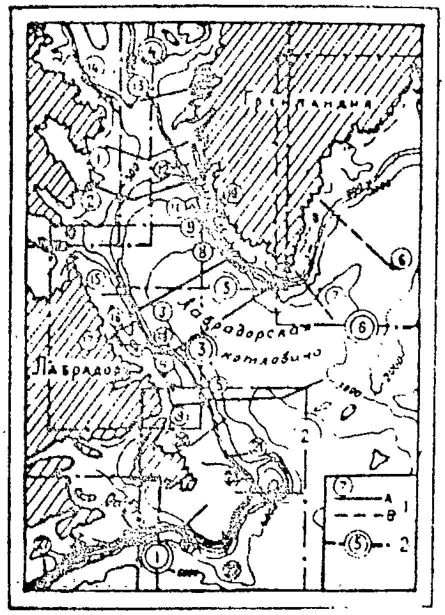

Fig. 1. Bathymetric scheme of the Northwest Atlantic.
1 -- location of bottom profiles:
A -- Soviet scientific ships,
B -- German scientific ships (70).
2 -- regions: 1 -- Nova Scotia,
2 -- Newfoundland, 3 -- Labrador,
4 -- Baffin Island, 5 -- West Greenland, 6 -- East Greenland.

The Northwest Atlantic continental shelf extends along the eastern coast of North America and fringes the east and west coast of Greenland. The depth and width of the shelf and its differentiation vary in the regions. The outer (marine) margin of the shelf is well indicated throughout by the discontinuity in the bottom level and is situated at various depths from 60 to 100 m southeast of Newfoundland to 300-400 m along Labrador and East Greenland. The width of the shelf varies from 30-100 miles at Greenland and Labrador to 200-300 miles in the area of Newfoundland (Fig. 1).

In Davis Strait, off the southeast extremity of Baffin Island, the surface of the East American Shelf gradually goes over into the surface of the ~~Greenland-Canadian submarine~~ Baffin-Greenland Rise

~~sill~~, which extends to the Greenland shelf. Water depth over the sill reaches 600-700 m. The ~~sill~~ rise separates the Baffin Sea basin on the north from the Atlantic Ocean basin to the south. On the east of Greenland, in the Strait of Denmark, there is also a ~~sill~~ rise, formed of the extensions of the Greenland and the Iceland shelves.

The continental slope begins at the edge of the shelf and extends to a depth of 2,500-3,000 m. Morphologically it is represented by a gigantic ledge, which is steeper in its upper part. In its lower part the slope drops off more gradually and its foot merges with the bottom of the ocean basin. The width of the slope zone is 30-50 miles. The inclination of the slope varies on the average from 3-5 to 6-10°, and in some places off Greenland up to 15-20°. In some places the continental slope is fairly even, but it is often cut up by deep submarine canyons, steps and ledges and exhibits the character of large-scale block break-up.

In the depression of the Northwest Atlantic there are two large basins -- the Labrador and the Newfoundland basin. The Labrador Basin is situated south of the ~~Greenland-Canadian~~ Baffin-Greenland ~~sill~~ Rise between Labrador and Greenland. Farther south it merges into the Newfoundland Basin, which in turn merges with the larger and deeper North American Basin of the Atlantic Ocean. The bottom of the basins is mainly level. Abyssal plains 26
within the basins are situated at depths of 3,000-5,000 m.

In the bathyal depression of the ocean there is the Mid-Oceanic Canyon. During the investigations in the Labrador

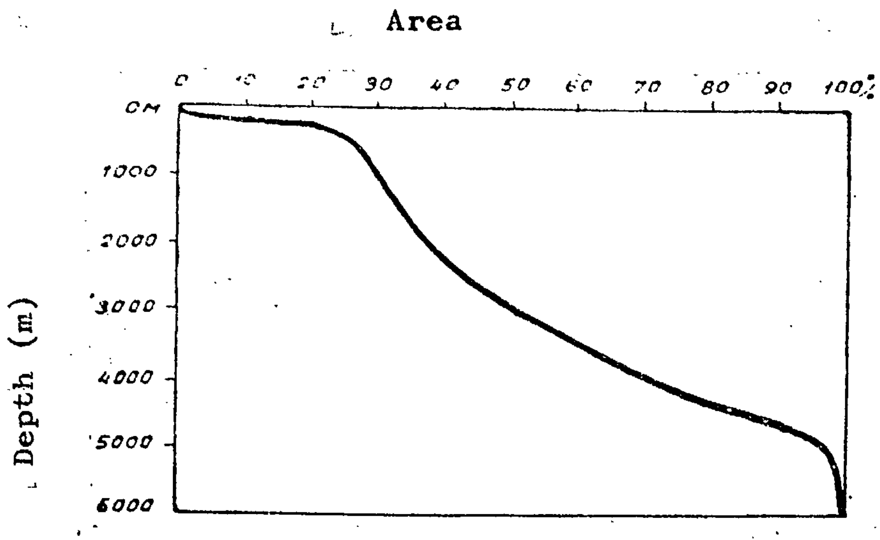

Fig. 2. Bathygraphic curve of area under study.

and Greenland areas with the SS Sevastopol, Akademik Knipovich and Persey-III the canyon was traversed and echo-sounded at several sections in the Labrador Basin. It extends approximately along the trough axis somewhat nearer the North American continental slope, has a flat bottom, and steep sides; its relative depth is 60-165 m, its width 2-5 miles (34).

On the east of the basin the northwestern part of the ocean is bounded by the Mid-Atlantic Ridge. The foothills of the Mid-Atlantic Ridge have a broken relief. Within its hilly margin fluctuations in relative heights amount to 300-600 m. The Reykjanes Ridge represents a massive uplift, whose relative elevation reaches 700-1,600 m. Most heavily broken up is its southwestern part, where the extension of the rift zone of the

North Atlantic Ridge contains several large longitudinal valleys and narrow, steep crests with high summits; within the ridge, the slope angle reaches 20-50° (69).

The ratio between the areas of the shelf, the continental slope and the bathyal depression, obtained by the approximation method (7), is shown by a bathygraphic curve in Fig. 2. A large part of the marine area (51.8%) is occupied by depths of 2,800-5,000 m and more. The shelf, with depths of 0-200 m, makes up 19.7%, and with depths of 0-500 m, 28.4%.

The morphology of the shelf exhibits features typical of all zones. At the same time, many morphological characteristics of the bottom in specific localities are related to the geological structure and the history of the adjacent land. We shall review six regions: Nova Scotia, Newfoundland, Labrador, Baffin Island, West Greenland and East Greenland (Fig. 1).

Review by Regions

The Nova Scotia shelf is divided by a broad longitudinal depression with a depth of up to 250 m into an inner (coastal) and an outer part and is cut up by two large transverse trenches extending from the Gulf of St. Lawrence and the 27
Gulf of Maine. Individual uplifts in the inner shelf are cut off at the level of the surface of the outer part of the shelf, which is mainly level (Fig. 1, 3; profiles 25-27). In its southwestern part (Georges Bank) there are sand ridges, extended in the direction of the existing tidal currents. At

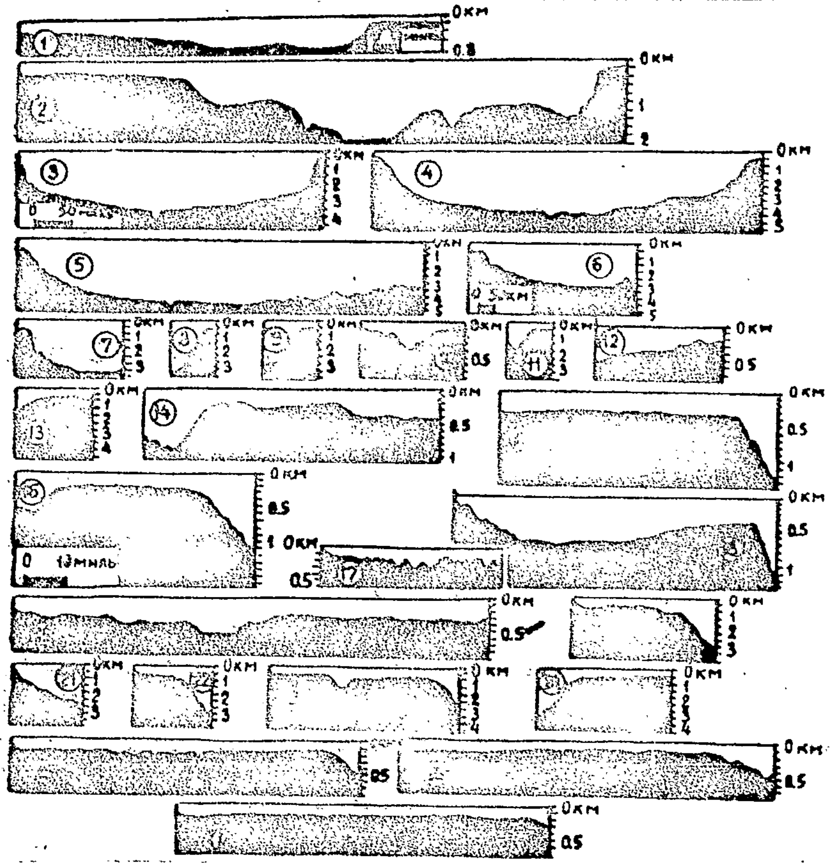

Fig. 3. Bottom profiles in the Northwest Atlantic. Ratio of vertical to horizontal scale 1:37, for German profiles, 1:50. Location of profiles shown in Fig. 1. (Distances in miles, depths in kilometers.)

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a depth of 200 m the shelf is bounded by the continental slope. The slope is broken up by steps and is cut up by deep canyons, the upper ends of which usually cut only through the margin of the shelf.

The Newfoundland shelf, in its hypsometric character, is divisible into two sub-regions. The northeastern part of the shelf is more depressed, and the margin of the shelf is situated at a depth of about 400 m. The shallow portions of the shelf's banks (Belle Isle and Northern Newfoundland) and the transverse trenches that divide them, like the adjacent land structures, have a northeastern strike.

To the east and southeast of Newfoundland the shelf is level, and a large portion has depths of less than 100 m; a somewhat greater depth is found only over the bank of Flemish Cap, separated from the main shelf mass by a trench with a depth of up to 1,200 m (Fig. 1, 3; profiles 19-24).

The Grand Bank of Newfoundland is bounded at depths of 60-200 m by the steep continental slope, and its southeastern margin is cut up by canyons. Along the Northern Newfoundland Bank the continental slope inclines gently (1-2°) 28
and evenly. At its northeastern extension, where the strike of the slope changes and where it intersects the submarine extension of the island structures, the slope angle increases (3-6°), and at a depth of 750-770 m there is a terrace representing a structural bench.

The <u>Labrador shelf</u> is situated at greater depth than the Grand Bank of Newfoundland, from which it is separated by a still deeper area. The dip from shelf to slope begins at a depth of 300 m. The southern part of the shelf is cut by a longitudinal trench with a depth of 500-600 m and a width of 10-25 miles, which runs for 350-400 miles at a distance of 10-30 miles from the shore and parallel to the latter up to 57°20' lat. The slope of the trench, on the coast side, rises by steep ledges with sharp outlines (Fig. 1, 3; profiles 15-19). The broken-up character of the slope is also typical of the coastal part of the shelf, while its outer part has a relatively level surface.

The shelf is also cut by two transverse trenches, situated along the extension of Hamilton Inlet, and at 56° lat., where a fracture extends to the coast that is also known in the interior (19).

The Labrador continental slope is heavily broken up. The average slope angle is 3-5°, but in its upper part and on the ledges it reaches 10-15°. At the extension of the transverse trench at 56° lat. the continental slope is cut by a deep canyon.

The <u>Baffin Island shelf</u>, along the northeast coast, is narrow (10-15 miles) and broken up by transverse trenches into a number of blocks. The margin of the shelf is situated at a depth of about 200 m. At the southeastern end of the island the shelf is less cut up, being traversed only by broad, shallow trenches, situated along the extensions of Frobisher and Cumberland bays. East of Baffin Island the shelf descends gradually, and a depth of 400-500 m it merges with the surface of the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise (Fig. 1, 3; profiles 1, 2, 14). In the southwestern part of the ~~sill~~ rise the gradual transition is disturbed by a more abrupt dip, and the bottom slope reaches 2-3°. In the northwestern part of the ~~sill~~ rise, approximately on the line of the aforementioned dip, there are ledges with a height of 30-40 m, facing Baffin basin. The southern slope of the ~~sill~~ Rise is fairly gentle, but at a depth of 2,000 m it is interrupted by a ledge with a height of 300-400 m. In the western part of the southern slope of the ~~sill~~ Rise, where it links up with the continental slope of Baffin Island, there is a depression with a depth of about 200 m.

The West Greenland shelf is separated from the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise by a distinct ledge with a height of 300-600 m and a slope angle of about 10°. Where the shelf and the ~~sill~~ Rise meet at the margin of the shelf, there is a well-developed terrace (64).

Typical of the West Greenland shelf, as of other regions, is a system of longitudinal and transverse trenches that divide its mass (2, 32, 52). The large blocks of the shelf are depressed to varying depths. At the latitude of the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise the margin of the shelf lies at a depth of 150-200 m, in the region of Disko Island it is at a depth of 400 m, and south of the sill, at 200-250 m.

The continental slope of Greenland, from the southern end of the island to the ~~Greenland-Canadian sill,~~ Baffin-Greenland Rise is high and steep (up to 15-20°). Along the ledge of the continental slope, where it meets the ~~sill~~ Rise, there is an extensive depression with a depth to 900 m (Fig. 1, 3; profiles 1, 2, 8-13).

The East Greenland shelf resembles that of West
Greenland (1, 2, 25), but it is much more depressed; its edge 29
lies mainly at depths of 250 to 400 m. Depths in the basins of longitudinal and transverse trenches reaches 500-900 m.

The continental slope of East Greenland has the shape of a massive ledge, whose southern part is heavily broken up (Fig. 1, 3; profiles 6, 7). The angle of the slope averages 6-8°, but in some parts reaching depths of 1,000-1,500 m it reaches 18-20° (6).

This brief review of the bottom morphology of the Northwest Atlantic shows that along with differences in the structure of the shelf in the various regions there are features common to the entire shelf. The large relief forms often indicate a direct regional link with the buried structures of the adjoining land areas, which in some places can be traced also within the continental slope. The similar structure of the Northwest Atlantic shelf undoubtedly reflects the existence during the past of a single relief-forming factor. A typical feature of the entire shelf is the system of longitudinal and transverse trenches that cut up the shelf and that typify the morphology of regions subjected to Quaternary glaciation.

Bottom Geomorphology

Morphostructure and Morphosculpture of the Bottom, Their Origin and Development

On the basis of geological and geomorphological data the Northwest Atlantic shelf is to be divided into two morphostructural types: (1) the continental shelf in the region of the Canadian-Greenland Shield -- the regions of Labrador, Baffin Island, and Greenland; (2) the shelf in the area of

Paleozoic folding -- the regions of Nova Scotia and Newfoundland.

The shelf in the regions of Labrador, Baffin Island and West and East Greenland represents a denudation plain developed on Precambrian structures of the shield in the course of its lengthy continental development and subsidence beneath the sea level during the inundation of the land. The base of the slightly undulating plain of the shelf off Nova Scotia and Newfoundland is provided by submerged Paleozoic folded structures, eroded to a considerable degree and overlain by a Mesozoic-Cenozoic mantle (Fig. 4).

The morphostructural features of the shelf are more distinct in the regions of Nova Scotia and Newfoundland, where the macrorelief of the bottom is controlled by the original relief of the submerged Appalachian structures.

The position of the large uplifts and negative relief forms of the shelf points to a direct link with the Caledonian structures of the continent. According to geophysical data, the uplift under Sable Island (51), situated on the outer part of the Nova Scotia shelf, as well as a large fracture extending from the Bay of Fundy to Newfoundland (29), possess, like the large features of the shelf relief, a northeastern strike, typical of the terrestrial Appalachian structures.

Apart from the longitudinal relief features, the Nova Scotia shelf has transverse features, the largest of which are the trenches of the Gulf of Maine and the Gulf of St. Lawrence. The St. Lawrence Gulf trench is laid down along fracture lines and follows the course of a pre-glaciation river (63).

The second trench appears to have an analogous origin. Although these fractures do cut through longitudinal structures, they may be of approximately the same age as the latter. Transverse structures are also known in the Appalachian system on land.

Seismic studies have shown that the Newfoundland 30
shelf is a structural extension of the Appalachian folded system (60). This is also indicated by the morphology of the shelf.

The morphostructural features of the shelf are even more distinct toward the northeast and southeast or south of the island, where the shelf (Grand Bank) has a general depth of less than 100 m and is undoubtedly a part of the heavily denudated land, further scoured by glaciation during a lower sea level, when the bank may have been a single whole with the island. Relief forms indicating a connection between the structures of the land and the shelf are broad valley-like depressions along the extensions of the southern bays of Newfoundland between the Grand Bank and Green Bank, and between Green and St. Pierre Banks (2, 24). Among such forms is also the hollow along the eastern shore of the Avalon Peninsula. All of them retain the northeast strike typical of Newfoundland.

Northeast of Newfoundland, along the strike of the island's Appalachian structures, the shelf strip is submerged more deeply than in the southern and southeastern sections, and

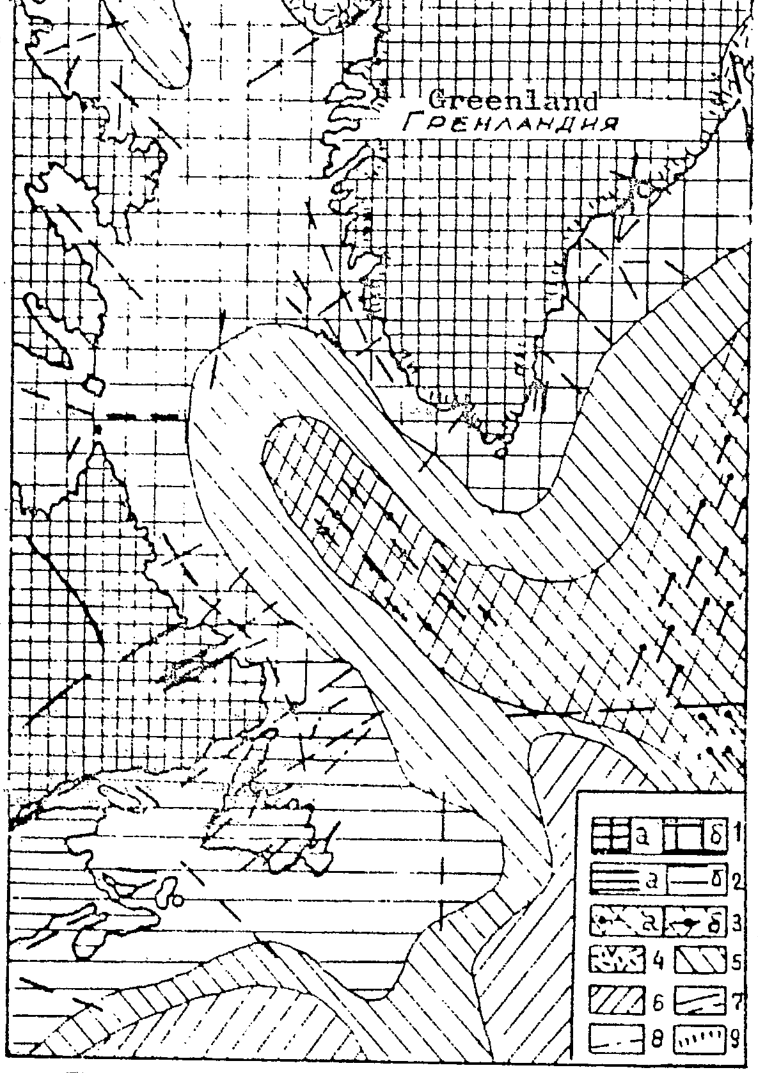

Fig. 4. Tectonic scheme of the Northwest Atlantic.
1 -- Canadian-Greenland Shield: a -- on land, b -- on the sea bottom with a continental-type crust; 2 -- region of Paleozoic folding in North America: a -- on land, b -- on the sea bottom with a continental-type crust; 3 -- system of the Mid-Atlantic Ridge (modern mobile belts): a -- North Atlantic and Reykjanes ridges, b -- buried range in the Labrador Basin ; 4 -- Cenozoic effusive mantles; 5 -- sea bottom with transitional type of crust; 6 -- sea bottom with ocean-type crust; 7 -- fractures and faults on land and, presumably, on the sea bottom (exhibited in the submarine relief); 8 -- axes of uplifts of Appalachian structures on the shelf; 9 -- margin of glaciation.

separates the Grand Bank from the Labrador shelf. Here the margin of the shelf is situated at a depth of about 400 m. The transverse trenches in the shelf, and also the shallow parts of the banks of Belle Isle and North Newfoundland, as well as a terrace on the continental slope on the northeastern extension of the latter, are situated at the extension of the island structures and have the same strike. The banks on the shelf undoubtedly correspond to the higher position of the submerged Appalachian structures of the island, while the formation of the terrace on the slope is due to the disturbance of the flexure of the continental slope by a fault. Small steps on the continental slope are also observable north of the terrace. Transverse trenches in the shelf relief represent a morphological expression of troughs and depressions along fractures subjected to river and later to glacial erosion. A similar structure is also known on the island itself (17).

The banks and trenches in this part of the shelf represent, essentially, reflections of the longitudinal structures of the Appalachian system, but as the general strike of the shelf at Newfoundland changes abruptly from a northeastern to a north by northwestern one, they are cut short by the plane of the continental slope and appear on the shelf as transverse relief features. The continental slope cuts through the Appalachian structures at the protrusion of the Northern Newfoundland Bank in the region of the terrace and farther north, while farther south it runs at an acute angle to the former. The slight gradient of the slope in the southern part of the Northern Newfoundland Bank may possibly be due to the submergence of the limb of one of the Appalachian folds, similar to what is happening on land, where the eastern slope of the Appalachians dips toward the ocean and is overlain by the deposits of the Atlantic Coastal Plain. In the region of the terrace and farther north, i.e., where the continental slope runs across the strike of the Appalachian structures, it is much steeper.

In the area of the Canadian and Greenland shields in the regions of Labrador, Baffin Island and Greenland, we find as distinct morphostructural elements large longitudinal and transverse depressions in the shape of submarine trenches that cut up the relief. If on the shelf in the area of Paleozoic folding large features of the submarine relief correspond to the strike of terrestrial folded structures, we find that in the area of the shield such a relationship is difficult to establish, apart from the large transverse depressions existing on land and traceable on the shelf.

In the Labrador region a large longitudinal trench is found in the southern half of the shelf. It extends southward onto the Newfoundland shelf, where it cuts buried Appalachian structures; it is therefore younger than the latter. In the northern part of the Labrador shelf the longitudinal trench gradually peters out. Along its extension there are several relatively shallow depressions. A nearly continuous depression, which is only occasionally interrupted by uplifts in individual shelf blocks, extends along the coasts of West and East Greenland.

The formation of large longitudinal depressions is 32
being ascribed to discontinuous dislocations accompanied by an increase in differentiating movements along the land-sea boundary during Alpine tectonogenesis. During the arched uplifting of terrestrial blocks, radial fractures might also have been laid down (4). This could have led to a revival of older dislocation zones. Lines of radial fractures are filled by many of the coastal fjords, which extend into the shelf in the shape of transverse trenches.

Large longitudinal and transverse depressions are typical of the shelf in areas of past and present glaciations. They are known along the coasts of Norway, Spitzbergen, and the Antarctic. Deep longitudinal depressions in the shelves of all these regions are situated along high, mountainous coast lines that bear traces of being uplifted during post-glaciation time,and these depressions separate the inner part of the shelves with an uneven relief from the relatively level outer part. The general patterns of the shelf structure of glacial regions demonstrate the enormous role of the Quaternary icesheets in the formation of their relief. Such a negative fact as the lack of analogous features in the shelves of non-glaciated areas (50) may also be taken as an indirect confirmation of this statement. The loading effect of thick continental ice can to a certain extent be correlated with the effect of the tectonic factor. With a density of the sub-crust material of 3.3 and that of the ice of 0.9, the ice load was bound to cause a depression and, therefore, its removal was bound to produce an isostatic rise of the earth's crust, corresponding approximately to 1/3 the thickness of the ice. We know that the glaciers of the Antarctic and of Greenland are isostatically compensated (8, 40, 41).

We also know that the Canadian Shield (like the Baltic Shield) experienced an uplift during pre-glacial time as well, i.e., an uplift not related to glacial loading. Consequently, the glacio-isostatic movements turned out to be superimposed on inherited tectonic ones (13). Fluctuations in the area and thickness of the glaciers during the Pleistocene undoubtedly led to the repeated revival of tectonically produced pre-glaciation depressions laid down during differentiated movements along the continental margins.

The formation of a broken-up relief on the interior shelf of the Antarctic is being ascribed to its recent freeing from ice and young disruptive dislocations in that area (14).

Reviewing the origin of the longitudinal depressions in the shelf off Scandinavia and Labrador, Holtedahl (45) notes that they may be of Pleistocene age. The contrasting relief in the region of the longitudinal trenches and the coastal part of the shelf appears to have a more recent, post-glaciation origin. This follows from a comparison of the morphology of the bottom and post-glaciation movements of the land margins.

In glaciated regions, the inner, coastal part of the shelf,

because of the abrasive-accumulative action of the sea during post-glacial time, is usually more levelled out than the outer part (3). In glaciated regions, on the contrary, the coastal part of the shelf is heavily broken up. This confirms once more the role of recent movements in the formation of the differentiated relief of the inner shelf of glacial regions. There appears to be some sort of inheritance of the primary-structural relief in the inner part of the shelf, causedby fractures at the land margin during Tertiary time. To some degree this relief could be preserved owing to the protective ice cover. The time difference between the freeing from ice of the inner and outer parts of the shelf, during the degradation of the ice cover (about 10,000 years ago), could 33
not have been great. The outer part of the shelf now lies at depths beyond the reach of active abrasion, and its relatively level surface is mainly inherited. Additional levelling of this part of the shelf may have taken place during lower sea levels. The rise in the level of the sea and a shift in the zone of wave action led to a levelling of the inner part of the shelf as well. The low rate of abrasion of resistant crystalline rocks and, perhaps, a temporal gap in this process, could not cause such a great difference in the degree of levelling between the inner and outer parts of the modern shelf in the region of the Canadian-Greenland Shield. This once more confirms the conclusion that the shelf represents an already heavily denudated depressed portion of the land, undisturbed in its outer part, and that the broken-up relief of the inner shelf is due to a break-up in a fracture zone.

Bottom profiles of the regions of Labrador and Greenland show that the interior slope of the longitudinal depression (on the land side) is much steeper than the outer one, it rises by ledges that are further broken up, and it undoubtedly contains outcrops of bedrock. A similar asymmetrical profile is also found in the longitudinal depression on the shelf of Eastern Antarctica(14). Typical is the bottom profile in the West Greenland region, where we can observe the contact of the ice-levelled slope of a transverse trench and the heavily cut up slope of a longitudinal trench (Fig. 1, 3; profile 10). The young features and the sharp difference in relief at the contact of the transverse and the longitudinal trench indicate post-glaciation dislocations in the area of the longitudinal depression.

Evidence of post-glaciation movements is also found in the bottom morphology at the latitude of the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise, where there are large depressions at the juncture of the ~~sill~~ rise with the shelfs of Baffin Island and Greenland. At the margin of the West Greenland shelf, where it meets the ~~sill~~ rise, there is a fairly broad terrace. It extends along the outer part of the shelf and is separated from the surface of the banks by a ledge with a height of up to 150 m. The terrace could have developed at a lower sea level during the Pleistocene, during a period preceding the post-glaciation transgression, when icesheets covered nearly the entire modern shelf, and the ledge of the terrace corresponded to the position of the shore line. The surfaces of the banks have a more varied micro-relief than the terrace. The abrasive-accumulative levelling of the banks began later than that of the terrace, during the withdrawal of the ice and the rise in sea level. The start of the post-glaciation transgression apparently also marks the rolling of the rock fragments on the shelf, rock fragments of igneous and metamorphic rocks and sedimentary rocks of the diamictite type, of Paleogene age. Samples of these were brought up near the terrace on ~~the~~ Banana Bank (52).

A large and undoubtedly tectonic depression which extends along the ledge of the continental slope off Greenland, enters into the shelf where it joins the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise and divides the terrace into two parts. The terrace is considerably deformed. The northern part of the terrace is submerged more deeply, its outer margin is situated at a depth of 300-360 m, while the margin of the southern half of the terrace is situated at a depth of 250 m, i.e., the shift amplitude of the surface of the formerly undivided terrace on either side of the depression attains 50-110 m. The fact that the depression at the ledge of the continental slope is not compensated by sediments is evidence of recent or renewed movements in the area of the juncture of the ~~Greenland-Canada sill~~ Baffin-Greenland Rise and the Greenland shelf. The movement affected the adjacent part of the shelf and deformed the abrasion terrace on its margin and it also formed a ledge (fault) with a height of 500-600 m, which is now observable in the bottom relief and which separates the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise from the Greenland shelf. Thus it happened that during the levelling of the shelf by exogenous processes during post-glaciation time its relief was also rendered more complex by endogenous factors.

The post-glaciation uplift of the land and the sea level proceeded at a considerable rate, being retarded non-uniformly. The rate of the rise of the land (according to radiocarbon dating) in East Greenland and Labrador, 6,700-9,000 years ago, was about 6-9 meters per 100 years; during the next 3,000-4,000 years it dropped approximately to 0.6-0.9 meters per 100 years, and later to approximately 7 centimeters per 100 years (62, 67, 71). The rate of the rise of the sea level, 14,000-6,000 years ago, was one meter per 100 years. About 9,000 years ago, the sea level was 15 meters lower than now, and about 5,000-5,500 years ago, about 3-4 meters higher. The most recent investigations and calculations show that the maximum rise in sea level during post-glaciation time could scarcely have been more than 120-135 m (26, 57, 65), whereas ancient shore lines in glaciated regions are lifted to a height of 200-300 m, and sometimes more. Thus, during the general rise of the land and sea level, there occurred an uneven relative rise of the land in glaciated regions. This rise in the land, with a shelf that remained relatively stable, was bound to be reflected in the submarine relief, increasing its variety along the weakened fracture zone within the shelf.

One of the additional factors contributing to the greater contrast of movements between the rising land and the shelf appears to have been the loading effect of the sea-water stratum on the margin of the submerged land. No data exist as to the qualitative, let alone quantitative assessment of this effect, but we are justified in raising this question (35).

It is assumed that in order to attain an isostatic equilibrium there occurs, in the region of uplift, a spreading of subcrustal material (37), or else the uplift is compensated by an inflow, by a shift from the region of subsidence (41). At the same time the region of the shelf, during the rise of the land and the degradation of the icesheet, was subjected to the action of a new exogenous factor — marine transgression, caused by a rise in sea level. In other words, on the shelf the ice loading was replaced by water loading, which obviously must have a certain effect on the stabilization of the shelf relative to the rising land. The action of this loading must apparently continue until some compensation level is attained, and it must be determined by the degree to which the earth's crust is capable of adapting to new, changed conditions disturbing the previously existing state of isostatic equilibrium. The same type of effect is produced by the loading of fragmented material carried into the sea during the denudation of the rising land. The mechanism of this process is bound to be the same as with glacial loading.

We do not, unfortunately, possess sufficient reliable data on the minimum dimensions of an icesheet capable of effecting a depression in the earth's crust. Such an icesheet would presumably have a thickness of 1 km and a diameter of about 500 km (62). According to other data, even a glacier with a thickness of a few hundred meters produces excess stress in the earth's crust (9). With an ice density of 0.9 and a seawater density of 1.03, a 200-meter layer of shelf water must produce a load corresponding to a glacier with a thickness of about 230 m. Consequently, Weight of the shelf water together with that of the water on the continental slope adds to the influences affecting the various movements along the
land margin, especially where a dislocation zone already exists within 35
the shelf, and contribute to the rejuvenation of the submarine relief.

The post-glacial uplift of the coasts of North America and Greenland proceeded unevenly. In the Nova Scotia region it is weak. The zero isobase runs through the Nova Scotia Peninsula and the island of Newfoundland. On the coast of Labrador the uplift attains 100 m, decreasing toward the northeast of the peninsula. The uplift of Baffin Island appears to have been independent. The east coast of Greenland is raised more than the west coast (28). A certain connection is observable between the degree of uplift of the land and the depth of the shelf: the greater the height of the rise of the land block, the more depressed is the shelf and the greater the depth of the longitudinal depressions within the shelf. Lesser depths and smoother shapes characterize the depressions in the region of Nova Scotia and south and southeast of Newfoundland. The position of the shelf surface at approximately the same hypsometric level on either side of the transverse trenches of Cabot Strait and the Gulf of Maine points to a lengthy relatively stable condition of the region, even though it was subjected to an earthquake in 1929 whose epicentre was located in the upper part of the continental slope at Cabot Strait. The relative stability of this region is also confirmed by level observations (28, 44).

Therefore, the flooding of the shelf in this area is due mainly to a rise in sea level in post-glacial time.

More distinct are the depressions off Labrador, and even more so along the coast of Greenland. The great general depth of the shelf in these regions is apparently due to a conjugate, compensatory depression of the shelf relative to the glacio-isostatic rise of the land. The higher position of individual shelf blocks against the background of a general submergence is probably due to regional effects. Along the coast of Labrador a longitudinal depression is more distinct in the southern part of the shelf than in the northern one.

The Canadian Shield, which as a whole is of pre-Cambrian origin, consists of parts of different ages. The lesser variety in the northern part of the shelf is apparently due to uneven block movements of the Shield and the reduction in the rate of post-glacial uplift toward the northeast of the peninsula.

A highly broken-up relief is found on the shelf off the west and east coasts of southern Greenland. The narrow shelf at this part of

Greenland, cut off by the steep, stepped continental slope, was apparently subjected to heavy break-up during differentiated movements along the land-sea boundary. The contrasts of the tectonically caused break-up of the shelf may have been reinforced later on by glacio-isostatic movements of the coasts and shelf as well as by water and ice erosion. Later on, the freeing of the Greenland shelf from the ice mantle, which still covers the island, contributed to the preservation of the differentiated relief, large depressions, which are typical of the shelf and the continental slope off Greenland.

The transverse trenches of the shelf are mainly of tectonic origin. In the regions of Nova Scotia and Newfoundland their origin is connected with longitudinal and transverse fractures of the Paleozoic folded base. In the area of the Canadian-Greenland Shield, all large trenches (at Labrador along the extension of Hamilton Inlet and at 56° lat., on the West Greenland shelf at the bay of Julianehaab, etc.) are located at the extension of fjords laid down along terrestrial fracture lines, and their tectonic origin is also beyond doubt.

The large fractures on land are obviously older than the 36
longitudinal depression of the shelf and (many of them, at least) may be of Paleozoic age or older. For example, a fracture at 56° lat. in Labrador, associated with which is a large transverse trench in the shelf, divides rocks of the Canadian Shield that are of different age but on the whole pre-Cambrian. Small transverse trenches may be due to radial fractures, approximately of the same age as the longitudinal depression. The transverse trench of Disko Bay was apparently caused by fractures of Tertiary age. On the east coast of Greenland, one of the fjords laid down

along a tectonic valley extends onto the shelf in the shape of a longitudinal trench rather than a transverse one. We see here a situation opposite to the one noted in the region northeast of Newfoundland. Because of the relationship between the strike of the coast and the shelf off Newfoundland, longitudinal structures find their morphological expression in transverse features, whereas off Greenland, transverse structures are expressed longitudinally. This would seem to emphasize once more their relationship and tectonic nature, rather than the excavation of the trenches by glaciers. Ice scouring turned out to be merely superimposed on depressions created previously by other forces.

All transverse trenches on the shelf, regardless of age and structural characteristics, share morphological features: smoothed lateral slopes, gentle sills in their mouths at the shelf margin and deep basins where they join up with longitudinal trenches. The similar morphologies of transverse trenches indicate that similar factors were at work on them during Quaternary glaciation. The smoothed sides and bottoms of the trenches may have been scoured by the ice during a lowering of the sea level, when the trenches served as channels for the runoff and the meltwater from the icesheet, as may be seen in some parts of the Greenland coast at the present time. Flint (42), who considered the origin of the basins and sills in the marginal parts of terrestrial fjords, ascribes it to overdeepening of the bottom by glaciers. P. A. Kaplin (18) believes that the overdeepening of the fjord bottoms is mainly tectonic, being caused by faults along the coast during the free rise of the land relative to a stable shelf. It seems that both of these factors were at work on the shelf. The overdeepening of the bottom at the juncture of transverse and longitudinal trenches on the shelf could be due mainly to tectonically and glacio-isostatically conditioned movements along fractures on the margin of the submerged land. At the confluence of these trenches, formed before glaciation, more favorable circumstances arose for the accumulation of great ice thicknesses which, in turn, led to heavier scouring and, therefore, contributed to the overdeepening of the glacier beds.

Gentle sills at the mouths of transverse trenches also seem to represent traces of glacier action. They could have been formed where ice flows descending along the trenches reached greater depths at the shelf margin. This led to weaker scouring of the trench bottom, as the ends of the glaciers began to float and broke off, forming icebergs. At the same time there could occur the accumulation of detritus at the margin of the trenches. Beneath a thin layer of modern deposits on the sills we often find dark, dense clay, which has been determined as glacial (50). Thus the location of the sills may indicate approximately the outer boundary of the Quaternary icesheet.

Transverse trenches usually terminate at the margin of the shelf. Along the coasts of Labrador and Greenland, large trenches, often
in the shape of deep submarine canyons, extend also on the continental 37
slope. Their connection with the shelf trenches, laid down along fractures, clearly determines the primary-tectonic nature of these canyons (Fig. 5). Small canyons, furrows, and fissures cut up the slope along the southeastern extension of the Grand Bank. Their upper ends break up the margin of the bank surface. It is possible that they are predetermined by structural characteristics of the rocks that make up the shelf. This does not exclude the erosion of the canyons by glacial meltwater in the past,

with a lower sea level and suspension streams in a submarine position.

During post-glacial time, the large structurally produced forms of the shelf relief (morphostructures) turned out to be within the sphere of action of marine (exogenous) relief-forming processes. A migration of the zone of wave action during the post-glacial rise in sea level contributed to a certain abrasional-accumulative levelling of the relief of the submerged land margin. The degree of this levelling depended on the rate of land uplift (shelf submergence) and the sea level and, therefore, on the rate of shift in the wave-action zone, the resistance of bedrock, the presence of unconsolidated deposits, etc.

In the regions of Labrador, Baffin Island and Greenland, which experienced a considerable post-glacial rise of the land massifs, the abrasional-accumulative levelling combined with other exogenous relief-forming processes did not lead to a substantial change in the structurally conditioned relief features of the inner shelf. We note only a partial erosion at a certain level in small crests which add variety to the larger features of the submarine relief. Little abrasion is also evident in the structural relief of the bottom northeast of Newfoundland.

In the region of Nova Scotia the abrasional-accumulative levelling of the inner part of the relatively stable shelf is more distinct. The surfaces of the uplifts -- the banks -- situated in a longitudinal intra-shelf depression, are at approximately the same level as the surface of the outer parts of the shelf. This indicates their abrasional erosion during the rise in sea level and the flooding of the land margin in this region.

The fact that in some places small undulations are preserved on the bottom of the intra-shelf depression is due to their more rapid removal from the wave-action zone, and the accumulation of sediments only partially contributed to a levelling of the bottom.

Considerable abrasional-accumulative levelling occurred in the outer part of the shelf. The distinct margin of the shelf is apparently due to additional abrasional scouring of the shelf at a lower sea level. The flat surfaces of the bank-uplifts in the outer shelf (Grand Bank, Belle Isle, Northern Newfoundland Bank, banks of Nova Scotia and Greenland) also owe their levelling, without doubt, to the action of abrasional-accumulative agents. The typically flat surface is also found on the top of Flemish Cap, although this bank, as a whole, is dome-shaped. The fact that these processes were also at work in the Newfoundland area is indicated by the surface of the Grand Bank, which cleanly cuts off the tops of underwater canyons on the continental slope. Also of abrasive origin are the low ledges (5-15 m) at depths of 200, 250 and 300 m, that make up terraces on the shelf in the area of the banks of Belle Isle and Flemish Cap. They may contribute to the change in the rate of post-glacial rise in sea level. As the sea level rose, the shelf was levelled by abrasion near the structural uplifts 39
along the submarine land margin. The subsequent shift of the wave-action zone led to the erosion of the tops of these uplifts. The terraces on the surface of Belle Isle Bank on the side of a longitudinal trench indicate an ingression of the sea along the depressions in the shelf, while the bank could have risen in the shape of a low island. The deep present position of the abrasional ledges on the shelf may be due to its general subsidence, combined with the post-glacial rise of the land.

On the whole, the fairly level surface of the shelf is often differentiated by microrelief in the shape of narrow depressions, grooves, small hillocks and ridges of various orientation. Small, narrow grooves or furrows and depressions alternate with flat, level portions, whose surfaces cut off, as it were, the upper parts of the transverse profile of the negative features. Such a combination and distribution of microforms seems to emphasize once more the participation of abrasion in the levelling of the shelf surface. The hills and ridges, or at least some of them, were built up by the glacial action; others may represent abrasional remnants (2, 32). It is difficult to classify them on the basis of existing data.

The existence of fairly coarse-grained sediments — sand, sand ooze (coarse siltstone) — on the outer shelf points to continuing reworking of the glacial deposits on the shelf by waves and currents, and to a ceaseless levelling of its surface. That storm waves act to a depth of up to 100 m is indicated by the crushing of the shell valves in the shelf sediments.

Naturally, marine relief-forming processes act together, so that no distinct boundaries exist between morphosculptures of different origin. The existence of larger-grained sediments and the greater depth of their outer boundary at the shelf margin and on the upper part of the continental slope may be due to a certain influence of tidal and constant currents. Constant currents, which in the region of Labrador and Newfoundland have a speed of 18-33 cm/second, and at East Greenland 7-14 cm/second (5, 46), are capable of effecting considerable erosion and of removing fine-grained sediments to greater depths. The presence of oozy sand (coarse siltstone) on the ~~Greenland-Canadian sill~~ Baffin-Greenland Rise also indicates the influence of the Canadian current upon the top surface of the ~~sill.~~ rise. This natural process, it seems, is now beginning to be strengthened by human action, in the shape of intensive trawl fishing on the shelf. Direct observations with submarine instruments

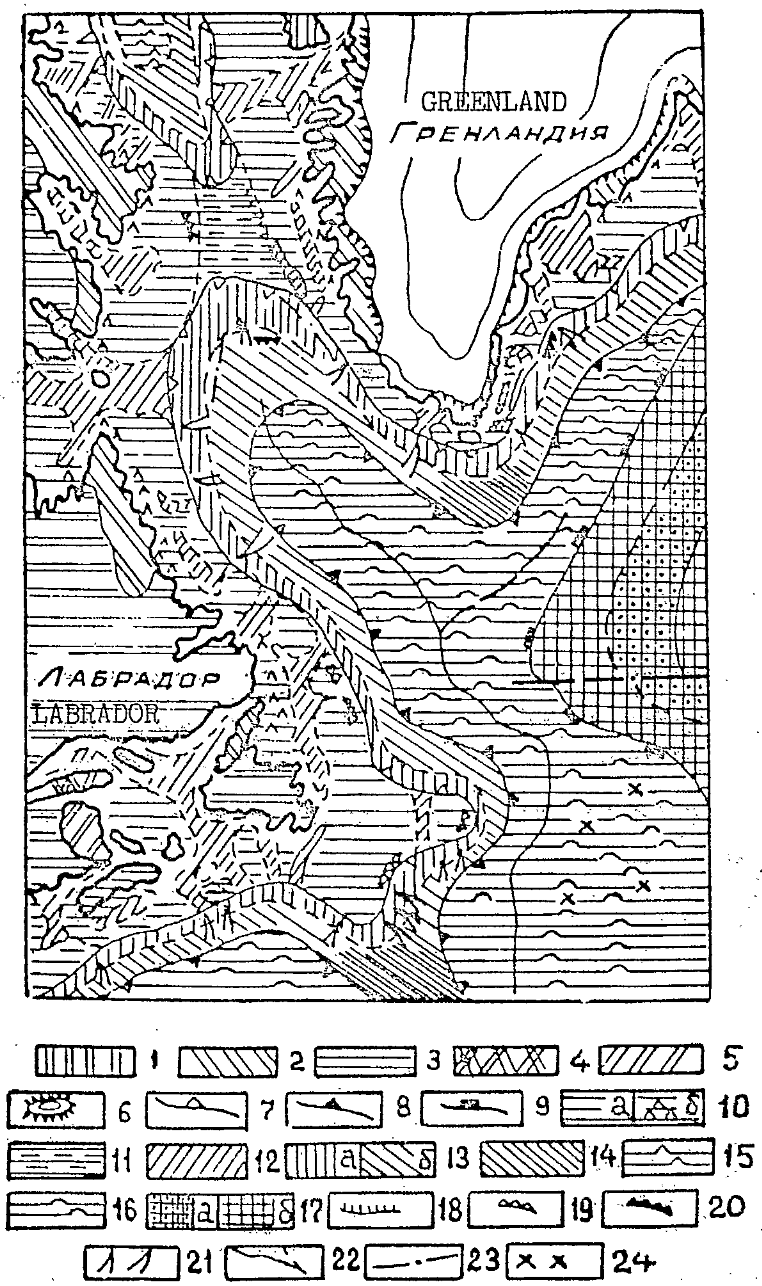

Fig. 5. Caption on page 35.

Caption for Fig. 5, page 34.

Geomorphological scheme of the Northwest Atlantic

Land: Morphostructures: 1 -- high lava plateau; 2 -- block ranges and highlands; 3 -- denudation plains and hills; 4 -- block-folded mountains of medium height; 5 -- stratified lowlands; 6 -- icesheet.

Sea bottom: Elements of geotecture: 7 -- boundary between submarine margin of continent and continental slope (shelf margin); 8 -- boundary between continental slope (including continental foot) and ocean bed; 9 -- boundary of Mid-Ocean Ridge. Morphostructures: 10 -- subhorizontal plains of the shelf existing in subsided denudational and glacial plains (a), including the inner shelf with rejuvenated relief (b); 11 -- ~~Greenland-Canadian~~ Baffin-Greenland ~~submarine sill~~ Rise; 12 -- longitudinal and transverse trenches and hollows in the shelf; 13 -- ledge of the continental slope (a) and continental foot (b); 14 -- block ranges; 15 -- basins in the zone of the continental slope; 16 -- subhorizontal abyssal ocean plains; 17 -- rift zone of the Mid-Atlantic Ridge (a) and its slopes (b). Individual features: 18 -- abrasional steps (terraces) ; 19 -- abrasional ledges; 20 -- tectonic ledges; 21 -- canyons on the continental slope; 22 -- Mid-Ocean Canyon; 23 -- depressions (axes of depressions); 24 -- seamounts.

of the action of bottom trawls show that they produce considerable bottom erosion. The mass of ~~friable~~ unconsolidated deposits stirred up by the trawls is further displaced by waves and currents. Even greater may be the effect of deep trawling on the continental slope, where the sediments are more fine-grained.

A considerable relief-forming role in the transformation of sculptural features is being played by tidal currents. This can be seen clearly in the Nova Scotia region, where in the Bay of Fundy the maximum height of the tide reaches 15-18 m. Georges Bank, situated on the outer part of the shelf, represents a barrier to the tidal waters entering the bays of Fundy and Maine. Sand ridges, which are typical relief features on this bank at depths up to 50-80 m, are drawn out in the direction of the tidal wave. The formation of these ridges is being ascribed to the working by tidal currents and waves of accumulations of glacial (water- 40
glacial) deposits on the bank. The speed of the tidal currents over the shallow portions of the bank averages 2-4 knots (1-2m/sec), but during hurricanes the current reaches speeds of up to 20 knots (59). The action of strong currents and storm waves effects a constant transformation and shifting of the sand ridges, which also contain deposits of gravel and pebbles (33). From surveys conducted at different times it has been established that during the last 25-28 years the ridges have been moved approximately 300 m to the west (66). The washing of the trench extending from the ~~Bay~~ Gulf of Maine and crossing the shelf by strong tidal currents is hindering the accumulation of fine sediments. The bottom and the sides of the trench are covered with gravel and pebble deposits with small boulders. This mantle of coarse deposits preserves the trench from heavy water erosion, but the tidal currents prevent the formation of an accumulative morphosculpture in the trench. The erosional action of the

tidal currents also produces the placement of the coarse gravel and pebble deposits in the narrows of Denmark Strait at the bottom of the valley between the Greenland and Iceland shelves (1, 25).

A quieter hydrodynamic environment, water circulation with reduced speed in the depressions within the shelf create conditions for the formation of morphosculptures of the accumulative type. The shelf trenches are filled with fine sediments, whose accumulation leads to the complete or partial obscuration of the originally uneven bottom. The bottom of the trenches in the East Greenland region is less levelled by accumulation; the trenches in the Labrador, Newfoundland and Nova Scotia regions are more levelled. Echo sounding in the Gulf of Maine often registers a "double bottom" -- lenses of unconsolidated deposits that fill out negative features in the submarine relief. The fine sediments in the trenches may be carried in either from the land or from deposits in the outer shelf. A part of these sediments settles within the shelf, another part is carried beyond the shelf to great depths and contributes to the accumulative levelling of the continental slope, its foot and the bottom of the ocean basin. Additional and, in some localities perhaps, predominant factors in the formation of the morphosculpture of the sea bottom at great depths outside the shelf are slumps or landslides of sediments and their removal by ~~suspension flows~~ turbidity currents. This is confirmed by the character of the bottom deposits at great depths, where we often observe the interbedding of coarse and fine sediments. In the area of the continental slope and its foot there originate inclined accumulative plains with various degrees of levelling. Distinctly observable is the fairly flat inclined plain on the continental slope in the area of the Northern Newfoundland Bank. Its inclination is 1-2^{o}. No such levelling is observed on the continental slope off Labrador and Greenland.

In the area of the continental slope there are usually preserved, along with accumulative levelling surfaces, large tectonic features of the original relief which, it seems, are not everywhere overlain by a mantle of unconsolidated sediments.

In the Labrador and Newfoundland basins abyssal plains are being created due to non-wave accumulation. Depending on the original configuration of the bottom, their relief is either hilly or almost completely level. The inclined plains of the continental foot and the abyssal plain of the Labrador Basin furnish one of the examples of non-correspondence between morphology and abyssal structures on the sea bottom. In respect of structure the inclined plains on the continental foot are situated in the 41
area of a trough in the crystalline foundation, filled with sediments (16, 43), while the abyssal plain of the Labrador Basin is formed on a buried mountain relief.

Development of the Northwest Atlantic Ocean Basin and Origin of the Shelf

The morphostructural characteristics of the continental shelf of the Northwest Atlantic show that the shelf represents a submarine part of the land and that its origin is due to the submergence of the land caused by the overriding action of tectonic forces during the deepening of the Atlantic Ocean Basin. Geophysical investigations in the Northwest Atlantic have established the structure of the earth's crust in the areas of the shelf, the continental slope and the ocean basin. Typical of the shelf is a continental type of crust. Crust thickness in the shelf is of the same order as on land; along the United States coast it amounts to 30-35 km. On the continental slope, toward the North American Basin, the thickness of the crust decreases and the granite layer gradually disappears. At a depth of 0.7-3 km the thickness of the crust amounts to 9-18 km. In the North American Basin, at a depth of 4 km, the thickness of the ocean crust is 4-10 km (11, 43, 56).

A distinction has been revealed between the structure of the crust in the southern and northern parts of the Northwest Atlantic Basin. North of the 50th parallel the thickness of the crust increases, and in the Labrador Basin it reaches 15 km (12). In the Labrador Basin, investigators have discovered a buried mountain range, which along the periphery of the basin is covered by a sedimentary stratum of 4-5 km, while in the axis of the basin it rises almost to the surface of the bottom (53).

It is noteworthy that the boundary between the bottom sections with different crustal structure appears to run along a latitudinal trough observable in the bottom relief at 52-53° lat., traceable from the margins of Caledonian and Hercynian folding in Ireland westward through the Mid-Atlantic Ridge approximately at 42°30' west longitude. The trough is more evident at the juncture of the Reykjanes and the North Atlantic ridges which represent parts of the Mid-Atlantic Ridge. The trough is determinable by the abyssal structure of the crust and an increase in the thickness of Quaternary deposits. The trough is a surface feature corresponding to a fault zone along whose axis the Reykjanes and North Atlantic ridges are displaced in relation to one another by approximately 370 km (21, 58).

On the American coast of the Atlantic Ocean the strike of the trough is marked by the fractures of the Newfoundland Appalachians and the fracture between the Canadian Shield and the Appalachian Caledonian rocks that divides the island of Newfoundland from the Labrador Peninsula. This fracture continues in the shape of a transverse trench on the Newfoundland shelf as well; this shelf forms a broad protrusion into the ocean. A small missing link of the trough would seem to be hidden in the depths of the Labrador Basin.

Northeast of the island of Newfoundland the Newfoundland Appalachians descend beneath the sea level. The position on the bottom of the Labrador Basin has not been established. The extension of the Appalachians should perhaps be sought not in the Caledonian rocks of Northeast Greenland but in the direction of their strike at the juncture of the North Atlantic and the Reykjanes ridges. Notable differences in the morphology and seismicity of these ridges (16, 70), their displacement along
a latitudinal fracture may indicate differences in the nature 42
and age of the ridges. At approximately the same latitude we note an eastward bend in the buried middle range of the Labrador Basin and perhaps its juncture with the Mid-Atlantic Ridge (30, 53). It is not excluded that in the past the area

of the juncture of the Reykjanes and North Atlantic ridges was a fairly complex mountain ~~node~~ nexus with varying ages.

At the same time a similarity has been established between the geological structure of Newfoundland on one side of the ocean and Scotland, the Hebrides and Ireland on the other (15, 61).

Thus the latitudinal trough extending between regions of Caledonian and Hercynian folding on opposite sides of the Atlantic appears to be an inherited structure that developed in the Paleozoic. What forces and when divided these regions which are at present separated by the ocean basin? Was it because of horizontal movements (drift), submergence of the land in the course of development, [sic] deepening of the Atlantic Ocean basin, or because of a combination of horizontal and vertical movements? The answer will probably be provided by future investigations.

An analysis of the geological history of North America and Europe during the Paleozoic points to the presence of continental links between them, to the existence of land in the northern part of the Atlantic. The ocean basin, as we know, intersects the continental structures of North America and Europe, and its age is established as Late Mesozoic-Cenozoic. The northern part of the ocean is the youngest, where the land was apparently preserved to the end of the Neogene (4, 15, 27, 31, 47, 49).

West of the ocean the spreading of the North American continent through the link-up of its pre-Cambrian core with Paleozoic land was replaced at the end of the Mesozoic by a process of break-up and submergence. The Triassic on the eastern coast of the continent is represented mainly by continental strata, the Lower Cretaceous sea occupied only the southern portion of the coast, but the Upper Cretaceous transgression was much more extensive (15). During the Cretaceous, it seems, Greenland began to separate from the continent (17, 19). The presence of Cretaceous marine deposits in the region of Disko Island, which overlie foundation rocks, shows that the Cretaceous sea extended northward between Labrador and Greenland where it apparently linked up with the waters of the Arctic Ocean and, along the weakened zone of the Canadian Shield in the area of Hudson Bay, it penetrated far south into the western part of the North American continent (28). During the Alpine tectogenesis there occurred the activation of the uplift of the Canadian-Greenland Shield, the rejuvenation of the Appalachians, the break-up of the Canadian Arctic Archipelago, which was undoubtedly accompanied by a subsidence in the area of the ocean basin. Considerable outpourings of basalt in Iceland, along the east and west coasts of Greenland and on the southeastern extremity of Baffin Island appear to have been the result of this process.

Geophysical and geomorphological data give evidence of fractures on the flooded margin of the land caused by the subsidence of the foundation, of dislocations of the flexure of the continental slope by faults. A series of structural terraces

and ledges are situated on the continental slope off the
east coast of the United States, where the slope surface in-
tersects Cretaceous and more recent strata gently inclined
toward the ocean (36, 43, 54). Differentiated movements in
the rigid structures of the Canadian-Greenland Shield were also
undoubtedly accompanied by series of large stepped faults and
lesser types of differentiations along the coasts of Labrador 43
and Greenland. Evidence of this may be found in the large
longitudinal depressions on the shelves. The Labrador shelf
is depressed along a fault line. Large depressions at the
shoulder of the continental slope off southwest Greenland and
Baffin Island, not filled by sediments, give evidence of
recent disjunctive dislocations in that region.

A latitudinal fracture between regions of Paleozoic
folding on opposite sides of the ocean may perhaps divide
parts of the North Atlantic of different age. South of the
latitudinal trough, in an area with a typically oceanic crust,
oceanic conditions apparently existed earlier than the subsidence
of the land to the north. The similarity between the marine,
littoral and continental pre-Paleogene faunas of Nova Scotia
and Newfoundland, on the one hand, and Ireland and Scotland, on
the other, points to possible migration paths of this fauna
along the southern coast of the North Atlantic land mass (15),
i.e., to a possible boundary of the land mass approximately
in the latitude of the trough. Remnants of this land mass may
perhaps be found in the chain of shallow sills between Greenland

and Iceland, Iceland and the British Isles (27, 48), the ~~submarine height of~~ Rockall bank etc. The absolute age of the granite in the Rockall bank ~~height~~ and the British Isles shows that they are coeval (50-60 million years, according to Miller) and belong to the Middle Tertiary, when this part of the Atlantic was apparently part of the European continent (21). Iceland may also be regarded as a part of the more extensive submerged land mass of the North Atlantic. The peculiar Icelandic crust, different both from the continental and the oceanic ones, may perhaps be due to its location in a seismically active zone, where the structures of submarine sills are torn apart by the Mid-Atlantic Ridge, and the transformation of the continental crust of the island base (48).

Some information as to the time of the separation of the land mass in the western and eastern parts of the North Atlantic may be obtained from biogeographical data, based on the analysis of the freshwater fishes of the river systems of Europe and North America. The similarity between families of freshwater and migrating fishes in both continents points to a faunal exchange between them. Such an exchange presupposes the existence of a perhaps not complete but direct contact between the river basins of North America and Europe. The area of contact between the river basins of the Paleo-Hudson and of the Paleo-Rhine could have been Iceland. Biographical /sic/ analysis shows that the contact between them continued to the end of the Miocene and the start of the Pliocene, when the subsidence of the land in this region separated the habitats of the freshwater fishes (22, 23).

The time of the deepening of the Labrador Basin may be determined approximately from the thickness of the sedimentary stratum. We know that the rate of sedimentation differs greatly from place to place and that it is usually higher near submerged land margins; it is also greater in respect of glacial and iceberg-type sediments than others. The average rate of sedimentation is 1-3 cm per 1,000 years (10), but in some places it greatly exceeds these averages. Along the coast of California the modern rate of sedimentation averages 2.6, and that of the late glacial ones, 16.9 cm per 1,000 years (68), i.e., it exceeds the modern by a factor of 6.5. In the North Atlantic we can observe 20 to 30 fluctuations in the rate of sedimentation, it varies from 1.4 to 41 cm per 1,000 years, and possibly even more (15, 55).

The accumulation of the thick stratum of sediments in the Labrador Basin apparently took place at a much higher
rate than in the North American Basin as a whole, where the 44
sedimentary stratum averages 1-1.5 km. During the Pleistocene the rate of sedimentation could have been much greater because of the removal of masses of ~~fragments~~ clastic material from Labrador and Greenland by continental ice and glacial waters and its deposition in the narrow space of the basin. During glacial time we note the intensive development of suspension ~~streams~~ currents which deposited thick beds of coarse-grained sediments. Undoubtedly, the runoff

of glacial meltwater contributed to the widespread development of ~~turbid streams~~ turbidity currents in the Labrador Basin and to its filling. Slides of ~~modern~~ recent sediments with a thickness of up to one meter, observable on the continental slope, may have been even more common during the past.

The rate of sedimentation was uneven, but if we assume an average rate of 30-40 cm per 1,000 years (0.3-0.4 mm per year), it follows that the subsidence of the basin bottom and the accumulation of 4 to 5 kilometers of sediments occupied 10 to 16 million years (Miocene-Pliocene). The reliability of this calculation is much reduced because of the lack of data on the actual rate of sedimentation in the Labrador Basin. If we also take into account the compacting of the sediments (10), we must assume that our figures are too low, and that the accumulation of the sedimentary stratum in the basin began much earlier.

In connection with the abyssal structure of the Labrador Basin revealed by geophysical investigations, our attention is drawn to the mid-ocean canyon which traverses the basin from north to south. An analysis of the morphostructural characteristics of the basin bottom permits the fairly reliable assumption that the origin of the canyon is connected with a submerged mountain relief (34). The central position of the canyon on the bottom corresponds to the position of the axial zone of a mountain range buried under the sediments. The canyon apparently follows one of the central intermountain valleys and is thus a surface reflection, on the modern bottom, of a nearly filled valley in the buried mountain range. Its preservation on the basin bottom is apparently due to the action of suspension ~~streams~~ currents. Information on similar morphostructural features of canyons in the North American Basin, where geophysical investigations have revealed a broken relief hidden under sediments (43), confirm our theory concerning the origin of the mid-ocean canyon in the Labrador Basin.

* * *

The modern submarine relief of the Northwest Atlantic represents a certain stage in the development of the continental shelf, the continental slope and the bottom of the ocean basin. Quaternary glaciation and post-glaciation rise of the land have left a substantial imprint upon the morphostructural appearance of the shelf in this region. The activity of exogenous relief-forming processes during post-glaciation time did not lead to the destruction of the morphostructural characteristics of the continental shelf, which indicate a genetic link between land and shelf or which originated during its formation. With the slow, mainly positive movements in the region of the North American Platform and associated movements of the submarine margin of the land, with a constant activity of the ocean, the development of the bottom relief of the Northwest Atlantic is still continuing.

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