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Geodynamic Evolution of Crust Accretion at the Axis of the Reykjanes Ridge, Atlantic Ocean

S. A. Merkur'ev[a], **C. DeMets**[b], **and N. I. Gurevich**[c]

[a] *St. Petersburg Branch, Institute of Terrestrial Magnetism, Ionosphere, and Radio Waves Propagation, Russian Academy of Sciences, Muchnoi per. 2, PO Box 188, St. Petersburg, 191023, Russia*
e-mail: sam@ns1480.spb.edu

[b] *Department of Geology and Geophysics, University of Wisconsin at Madison, 1215 W Dayton St., Madison, WI, 53706, USA*

[c] *St. Petersburg Laboratory, Geological Institute, Russian Academy of Sciences, nab. reki Moika 120, room 46, St. Petersburg, 191021, Russia*

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Abstract—The results of analysis of the anomalous magnetic field of the Reykjanes Ridge and the adjacent basins are presented, including a new series of detailed reconstructions for magnetic anomalies 1–6 in combination with a summary of the previous geological and geophysical investigations. We furnish evidence for three stages of evolution of the Reykjanes Ridge, each characterized by a special regime of crustal accretion related to the effect of the Iceland hotspot. The time interval of each stage and the causes of the variation in the accretion regime are considered. During the first, Eocene stage (54–40 Ma) and the third, Miocene–Holocene stage (24 Ma–present time at the northern Reykjanes Ridge north of 59° N and 17–11 Ma–present time at the southern Reykjanes Ridge south of 59° N), the spreading axis of the Reykjanes Ridge resembled the present-day configuration, without segmentation, with oblique orientation relative to the direction of ocean floor opening (at the third stage), and directed toward the hotspot. These attributes are consistent with a model that assumes asthenospheric flow from the hotspot toward the ridge axis. Decompression beneath the spreading axis facilitates this flow. Thus, the crustal accretion during the first and the third stages was markedly affected by interaction of the spreading axis with the hotspot. During the second, late Eocene–Oligocene to early Miocene stage (40–24 Ma at the northern Reykjanes Ridge and 40 to 17–11 Ma at the southern Reykjanes Ridge), the ridge axis was broken by numerous transform fracture zones and nontransform offsets into segments 30–80 km long, which were oriented orthogonal to the direction of ocean floor opening, as is typical of many slow-spreading ridges. The plate-tectonic reconstructions of the oceanic floor accommodating magnetic anomalies of the second stage testify to recurrent rearrangements of the ridge axis geometry related to changing kinematics of the adjacent plates. The obvious contrast in the mode of crustal accretion during the second stage in comparison with the first and the third stages is interpreted as evidence for the decreasing effect of the Iceland hotspot on the Reykjanes Ridge, or the complete cessation of this effect. The detailed geochronology of magnetic anomalies 1–6 (from 20 Ma to present) has allowed us to depict with a high accuracy the isochrons of the oceanic bottom spaced at 1 Ma. The variable effect of the hotspot on the accretion of oceanic crust along the axes of the Reykjanes Ridge and the Kolbeinsey and Mid-Atlantic ridges adjoining the former in the north and the south was estimated from the changing obliquity of spreading. The spreading rate tends to increase with reinforcing of the effect of the Iceland hotspot on the Reykjanes Ridge.

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INTRODUCTION

The main objective of this study is to trace the variation of the geodynamic regime of crustal accretion at the Reykjanes Ridge, related to the effect of the Iceland hotspot on the spreading axis during the ridge evolution, and to ascertain the cause of this variation on the basis of detailed original magnetic and bathymetric data and the results of previous investigations. Previous studies have described the changes that occurred in the accretion regime at the low-velocity Reykjanes Ridge as a result of interaction with the Iceland hotspot; the changes in the parameters of this ridge itself have also been studied. These topics are discussed in the next section of this paper.

The solution of the issue set forth will require study of the fine spatiotemporal structure of the anomalous magnetic field.

The extensive volcanic plateau of Iceland is a product of mantle plume activity that started about 20 Ma ago and resulted in the appearance of the Iceland hotspot. It is suggested that shortly before the onset of the opening of the North Atlantic (56 Ma ago), the hotspot was located beneath Greenland [19].

Hotspots and mid-ocean ridges (MOR) are the main manifestations of mantle upwelling and magma generation [16]. It is commonly assumed that spreading axes are supplied with melt from the upper, depleted mantle, whereas hotspots are a result of plume ascent from the deeper, fertile mantle. The mantle flow may, however, propagate from a hotspot along the adjacent spreading axis, giving rise to interaction between the hotspot and MOR. Such interaction is expressed in thermal anomalies, geochemistry, petrology, bathymetry, increase in the crust thickness, and anomalous geometry of the spreading axis [4]. Iceland is unique in its location close to the spreading axis. Therefore, the interaction between the spreading axis and hotspot is especially evident here [37]; the result of this interaction is most distinctly displayed at the Reykjanes Ridge.

The oceanic Reykjanes Ridge is bounded in the north by the South Iceland seismic zone, related to shear stresses concentrated between the overlapping Western and Eastern rift zones. It is suggested that this zone has developed due to the southwestward propagation of the Eastern Rift Zone over the last 3 Ma [12]. The southern termination of the Reykjanes Ridge is the transform Bight Fracture Zone that crosses the ridge axis at 56°47′ N. This fracture zone is right-lateral with a 15-km offset of the spreading axis; it extends up to the crust 36 Ma in age [5]. Nontransform offsets develop in such cases at slow-spreading MORs. Further to the south, the Mid-Atlantic Ridge (MAR) strikes at 5° NNE normally to the direction of spreading. To the north, the spreading axis deflects from this direction through 31° clockwise, separating orthogonal spreading at the MAR from oblique spreading at the Reykjanes Ridge. A tendency exists of MORs to approach a hotspot [16]. Oblique spreading at the Reykjanes Ridge may be explained by this tendency.

Since the Reykjanes Ridge differs from other slow-spreading MORs [9], it has attracted special attention and was intensely studied in the 1960s, 1970s, and 1990s, including its regional and local bathymetry, gravity measurements, and reflection seismic surveying. Several modifications of refraction seismic profiling were carried out along the ridge axis, along some isochrons, and at various angles to the ridge strike. In Leg 49 DSDP, holes 409, 408, and 407 were drilled through crust 2.4, 23, and 37 Ma in age, respectively. Deep-sea drilling was performed at continental margins near southeastern Greenland (Legs 152 and 163 ODP) and on the Hutton Bank (Leg 81 DSDP). The geochemistry of the igneous rocks was studied at the axis of the Reykjanes Ridge and in the cores of boreholes. The results of all these studies have been reported in numerous publications, which cannot be listed in a short paper. The integral characteristics of the Reykjanes Ridge were considered in [5, 7, 18, 20, 26, 27, 32, 35].

MAIN CHARACTERISTICS OF THE REYKJANES RIDGE AND ADJACENT BASINS: AN OVERVIEW

All seismic experiments have shown that the basins adjoining the Reykjanes Ridge are underlain by oceanic crust. The crust thickness of this ridge gradually diminishes moving away from the Iceland hotspot from 12.7 km at 63°06′ N to the normal value of 7 km at 57°30′ N [24]. The same trend was established near the continental margins [27].

The Iceland hotspot affected the evolution of the continental margins in the North Atlantic [28]. The breakup of the continents was accompanied here by voluminous volcanism over a vast territory of volcanic margins. The time span between the onset of stretching of the continental crust and the beginning of spreading in the North Atlantic was extremely short: 4–6 Ma vs. 25 Ma at typical nonvolcanic margins. The continent–ocean transition zone is very narrow: only a few tens of kilometers. Smallwood and White [28] supposed that this circumstance was caused by attenuation of the stretched continental lithosphere owing to the enormous volume of melt.

A part of the Reykjanes Ridge 300 km long to the south of 58°47′ N (the southern ridge) is similar to the slow-spreading MAR in morphology and segmentation. The depth of the valley is small (0.5 km) in comparison with the MAR (1–3 km). The recent volcanic activity is concentrated within the inner valley. The axial valley depth decreases northward, and at 58°47′–59° N the valley gradually passes into a wide axial volcanic rise (the northern ridge). The Reykjanes Ridge rises to the north, largely owing to thickening of the crust. The northward diminishing Bouguer anomaly confirms this conclusion. Searle at al. [24] explain this phenomenon by the greater degree of partial melting induced by heating related to the asthenospheric flow from the Iceland hotspot. The second cause of the rise is isostatic uplift above the hot mantle [24]. Earthquakes in the northern ridge are related to the deepest sources (8–10 km), which, however, remain in the crust. The maximal depth of earthquake sources marks the lower boundary of the elastic (brittle) crustal material, so that a considerable part of the lower crust may be rather hot [31], as follows from the apparent thickness of the elastic lithosphere calculated by Owens [24]. The elevated temperature of the lower crust prevents variations in the thickness of the crust and its segmentation [6, 35].

The neovolcanic zone of the Reykjanes Ridge consists of extended, right-lateral en echelon arranged axial volcanic ranges orthogonal to the direction of spreading. The volcanic ranges are bounded by faults, which are orthogonal to the direction of spreading in the neovolcanic zone and turn parallel to the ridge beyond its limits [22].

Appreciable linear V-shaped structural elements crosscutting the crustal isochrons are characteristic of the Reykjanes Ridge. These structural elements are expressed more distinctly in free-air gravity anomalies than in topography. The sides of the V-shaped structural elements converge southward to meet at the axis of the Reykjanes Ridge. This structural pattern was first reported by Vogt [33]. It is assumed that the V-shaped ranges are related to temporary variations in magma generation along the ridge axis induced by fluctuations of plume [15]. The V-shaped ranges are bounded by nonsegmented crust [17]. The difference in the crust thickness between the V-shaped ranges and intermediate troughs is 2 km [37].

The interaction of the hotspot with the MAR produces chemical anomalies in the oceanic basins. On this basis, Taylor et al. [32] inferred that the lavas of the Reykjanes Ridge contain a contribution (>20%) of the Iceland hotspot at all distances from its center.

Only one crustal magma chamber at a depth of 2.5 km from the oceanic floor was detected at 57°45′ N beneath the axis of the Reykjanes Ridge [25] and only one site of hydrothermal activity at 63°06′ N is known [11]. The many similar features of the Reykjanes Ridge and the East Pacific Rise (elevated mantle temperature, axial volcanic rise instead of rift valley, absence of systematic variation in crust thickness, and insignificant systematic fluctuations of Bouguer anomalies along the axis) indicate that a long-lived crustal magma chamber exists beneath the northern Reykjanes Ridge. One of the factors indicating the effect of the Iceland hotspot is the low permeability of the oceanic lithosphere beneath the axis of the Reykjanes Ridge due to the small umber of fractures and faults in the bottom and decrease in the depth of their penetration owing to ductile behavior of the lower crust and the upper mantle. Thus, it may be suggested that the hydrothermal system beneath the Reykjanes Ridge operates at a deeper level than elsewhere in the MAR [9], and hydrothermal solutions do not vent on the oceanic floor.

Clearly expressed symmetric magnetic anomalies 1–24 are detected above the Reykjanes Ridge and the adjacent basins [13, 30, 31]. A plate-tectonic reconstruction of the magnetic anomalies was proposed for the first time by Pitman and Talwani [23]. Two areas of the oceanic crust unbroken by faults are recognized near the Reykjanes Ridge: the older crust formed during the early stage of spreading and extending for 1300 km to the south of the hotspot center and the younger crust near the axis of the Reykjanes Ridge, which extends for 1000 km from the hotspot center. In both areas, the crust thickness is increased to 10–11 km in comparison with 6–7 km typical of the normal oceanic crust. It is suggested that this difference indicates an elevated mantle temperature. The above-mentioned areas are separated by normal oceanic crust. The ridge axis is orthogonal to the direction of spreading, the ridge is segmented, and the segments are divided by numerous fracture zones (disturbed magnetic zone), as was established for the first time by Vogt [33] on the basis of sporadic sections and has been supported by more detailed data on potential fields [38].

The change in the geometry of spreading axes has been attributed to the character of interaction between the hotspot and spreading axis, the variation of asthenospheric flow issuing from a plume, or variation in plume temperature [4, 34, 38].

RESEARCH METHOD AND FACTUAL DATA

The main method used in this study was detailed analysis of the magnetic anomalies and geological history of the Reykjanes Range and the adjacent basins using all available information from the literature. The factual basis of the study includes original data obtained with participation of the authors in the course of Russian oceanographic expeditions over several decades (Figs. 1, 2). The survey tracks of systematic surveying were spaced at 5–7 km in the axial zone, at 15–20 km at the flanks of the ridge, and up to 50 km in the adjacent basins. The surveying accuracy was 0.5 km.

For the segment of the Reykjanes Ridge north of 60° N, which was not covered by our magnetic survey, we used the available data from international databases (National Geophysical Data Center, NGDC), including the data from of expeditions CD87 and EW9008 [20] in the axial zone of the Reykjanes Ridge between 58° and 62° N within a tract up to 100 km wide on both sides of the axis [22]. Our bathymetric grid was supplemented by grid ETOPO2v2 ($2' \times 2'$) obtained from satellite data. Using the above information, we compiled a magnetic and bathymetric database. The topographic map of the oceanic bottom near the axis of the Reykjanes Ridge is shown in Fig. 1; a shaded map of the anomalous magnetic field of the same territory with axes of the identified magnetic anomalies and an example of identification is presented in Fig. 2.

Although the Reykjanes Ridge is the main objective of our study, for analyzing magnetic field, we added the vast Iceland region of the North Atlantic, including the Kolbeinsey Ridge and the northern Mid-Atlantic Ridge close to the Charlie Gibbs Fracture Zone (Fig. 3). The expanded study territory was dictated in part by the need to obtain more reliable estimates of the rotation poles. Expansion of the study territory to the north of Iceland in combination with the investigation of the Reykjanes Ridge makes it possible to compare the effect of the hotspot on the spreading axis north and south of Iceland.

Our magnetic database allowed us to depict a detailed pattern of the regional anomalous magnetic field that extends from the spreading axes of the aforementioned ridges to the crust 20 Ma in age (Anomaly 6) on both sides of the axis. As a result, we provided insights into the geochronology of the magnetic anomalies and identified the entire succession of spreading magnetic anomalies from Anomaly 6 to the axial anomaly. The axes of the linear magnetic anomalies for each chron were digitized to compile a digital map of the axes (Fig. 2). The rotation poles of the North American and Eurasian plates were calculated for the first time for each of 21 magnetic inversions over the last 20 Ma.

The kinematic parameters of the opening of the North Atlantic were estimated on the basis of the calculated poles. Specially developed original software for geochronological analysis of the anomalous magnetic

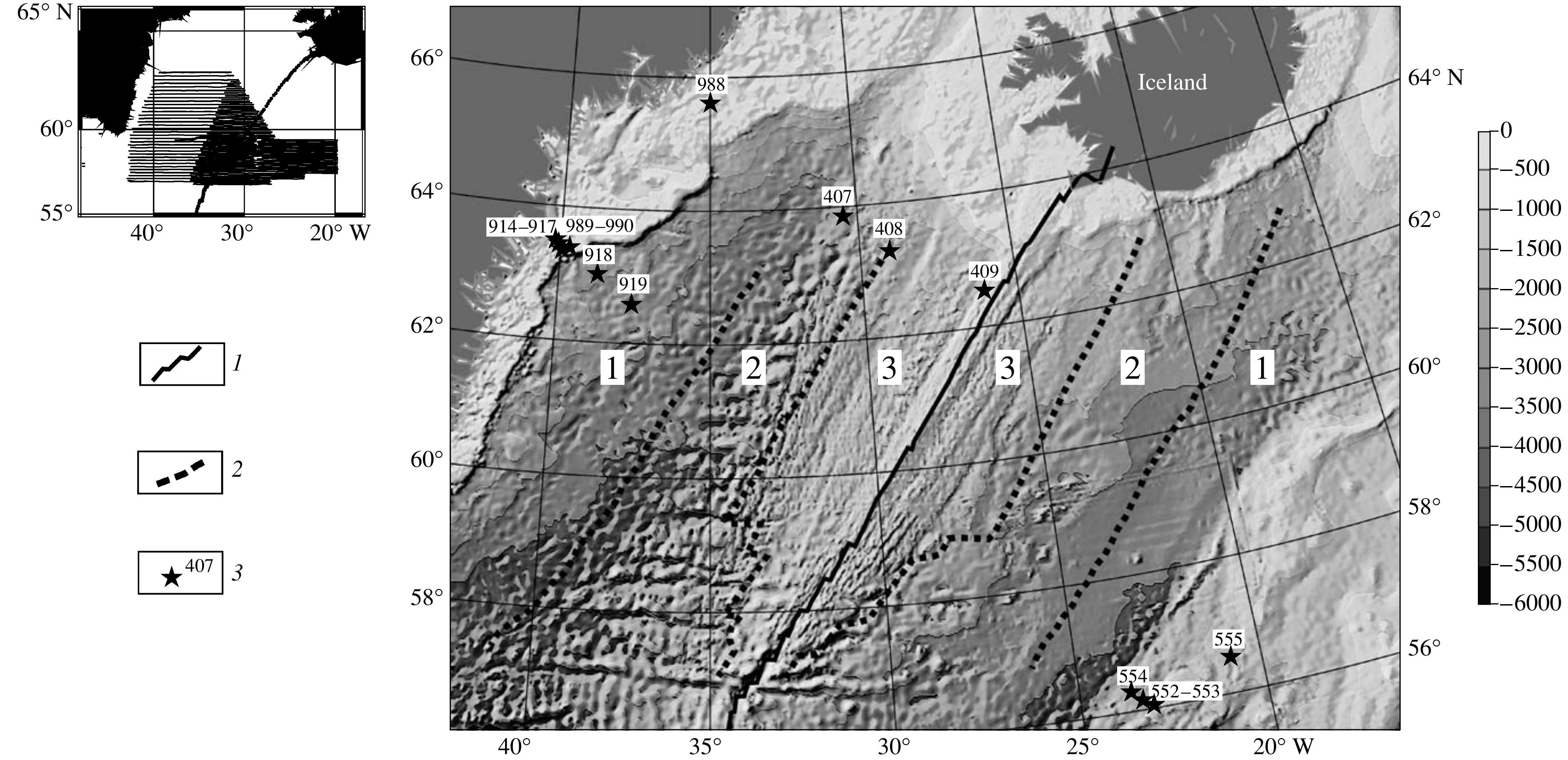


Fig. 1. Topography of ocean floor at the axis of the Reykjanes Ridge based on Russian bathymetric grid supplemented by ETOPO2v2 $(2' \times 2')$ grid obtained from satellite data. (*1*) Axis of the Reykjanes Ridge; (*2*) boundaries of the ocean floor areas formed during different stages of the ridge evolution; numerals 1–3 denote stage numbers; (*3*) holes of deep-sea drilling.

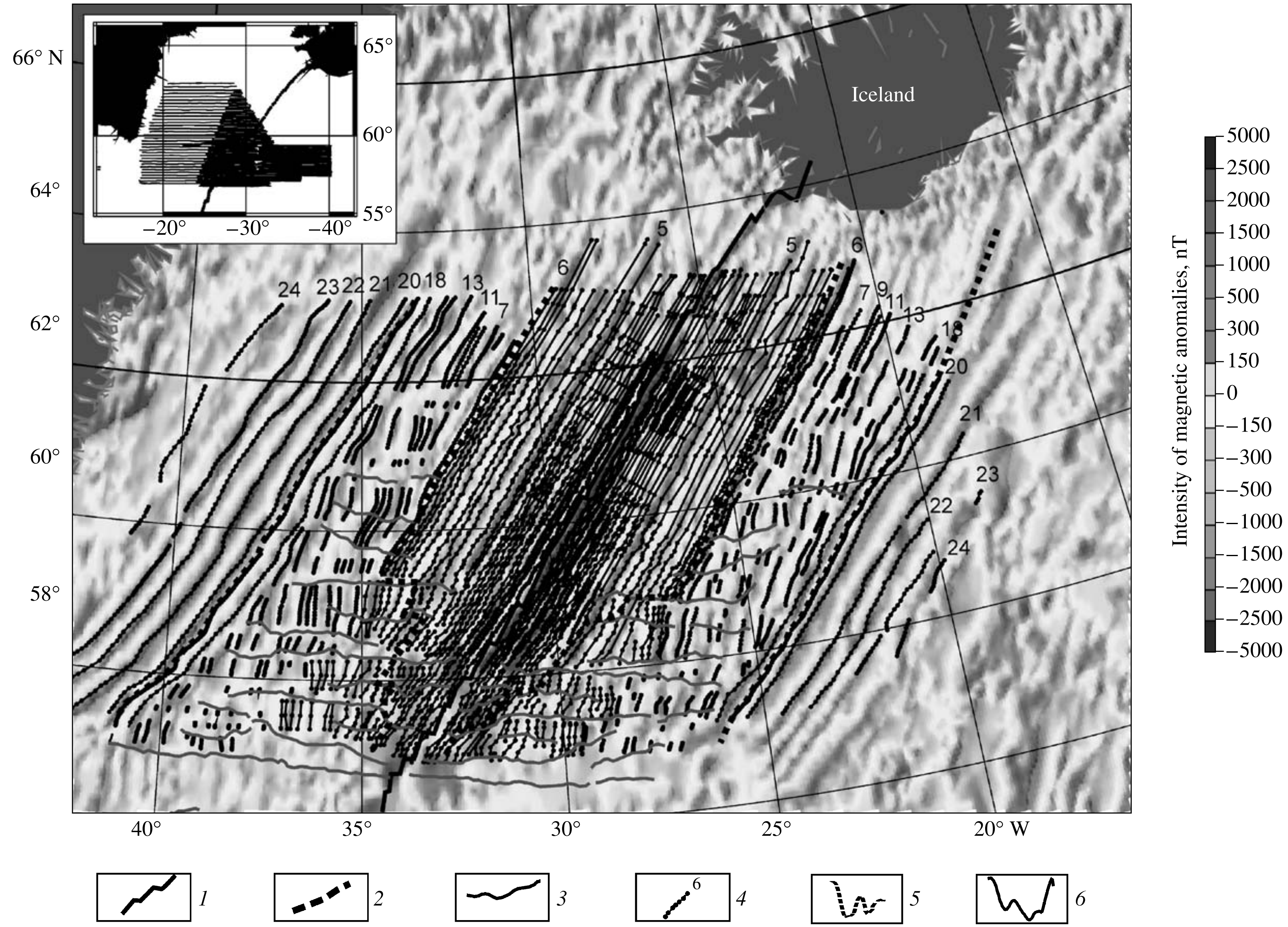
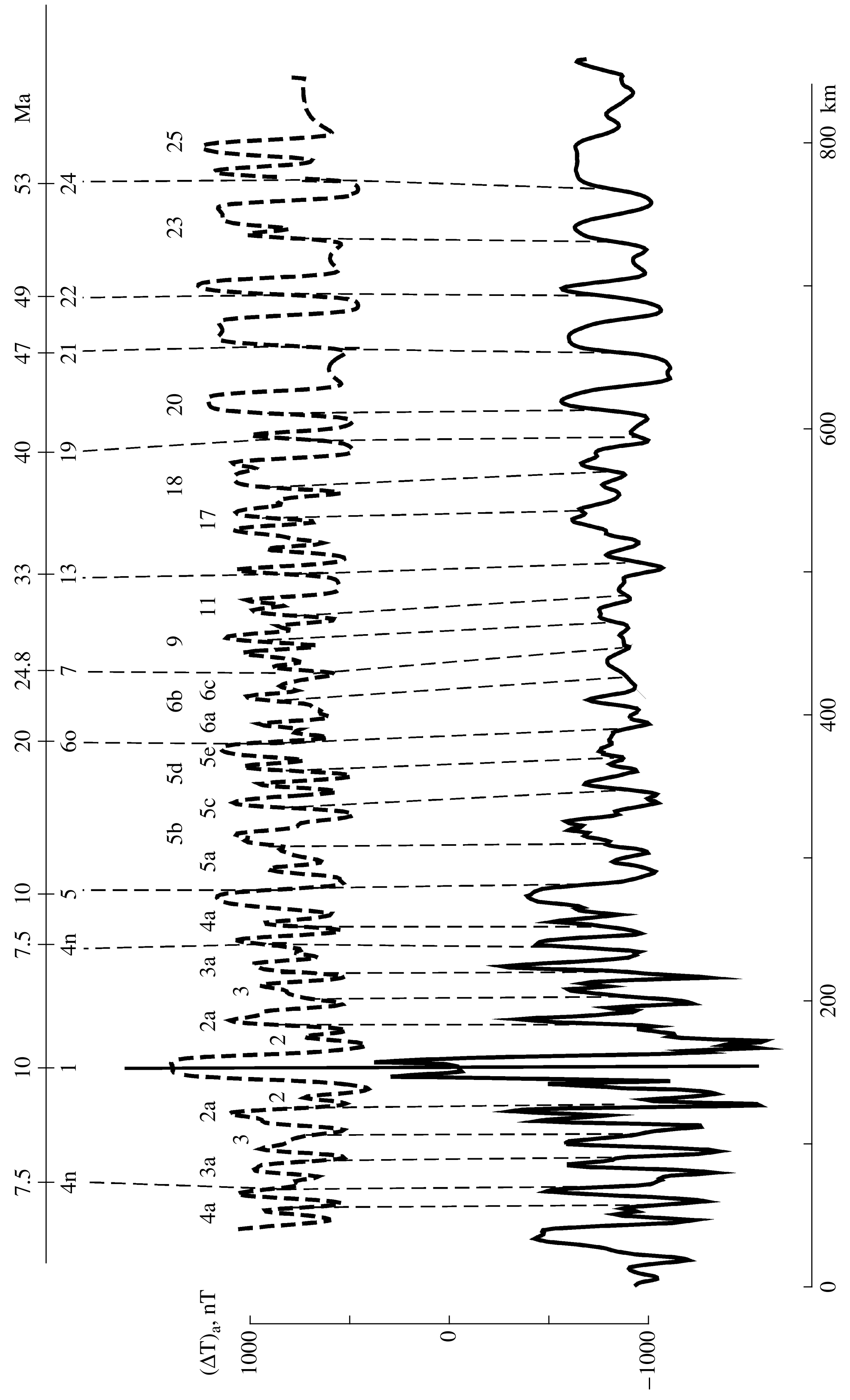


Fig. 2. Shaded map of anomalous magnetic field of the Reykjanes Ridge and the adjacent basins with axes of magnetic anomalies and an example of their identification. The map is based on the magnetic database that comprises the results of Russian magnetic syrveying supplemented by the data from expeditions CD87 and EW9008 covering the axial part of the Reykjanes Ridge from 58° to 62° N within a tract 100 km wide on both sides of the axis [20, 22].

(*1*) Axis of the Reykjanes Ridge; (*2*) boundaries of the bottom areas formed during different stages of the ridge evolution; (*3*) nontransform offset; (*4*) axis of magnetic anomaly and its number; (*5*) model field $(\Delta T)_a$ with magnetic anomaly numbers, after the geomagnetic polarity timescale proposed by Cande and Kent [8]; (*6*) observed field $(\Delta T)_a$ along the line LD850320 that crosses the axis of the Reykjanes Ridge at 59.9° N. The correspondence of the model and observed anomalies is shown by thin dashed lines; the axial anomalies are connected by a solid line. The lines of Russian hydromagnetic surveying are shown in the inset.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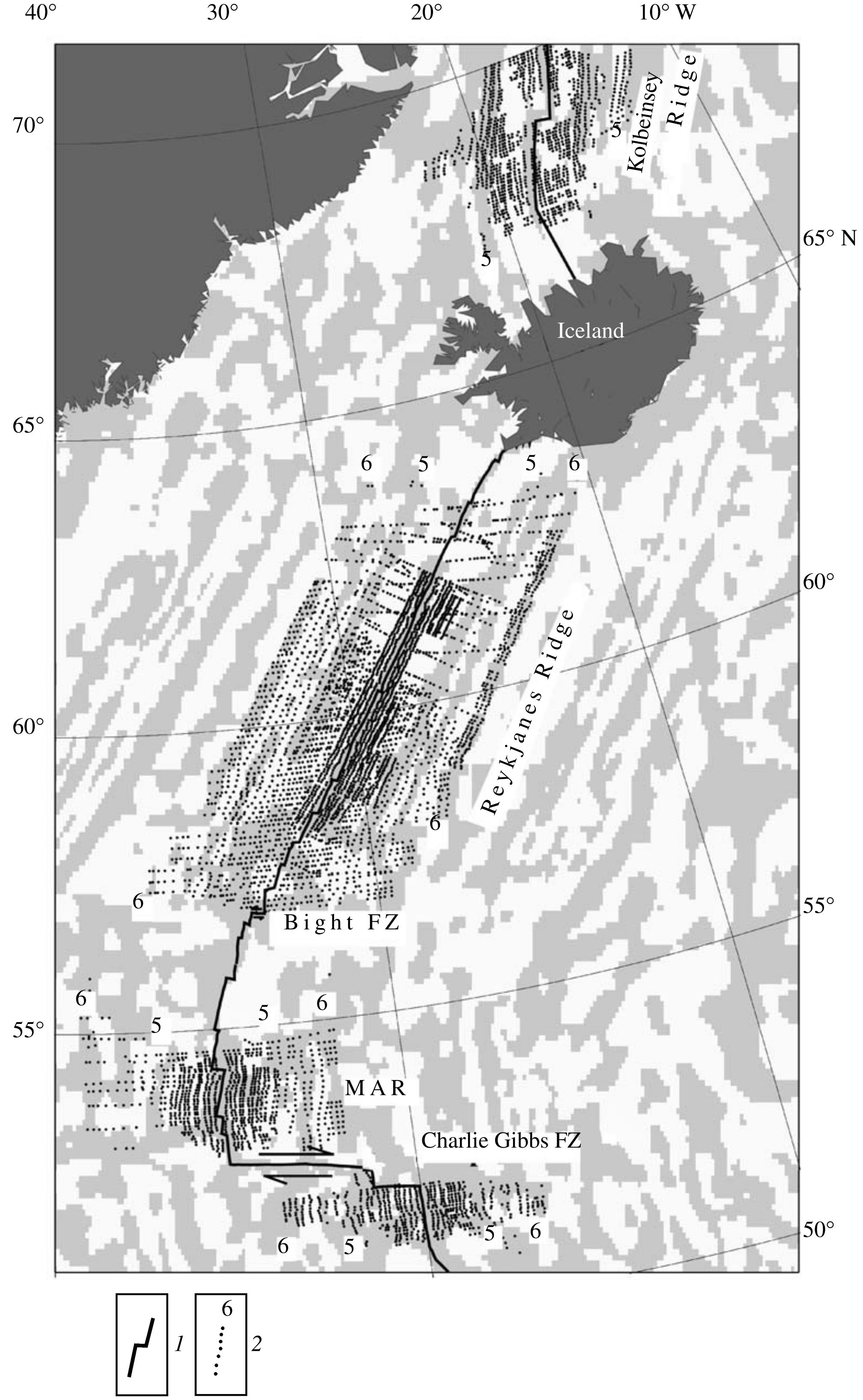

Fig. 3. Shaded map of magnetic anomalies in the Iceland region of the North Atlantic, including the northern MAR and the Reykjanes and Kolbeinsey ridges with axes of magnetic anomalies.

(*1*) Spreading axes with transform fracture zones and nontransform offsets; the arrows at the Charlie Gibbs and Bight fracture zones indicate the direction of relative motion of the oceanic floor; (*2*) axis of magnetic anomaly and its number.

field [1, 3] was used for solving the problems listed above.

The overall succession of magnetic anomalies in the disturbed magnetic zone was identified for the area covered by Russian investigations [2, 21].

Three regions with different features of spreading magnetic anomalies were confirmed, their boundaries were specified, and the pattern of anomalous magnetic field in each region was detailed.

In addition to the kinematic parameters of ocean floor spreading, a value for the obliquity of plate spreading relative to the axis of the Reykjanes Ridge was determined and compared with the obliquity of the neighboring segments of the boundary between the North American and Eurasian plates. The value of obliquity is the angle through which the axes of the magnetic anomalies deflect from the line perpendicular to the direction of the oceanic bottom spreading.

Using the poles of opening of the oceanic bottom off the axis of the Reykjanes Ridge, the angular rates of spreading and the rates of spreading along the line of drifting which crosses the ridge axis at 59.6° N were calculated. The rotation poles of the lithospheric plates over the last 20 Ma were determined from the axes of the identified magnetic anomalies [21]. The poles related to spreading before 20 Ma ago were taken from [29].

The performed investigations allowed us to ascertain the causes of the variable kinematics of spreading off the axis of the Reykjanes Ridge during its evolution, to establish the main stages of this evolution, and to estimate the effect of the Iceland hotspot on the crust accretion.

RESULTS

Main Stages in Evolution of the Reykjanes Ridge

The detailed analysis of the magnetic anomalies confirmed the previously obtained data on the occurrence of two areas of oceanic crust unbroken by faults in the Reykjanes Ridge and the adjacent basins. These areas are separated by normal oceanic crust. This feature of anomalous magnetic field was first pointed out by Vogt [33], who noted a transition from older, nonsegmented crust to normal slow-spreading oceanic crust broken by numerous faults. This transition is confined to Anomaly 19 on both sides of the axis. Later on, Vogt and Avery [34] showed that the Reykjanes was a normal segmented spreading ridge until the early Miocene, approximately 18 Ma ago. White [38] called attention to the difference in the strikes of the anomalies and in their extents between the two areas of nonsegmented crust. In his opinion, the spreading was orthogonal to the axis in the older crust and oriented at an angle of 30° in the younger crust. The older nonsegmented crust extends for 1300 km from the center of the hotspot, whereas the younger crust extends only for 1100 km up to 58° N. In both areas, the crust thickness is increased to 10–11 km in comparison with 6–7 km of the normal oceanic crust located between the two areas considered above. According to White [38], the older nonsegmented crust is separated from the normal oceanic crust by Anomaly 19 (42 Ma). Jones et al. [17] suggested that the direction of spreading at the Reykjanes Ridge changed between anomalies 17 and 18 (early Eocene).

Vogt [33] explained the oblique orientation of the ridge relative to the direction of spreading by the stress field related to the asthenospheric flow from the Iceland hotspot. White [38] referred the changed style of the oceanic crust formation to the increase of mantle temperature. According to his calculations, the rise of temperature by 50°C brings about an increase in crust thickness by 30% and allows the mantle to remain too hot and to react to extension of the axis as a ductile rather than elastic (brittle) material. As a result, crust devoid of faults and with an axial rise instead of a rift valley is formed.

The magnetic database allowed us to determine the character of the magnetic anomalies and its spatiotemporal variations more exactly. The oldest anomalies 24–19 (54–40 Ma) are linear, parallel to one another and to the Reykjanes Ridge, and not displaced. To the west of the ridge, this group of anomalies was traced from 63.15° to 57° N, while to the east, from 60° to 57° N. Over this period, the spreading from the Reykjanes Ridge was the fastest: the half-rate of spreading was 2.1 cm/yr.

A disturbed magnetic zone adjoins the Eocene magnetic anomalies. The width and age interval of this zone vary along the axis. North of ~59° N (northern Reykjanes Ridge), this zone is limited by magnetic anomalies 19 and 6 (40–24 Ma). Between 59° N and the Bight Fracture Zone, the disturbed magnetic zone gradually widens southward at the expense of younger anomalies. At 59° N, its young boundary corresponds to Anomaly 5D, whereas at the Bight Fracture Zone it corresponds to Anomaly 5n.2 (17 and 11 Ma, respectively). Rearrangement of the spreading axis in the disturbed magnetic zone occurred in the Oligocene, owing to the change in the kinematics of plate motion in the region adjacent to the Reykjanes Ridge. The changed relative motion of the plates affected the segmentation of the plate boundary. Two periods of rearrangement are distinguished (Fig. 4). During the first period, from Anomaly 19 to Anomaly 13, the geometry of the axis of the Reykjanes Ridge changed from a rectilinear single axis (A19) to a series of displaced segments (A18, A16, A13). At the same time, the axis strike changed from northeastern to northwestern. The first period of rearrangement coincided in time with deceleration of the spreading rate at the Ran Ridge in the Labrador Sea. During this period, the spreading rate at the Reykjanes Ridge also decreased to 0.8 cm/yr and its axis was broken into segments 30–80 km long. The strike of the segments became approximately perpendicular to the new,

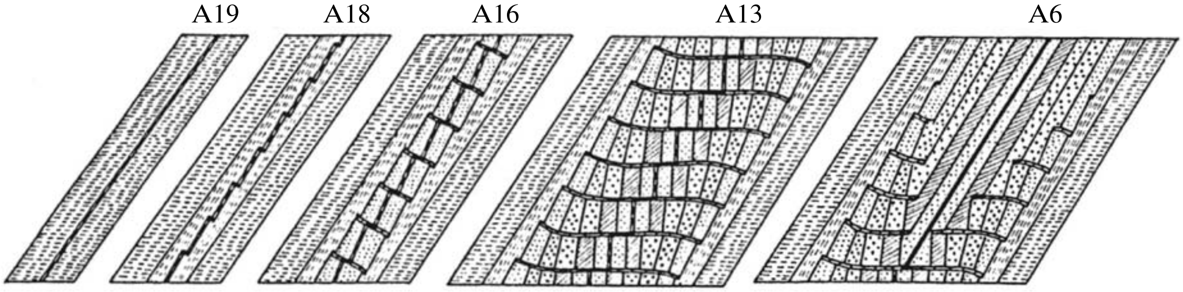

Fig. 4. Rearrangement of the axis of the Reykjanes Ridge during the second stage of its evolution. The numbers of the anomalies corresponding to the given axis configuration are written above. The ocean floor areas formed between the indicated anomalies are shown by various patterns.

nearly east–west direction of spreading. The second period of rearrangement of the Reykjanes Ridge started during the epoch of Anomaly 13 (~35 Ma ago) and coincided in time with the completion of spreading in the Labrador Sea and Baffin Bay. During this period, the rift of the Reykjanes Ridge propagated to the southwest (Figs. 2, 4, A13–A6). During the epoch of anomaly 6c (~26 Ma ago), the activity of the Eigyr Ridge terminated; spreading started at the Kolbeinsey Ridge, and the half-rate at the Reykjanes Ridge increased to 1.1 cm/yr.

The rearrangement of the spreading axis continued until 20 Ma ago (Anomaly 6) in the northern Reykjanes Ridge, until 17 Ma ago (Anomaly 5D) in the northern part of the southern Reykjanes Ridge, and until 11 Ma ago (Anomaly 5n.2) in its southernmost part. After completion of the rearrangement, the axis of the Reykjanes Ridge and magnetic anomalies rotated approximately 30° clockwise and retained the same strike as at present, testifying to oblique spreading in the Neogene. The Neogene magnetic anomalies are similar to the Eocene anomalies in their characteristics: they are linear, parallel, devoid of offsets, and oriented obliquely to the line perpendicular to the direction of spreading. The half-rate of spreading varies near 1 cm/yr.

Taking the differences in features of the magnetic anomalies into account, the evolution of the Reykjanes Ridge may be subdivided into three stages (Figs. 1, 2):

(1) initial, relatively fast opening in the Eocene (54–40 Ma); no segmentation of the crust and rectilinear spreading axis without changing its strike;

(2) ultraslow-spreading in the late Eocene–Oligocene (40–24 Ma) at the northern Reykjanes Ridge and in the late Eocene–early Miocene (40 to 17–11 Ma) at the southern Reykjanes Ridge; the crust is segmented, ridge axis is perpendicular to the direction of spreading, axis is repeatedly rearranged;

(3) oblique slow spreading in the Neogene and Quaternary (<24 Ma in the northern Reykjanes Ridge and <17 Ma in the southern Reykjanes Ridge); no segmentation of the crust and rectilinear spreading axis without changing its strike.

The lack of segmentation of the oceanic crust established from the magnetic data is an indicator of the effect of the hotspot on the accretion of the oceanic crust at the Reykjanes Ridge during the first stage of its evolution. The increasing thickness of the crust and the gradually increasing concentration of magmatism along the hotspot trail established by drilling and reflection and refraction seismic surveying [14] confirm this statement and testify to the elevated temperature of the upper mantle.

The segmentation of the oceanic crust, its normal thickness (7 km for the crust 37 Ma in age [37]), and the rearrangement of the previously existing spreading axis imply that the hotspot did not affect the Reykjanes Ridge during the second stage of its evolution. Probably, the faults that arose as a result of the rearrangement of the ridge axis hindered the propagation of asthenospheric flow from the hotspot to the ridge axis.

The axis of the Reykjanes Ridge formed during the third stage of its evolution in the Neogene, when the Kolbeinsey, Reykjanes, and Mid-Atlantic ridges served as a boundary between the North American and Eurasian plates, was characterized by lack of segmentation and by oblique spreading as indicators of the effect exerted by the Iceland hotspot.

The following attributes confirm the substantial effect of the Iceland hotspot on the accretion of the oceanic crust at the Reykjanes Ridge during the third stage of its evolution: the previously established geological and geophysical features of the Reykjanes Ridge; the asthenospheric flow along the ridge axis from the hotspot; the heated upper mantle and lower crust; the shallow depth of the bottom and the development of an axial rise instead of a rift valley in the northern Reykjanes Ridge; the increasing thickness of the crust and its gradual decrease moving away from the hotspot; and the V-shaped ranges that crosscut the isochrons of oceanic floor [24, 32, 33].

Spatiotemporal Variation of Spreading Obliquity

The first investigations, performed in the 1970s [33, 34], showed that the Reykjanes Ridge is characterized

Ultimate rotation poles of the North American and Eurasian plates over the last 20 Ma

Chron	Age, Ma	North latitude, degree	East longitude, degree	Angle, degree
1n	0.781	67.582	136.599	0.1975
2n	1.778	61.905	138.747	0.3828
2An,1	2.581	62.696	136.557	0.5498
2An,3	3.596	61.553	138.541	0.7566
3n,1	4.187	62.671	135.515	0.8774
3n,4	5.235	62.770	137.83	1.1138
3An,1	6.033	63.125	134.918	1.2515
3An,2	6.733	64.491	134.442	1.4333
4n,1	7.528	61.246	136.869	1.5508
4n,2	8.108	64.277	137.157	1.7785
4A	8.769	64.883	135.637	2.0531
5n,1	9.779	65.974	137.223	2.2624
5n,2	11.040	67.518	133.047	2.6118
5An,2	12.415	67.201	133.855	2.9883
5AC	13.734	66.892	132.917	3.3234
5AD	14.581	69.422	127.737	3.6814
5Cn,1	15.974	69.282	131.553	4.084
5D	17.235	68.786	129.891	4.3813
5E	18.056	70.157	129.117	4.7072
6ny	19.722	72.610	126.049	5.0884
6no	20.040	69.298	131.192	5.0733

by oblique spreading, when magnetic anomalies and isochrons are not perpendicular to the direction of lithospheric plate motion. As is known, hotspots may be a cause of time-dependent variations in the geometry of spreading axes. In particular, the stronger the effect on the spreading axis the stronger the tendency of the axis to approach the hotspot [16]. At an approximately equal distance of the spreading axis from the hotspot (in plan view), the obliquity of the spreading axis, defined as the angle of deflection of the magnetic anomaly axes from the line perpendicular to the spreading direction, is the greater the more strongly the hotspot affects the spreading axis. To test this relationship, the spatiotemporal variations of spreading obliquity were analyzed for the Reykjanes, Kolbeinsey, and Mid-Atlantic ridges with help of maps compiled on the basis of the available magnetic data (Fig. 3). The axes of magnetic anomalies shown in the map were identified by the authors of this paper. The isochrons drawn in this map are spaced at 1 Ma and cover the time interval from 0 to 20 Ma.

The rotation poles for the North American and Eurasian lithospheric plates were calculated with a step of 1 Ma (Table). Previously, the rotation poles of plates had been calculated only for anomalies 5 and 6 (10 and 20 Ma in age). Pitman and Talwani [23] were the first to calculate the rotation poles. They showed that since the time of Anomaly 5, the opening of the North Atlantic from the Azores–Gibraltar Ridge to the Spitsbergen Zone can be described as a rotation relative to the pole located at 68° N and 129.9° E with a full angle of opening equal to 2.5° [23]. The position of the pole determined by us significantly differs from these coordinates. The discrepancy is caused by the insufficient coverage of the magnetic survey and the obsolete technique of pole calculation used by Pitman and Talwani. Attempts to calculate the poles of opening of the North Atlantic and the Eurasia Basin of the Arctic Ocean were made repeatedly in the 1970–1990. The poles were calculated for various segments of plate boundaries; various magnetic data were used for this purpose; and different results were obtained. Our data turned out to be close to the results published by Gaina et al. [10], who calculated the poles on the basis of anomalies 5n.2 and 6 at the Gakkel Ridge. The coordinates of these poles are 66.44° N, 132.98° E, and 68.91° N, 132.59° E, respectively. The angles of opening of the oceanic floor corresponding to the epochs of the above-mentioned anomalies—2.57° and 5.09°—are close as well.

On the basis of Fig. 3, the strikes of the lines perpendicular to the directions of spreading were predicted. These directions are shown in Fig. 5 as solid lines. The filled circles indicate the average weighted orientation of the magnetic anomaly segments. The orientation of the axial volcanic ranges, which determines the present-day position of the spreading axis (0 Ma in age) along the Reykjanes Ridge, is shown as well. The vertical band filled with dots indicates the time when the location of the opening pole was changed. As can be seen from the graphs, the obliquity of spreading changed in a different way at the studied spreading axes. The highest, and practically unchanged with time, obliquity of spreading (~30°) was established in the northern Reykjanes Ridge, where the effect of the Iceland hotspot on the ridge axis, judging from geophysical and geochemical investigations, was the strongest. In the southern Reykjanes Ridge, the obliquity of spreading generally increased with time. It was ~5°. 20–17 Ma ago, attained 13° 17 Ma ago, continued to grow up to 25° by 11 Ma ago, and then decreased to 20°. The next increase in the obliquity of spreading to an average weighted value of ~30° at the southern Reykjanes Ridge occurred about 7 Ma ago, when the rotation pole changed. Although the average weighted obliquity of spreading has been almost the same in the northern and southern Reykjanes Ridges over the last 7 Ma, the azimuths of particular segments of mantle isochrons (open circles) in the southern Reykjanes Ridge are scattered to a greater extent. A similar situation is characteristic of the time interval of 16–8 Ma, probably as a response to the diminishing effect of the Iceland hotspot on the southern ridge. This is supported by geological and geophysical data, in particular, by the

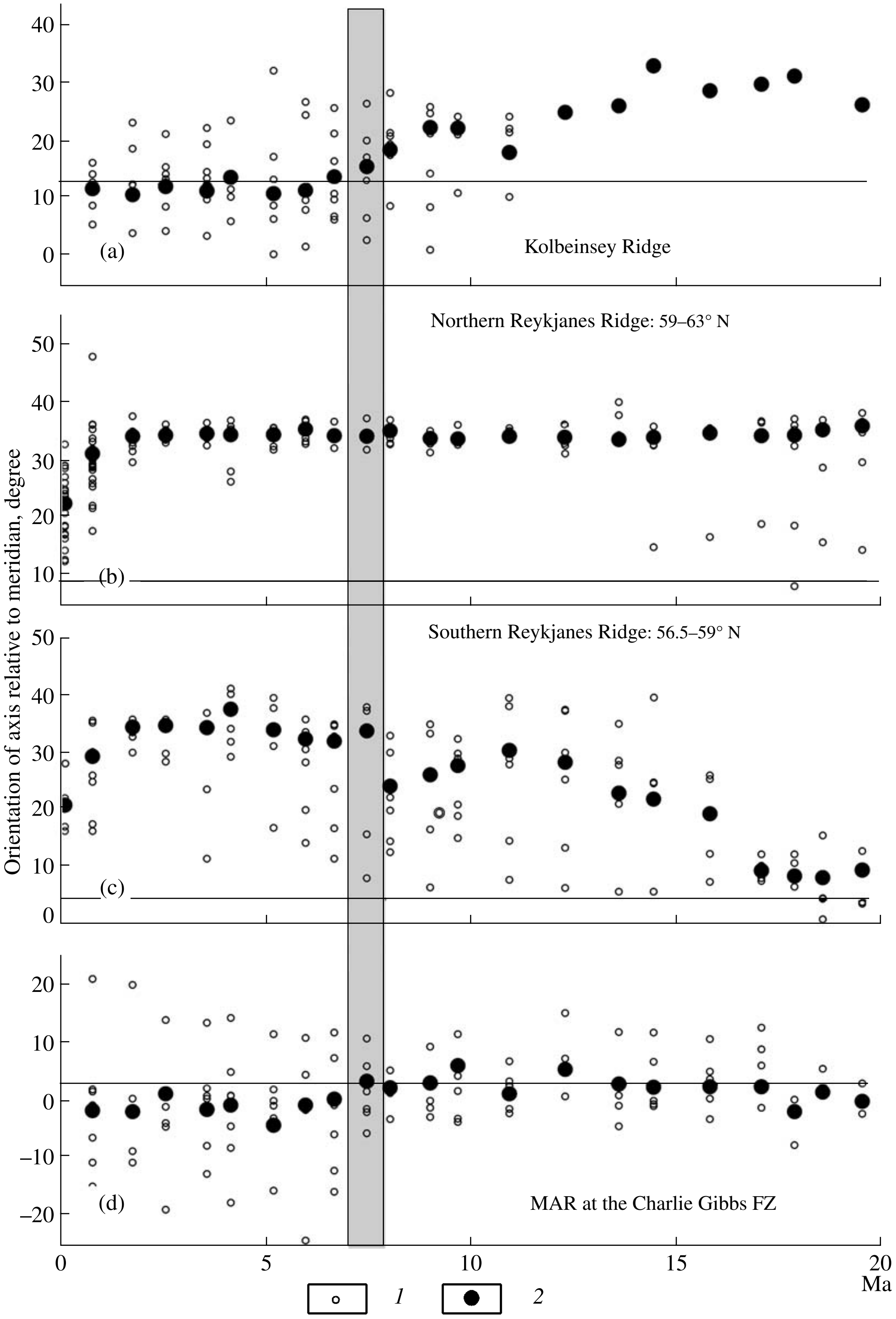

Fig. 5. Spatiotemporal variation of spreading obliquity. (*1*) Azimuths of particular segments of magnetic isochrons, (*2*) average weighted spreading obliquity. Negative values of orientation of magnetic isochrons correspond to the deflection of them to the west of the meridian. The gray vertical band indicates a period of changing of the ocean floor opening pole.

appearance of a rift valley instead of an axial rise, the decrease in crust thickness, and the greater depth of the oceanic bottom.

In the MAR near the Charlie Gibbs Fracture Zone, spreading was practically orthogonal to the ridge axis over all this time, though the azimuths of particular segments of magnetic isochrons has varied significantly, especially during the last 7 Ma. The obliquity of spreading along the Kolbeinsey Ridge was less than at the Reykjanes Ridge over the entire period under consideration, likely due to the lesser effect of the Iceland hotspot. Over the last 7 Ma, spreading at the Kolbeinsey Ridge was orthogonal. The transform Tjern Fracture Zone, which developed along the zone of maximal shear stress between the ends of the rift zones of the Kolbeinsey Ridge and northern Iceland [12], has approximately the same age (7–9 Ma). Thus, the development of the transform fracture zone became an obstacle to the propagation of the asthenospheric flow from the Iceland hotspot to the Kolbeinsey Ridge, and the attraction of its axis to the hotspot ceased.

The assessment of the obliquity of spreading made it possible to estimate the temporal variation of the effect of the Iceland hotspot on the axes of the studied ridges and led to the following conclusions:

(i) the northern Reykjanes Ridge has been affected by the Iceland hotspot almost over the last 20 Ma;

(ii) the effect of the Iceland hotspot on the southern Reykjanes Ridge was insignificant 20–17 Ma ago and then increased 16 and 11 Ma ago; since 7–8 Ma ago, the effect of the hotspot has grown substantially, remaining, however, less than the effect on the northern ridge;

(iii) the Iceland hotspot affected the Kolbeinsey Ridge to a lesser extent than the Reykjanes Ridge, and this effect terminated altogether upon the emergence of the transform Tjern Fracture Zone;

(iv) as follows from the appreciably scattered orientation of the segments of magnetic isochrons, the effect of the hotspot on the MAR near the Charlie Gibbs Fracture Zone started to develop 7 Ma ago.

Temporal Variation of Spreading Rate at the Reykjanes Ridge

Using the ultimate rotation poles, we calculated the differential rotation poles for anomalies 4n.1, 6no, 7, and 19 corresponding to the ages of 7.5, 20, 24, and 40 Ma, respectively. The differential rotation poles for anomalies 13, 21, 24, and 25 identified by other authors [29] were calculated as well. The angular rate of spreading and the rate of spreading along the line of drifting, which crosses the Reykjanes Ridge at 59.6 Ma, were calculated for each of the above-listed rotation poles. Because the poles of oceanic floor spreading were moving, the angular rates characterize the real variations of spreading rates. Nevertheless, the variations of both the angular and linear rates turned out to be similar (Fig. 6). The performed analysis demonstrates a tendency towards increase in the spreading rate at those stages of the evolution of the Reykjanes Ridge when it was affected by the hotspot. This is especially evident for the moment of continent breakup and the initial stage of spreading, when, as judged from drilling results and seismic surveying, the magmatic activity was the most intense. The direction of spreading along the Reykjanes Ridge changed abruptly 7.5 Ma ago along with a decrease in the spreading rate. This event coincided in time with the eastern shift of the spreading axis in Iceland as a response to the western displacement of the plate boundaries relative to the center of the Iceland hotspot. In this period, both the angular and linear rates became commensurable with the spreading rate during the second stage, when the effect of the Iceland hotspot was at a minimum.

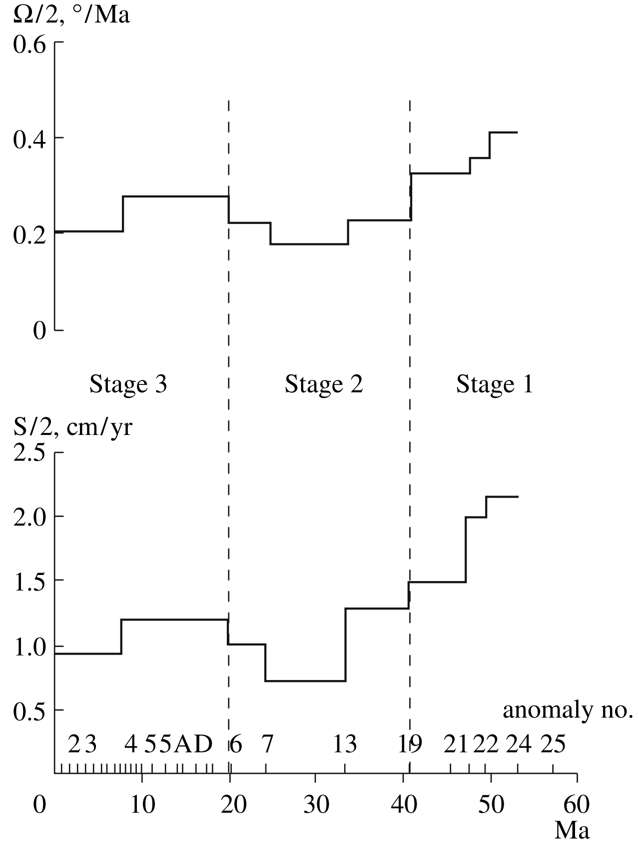

Fig. 6. Variations of angular and linear half-rates of the ocean floor accretion off the axis of the Reykjanes Ridge.

CONCLUSIONS

The new magnetic database comprises the results of the detailed Russian hydromagnetic surveys supplemented by the data from foreign magnetic measurements. The magnetic data together with all available information on the Reykjanes Ridge and the adjacent basin taken from the literature allowed us to recognize three stages in the evolution of this ridge, which differed in the geodynamic regime of oceanic crust accretion depending on the effect of the Iceland hotspot on the spreading axis.

Detailed consideration of the geological history of the magnetic anomalies made it possible to estimate the time intervals of each stage and to ascertain the causes of the variable regime of crustal accretion.

The first stage is dated at the Eocene (54–40 Ma ago). The spreading axis was rectilinear and attracted to the hotspot. The crust is not segmented. These attributes did not hinder the asthenospheric flow from the Iceland hotspot from propagating along the axis of the Reykjanes Ridge. The geodynamic regime of crustal accretion was controlled by interaction of the spreading axis with the hotspot.

The second stage covered the late Eocene–Oligocene (40–24 Ma) in the northern Reykjanes Ridge and the late Eocene–early Miocene (40 to 17–11 Ma) in the southern Reykjanes Ridge. The repeated rearrangement of the ridge axis was related to the changing kinematics of the plates adjacent to the Reykjanes Ridge. The ridge axis and the crust were broken by numerous faults and nontransform offsets into segments 30–80 km long. The strike of the segment was approximately perpendicular to the direction of spreading. The faults that crosscut the spreading axis prevented propagation of the asthenospheric flow from the hotspot to the spreading axis. The geodynamic regime of crust accretion was typical of normal, slow-spreading oceanic crust.

The third stage developed in the Miocene and Holocene: <24 Ma in the northern Reykjanes Ridge north of 59° N and <(17–11) Ma in the southern Reykjanes Ridge south of 59° N. The spreading axis was rectilinear, oriented obliquely relative to the direction of spreading, and directed toward the center of the Iceland hotspot. The crust was not segmented. These circumstances allowed the asthenospheric flow to move from the Iceland hotspot to the axis of the Reykjanes Ridge, propagating its axis due to decompression in the axial zone. The regime of crustal accretion was affected by interaction of the hotspot and spreading axis.

Detailed geochronological analysis of magnetic anomalies 1–6 (up to 20 Ma in age) allowed us to depict with a high accuracy (for the first time) the isochrons of the oceanic bottom spaced at 1 Ma. This, in turn, made it possible to estimate spatiotemporal variations in the obliquity of spreading over the last 20 Ma and to establish, on this basis, the variable effect of the hotspot on the Kolbeinsey and Mid-Atlantic ridges adjoining the Reykjanes Ridge in the north and the south.

(i) The northern Reykjanes Ridge was affected by the Iceland hotspot over all 20 Ma.

(ii) The effect of the Iceland hotspot on the southern Reykjanes Ridge is not documented before 17 Ma ago and markedly increased 7 Ma ago, when the location of the rotation poles changed.

(iii) The Iceland hotspot influenced the Kolbeinsey Ridge to a lesser extent than the Reykjanes Ridge, especially later than 12 Ma ago.

(iv) The effect of the Iceland hotspot on the Kolbeinsey Ridge terminated about 7 Ma ago, owing to the origin of the transform Tjern Fracture Zone, which created an obstacle to the asthenospheric flow from the hotspot.

(v) The Iceland hotspot affected the MAR near the Charlie Gibbs Fracture Zone beginning from 7 Ma ago; this effect was not as strong as on the Reykjanes Ridge.

The tendency towards increasing rate of spreading with reinforcing of the effect of the Iceland hotspot on the Reykjanes Ridge is outlined.

Thus, the results obtained provide additional insights into the accretion of the oceanic crust along the Reykjanes Ridge.

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