ISSN 0016-8521, Geotectonics, 2021, Vol. 55, No. 2, pp. 161–178. © Pleiades Publishing, Inc., 2021.
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Methods for Medium-Scale Tectonic Mapping of Deep Ocean Areas

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Received May 13, 2020; revised August 26, 2020; accepted January 28, 2021

Abstract—In our overview, we describe the evolution of methods and approaches for medium-scale tectonic mapping of deep ocean areas at scales from 1 : 1000000 to 1 : 15000000 and smaller, which is a synthesis of data on the structure of the bottom and a theoretical geodynamic model that interprets the genesis of the observed structures. Changes in the content of map legends are shown depending on the instrumental level of research and theory of tectogenesis to the level developed for land tectonics. Until 1970, the development of tectonic ocean mapping followed the path of direct convergence of the composition of map legends with their land counterparts, since data were interpreted based on fixism theory. When the ideas of mobilism were formed in the theory, the content of ocean maps acquired tectonic elements that differ from land, peculiar only to oceans. By 1970, extensive geological and geophysical data and their interpretation based on plate tectonics finally resulted in a specific tectonic legend for oceans. Tectonic maps were constructed with a new set of legend elements for all oceans, which were part of general tectonic maps of the framing of continents. The age gradation of the oceanic basement was created, based on the indexation of linear magnetic anomalies and the primary classification of younger intraplate structures overprinted on the basement. The use of satellite altimetry data, which has dense and uniform coverage at medium scales, gave new impetus for mapping the ocean floor and basement structures, even in areas where they are overdraped by sedimentary cover and are not highlighted in the ocean floor relief. This led to new-generation maps with a no less reliable topographic basis than spatially nonuniform echosounding. At the end of the 1980s, there began a fundamentally new stage of accumulation of instrumental measurement data and attempts to rationally adapt them into a theoretical geodynamic model. In the structure of oceanic crust, previously unknown tectonic elements were identified that had not been recorded during nonuniform shipboard surveys. New tectonic elements, established according to modern data, received a rational geodynamic interpretation using plate tectonics theory, assuming the block and tectonically stratified structure of moving plates. New tectonic maps and reference data are so saturated with information that it is necessary to move from small scales to 1 : 10000000 to display the details of the topographic bases on which they were interpreted. In our review, we address the unsolved problems that currently arise in compiling medium-scale tectonic maps of deep ocean areas, which are the structural features of intraplate deformation and magmatic structures.

Keywords: tectonic map, ocean floor, topography, geophysical fields, sedimentary cover, basalt basement age, intraplate deformations, tectonic elements

DOI: 10.1134/S0016852121020096

INTRODUCTION

The deep-water part of oceans, excluding the shelf and continental slope, makes up about 60% of the Earth's surface and is its least studied part. Its research differs from onshore work by the prevalence of remote geophysical methods over direct bottom probing and drilling. A specific feature of offshore operations is that cost-intensive research methods focus on key seafloor morphostructures (mid-ocean ridges, aseismic uplifts, etc.), which are hundreds and sometimes thousands of kilometers apart. This specific feature leads to the fact that the structure of the seafloor space between these morphostructures in a water area is substantiated solely by geophysical data used for interpolating between objects that have been studied directly. In addition, the extent of knowledge about the water area using traditional methods—bathymetry, seismic survey, gravimetry, magnetic surveys, etc.—carried out aboard ships is also nonuniform. The largest array of deep-sea data consists of bathymetric seafloor measurements, and for a long time the topography was the basis for identifying and interpreting the genesis of tectonic elements of oceanic structures. The explosive growth of marine research after World War II, in addition to an increased extent of knowledge, resulted in new research methods and tectonic concepts that explain the genesis of the identified structures and their deep structure. This gave impetus to develop tectonic seafloor mapping, which introduced well-substantiated new tectonic elements into map use, followed by a theoretical concept adequate to the facts.

Satellite methods since the late 1980s, providing uniform coverage and making it possible to generate maps at scales up to 1 : 1000000, made it possible to extend the interpretation of tectonic elements from areas with good on-board exploration to the entire water area, which was a breakthrough in marine tectonic mapping. Another breakthrough technology was multi-beam echo sounder systems, which make it possible to obtain data with a detail of 1 : 100000 and larger in the case of bottom surveys, and, accordingly, to create tectonic maps of these scales. However, at present, the extent of study by this type of survey is comparable to that of bottom probing; it only covers local objects in the tens or first hundreds of kilometers and cannot be used to create a uniform topographic basis for a tectonic map of such a large scale for the entire ocean.

This review focuses on methods for compiling medium-scale tectonic maps of the ocean: from a scale of 1 : 1000000 to 1 : 15000000 and smaller. Available data at the present stage make it possible to determine and substantiate new tectonic elements of ocean structures in addition to the classical set used in the 20th century. These elements have been confirmed in local detailed surveys and, using satellite data, can be traced to regions of the water area where detailed onboard surveys have not been conducted. In the first decades of the 21st century, interpretations of the tectonic elements of the ocean began to appear, carried out by lineament analysis of satellite data, the results of which in most cases have been confirmed by onboard studies. However, for different tectonic models, these results give rise to different interpretations of the tectonic structure of the ocean floor.

Another problem requiring a well-substantiated development of tectonic maps of the oceans is the age factor. Reconstructed from data on linear magnetic anomalies and drilling of rocks of a basement that formed from spreading accretion, the age structure of the ocean floor has a more or less monotonically increasing character from the axis of a mid-ocean ridge to the margins. However, this pattern is disrupted by overprinted volcanic edifices younger in age than the basement. In addition, in a number of regions, intraplate deformation structures have been identified, which were also overprinted on the primary basement, but without direct data, they show a significant scatter in formation time estimates. The development of a modified age legend associated with the age of spreading based to magnetic data and the compilation of tectonic maps of oceans with this information is a promising direction for this type of mapping. Account for the age determinations for overprinted structures and information on the distribution of the thickness of the sedimentary cover increases the information saturation of the maps, which makes it necessary to increase the scale of tectonic maps of oceans to 1 : 10000000, bringing it to the detail of GEBCO relief maps as of the beginning of the 2000s. In addition to the historical aspect, this paper analyzes the paths for further development of tectonic ocean floor mapping at this large-scale level.

SMALL-SCALE MAPPING BEFORE 1970

Tectonic maps, in Yu.M. Pushcharovsky's definition [18], depict structures of the Earth's crust and natural combinations thereof, or, equivalently, structural forms and tectonic zones of different orders and properties. This is a reflection of the structure, movements, and deformations of the lithosphere and its development in relation to the evolution of the Earth.

Tectonic land mapping developed with the study of the geology of continents and individual regions. In the middle of the 20th century, the transition from small-scale schemes to survey and regional tectonic mapping occurred largely owing to the works of Soviet geologists N.S. Shatsky, A.A. Bogdanov, A.L. Yanshin, and other researchers. Starting with the "Tectonic Scheme of the USSR" [3] and "Tectonic Map of the USSR and Neighboring Countries" [26], the basis of domestic and foreign maps of individual countries and regions was the historical–geological principle, and the most expressive means of cartography was color coding of tectonic elements, which characterized their age. All maps were based on the geosynclinal concept, within which two complexes were distinguished: geosynclinal and platform. The maps used color to indicate the ages of folding and formation of continental crust.

The lack of data on ocean floor geology led to selection of tectonic elements based on bathymetric mapping and scant geophysical data. Bathymetric mapping began to develop actively after the Second World War with the introduction of echosounder recorders for scientific research. The previously existing bathymetric maps were based on point measurements, the number of which, e.g., in the third edition of the international General Bathymetric Chart of the Oceans (GEBCO) reached 300000. Owing to these works, the main elements of the structure of the ocean floor—continental slopes, ridges, and basins—were specified. The tectonic nature of these morphological elements was explained by various researchers in accordance with their theoretical concepts. An overview of these concepts for the Atlantic Ocean, the most extensively explored, is given [12], which were reduced to two main theories: mobilism and fixism, reflected in tectonic schemes.

Despite the increase in the number of expeditions, research was carried out mainly in the northern hemisphere, and the general study of the ocean floor remained very insignificant. The third edition of GEBCO spanned from 1935 to 1953; it was discontinued during the Second World War, and was obsolete as soon it was published. In the fourth edition, from 1958 to 1970, only six out of 24 pages were published, and

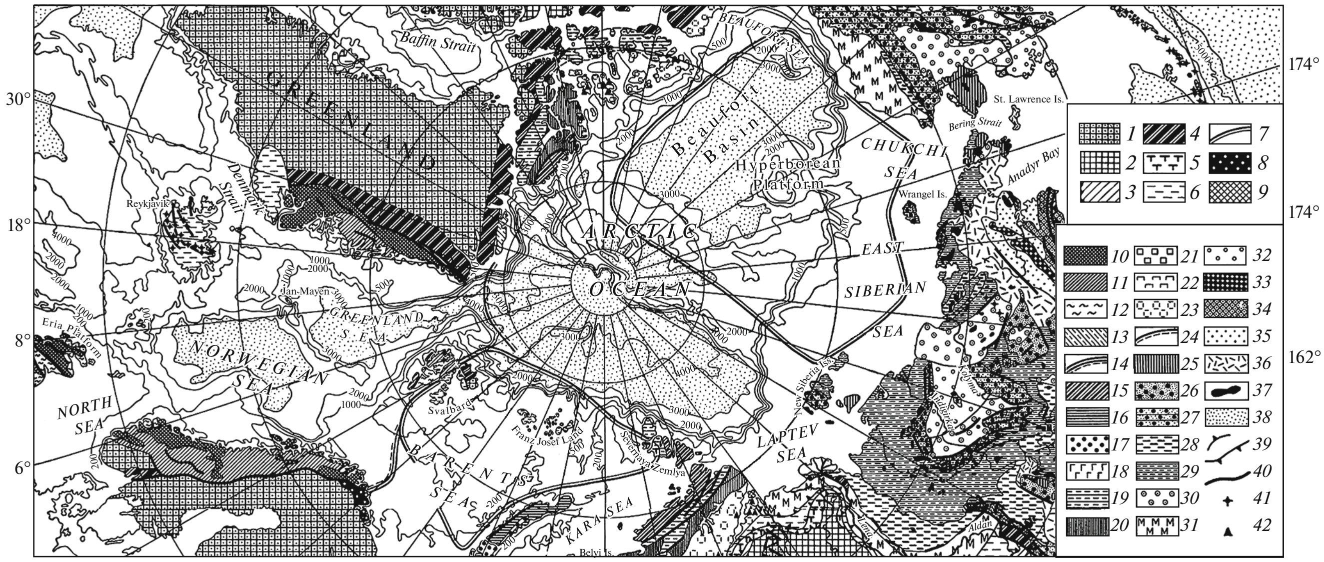

Fig. 1. Fragment of schematized tectonic map of Arctic (after [17]). *1*, Highs in the folded base of ancient platforms. Platform cover; *2*, thickness up to 2000 m; *3*, thickness over 2000 m; *4*, without separation by thickness; *5*, Middle and Upper Paleozoic; *6*, Mesozoic; *7*, inferred boundaries of ancient platforms in water areas; *8–9*, areas of Baikalian folding: *8*, Precambrian folded complexes; *9*, platform cover of Epiriphean platforms; *10–14*, areas of Caledonian folding: *10*, highs in pre-Riphean folded basement and lower structural layer; *11*, middle structural stage; *12*, upper structural stage; *13*, damping zones the Caledonides; *14*, inferred Caledonian boundaries in water areas; *15–16*, Hercynian fold zones; *15*, highs of pre-Riphean folded basement; *16*, lower and middle structural stages; *17–18*, upper structural stage: *17,* inner basins; *18*, foredeeps; *19–20*, damping zones of Hercynides and similar formations: *19*, lower and middle structural stages; *20*, upper structural stage; *21–24*, platform cover on Epipaleozoic platforms: *21*, thickness up to 3000 m; *22*, thickness over 3000 m; *23,* cover without division by thickness; *24,* inferred boundaries of Hercynides in water areas; *25–27*, Mesozoic fold zones: *25*, folded rocks of Precambrian; *26*, with platform cover of Paleozoic; *27*, folded, but not geosynclinal rocks of Lower and Middle Paleozoic; *28–29*, lower structural stage: *28*, lower substage; *29*, middle and upper substage; *30–32*, upper structural stage: *30*, inner basins; *31*, foredeeps, *32*, inner Cenozoic basins; *33–36*, Kamchatka fold zones: *33*, highs in Precambrian and Paleozoic folded basement and lower structural stage; *34*, middle structural stage; *35*, upper structural stage; *36*, volcanic complex of Cenozoic marginal fold belt; *37*, Mesozoic and Cenozoic granitoids; *38*, areas of large overprinted subsidence (deep-sea basins); *39*, contours of large tectonic structures; *40*, faults; *41*, volcanoes; *42*, salt domes.

publication was discontinued because it did not meet the requests of oceanographers and geologists. The creation of a new bathymetric map of the World Ocean and the basis for geological-geophysical and oceanographic studies was the updated task of the GEBCO program in 1973, which combined the efforts of the scientific community and hydrographic services represented by the Intergovernmental Oceanographic Commission of UNESCO (Paris, France) and the International Hydrographic Organization (Monaco).

In the 1960s, data on individual areas of the ocean were accumulated and regional maps appeared. A significant step in understanding of the ocean floor was the publication of the book by B. Hazen, M. Tharp, and M. Ewing "The Atlantic Ocean Floor" in 1959 [31] (its Russian translation was published in 1962), which included a physiographic map. In addition to the vast amount of material it summarized, the first such visual representation of the complexity and diversity of the ocean floor relief gave a powerful impetus to further research and attempts to explain the structure of the Earth's crust.

Until the early 1960s, most tectonic maps in oceanic areas showed only bathymetry, e.g., the "International Tectonic Map of Europe at a scale of 1 : 2500000" (edited by N.S. Shatsky, G. Shtille, A.A. Bogdanov, and F. Blondel [15]), "Tectonic Map of Europe" (edited by A.L. Yanshin [24]), as well as the 1964 edition "Physico-Geographical Atlas of the World." Tectonic survey maps, including both continental and oceanic spaces, appear for individual oceans, primarily, the Arctic Ocean.

In 1959 at the Geological Institute of the USSR Academy of Sciences (Moscow, USSR), a tectonic map of the Arctic was compiled, edited by N.S. Shatsky, in a polar cartographic projection at a scale of 1 : 7000000. This scale made it possible to present the structural features of crust in the Arctic in much greater detail. Yu.M. Pushcharovsky, presenting this map at the general assembly of the USSR Academy of Sciences, published together with a report on the tectonic scheme, noted the great importance of data on the bottom relief of marine and oceanic spaces for understanding the structure of the crust in the Arctic [17] (Fig. 1). One of the most important achievements in this area was Soviet researchers' discovery the underwater Lomonosov Ridge, shown on the newest bathymetric map of the Arctic, created under the supervision of A.F. Tresh-

Fig. 2. Fragment of Tectonic Map of Arctic (after [4]). *I*, plates with nonuniformly developed Mesozoic–Cenozoic cover; *II*, plates with predominantly widespread Meso–Cenozoic cover; *III*, Archean and Proterozoic fold systems; *IV*, Baikalides; *V*, Caledonians; *VI*, Hercynides; *VII*, Late Hercynides; *VIII*, Mesozoides; *IX*, Alpides (modern mature geosynclines); *X*, parageosynchronous basins and troughs; *XI*, foredeeps; *XII*, Greenland–Okhotsk volcanic belt; *XIII*, oceanic trenches; *XIV*, oceanic troughs; *XV*, mid-ocean ridges and rises; *XVI*, island arcs; *XVII,* oceanic troughs; *XVIII*, regional neotectonic fault zones.

nikov in 1960, which became the topographic basis for tectonic map [17], which distinguishes, against the bathymetry in the polar basin, the boundaries of ancient platforms and areas of large overprinted subsidences (deep-water basins).

In 1964, the "Tectonic Map of the Arctic and Subarctic" on a scale of 1 : 5000000 was published (edited by I.P. Atlasov [4]) (Fig. 2). For the first time, an attempt was made to depict the tectonic structures of the land, shelf, and ocean floor in a single system of conventional notation and similar degree of detail. To interpret the tectonic structures of the ocean floor in the map [4], the "Geomorphological Map of the Arctic Ocean" on a scale of 1 : 5000000 was used, compiled by V.D. Diebner, J. Gakkel, V.M. Litvin, V.T. Martynov, and N.D. Shurgaeva. In compiling the map, the geophysical data available by 1963 were used, as well as the results of studying coarse-grained material recovered from different seafloors. The map is based on the hypothesis of the genesis of structural forms of the ocean floor resulting from oceanization of the continental crust. Accordingly, two genetic series of structures were distinguished: continental and oceanic, as well as a group of parageosynclinal basins of intermediate genesis [4].

In the area of the continental crust, which includes most of the Arctic and Subarctic, fold systems, modern geosynclines, and parageosynclines are distinguished. The former include, e.g., the Caledonian fold structures of the Lomonosov and Mendeleev ridges. Parts of the shelfs (of the Barents, Kara, East Siberian, and Chukchi seas), together with the adjacent parts of continents, are separated into plates, with predominant plunging movements in the Mesozoic and Cenozoic. Parageosynclinal basins with prolonged and intense subsidence include the Canadian–Beaufort and Mackenzie. Island arcs and associated oceanic trenches (Aleutian, Kuril) are attributed to young geosynclines. In the spreading area of oceanic crust, mid-ocean ridges are shown, which formed in association with deep-seated faults and Neogene–Anthropogenic volcanism, and oceanic basins formed as a result of the widest manifestation of oceanization (Labrador, Greenland, Lofoten, Amundsen, and Nansen basins). Oceanic trenches (Baffin, Marvin, Lena, Iceland–Greenland, Irish, Faroe–Shetland, St. Anne, TINRO) are distinguished as a separate group of structures.

In the later "Tectonic Map of the Earth's Polar Regions" (edited by B.Kh. Egiazarov, I.P. Atlasov, and M.G. Ravich [9]), tectonic subdivisions in the nomenclature are divided into three categories:

• platforms and mid-ocean massifs, including:

—fold-basement highs (shields),

—subgeoanticlinal plates in the Mesozoic and Cenozoic,

—coeval subgeosynclinal plates;

• structures of intermediate significance and tectonic activation, including:

—pericratonic, marginal, and foothill troughs,

—parageosynclines,

—zones of active effusive magmatism,

—fault zones along the margins of oceanic troughs;

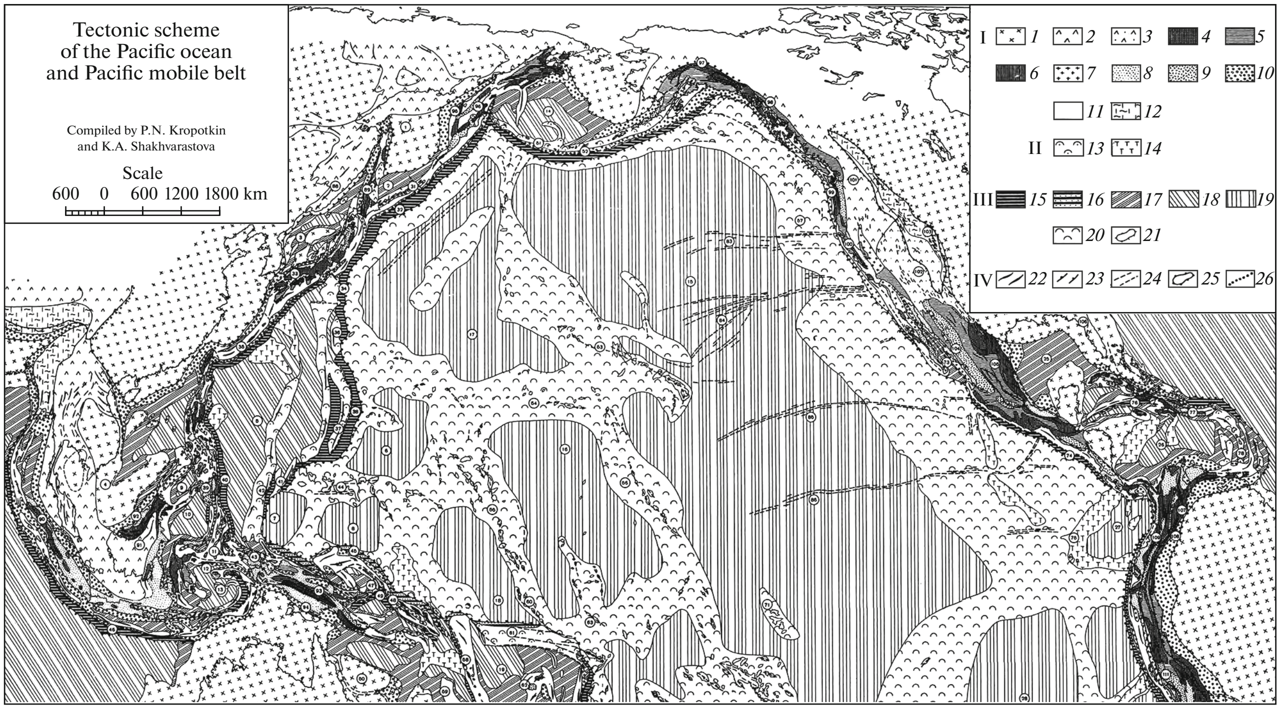

Fig. 3. Fragment of Tectonic Scheme of Pacific Ocean and Pacific Ocean Mobile Belt (after [11]). Notation: I, areas with continental crust; II, areas with unexplained structure or transitional type of crust; III, areas with oceanic crust; IV, tectonic dislocations and inferred character of deep movements. *1–3*, zones of early consolidation: *1*, Precambrian and Paleozoic platforms and massifs; *2*, Mesozoic fold zones; *3*, zones of Paleozoic and Mesozoic consolidation are partially reworked; *4–7*, Cenozoic fold and geosyncline zones of Pacific mobile belt: *4*, outcrops of Precambrian and Lower Paleozoic metamorphic basement and lower substage of lower structural stage; *5*, upper stage of lower structural stage (marine sediments of Triassic, Jurassic, Lower Cretaceous, and Mesozoic granitoids); *6*, middle structural stage (Upper Cretaceous–Paleogene marine and continental deposits); *7*, granitoids of middle stage of development (Upper Cretaceous, Paleogene); *8*, *9*, upper structural stage, including: *8*, marine sediments of Neogene, partly of Paleogene and Quaternary system and continental Tertiary sediments of intermontane troughs and grabens; *9*, thick Cenozoic volcanic complexes, mainly of the Neogene and Quaternary systems; *10*, Upper Neogene and Quaternary undislocated deposits of overprinted basins, Cenozoic deposits of foredeeps and geosynclinal troughs, filled with sequences of Cenozoic deposits and not yet involved in uplift; *11*, geoanticlinal uplifts in water areas and small islands involved in Cenozoic folding; *12*, Upper Cretaceous and Cenozoic fold zones, not subdivided into structural levels; *13–14,* zones with unexplained structure or transitional type of crust: *13*, geoanticlinal uplifts of volcanic island arcs; *14*, underwater plateaus and mountains, possibly representing subsided sections of continental platforms; *15–18*, areas with oceanic crust within Pacific Mobile Belt, Atlantic Ocean, and Indian Ocean: *15*, deep trenches along periphery of oceanic trenches; *16*, analogs of peripheral trenches with depths of 4–5 km; *17*, basins and wide troughs with suboceanic crust (basalt and thick sediments) with a depth of 2–4 km, formed in the Mesozoic and Cenozoic; *18*, basins with oceanic crust (usually deeper than 4 km), formed in Mesozoic and Cenozoic; *19–21*, areas with oceanic crust within the Pre-Mesozoic inner part of the Pacific Ocean: *19*, basins with depth of more than 4–5 km with relatively thin basalt crust (3–10 km); *20*, oceanic ridges and rises with basalt crust with increased thickness (7–20 km); *21*, elevations of volcanic origin, above 2 km isobath; *22–26*, tectonic dislocations and inferred character of deep movements: *22*, axes of anticlines, anticlinoria, and geoanticlinal uplifts; *23*, thrusts, reverse faults, and nappes; *24*, faults (strike-slip, normal, and reverse), crush zones, and shear zones; *25*, areas with doubled crustal thickness (60–80 km); *26*, boundary of Pacific mobile belt.

• oceanic structures, where the following are distinguished:

—oceanic protrusions,

—mid-ocean rises or rift zones of volcano-tectonic highs (volcanoria),

—trenches.

Of these, the first two categories are distinguished both on shelfs and on the ocean floor. In particular, plates on the Post-Baikal folded basement are shown on the underwater Lomonosov Ridge and the North Plateau. Here, as well as in the axial parts of the mid-ocean ridge, highs on the surface of the Caledonian folded basement are shown.

In 1964 P.N. Kropotkin, K.A. Shakhvarstova, and N.A. Fedorov compiled the "Tectonic Map of the Pacific Ocean and the Pacific Mobile Belt" on a scale of 1 : 15000000, as part of the monograph *Geological Structure of the Pacific Mobile Belt* [11] (Fig. 3). The bathymetric basis for this map was 1960s relief maps of the Pacific Ocean floor compiled by G. Menard, G.B. Udintsev, and J. Mammeriks, as well as certain geophysical data with a tectonic interpretation. On the map, the water area of the Pacific Ocean and adjacent continental areas are subdivided into three categories of areas based on types of crust:

—continental;

—undetermined structure or transitional;

— oceanic.

Areas with continental crust including areas of Cenozoic folding and geosynclines of the Pacific Mobile Belt were further divided based on the age of folding [11].

In their monograph, P.N. Kropotkin and K.A. Shakhvarstov note [11] that the basic principles of tectonic zoning of the Pacific region adopted in compiling the map are a further development of the ideas of A.D. Arkhangelsky and N.S. Shatsky and published by the former in 1941.

A.D. Arkhangelsky's map distinguished the following in the Pacific Ocean:

—platform areas in its deep-water parts (Northwest, Northeast, Central, Marshall, Southwest, etc.);

—analogs of young folded mountain structures on islands and underwater ridges separating these platforms (Hawaiian, Mid-Pacific, Marshall, Tuamotu, etc.);

—deep-water trenches along the periphery of the ocean.

P.N. Kropotkin, K.A. Shakhvarstova, and N.A. Fedorov [10] preserved this main tectonic zoning on their map. Basins (oceanic plates or platforms) and elevations (marginal rises) are shown within the Pacific Ocean; they adjoin deep trenches from the ocean side (Japan–Kuril rise, Aleutian rise, etc.), as well as underwater ridges separating the basins from one another. In their publication, the authors hew to the opinion on the antiquity (primacy) of the Pacific Ocean and at least the Upper Proterozoic age of the Pacific Basin. Note that the ridges on the Pacific Ocean floor are shown with one sign, without distinguishing the East Pacific Rise as a link in the mid-ocean ridge system. However, P.N. Kropotkin et al. [10] mention in the footnotes G. Menard, J. Wilson, and R. Dietz' hypothesis about the young age of the southeastern Pacific Ocean, on both sides adjoining the South Pacific and East Pacific rise, i.e., a continuation of the mid-ocean ridge here.

The structural forms of the floors of the Pacific, Arctic, and Indian oceans in areas adjacent to Eurasia were identified and categorized in compiling the "Tectonic Map of Eurasia" at a scale of 1 : 5000000 (edited by A.L. Yanshin with an explanatory note to it [33]) (Fig. 4). A.L. Yanshin and G.B. Udintsev's classification was based on the historical–geological principle.

The three most important types of tectonic regions, differing in the geological history of their evolution, were shown in the seas and oceans washing Eurasia development [33]:

—the underwater parts of continental structures, represented by areas of pre-Cenozoic folding of different age;

—Cenozoic fold and geosynclinal zones that had recently completed, were completing, or continuing geosynclinal development. This type of regions includes the underwater parts of the Alpine and Pacific (Cenozoic) belts with their modern geosynclinal basins, troughs, and fold structures;

—Areas of ancient and young oceanic platforms (thalassocratons), which arose in different periods of the Paleozoic and Mesozoic as a result of subsidence of former continental structures. The problematic Eria, Barents Sea, and Hyperborean platforms are classified as ancient platforms. At the same time, the Hyperborean and, partly, the Barents Sea platforms intersect within their boundaries with the next gradation of tectonic regions—young oceanic platforms. Thus, the Beaufort Basin (oceanic plate) and Mendeleev Ridge (arched oceanic rise) are simultaneously parts of the young Arctic Ocean thalassocraton and the ancient Hyperborean Platform [33].

MEDIUM-SCALE MAPPING AFTER 1970

By the early 1970s, a large dataset was compiled, acquired under the International Geophysical Year (1958) by all countries participating in this project. As a result, in 1970, the "Tectonic Map of the Pacific Segment of the Earth" was compiled, edited by Yu.M. Pushcharovsky and G.B. Udintsev [18, 27, 29]. For this project, seafloor survey materials obtained as a result of international exchange were generalized, including echosounding, continuous seismic profiling, gravimetry and magnetic measurements, seafloor sediment and bedrock probing, seafloor photography, and much more. A distinctive feature of this map was the filling of the space of the deep ocean with new tectonic elements framed by continental tectonic structures. The main informational layer that formed the picture of oceanic structures was the seafloor topography, which, after geomorphological generalization of the results, made it possible to construct a topographic basis on a scale of 1 : 10000000 for the entire water area. An equally important aspect was that this basis was structurally interpreted using the mobilist geodynamic model, which made it possible to adapt and rationally explain many bottom structures and substantiate the introduction of new tectonic elements into the legend.

Together with the data on the relief [8, 38], plate tectonic theory explained the configuration of anomalous components of the gravity and magnetic fields [6, 54], the distribution of seismicity, the sedimentary cover, seismic wave velocities in the consolidated crust and upper mantle, the geochemistry of the bedrock, and the age structure of the spreading basement, confirmed by drilling. The plate movement mechanism was based on thermal mantle convection [32, 45], which in the first approximation yielded a consistent correlation of all geological and geophysical data. Of particular interest are the generalizations of the

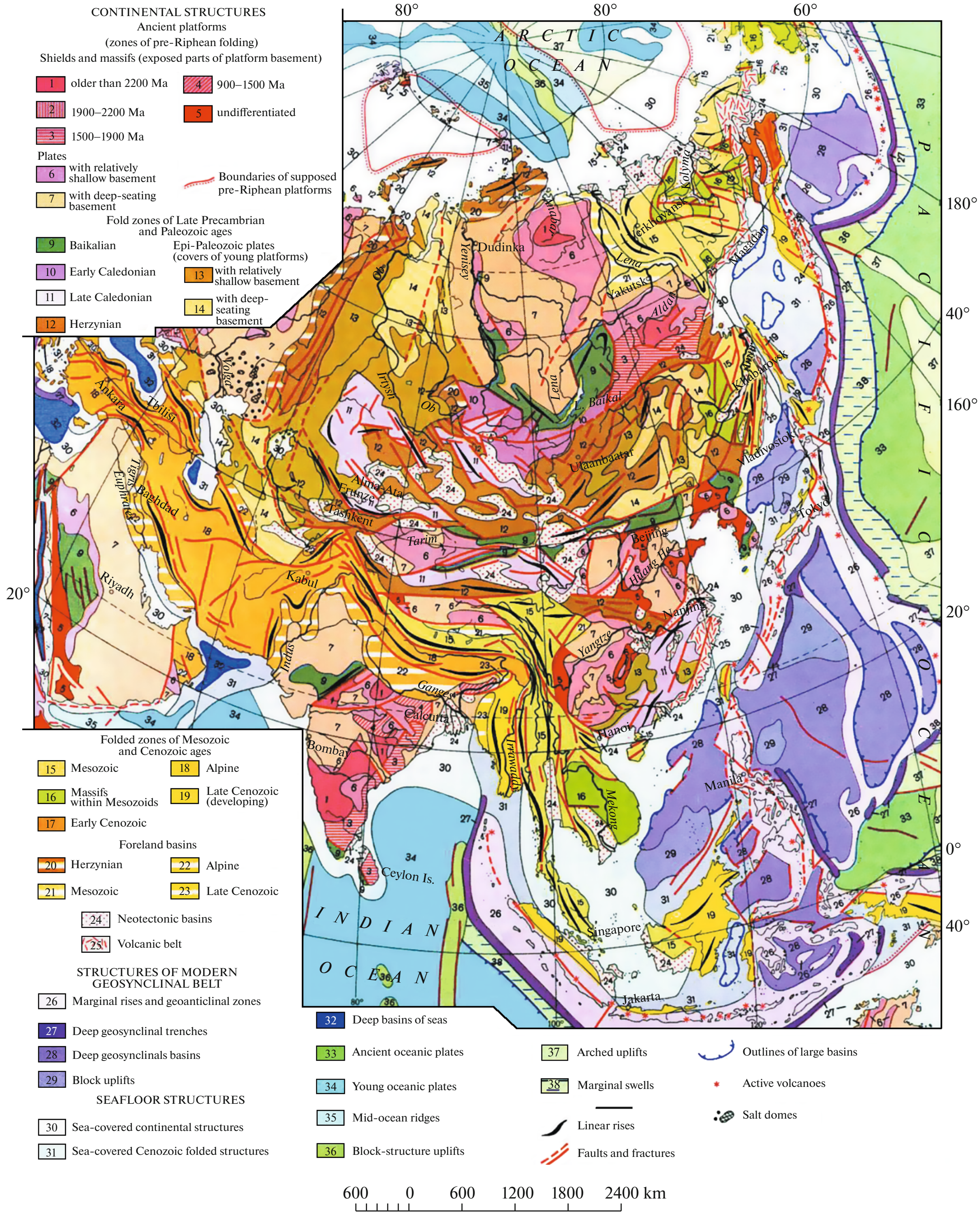

Fig. 4. Adaptation of the tectonic map of Eurasia with scale of 1 : 5000000 [33] to scale of 1 : 60000000 for Great Soviet Encyclopedia [5].

bathymetry data by B. Hazen et al. [44]. The regular set of structural terms was augmented by such concepts as mid-ocean rift and transform faults [56], which were the structural expression of ocean formation processes occurring along divergent plate boundaries. The rest of the plate space was considered rigid [16], with sediments gradually accumulating on the spreading basement with increasing age.

The "Tectonic Map of the Pacific Segment of the Earth" [27], a fragment of which is shown in Supplement 1 (Part 1), was compiled taking into account the new elements and is a synthesis of continental and oceanic tectonic structures, including transition zones. Structural elements along the Mid-Ocean Ridge (MOR) is represented by two groups: the ridge structures and the orthogonal fault zones that interrupt it, including:

—rift axes;

—uplifts along active zones (analogous to the ridge flank concept);

—flow lines along active zones;

—fracture and suture zones displacing active zones;

—normal, thrust, and transform faults.

Outside the MOR, island ridges, deep-water trenches, and guyots have been identified. These elements are determined from the seafloor topography and, together with other geophysical data that substantiate their geodynamic nature within plate tectonic theory, form the skeleton of the tectonic legend for oceans. The axes of magnetic anomalies and isopachs of the thicknesses of sediments overlying the magmatic basement are separate elements of the legend. Not all of these elements are represented on the 1970 map, but they are necessary for the content of the tectonic map. Twenty years later, magnetic anomalies allowed construction of the age model for the spreading basement. Their fragmentary inclusion in the map was an important innovation. The map also shows rare point dating of rocks recovered by bottom sampling. The map's legend also contains a section on thalassocratons. It includes large intraplate uplifts associated with vertical movements and magmatism. These are arch and block uplifts, associated troughs, and marginal rises on the oceanic sides of troughs. These elements, as shown on the map, bear a distinct geodynamic sense associated with extensive intraplate magmatism, structures along the sides of fracture zones, and plate interactions at convergent boundaries. The map's depicted set of ocean tectonics elements developed by 1970 represented the rational synthesis of acquired data and theoretical substantiation of their genesis.

A similar presentation of the tectonic structure for all oceans, including the Arctic, was done in 1982 on a map edited by Yu.G. Leonov and V.E. Khain [25], simultaneously in two scales: 1 : 15000000 and 1 : 45000000. Since the classification of tectonic elements for the ocean at both scales is almost the same, the description is based on a smaller-scale version. The legend to this map calls the transform faults displacing the MOR "fracture zones" with a variant for inferred elements, which has already been decisively fixed in oceanic terminology, simplifying the general classification of deep-sea fault types. For deep fault troughs, separate notation has been introduced for near-fault basins not related to the troughs. The axial part of the rift zone remained unchanged in the legend, but due to the extent of study of the MOR, its depiction became more detailed. The uplifts of the active zone of the divergent boundary of the MOR were replaced by the Pliocene–Quaternary ages of the basement, which coincides with had previously been shown only based on relief data. The age gradation of the spreading basement, based on linear magnetic anomaly data [36], is included as a necessary element of the legend. In accordance with the time intervals N_2–Q, ₽$_3$–N_1, ₽$_{1–2}$, K_1, K_2, J_3, a color classification of the age of the ocean floor was produced. These intervals are quite large and do not show local features of accretion of the magmatic basement over time, but the continuous age indexing in the absence of detailed sampling and dating of material is indicative. In the intraplate space, the map shows the contours of abyssal basins and volcanic uplifts with age indexing younger than the basement, since overprinted intraplate magmatism formed these uplifts after formation of the basement. Another new element is the identification of thickened oceanic crustal blocks and paleorift axes that were abandoned as a result of local jumps of the spreading axes. The development of the legend for oceanic tectonic elements reached a level of sufficiency and remained as such until the advent of satellite data, which gave new impetus to mapping.

Satellite altimetry data [48] possess uniform detail up to 1 : 1000000 and show such new features of the gravity field, reflecting the relief of the bottom and magmatic basement, as:

—convergence of the passive parts of transform faults;

—an increase in the number of troughs in undulation zones in the passive parts of faults;

—fracture zones and troughs obliquely oriented with respect to the main structural elements;

—pull-apart structures in the passive parts of transform faults filled with sedimentary cover;

—many other structures reliably distinguished in the configuration of the anomalous field.

These capabilities have led to new attempts to augment map legends with a new system of elements and their geodynamic interpretation. Tectonic elements that find nor rational explanation within the general theory are rarely shown on the maps. A.O. Mazarovich [13] completely depicts the entirety of visible linear structures in the basement using the Equatorial Atlantic segment as an example. In addition, he provides an extended classification [13] of the types of rift–fault relationship, which gave way to a differentiated tectonic legend (Fig. 5), extending the classical set of elements for the deep ocean. Satellite data processing made it possible to identify all objects depictable on medium-scale maps.

The intensive growth of instrumental measurements of active tectonic process indicators led to the creation of a specialized type of maps that depict only the parameters of these processes. A overview of these data in the form of a map be found on the Digital Tectonic Activity Map website [39]. In particular, it shows the determinations of motion vectors of observation

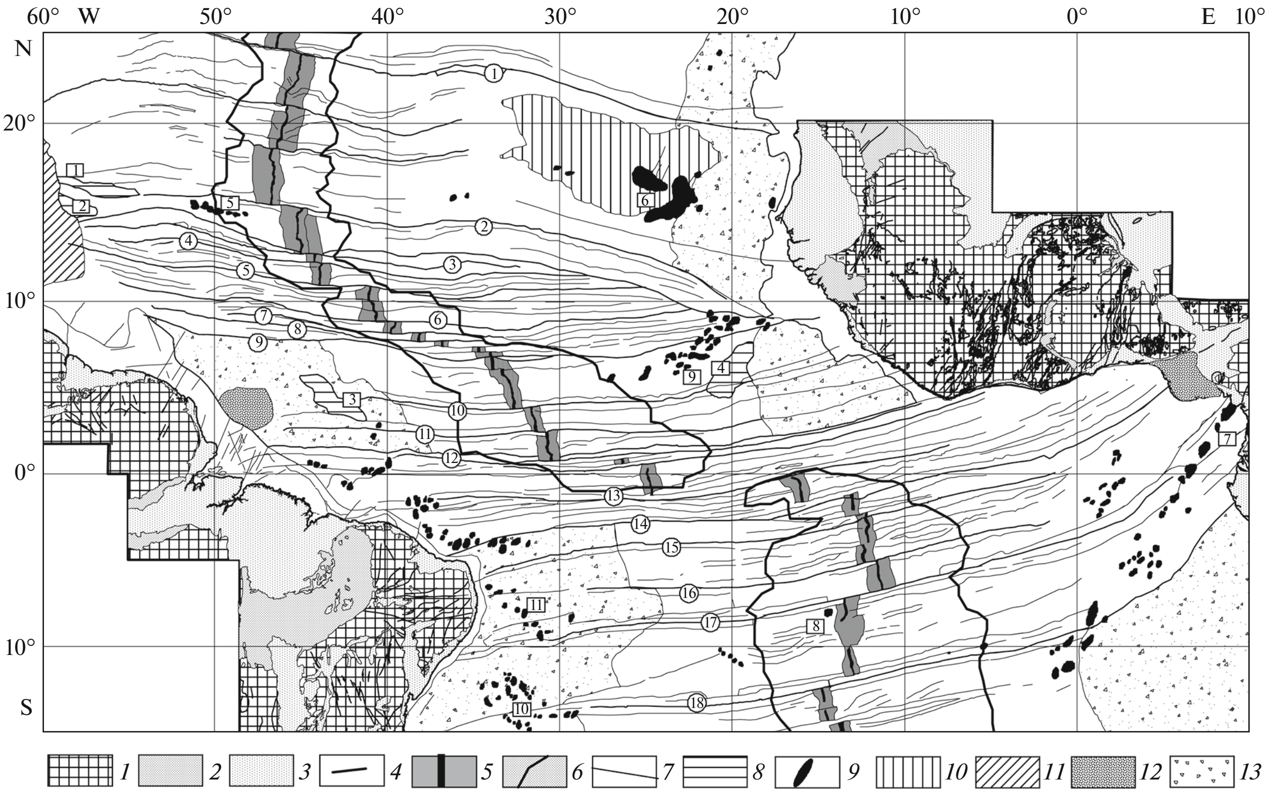

Fig. 5. Map of fault structures of Central Atlantic (after [13], with changes). The following faults are shown (numerals in circles): 1, Kane; 2, Cape Verde; 3, Marathon; 4, Mercury; 5, Vema; 6, Arkhangelsk; 7, Doldrums; 8, Vernadsky; 9, 7°10′ N; 10, Strakhova; 11, St. Peter; 12, São Paulo; 13, Romanche; 14, Chain; 15, Charcot; 16, Tetyaeva; 17, Ascension; 18, Bode Verde. The following are shown (numerals in squares): 1–5, ridges and rises: 1, Barracuda; 2, Tiburon; 3, Ceara; 4, Sierra Leone; 5, Researcher; 6, Cape Verde Islands; 7, Cameroon Line; 8, Ascension Island; 9–11, groups of seamounts: 9, Bathymetrists, 10, Baja, 11, Pernambuco. *1*, undissected highs in crystalline basement of continental crust (including Mauritanides in Africa); *2–3*, overprinted basins: *2*, Paleozoic, *3*, Meso–Cenozoic; *4*, faults and trends of main structures; *5–6*, MAR: *5*, rift zone, *6*, flanks; *7*, faults; *8–9*, uplifts: *8*, aseismic, *9*, volcanic islands and seamounts, undissected; *10*, area of intense gravity anomalies (inferred area of Miocene magmatism); *11*, Barbados accretionary wedge; *12*, deltas; *13*, areas of flat acoustic basement.

control points based on GPS data [42], seismicity according to [53], spreading rates according to [37], volcanism, the positions of active divergent and convergent plate boundaries, etc. These data do not directly constitute the mapping of tectonic elements of structures, but they are actively used in interpreting the modern contours of the crust and upper mantle, which fragmented into blocks and are mobile relative to each other.

With the accumulation of anomalous magnetic field data and identification and indexing of linear magnetic anomalies in it, the age classification of the oceanic basement became more and more detailed. The latest version of this classification is [47]. It is supplemented by an electronic application containing a digital layer of age values for all water areas where magnetic anomalies with a spreading linear structure have been detected. This layer is used in many studies, where the age of the basement is one of the analyzed factors. It should be noted that, despite information support, maps with tectonics of the ocean floor began to contain a significantly simplified depiction of structures, including age classification, shaded relief, and transform fault lines without division into types and position of the MOR axis [52]. Formally presented information content in a fragment of the map [52] reflects the modern level of instrumental knowledge of knowledge about the ocean (see Supplement 1, Part 2). Essentially, such a depiction lacks a reasonable interpretation of the genesis of the identified structures, which are more diverse than the primary formulations of plate tectonics concerning the main tectonic elements bottom.

An important step in understanding and including structural elements visible from altimetry data into the legend of a tectonic map is the identification of objects like those presented by Matthews et al. in [46] (see Supplement (and through the rest part of the text) 1, Part 2):

—fault troughs not parallel to the main transform faults;

—intraplate uplifts and mountain chains according to new bathymetric data;

—fault zones obliquely oriented with respect to the main structural elements.

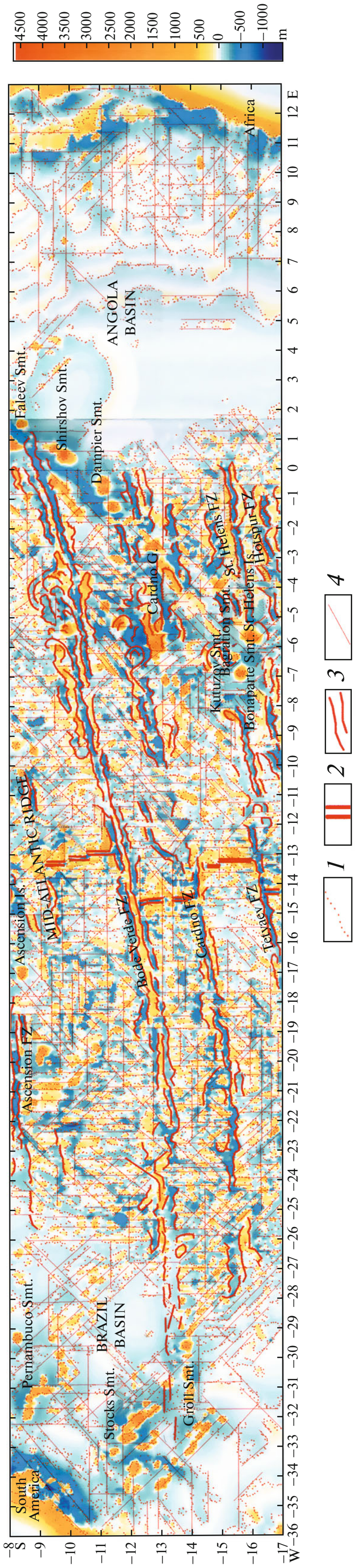

Fig. 6. Angola–Brazil geotraverse. Structure of high-frequency bottom topography (after [1], with changes). *1*, position of maximum values of relief gradient; *2*, rift valley; *3*, fracture zones; *4*, intraplate faults.

The lineament analysis of satellite data presented by Matthews et al. in [46] substantiated the concept of discordant zones—faults in the oceanic basement that are not conformal to the main tectonic elements: rift segments of the MOR and transform faults.

Discordant zones can have different angles with respect to the main structural elements; they can be tortuous and may not coincide with the general trend of spreading. The availability of new digital bathymetry data based on satellite measurements [49], as well as the idea of the presence of a relief trend descending from the MOR axis associated with cooling of the lithosphere, allowed Matthews et al. [46] to calculate the residual relief as a result of high-frequency spatial filtering, from which the component associated with the general trend has been removed. This approach to processing bottom topography data and constructing on its basis a diagram of tectonic elements has been known for a long time and was used in [1] for compiling maps along transoceanic geotraverses (Fig. 6). Filtering ultimately yielded an information layer containing mountains and larger intraplate uplifts, which are overprinted volcanic edifices with different magmatic productivity. These objects are also included in the legend of tectonic map [46], but with no age datings younger than the basement.

An updated version of the Tectonic map of the Pacific region at a scale of 1 : 17000000, published by the US Geological Survey [51] was compiled taking into account the latest data on the relief, anomalous geophysical fields and tectonics of the continental frame (see Supplement 1, Part 3). The structure of its legend for the oceanic part does not fundamentally differ from earlier variants. The configuration of the main tectonic elements—fault network, rift valley, contours of mountains and uplifts—is presented in detailed form corresponding to the current level of survey data. The age classification of the basement and intraplate magmatic formations have been substantially augmented, the contours of which are shown by the color of the corresponding age class of the basement. In addition, speckling was introduced for overprinted magmatic edifices, reflecting the composition of the products of magmatism.

Progress in studying the Arctic, associated with targeted research on expanding the outer boundary of the continental shelf, was accompanied by the emergence of a new concept of tectonic development of the Arctic, based on development of the ideas of L.P. Zonenshain and L.M. Natapov on the Precambrian paleocontinent of Arctica [7]. This led to the creation of conceptual tectonic maps, which, using special mapping of large provinces, tectonic, and geomorphological elements on a small scale, demonstrates an updated interpretation of the tectonic structure and development of the region. A novelty of the map in the oceanic part of the region is the appearance of ancient blocks with continental crust. In addition, note that the new concept is also based on seismic tomography data [7], from which the most detailed model of the distribution of velocity variations in the upper mantle for the Arctic region was obtained.

A significant achievement in international scientific cooperation was a project with the participation of all Arctic states to create a tectonic map of the Arctic on a scale of 1 : 10000000 [28] (see Supplement 1, Part 4). The map legend is the result of many years of coordinated work of all participants and in general terms reflects the synthesis of various viewpoints on the tectonic zoning of the region. The depiction of tectonic elements in the young Eurasian Basin corresponds to the classical set of elements of rift and transform structures. In addition, a continent–ocean boundary line has been introduced. The Cenozoic Oceanic Basin is shown with basement age classification and linear indexed axes of magnetic anomalies. For areas with magmatism with increased productivity and outcrops of mantle peridotites, speckling was introduced, reflecting the rock composition. In the Amerasian Basin and shelf basins, gradation of the thickness of the sedimentary cover in different areas was introduced based on the age of the oldest complexes at the base of the section. In particular, the Amerasian Basin is shown as an area with a sedimentary section starting from the Lower Jurassic. Only a small part of the Canadian Basin contains an Upper Jurassic section and is outlined as a continental block. Seamounts and individual centers of a migrating mantle plume are shown. It should be noted that the principle of depicting sedimentary cover with different ages at the base of basins used for deep-water part of the Arctic was tested in tectonic maps edited by V.E. Khain and N.A. Bogdanov for the shelf seas of the Russian Arctic in the second half of the 1990s.

MEDIUM-SCALE MAPPING RESULTS IN THE EQUATORIAL ATLANTIC SEGMENT

In addition to the classical set of structural elements, satellite data and the bottom topography with uniform medium-scale detail derived from them, make it possible to reveal the following features of ocean floor structures:

—convergence of the passive parts of transform faults;

—an increased number of troughs in the undulation zones of the passive parts of faults;

—fault zones and troughs obliquely oriented with respect to the main structural elements;

—pull-apart structures in the passive parts of transform faults filled with sedimentary cover.

These features are reliably distinguished in the configuration of the relief obtained from the initial data, which is of a gravitational nature [49] and therefore allows tracing of basement structures under the sedimentary cover. In addition, not all of these elements

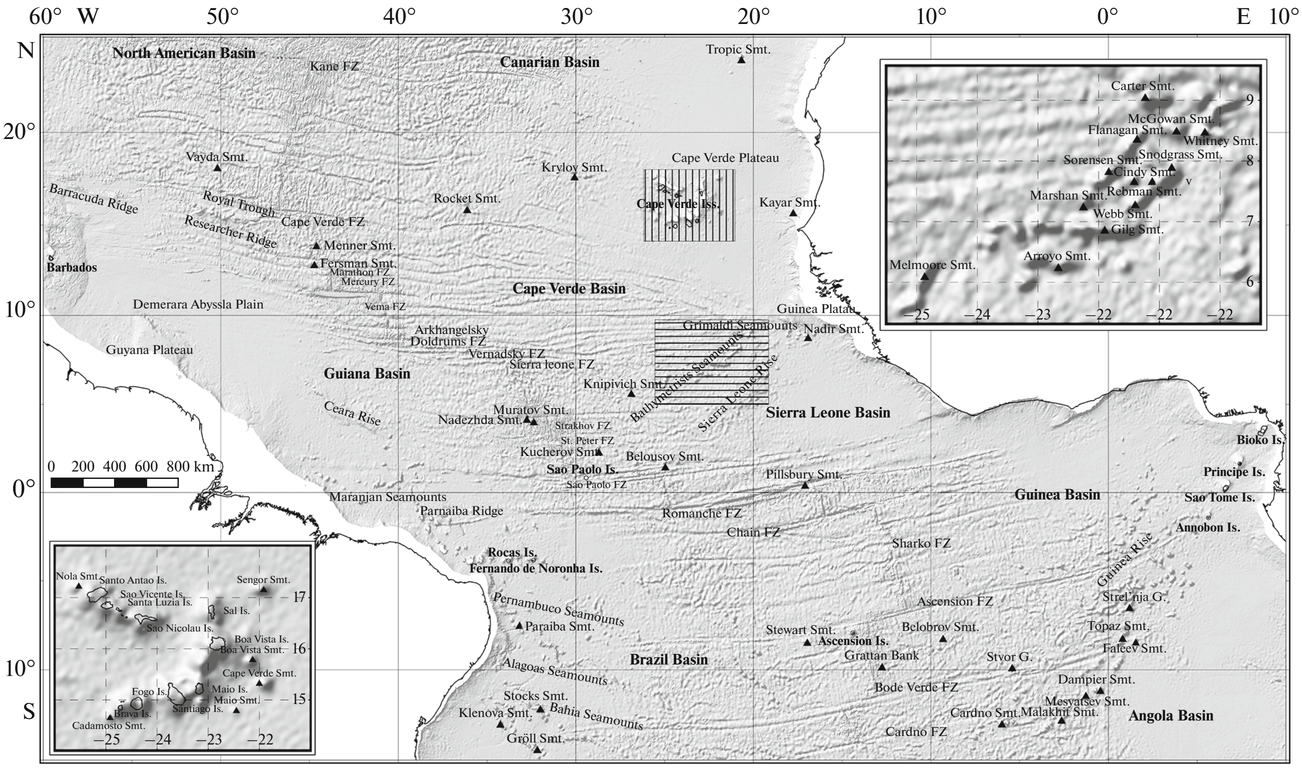

Fig. 7. Toponymy of Equatorial Atlantic segment. General topographic base according to GEBCO data, 2014 [40]. Shown in inset: areas of the Cape Verde Islands and Bathymetrists Seamounts. Triangles: seamounts, the names of which were approved by GEBCO subcommittee on names of the underwater landforms.

find rational explanation or adaptation to general geodynamic plate tectonics theory. However, their reliable identification based on modern data requires mandatory inclusion of the new tectonic elements into the legend. As shown in [23], a consistent interpretation of their genesis using plate tectonics concepts is possible assuming a block and layered structure of lithospheric plates [30], introduced into the main postulates of the modern global geodynamics concept. Studies [22, 23] propose a map of tectonic elements of the bottom of the Equatorial Atlantic segment, acquired as a result of vectorization of the bottom topography and gravity anomalies on a scale of 1 : 35000000. In addition, it contains a number of elements derived from analysis of Bouguer gravitational and magnetic field anomalies. It differs from previous analogs of bottom tectonics maps by a significantly more differentiated legend of types of lineaments described in the literature and added to the cartographic display. Seafloor tectonics, based on interpretation of the relief, should have its content visible on the map, but at a scale of 1 : 35000000 it is almost impossible to show it in the detail need to depict the new elements. This problem is solved with a map at a scale of 1 : 10000000, which makes it possible to depict the detail of used relief, compiled from data of the international GEBCO project [40, 55]. The names of the underwater landforms in the Equatorial Atlantic segment are given in Fig. 7.

The main tectonic elements—rift segments of the axis of the Mid-Atlantic Ridge (MAR), single transform faults and their separate active zones between rift segments—are distinguished in all versions of the interpreted oceanic basement tectonics (see Supplement 1, Parts 5, 6). The heterogeneous structure of its top is clearly determined from the bottom topography [40, 55], which is the topographic basis of the map (see Supplement 1, Part 5). General geodynamic meaning of these elements has not changed since the formation of plate tectonics, being a divergent boundary between plates along which horizontal accretion of the crystalline crust, segmented by transform boundaries, occurs due to the accumulation of products of basaltic magmatism. The depiction of the main elements and interpretation of the genesis of new elements are refined with progressive development of detail of the surveyed seafloor and potential fields and with the theoretical advancements in the field of geodynamics [30].

Analysis of the main tectonic elements in the coordinates of the lengths of MAR segments and the lengths of the active parts of transform faults has shown [23] that short (from 20 to 55 km) rift segments of the MAR and displacements along faults from 10 to 80 km form a compact group, which sharply differs from other elements by these characteristics. It can be identified as a separate type of tectonic elements—double and multi- (three or more) fault systems (see Supplement 1, Part 5). These systems are expressed over "cold" mantle blocks [23] and in zones with large lateral displacement of MAR segments. They are shown on the map with different signs (see Supplement 1, Part 5). The two largest multifault systems frame the southern part of the Equatorial Atlantic segment, within which the configuration of the main elements is close to the classical one; moreover, a significant (from 300 to 900 km) offset of MAR segments occurs in the frame of the Equatorial Atlantic segment. The MAR zone along the 4000 m isobath tends to increase from 300–400 km in the northern part of the Equatorial Atlantic segment to 700–800 km in its southern part (see Supplement 1, Part 5). This trend agrees well with the spreading rate data [47], according to which there is an increase southward from the Euler pole of the African and American plates, at approximately 60° N.

A separate sign on the map shows "hermit" faults, after [13] (see Supplement 1, Part 5). These structures do not displace or intersect the MAR axis. The genesis of these structures is unclear, but there is a hypothesis [23], according to which their origin can be explained by equalized spreading rates in cases when these rates differ on the flanks of a transform fault. Rate equalization leads to disappearance of the fault separating blocks with different rates, and to additional deformations of newly formed crust: extension on the slower block and compression on the faster. This hypothesis is well illustrated by an analysis of a map of the spreading half-rates [23] for the western flank of the MAR at about 15° S, where as a result the difference in rates, which reached 60% near the 16 Ma isochron, the rates equalized, and there is no difference for the 4 Ma isochron.

Of particular interest are the "blind troughs" after [13], which are branches from single transform faults situated in parallel to the latter (see Supplement 1, Part 5), a parallel branch in terms of the map. They have a spatial orientation conformal to the main faults from which they branch, and their origin is unclear. The following is observed:

—En echelon branches on both sides of the MAR, which indicates the origin of these forms, associated with variation in the conditions of the ridge's axial zone. The forming factor may be overflow of material along the axis [2], which, in addition to jumps in the MAR axis within the segment, can lead to displacement of the boundary faults of the ridge segment and breakup of the segmenting transform element. Rift segments previously separated by faults combine and the number of faults decreases. Most branches are directed by the junction point towards the MAR, which shows a decrease in the number of segments over time. There is an exception in the north along the São Paulo Fault, in which segmentation has become more complicated over time: a branch appeared about 60 Ma.

—Asymmetrical position of parallel branches. This element is manifested in the northern part of the Equatorial Atlantic segment between the multifault system consisting of the Doldrums–Vernadsky fault at 7°24′ N, Bogdanov Fault at 6°52′ N, and the Vema Fracture Zone. A peculiarity of these branches is doubling of the total number of troughs compared to ordinary branches displacing segments of the MAR. The junctions points are located in the undulation region of the passive parts of ordinary faults, manifested in the entire North Atlantic in the age interval from ~50 to ~70 Ma [47], during which there occurred a jump in the Euler poles and formation of a failed rift in the Labrador Sea. Since reorganization of the orientation of the Vema Fracture Zone located in this segment, known from [34], is temporally related to the formation of the Antilles arc and its longitudinal action, opposite the MAR axis, on this segment of the Atlantic, as well as to the formation of kink bands in the structure, it can be suggested that the noted system of fault branches resulted from concomitant deformation processes.

Discordant zones introduced into the tectonic legend in [46] are distinguished as a separate element of the tectonic map. They also have the property of symmetry with respect to the MAR; there are also asymmetric variants. Most of these zones are symmetrical and located between inflectionless transform faults (see Supplement 1, Part 5). This indicates the absence of a relationship between discordant zones with the general spreading vector, and that their origin, as in the case of symmetric parallel branches, is associated with axial processes within the segment. Another factor that can form such a structural pattern is the difference in spreading rates between plate segments separated by transform faults.

Asymmetrical discordant elements form a system oriented towards transform faults at an angle of ~45° (see Supplement 1, Part 5). The northwestern direction predominates [14]. Faults oriented at this angle, having a long and straight configuration, are identified as a separate element of the tectonic map. Orientation at the same angle to the rift and faults indicates the displacements along shear stresses. This points to changes in the elastic state of the lithosphere at large (up to 1000 km) distances. Thus, the lithosphere has a dual nature: it is simultaneously an elastic medium and a block complex. Long oblique faults have been identified in the abyssal far from the flanks of the MAR, where the lithosphere is colder than in the rift zone.

An additional element of the map is nontransform offsets of the MAR axis, which are rift segment displacement zones having no transform fault (see Supplement 1, Part 5). The reason for the occurrence of these structures is contrastingly low viscosity of local mantle areas arising in the presence of abnormally heated areas, identified by seismic tomography data, or in the presence of ultramafic serpentinization zones [19]. Nontransform offsets often combine with NW-trending faults. Repeat dredging of bottom rocks carried out by GIN RAS (Moscow, Russia) [13] and researchers from other institutes, in addition to basalt and gabbro, revealed widespread serpentinized ultramafic rocks, which confirms the version of the origin of nontransform displacements.

The map legend included the MAR paleoaxis, having a supposed genesis within the topographic map (see Supplement 1, Part 5). Since, according to the analysis of the anomalous magnetic field, short-term jumps in the axis over short distances within the first magnetic chrons are possible [2], asymmetric paleoaxes could have formed on any flank of the MAR. Reliable data have been obtained on large, depending on distance, jumps to the transition of the axis from the Aegir Ridge to the Kolbensei Ridge (North Atlantic) and to the transition of the axis on the eastern flank of the MAR south of the Agulhas Fault. The rest of the inferred paleoaxes are identified from the seafloor morphology, similar to that of the MAR, and, in some cases, by the form of magnetic anomalies.

Another tectonic element of the deep-water part is pull-apart basins adjacent to the passive parts of transform faults near the continental margins (see Supplement 1, Part 5). The configuration of these basins, which in some cases is rhomboid, can be read from free-air gravity anomalies [23]. Their most likely occurrence mechanisms are:

—the difference in spreading rates in segments between faults;

—displacement along the passive parts of faults.

Most of the troughs are located within the 200-mile exclusion zone of coastal states, but the rhomboid structure to the north of the Sierra Leone Rise in international waters was traced by an en route geophysical survey on the cruise 23 of the R/V *Akademik Nikolaj Strakhov* (GIN RAS, Moscow, Russia) in 2006 [20] (see Supplement 1, Part 5). On the southern side of the basin, deformational thrust structures of southern vergence were found, the occurrence of which would have required a submeridional motion component of the masses. The component could have resulted from offsets in the following variants [57]:

—submeridional displacement of plate blocks at different rates;

—sublatitudinal shear displacement along an indirect fracture path, forming so-called hummocking bends.

Since there are no instrumental data on movement rates in the water area, it is rather difficult to substantiate the first variant, but the second, based on latitudinal displacement along an indirect trajectory, is quite plausible. Thrust structures of submeridional vergence were found along the side of another basin, identified by altimetry along the passive part of the Charcot Fracture zone near the Niger River [35] (see Supplement 1, Part 5).

A number of individual elements within the topographic map are shown with separate signs (see Supplement 1, Part 5). One is the Antilles arc. The plate boundary running along the western part of the fault at 15°20′ forms a triple junction with the MAR, as indicated by copious and different types of data (GPS, seismicity, etc.). The Cape Verde escarpment is shown as a unique structure with a separate sign; it is the eastern continuation of the Mercury Fault, along which asymmetric parallel branches of the northern Equatorial Atlantic segment jut out. This phenomenon was called convergence of the passive parts of transform faults and currently does not have a clear geodynamic interpretation.

On the map, the shelf is shown along the 400 m isobath, since some shelf areas are deeper than 200 m. On the map scale in plan view, the position of the 400 m isobath on the slope is almost the same as the 200 m isobath. Seamounts and ridges are shown by the excess of the GEBCO high-frequency residual relief on a 30" grid over a smoothed relief (similar to the basement) greater than 1000 m. Mountains and ridges are shown by the +1000 m isobath along the residual relief. It follows from the map that most of the seamounts are grouped into chains, the orientation of which coincides with the passive parts of transform faults or faults oriented at an angle of ~45° to the main structural elements.

The listed new tectonic elements, mapped in addition to the main elements with the classical explanation, can be interpreted as a result of the action of the following factors, expanding the range of forces and processes influencing tectogenesis [23]:

—overflow of heated matter along the axis, leading to the formation of discordant zones and breakup of segmentation of the MAR by transform faults or the occurrence of additional segmentation;

—interaction of blocks of the oceanic lithosphere on different flanks of transform faults, including passive parts, arising due to different spreading rates in the blocks;

—the occurrence of an additional fault network due to changes in the Earth's rotation and surface curvature;

—additional displacement of the northern part of the Equatorial Atlantic segment under lateral impact from the Antilles arc.

DEVELOPMENT OF MEDIUM-SCALE MAPPING IN THE EQUATORIAL ATLANTIC SEGMENT

The current level of knowledge on the age of the oceanic basement obtained from interpreting indexed magnetic anomalies [47] and the thickness distribution of the sedimentary cover on the spreading basement with different age, obtained predominantly from continuous seismic profiling data [50], has made it possible to compile a map of new tectonic elements of the ocean, similar to the maps of the shelf and the Arctic (see Supplement 1, Part 6). The age of the basement is differentiated in a semitransparent mode over the shaded bottom topography, which simultaneously reproduces its inhomogeneities and the age values of the crust that formed in the accretion zone. In the absence of sediments, the bottom topography corresponds to the top of the crystalline basement. In areas with sedimentary cover, tectonic elements are identified from altimetry data, which is sensitive to the configuration of the boundary at the base of the cover with a density contrast between sediments and basement. Owing to this information, the topographic basis for the classical and new tectonic bottom elements approaches the information load normal for continents and shelfs (see Supplement 1, Part 6). By virtue of the starkly expressed age gradient of the spreading basement from the continental margin to the divergent boundary, it makes no sense differentiate the age of the basin's basement for the sedimentary cover. The thickness of sediments is shown by isopachs on top of the combined topographic base from the bottom topography and age, which quite cognitively reflects all spatial information.

The low density of direct sampling of bottom rocks compared to continental structures makes it impossible to date bottom structures similarly to land-based structures. The basement was uniformly classified by age according to indirect magnetic survey data, calibrated at separate rare points by deep-water drilling data in cases when a borehole reached the top of the basement. In the deep-water part of the ocean, younger structures were overprinted on the primary basement. Such structures are intraplate volcanic edifices occurring in the form of extensive rises, islands, and individual mountains, and intraplate deformation zones, revealed by fold formations and disjunctive faults in the sedimentary cover.

The overprinted off-axis magmatism in the Equatorial Atlantic segment is due to local branches of superplumes that approached the surface beyond the spreading axis. For Iceland and the Azores, the plume branches intersect the MAR. When sampling is complete enough to characterize the structure as a whole, its age can be indicated by a color-coded contour, as done on the map of the Pacific Ocean [51]. Another way, if there is an insufficient number of samples to date overprinted magmatic structures, points with numbers can be assigned. This method was used for the Equatorial Atlantic segment (see Supplement 1, Part 6). The age values were taken from database [41] and expeditionary works of GIN RAS (Moscow, Russia) [21]. This method avoids interpretation to the maximum extent, displaying only factual data. The latter are almost always incomplete, but this approach does not violate objectivity.

More complex is the problem of determining the ages and spatial distribution of intraplate deformations overprinted on the primary basement. Since these structures are determined from seismoacoustic data of subway ship-based and polygon survey measurements, the information on the detected deformations is nonuniform and extensive deformed areas are frequently intersected by single sections. These areas can be contoured with combined continuous seismic profiling and satellite altimetry, but a methodology has not yet been developed. According to [23], in the Equatorial Atlantic segment, the following types of deformations have been revealed from the characteristic configuration of the wave field in the sedimentary sequence:

—stamp folds;

—piercement structures,

—imbricated thrust fault systems;

—horizontal and vertical acoustic blankings in the seismic record;

—normal faults.

Most of these structures are associated with positive vertical movements of crustal and upper mantle blocks under sedimentary cover in the predeformation period. These movements are interpreted as the result of decompaction and an increased volume of local zones in the upper mantle during serpentinization, which makes it possible to develop a method for identifying young intraplate deformations by gravity and magnetic fields necessarily combined with direct continuous seismic profiling data.

In addition to the method of identifying deformation structures, there is the problem of their dating. A rare network of deep-water boreholes, even when the deformation zone reflectors are referenced to the drilled section, does not allow reliable correlation of reflectors over distances of hundreds and thousands of kilometers through sediments that have discontinuously filled irregularities in the acoustic basement. Thus, estimation of the age of deformation structures is based on:

—comparison of the general configuration of the wave field with analogs in the vicinity of boreholes;

—comparison with reflectors referenced to the general pattern of sedimentation cycles in water areas, after [43];

—identification of erosion degree of deformed layers;

—overlying destruction products of reflectors in the frame of the structure;

—determination of the age of reflectors in the top of deformation structures based on sedimentation rates;

—determination of the thickness of layers along the seismic section.

The listed approaches, with a sparse observation network, the availability of satellite data, and absence of direct dating, must to be developed to create the kind of complete mapping of the tectonics of overprinted intraplate structures that has become classical in tectonic maps.

CONCLUSIONS

(1) The basis of medium-scale tectonic mapping of the deep-water part of oceans in the 20th century was the synthesis of the seafloor topography and a theoretical geodynamic model that interprets the genesis of the observed structures from the standpoint of fixism and, later, mobilism. After the end of the Second World War, the rapid growth in interest in studying the oceans led not only to the development of expeditionary research into ocean floor topography, but also to development of Earth research from space and the acquisition of data on geological and geophysical characteristics by means of satellites with uniform coverage of deep-sea spaces in the medium scales from 1 : 1000000 to 1 : 15000000. This resulted in the well-founded introduction of new tectonic elements into map legends and partly brought their structural and age saturation closer to continental tectonic maps.

(2) Until 1970, the development of tectonic mapping of the oceans followed the way of direct convergence of the composition of the map legends with land analogs, since their textural basis consisted mainly of a few point measurements of the bottom topography, which were interpreted with fixism and geosynclinal theory. By the end of this period, interpretation of ocean data using mobilism theory was ultimately acknowledged due to proof of the main provisions and sharp increase in the amount of instrumental data on which this evidence relied. The composition of the legends of tectonic maps of oceans has acquired elements differing from land, characteristic only of oceans.

(3) By 1970, extensive geological and geophysical material obtained in national and international programs, as well as its interpretation based on plate tectonics theory, finally confirmed the specific oceanic legend of tectonic elements, substantiated by many theoretical advancements that radically changed the concept of global tectogenic and oceanic tectonic processes. Mapping projects representing land–marine synthesis, taking into account the latest achievements in geology and geophysics of the oceans, have obviously been successful.

(4) The compilation of tectonic maps with a new set of legend elements was extended to the areas of all oceans, even the poorly studied Arctic Ocean.

(5) By the beginning of the 1980s, the global tectonic base of the oceans was formed, which became part of the tectonic maps of the world. In addition to the structural component of the tectonics of divergent oceanic plate boundaries—rift and transform elements—the age gradation of the oceanic basement was created, based on indexing of linear magnetic anomalies, and the primary classification of younger intraplate structures overprinted on the basement.

(6) The introduction of interpreting satellite altimetry data into mapping practice, which, in contrast to ship-based surveys, offers continuous and uniform coverage at the medium scale of detail, gave new impetus to mapping seafloor and basement structures even in areas devoid of no sedimentary cover and not distinguished in the seafloor topography. This led to the formation of a new generation of maps, on which model structural lines are significantly substantiated, in contrast to interpretations made from inhomogeneous echosoundings. End of the 1980s saw the beginning of a fundamentally new stage in the accumulation of instrumental measurement data and attempts to rationalize them into a theoretical geodynamic model.

(7) The modern set of instrument measurements marked the stage of identifying previously unknown structures in oceanic crust—different forms of active and passive parts of transform faults, discordant zones, seamounts, etc.—that had not been recorded with nonuniform onboard surveys. Advances in satellite coverage led to a new approach in searching for objects for ship-based research and changed the process of obtaining a priori data to acquiring them instrumentally, although such data are somewhat inferior to onboard instrument in level of detail. The amount of seafloor probing of bedrock and their dating increased, which made it possible to add age and material markers for overprinted structures to structural edifices on the maps of many regions of the World Ocean.

(8) New tectonic elements established according to modern data —convergence zones of transform faults, double and multifault systems, nontransform displacements of the MAR axis, branching and "hermit" faults, oblique faults with respect to the main elements, single and groups of seamounts, pull-apart basins in the passive parts of faults—have been rationally interpreted by the plate tectonics geodynamic model under the assumption of a block and layered structure of plates moving on the surface of a rotating spheroid.

(9) The informational richness of the tectonic map compiled from new data for the Equatorial Atlantic segment dictates to a high degree that the scale of the tectonic map be increased to 1 : 10000000. In this case, it becomes possible to depict all details of the topographic base used for the interpretation. The need to depict on the map, in addition to the detailed relief of data on the ages of the basement, individual seamounts, structure of the sedimentary cover, and many other parameters used for tectonic interpretation, has led to the creation of a series of maps with a similar updated set of tectonic elements, but with different topographic bases.

(10) Today, unresolved problems in compiling medium-scale tectonic maps of the deep ocean are

identification, delineation, and dating of intraplate deformations determined by the configuration of the sedimentary cover in seismic reflection records and insufficient sampling of bedrock overprinted on the primary basement of intraplate magmatic structures.

ACKNOWLEDGMENTS

The authors are grateful to reviewer Prof. E.P. Dubinin (Moscow State University, Faculty of Geology, Moscow) and an anonymous reviewer for useful comments that helped improve the article.

FUNDING

The study was supported by the Russian Foundation for Basic Research (project no. 19-15-50139).

SUPPLEMENTARY INFORMATION

The online version contains supplementary material available at https://doi.org/10.1134/S0016852121020096.

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