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OCEANOLOGY

Evolution of the Rift Zone Morphostructure in the North Atlantic Magmatic Province

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The North Atlantic region, which is located between the Charlie Gibbs Fracture Zone in the south and the Nansen Ridge in the north, has long been known as the Tule volcanic province coined after the ancient name of Iceland Island holding a central position in the province. Tule Province, ~3500 km long, was the last fragment of the continental crust in the Atlantic Ocean. In the Tertiary, the whole region underwent intense tectonomagmatic activity.

The present-day morphostructure of the ocean floor within Tule Province is inherited from the trap formation, traces of which have been retained on the shore and, according to deep-sea drilling data, on submerged blocks of the continental margin [1]. Subsequent geological transformations within Tule Province are represented in the general schematic map (Fig. 1). It shows that the first signs of separation of Europe and North America in this part of the Atlantic are related to the spreading center inception at the site of the Rockall Trough ~80 Ma ago. At that time, the Rockall Rise was detached from Great Britain during a short-lived phase. New spreading centers of the Reykjanes, Aegir, and Mona mid-ocean ridges (MOR) emerged approximately 55–60 Ma ago. Since that moment, the Reykjanes and Mona ridges evolved in the regime of continuous (in general, symmetric) spreading. The Aegir Ridge lost its activity in the Early Oligocene (magnetic anomalies 12–13). The spreading center of this ridge constantly shifted westward until it occupied the present-day position of the Kolbeinsey Ridge. The sequence of magnetic anomalies formed within the Kolbeinsey Ridge is traced only to Anomaly 7 identified at the Jan Mayen Ridge foothill. The scenario of events within the A7–A12 interval is yet to be explained. It is probable that oceanic rifts are buried deep beneath the Iceland Plateau, which is often regarded as a continental structure. Low ridges (200–300 m high) parallel to the Kolbeinsey Ridge could be an indirect confirmation of such an inference [2].

The counter motion of blocks in the Earth's crust from the spreading centers of the Mona and Aegir ridges could be responsible for a substantial modification of the eastern part of the Jan Mayen Fracture Zone—an echelon system of NW-trending tectonic dislocations.

The Mona Ridge spreading center advanced later northward to form a new (Knipovich) rift ridge. It is untimely to surmise about the evolution of this ridge, since magnetic anomalies north of the Greenland Fracture Zone have been identified only up to A5 and A6. All the space between the Greenland, Spitsbergen, and Hovgaard fracture zones remains terra incognita. Conditions and consequences of interaction between the rift zone of the Knipovich Ridge and the continental margin of the Barents Sea are unclear.

General features of the evolution of Tule Province are substantially supplemented with data on rift zone morphostructures (RZM) of the Reykjanes, Mona, Kolbeinsey, and Knipovich ridges based on detailed profiling of the seafloor relief according to the method proposed in [3]. Morphostructures of the mentioned ridges are different (Fig. 2). Axial zones of the Reykjanes and Kolbeinsey ridges lack the rift valley over a long distance. Its place is occupied by axial volcanic massifs resembling in the cross section gentle domes 600–800 m high and 60–70 km wide. The rift valley or its forerunners as local depressions appear only at a great distance (up to 1000 km) from Iceland at the terminal flanks of the Reykjanes and Kolbeinsey ridges (Figs. 2b, 2d). The rift valley is 25–35 km wide and 800–900 m deep.

The axial zone of the Mona Ridge is represented by a large rift valley with the depth exceeding 500 m but rarely reaching 1000 m. The valley width varies from 30 to 40 km. The rift zone of the Knipovich Ridge has approximately similar parameters. Contrast in the heights of mountains in the rift valley of both ridges is 100–300 m at an average horizontal spacing of 9–12 km.

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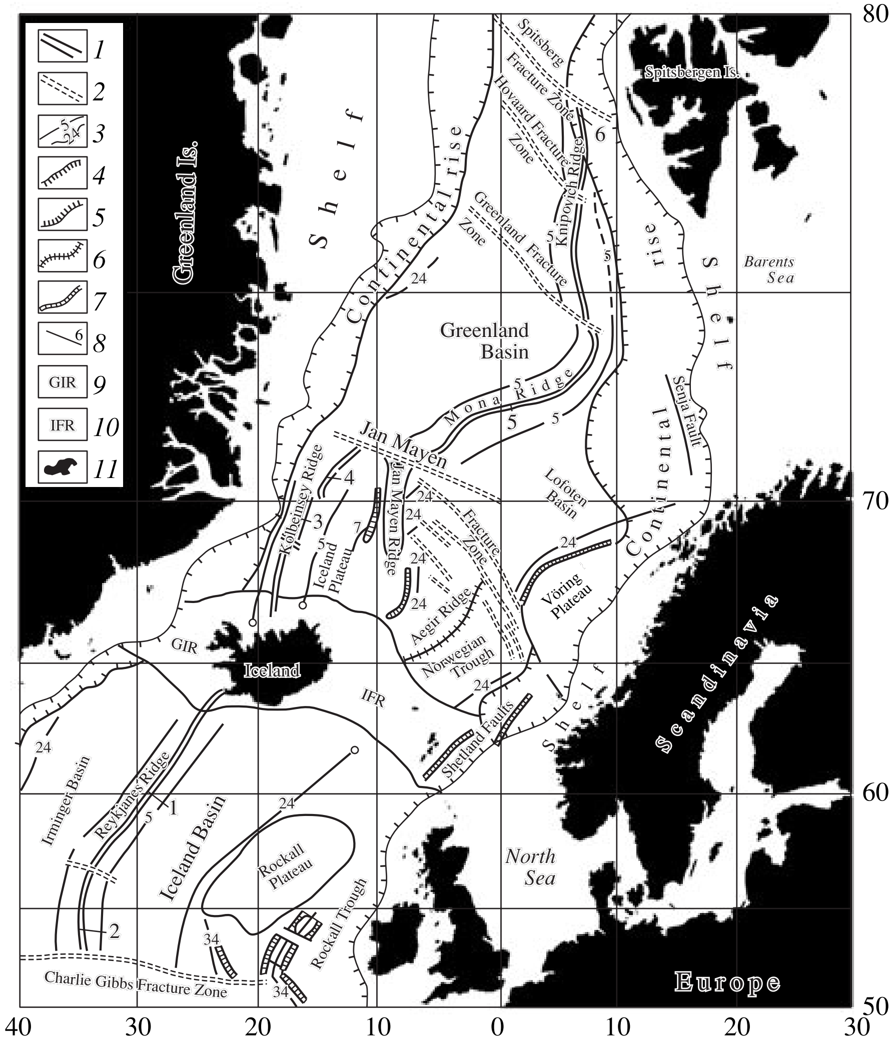

Fig. 1. Principal elements of the recent morphostructure of the Tule tectonomagmatic province. (*1*) Rift valleys of mid-ocean ridges (MOR); (*2*) transform faults; (*3*) key magnetic anomalies; (*4*) outer edge of the shelf; (*5*) outer boundary of the continental foothill; (*6*) inactive (fossil) spreading center; (*7*) initial stage of spreading, ruptures in the sequence of magnetic anomalies, and migration of spreading centers; (*8*) position of bottom relief profiles across MOR rift zones; (*9*) Greenland–Iceland Ridge (GIR); (*10*) Iceland–Faeroe Ridge (IFR); (*11*) islands and continents.

Morphometric data on the Reykjanes and Kolbeinsey ridges show substantial variations in their morphology as compared to typical mid-ocean ridges. The structural relief of the ridges in axial zones is represented by central volcanic rises exhibiting in places a slight ruggedness of the relief at the top.

An overwhelming influence of volcanism on the formation of the Mid-Atlantic Ridge (MAR) within the ridges mentioned above suggests its relation to the Iceland superplume that supplied giant volumes of deep volcanic material onto the ocean floor. The undulating relief of slopes of central ridges indicates an irregular input of the volcanic material with time. Typical are massive lateral ridges or ranges extending along the strike of axial ridges and resembling in the section peculiar "spurs" on the body of central rises. These ranges are regarded as purely volcanic structures formed on the Reykjanes and Kolbeinsey ridges during the maximum manifestation of magmatism. The formation of the mentioned ranges was associated with wedge-shaped lava flows southward and northward from Iceland [4]. In Figs. 2a and 2c, the most massive ranges are shown by arrows.

According to P. Vogt's calculations, the flow rate could reach 20 cm/yr. Temporal variation in the intensity of the flow affected its rate and external structural features. The undulating nature of the longitudinal section of "spurs" may indicate a discrete influx of the volcanic material along lateral ridges. Volcanic domes formed in this process were separated by saddles, where the intensity of the volcanic material influx was minimal. The wedge shape of the flow indicates the extinction of its energy southward and northward off Iceland. Therefore, the orientation of lava flow and its

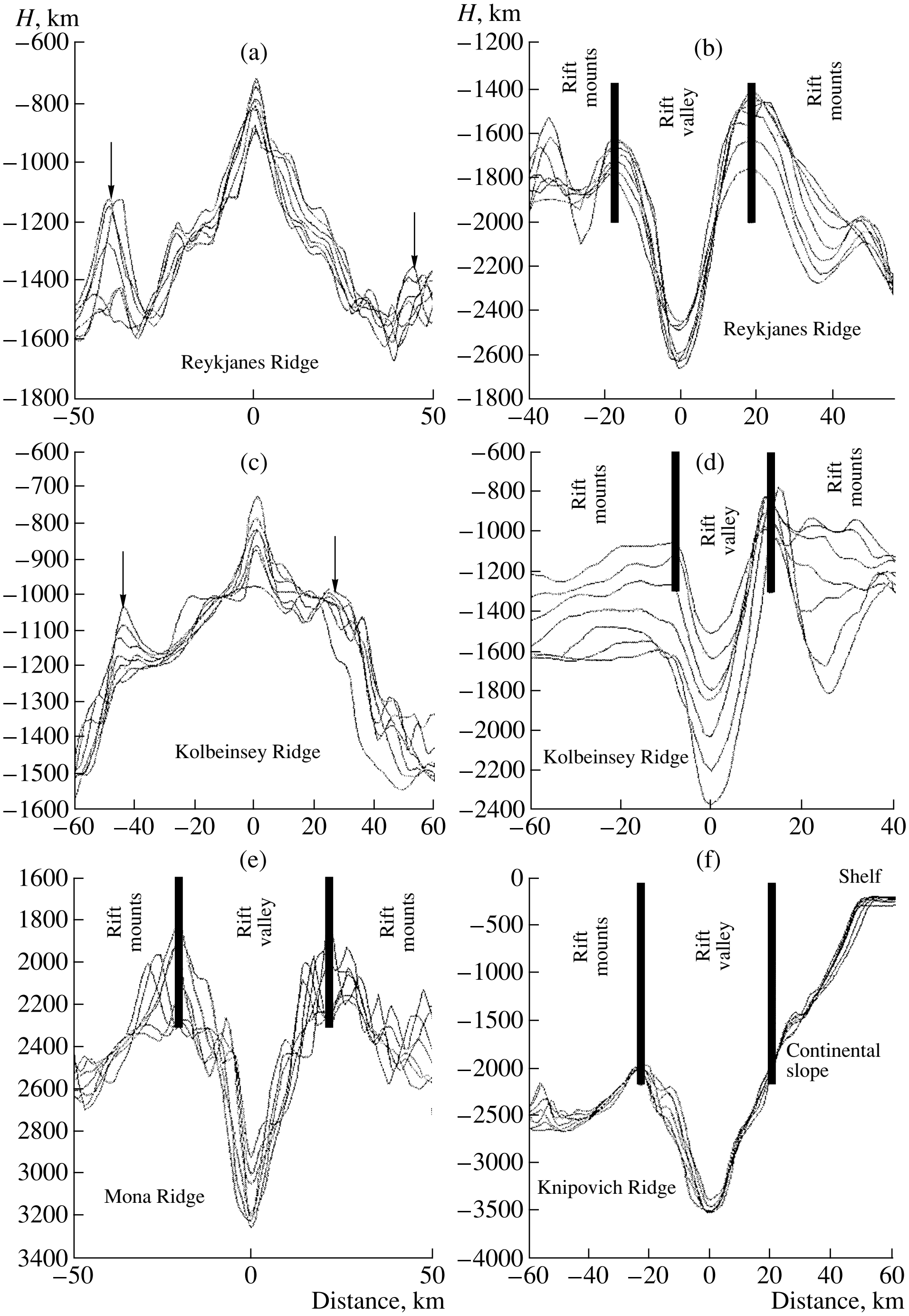

Fig. 2. Superposed profiles of the structural relief in the rift zone of the Reykjanes, Kolbeinsey, Mona, and Knipovich ridges. (a) Central point of the region: 60.27° N, 29.12° W, A = 37°; (b) central point of the region: 54° N, 35.26° W, A = 3.2°; (c) central point of the region: 69.53° N, 16.41° E, A = 23.7°; (d) central point of the region: 70.58° N, 14.74° W, A = 27.4°; (e) central point of the region: 73° N, 5.43° E, A = 60°; (f) central point of the region: 78° N, 7.47° E, A = 353°.

volcanic ranges have crosscutting relations with magnetic anomalies. The wedge-shaped structure of the flow is especially prominent in the morphology of the Reykjanes Ridge.

The influence of the Iceland superplume was also clearly manifested north of Iceland up to the Jan Mayen Fracture Zone. This area was marked by multiple migration and jumps of the spreading center. Thus, continental crust fragments (e.g., the Jan Mayen Ridge and, probably, the Iceland Plateau) were left in the rear zone (Fig. 1). In general, the intense influence of the Iceland superplume on the evolution of the morphostructure and deep structure of the Earth's crust was most conspicuous in the region bounded by the Jan Mayen Fracture Zone on the north and the Charlie Gibbs Fracture Zone on the south. Farther away from Iceland, the influence attenuated and the role of rift processes became more remarkable. For example, the long-term symmetric spreading of the Mona Ridge produced the Lofoten and Greenland abyssal basins. The rift of the ridge is prominent, although it looks reduced, in contrast to older spreading centers of the MAR. A sharp change of the rift zone morphology at the boundary of the Jan Mayen Fracture Zone suggests that this zone serves as a powerful tectonic boundary for the Iceland superplume activity north of the fracture zone. The Charlie Gibbs Fracture Zone can be regarded as a similar boundary for the Iceland plume on the south.

The crustal infrastructure of the Knipovich Ridge rift zone is insufficiently studied. Its western slope is characterized by a more diverse structural relief. A major portion of the eastern slope is buried beneath the continental margin. The slope of the rift valley adjoins the continental slope of the Barents Sea along the vertical plane. Therefore, the continental slope rises to 3200–3300 m (Fig. 2f). Intrusion of the ridge rift into the continental margin is indicated by relicts of continental rocks (mudstones) in the Knipovich Ridge.

According to petrological data, the Knipovich Ridge and, probably, the Mona Ridge are analogs of the MAR in the Atlantic "cold belt of the lithosphere" with a low intensity of mantle upwelling and a low productivity of magmatism [5]. In other words, the basic role in the formation of RZMs in the mentioned ridges belongs to tectonics, in contrast to the dominant role of plume volcanism on the Reykjanes and Kolbeinsey ridges. The conjunction of the Knipovich Ridge rift zone with the continental margin on the east and its distal position (relative to the submarine margin) on the west suggest asymmetric spreading of the ocean floor between the Greenland and Spitsbergen fracture zones.

When assessing the role of different geological conditions determining the evolution of the RZM in Tule Province, we should mention the following point. Along with the formation of rifts related to the lithospheric plate motion in this region, the activation of the Iceland superplume in the initial Eocene and its subsequent impact on the morphostructure evolution should be considered the most important factor responsible for the origin and evolution of many features of the structural relief. Morphometric data on rift ridges illustrate the influence of the Iceland plume on the evolution of the Tule tectonomagmatic province, especially on the seafloor area bounded by the Jan Mayen and Charlie Gibbs fracture zones. The available great body of data on the RZM provides new insights into the evolution of the oceanic crust and distinctions in the evolution of adjacent MOR regions. Therefore, the structural–geomorphologic regionalization of rift zones at the scale of the whole World Ocean is a pressing issue.

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