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The Main Stages of Formation of the Fram Strait in the Neogene: Analysis of Geological and Geophysical Data

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Abstract—The opening of the Fram Strait began in the Lower Miocene (~19.5 Ma) as a result of movements of the North American and Eurasian plates, which resulted in the formation of the narrowest segment of the strait, the Lena Trough. In the Early and Late Miocene (~19.5–9.8 Ma), the opening of the central part of the Fram Strait led to the formation of the central and northwestern parts of the Molloy Basin, which had an extended basement consisting of blocks of the West Spitsbergen fold-and-thrust belt. In the Late Miocene (~9.8 Ma), in the central part of the Fram Strait, a jump of its opening axis to the east occurred in the segments between the Molloy and Spitsbergen fracture zones, and spreading began in the northernmost segment of the Knipovich Ridge. In the Late Miocene (~9.8 Ma), deep-sea exchange of waters between the North Atlantic and the Arctic Ocean took place west of continental "fragments" of the Barents Sea: the Hovgaard Ridge and Mt. Hovgaard. In the Late Miocene (~6.7 Ma), the Molloy Basin began to open, which coincides with the beginning of continuous subsidence of the Hovgaard Ridge, which was in subaerial conditions, and with a threefold increase in the sedimentation rate in the central Molloy Basin. In the Late Miocene–Early Pleistocene (~9.8–1.8 Ma), a warm current from the North Atlantic could have passed along the eastern continental margin of Greenland and, at the peak of its maximum intensity, ensured the existence of biological diversity in the "polar desert" and "polar night" conditions in north–northeast Greenland and the shallow sea areas adjacent to the coast. The modern direction of cold and warm currents in the Fram Strait could have formed in the Early Pleistocene (~1.8 Ma) and may be associated with opening of the northernmost segment of the Knipovich Ridge.

Keywords: Eurasian Basin, spreading, geodynamics, anomalous magnetic field, theoretical axis of linear magnetic anomalies, seismic stratigraphy of sedimentary cover, Fram Strait, Knipovich Ridge, Molloy Basin, continental margin of the Barents Sea, North Atlantic, Arctic Ocean, directions of ocean currents

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INTRODUCTION

The Fram Strait is located between Greenland and Svalbard and connects the Norwegian–Greenland and Arctic basins (Fig. 1).

Tectonically, the Fram Strait is much longer and wider than geographically. In the south, the structure of the Fram Strait includes the northern part of the Norwegian–Greenland Basin, located above the Greenland Ridge; the northern continuation of the Fram Strait is the southwestern Eurasian Basin, located between reduced blocks of continental crust: the Yermak Plateau and Morris Jesup Rise [18].

The opening of the Fram Strait, which connected the North Atlantic–Arctic region, ensured deep water exchange between the North Atlantic and Arctic Ocean and influenced the global circulation of ocean waters and Earth's climate [10, 18, 19, 22].

Within the Fram Strait is the spreading Knipovich Ridge, which, through the Molloy and Spitsbergen fracture zone, bounds the basin and the Molloy spreading segment and connects with the Lena Trough, the continuation of which in the Eurasian Basin of the Arctic Ocean is the mid-ocean Gakkel Ridge (Fig. 1a).

One of the structural features of the Knipovich Ridge is its sharply asymmetrical position within the Norwegian–Greenland Basin, which is expressed in the significant proximity of the ridge to the western edge of the Barents Sea shelf compared to the distance to the western edge of the eastern shelf of Greenland. To explain the asymmetry, assumptions were made about restructuring of the system and the resulting jump/jumps (?) or straightening of the opening axis of the Knipovich Ridge [2, 6, 15, 18].

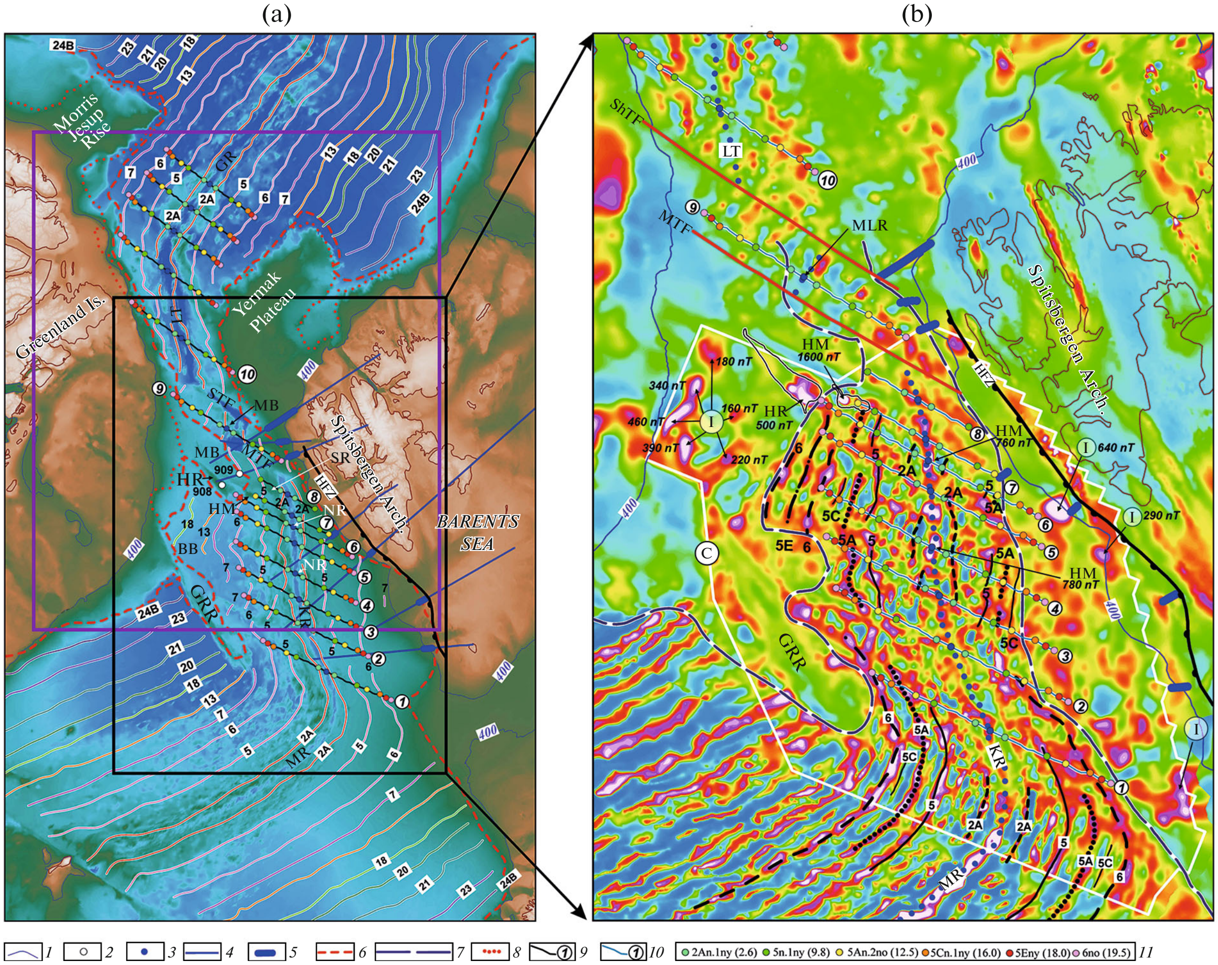

Fig. 1. Comparison of results of identification of axis of linear magnetic anomalies (LMA) in Fram Strait (according to data from [1, 3, 4, 6, 12, 14, 19, 24, 27, 33, 36]). (a) Position of LMA (according to [18]), based on IBCAO v.4 digital elevation model with Greenland ice sheet removed (according to [22]); (b) position of LMA (according to [15]) based on digital model of anomalous magnetic field (according to [15]). Shown (purple frame): theoretical position of axis of linear magnetic anomalies. Notation: GR, Gakkel Ridge; KR, Knipovich Ridge; MR, Mohns Ridge; MLR, Molloy Ridge; LT, Lena Trough; HR, Hovgaard Ridge; MH, Mt. Hovgaard; GR, Greenland Ridge; NR, neovolcanic ridges in rift valley of Knipovich Ridge; SR, Svyatogor Rise; MB, Molloy Basin; BB, Borea Basin; SFZ, Spitsbergen fracture zone; MFZ, Molloy fracture zone; HFZ, Hornsund fracture zone; 2A–2B, axis of linear magnetic anomalies; C, contour of modern aeromagnetic survey; I, local positive anomalies of anomalous magnetic field (AMF) above intrusive objects (maximum AMF values (160–1600 nT), 2A–24B, LMA axis). *1*, 400 isobath m; *2–5*, position of: *2,* wells ODP 908 and ODP 909; *3*, modern spreading axis based on bathymetric data; *4*, deep seismic profiles; *5*, continent–ocean transition zones based on seismic data; *6–7*, continent–ocean boundaries: *6*, according to [18]; *7*, according to [15, 16]; *8*, beginning of continent–ocean transition zone from continental margin (according to [18]); *9–10*, DLs and their numbers; *11*, theoretical position of Chron (name, age in Ma) on DL.

Due to the oblique opening rift system, the anomalous magnetic field above the Knipovich Ridge and its flanks is characterized by a mosaic structure, which complicates identification of the axis of linear magnetic anomalies, resulting in various tectonic models for the opening of the system [6, 16, 18].

The aim of this article is to study the stages of opening of the Fram Strait, starting from the Early Neogene, for which we have calculated the position of the axis of theoretical linear magnetic anomalies and compared them with geological and geophysical data.

GEOLOGICAL AND GEOPHYSICAL DATA

The Fram Strait was studied using multibeam echo sounding (MBE). The Knipovich Ridge and northern part of the Mohns Ridge, the central part of the Lena Trough, the rift valley of the southwestern part of the Gakkel Ridge, and the central parts of the Spitsbergen and Molloy fracture zones are covered by MBE data with digital elevation models (DEM) on a 50 × 50 or 100 × 100 m grid. These data were used to create the IBCAO v.4 DEM, the resolution of which is 200 × 200 m [22].

Table 1. Identified linear magnetic anomalies (LMA) in segments of Fram Strait (according to [18], modified)

Region	Subregion	LMA (chron, age, Ma)
Borea Basin		C13 (C13n, 33.47), C18 (C18n.1n–C18n.2n, 39.24)
Knipovich Ridge	Southern, Central	C2A (C2An.1n, 2.81), C5 (C5n.1n–C5n.2n, 10.4), C6 (C6n, 19.09), C7 (C7n.1n, 24.04)
	Northwestern flank	C2A (C2An.1n, 2.81), C5 (C5n.1n–C5n.2n, 10.4), C6 (C6n, 19.09)
	Northeastern flank	C2A (C2An.1n, 2.81)
Molloy Depression	Central part	C2A (C2An.1n, 2.81), C5 (C5n.1n–C5n.2n, 10.4), C6 (C6n, 19.09)
Lena Trough	Northwest flank	C2A (C2An.1n, 2.81), C5 (C5n.1ny–C5n.2n, 10.4), C6 (C6n, 19.09)
	Northeastern flank	C2A (C2An.1n, 2.81), C5 (C5n.1ny–C5n.2n, 10.4)
Gakkel Ridge	between Yermak Plateau and Morris Jesup Rise	C2A (C2An.1n, 2.81), C5 (C5n.1n–C5n.2n, 10.4), C6 (C6n, 19.09), C7 (C7n.1n, 24.04)*

*—Linear magnetic anomaly identified only in northern part of segment (Chron C8n, 25.5 Ma (according to [3])).

Analysis of the stages of opening of the Fram Strait [6, 18] was for a long time based on the results of aeromagnetic studies with an interprofile distance of ~8–10 km, carried out by the US Naval Research Laboratory (NRL) in 1972–1974. These data are characterized by navigational errors [6, 18, 37, 38]. However, for the southwestern Eurasian Basin, navigation errors were taken into account by comparison with 1998–1999 NRL surveys, carried out with high-precision GPS navigation [3].

For the Molloy Basin and the southern Borea Basin, several aeromagnetic profiles were done in 2002 by helicopter from the R/V *Polarstern* (Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany) [17]. In 2016 and 2018, researchers from the Geological Survey of Norway (Trondheim, Norway) conducted a high-precision aeromagnetic survey for the northern part of the Norwegian–Greenland Basin (aircraft flight altitude 120 m, interprofile distance of the ordinary grid was 5.5 km) with the direction of the ordinary grid, which corresponded to opening of the Knipovich Ridge [15] (Fig. 1b).

Gravimetric observations are scant, so the interpretation is mainly based on the results of satellite altimetry compilations [18].

The study of the Fram Strait using seismic methods was carried out by Russian researchers, specialists from Norway and Germany [2, 17, 18]. Significant volumes of data were obtained using the CDP method for the Knipovich Ridge, its flanks and continental margins. Several deep seismic profiles start on the western shelf of the Barents Sea, cross the continental slope and continue into the Norwegian–Greenland Basin [1, 12, 14, 28, 33, 36] (Fig. 1a).

Within the Fram Strait, deep-sea wells were drilled under the Ocean Drilling Program, the results of which were summarized [2, 31]. Of particular interest in this study are the core analysis results from well ODP909 drilled in the Molloy Basin and well ODP908 drilled on the Hovgaard Ridge [19, 25] (Fig. 1a).

GEOLOGICAL HISTORY OF THE OPENING OF THE FRAM STRAIT

The ideas about the earlier opening of the segments of the North Atlantic–Arctic system that bound the Fram Strait are presented in [18]. In the Norwegian–Greenland Basin segment, which has in its structure the modern spreading Mohns Ridge, and the main part of the Eurasian Basin in the area located north of the Yermak Plateau and Morris Jesup Rise, the earliest reliably identifiable linear magnetic anomaly (LMA) C24B is estimated to be ~53.9 Ma (C24n.3no) (Fig. 1a). In the Fram Strait, a later LMA sequence has been established, sharply rejuvenating its central part (Fig. 1a; Table 1).

Transform movement of the Greenland Plate with respect to the western margin of the Barents Sea (Eurasian Plate) occurred in the Eocene–Early Oligocene (Chrons C24no–13n, ~53.9–33.5 Ma) along the De Geer megafracture zone, the end of which limits the age of the beginning of the formation of the Fram Strait [18].

According to plate tectonic reconstructions, in the Early Oligocene (C13n, ~33.5 Ma), from the moment of cessation of spreading in the Labrador Sea–Baffin Bay system, the Greenland Plate became part of the North American Plate. At the same time, there was a change in direction of opening in the Norwegian–Greenland basin. Only in the southern Fram Strait was there a sedimentary basin, bounded by fragments of the continental margin of the Barents Sea, which are represented by the Hovgaard (in the north) and Greenland Ridge (in the south). The extension axis was located west of the Hovgaard Ridge [18].

The Yermak Plateau and Morris Jesup Rise, which are continental blocks, were adjacent to each other in the north of the Fram Strait. The De Geer megafracture zone was located between Northern Greenland and the western edge of Svalbard. In the Miocene (~20–15 Ma), initial formation of the oceanic strait took place. During Chron C6 (C6n, ~19.1 Ma), the southern strait significantly expanded and connected with the Northern Atlantic.

In the north, between the Yermak Plateau and Morris Jesup Rise, a section of oceanic crust formed, but within the De Geer megafracture zone, local sections of spreading crust arose only between the Spitsbergen and Molloy fracture zones and in the north of the future Lena Trough. The extension axis was located west of the Hovgaard Ridge. During Chron C5B (C5Bn.1n, ~14.8 Ma), narrow sections of oceanic crust formed in the southern Lena Trough, between the Hovgaard Ridge and the western continental margin of Svalbard, which led to formation of the northernmost fragment of the Knipovich Ridge.

During Chron C5 (C5n.1n–C5n.2n, ~10.4 Ma), spreading crust formed throughout the former De Geer megafracture zone, but in the northern segment of the Knipovich Ridge, the extension axis was closely adjacent to the western continental margin of Svalbard, with the section of oceanic crust located to the west between the extension axis and the Hovgaard Ridge.

Based on interpretation of new aeromagnetic data, new assumptions were presented on the history of the opening of the Knipovich Ridge [15, 16], largely based on identification of the continent–ocean boundary (COB) from magnetometric data. It was proposed to limit the area of oceanic crust formed as a result of spreading in the Knipovich Ridge to the zone of formation of intense segmented-linear magnetic anomalies [15, 16] (Fig. 1b). This means that formation of the entire Fram Strait, with the exception of its northern segment in the Eurasian Basin, began ~20 Ma ago, slightly earlier than Chron C6n (~19.1 Ma) [15]. In addition, a segment with a formation age of ~20–18 Ma ago was identified in the Borea Basin, which formed within the interrupted paleosegment of the Knipovich Ridge [16] (Fig. 1b).

COMPARISON OF THE POSITION OF THE THEORETICAL LMA AXIS WITH GEOLOGICAL AND GEOPHYSICAL DATA

Tectonic Conditions of Formation of the Fram Strait

The drift lines (DL) and positions of the theoretical axis of linear magnetic anomalies (TLMA) have been calculated from the positions of the instantaneous opening poles for the Eurasian and North American plates [30]. Earlier, a similar analysis was carried out for the Eurasian Basin [3]. The current position of the opening axis according to bathymetric data was taken as the initial reference point. Basically, the axis of opening was occurred due to characteristic neovolcanic structures (ridges, volcanoes) within the rift valley of the ridges. In segments where such structures are absent, the position of the opening axis was taken to be the center of the rift valley. The half-rates of opening on both sides of the divergent boundary were assumed to be symmetrical.

The average frequency of calculations was ~1 Ma for the 21st rotation pole for the Early Neogene–Quaternary time interval (C1no (~0.8 Ma)–C6no (~19.5 Ma)) [30].

Our study presents only the results of calculations of the theoretical axis of linear magnetic anomalies (TLMA) closest in age to those identified by LMA in the works [15, 16, 18], and key additional TLMA, characterizing the stages of development of the Fram Strait.

The southwestern section of the Eurasian Basin between the Yermak Plateau and the Morris Jesup Rise opened strictly orthogonally to the divergent boundary, as evidenced by the direction of the DL (Fig. 1a).

For this segment, the modern reference LMAs C2A, C5, and C6 are almost identical and there is good agreement between the TLMA and results of LMA identification, which was done at the center of positive LMAs [18] or at the beginning or end of positive LMAs [30]. Minor discrepancies in the positions of LMAs and TLMAs on the DL are explained by the nonstationarity of spreading and different approaches to identifying LMAs.

For the same LMAs identified in different ways (by the center or the beginning/end of the normal polarity Chron), the age difference is <0.5 Ma, which, in our opinion, is insignificant when making a comparison. For the Knipovich Ridge, good comparability of LMAs and TLMAs is also observed (Fig. 1a).

Analysis of the comparability of the curves of the anomalous magnetic field (AMF) data of NRL (Washington, USA), obtained in 1972 [18], with the results of new aeromagnetic data [15] showed that the navigation error in the retrospective data can reach 4.7 km. Significant discrepancies in the position of TLMA and LMA C2A and C5 west of the spreading axis along DL-3 are caused by the fact that the retrospective data for this area contain variations in the magnetic field.

For the southern Knipovich Ridge (DL-1), magnetic anomaly lines have mutual correspondence [15, 16, 18] and correspond to the position of the TLMA (Fig. 1b). A significant discrepancy with the results of [15] is recorded in the central part of the Knipovich Ridge, which is shown by DL-4. In this segment of the system (between DL-3 and DL-5) in the Borea Basin, the the existence of a paleosegment of the Knipovich Ridge ~20–18 Ma ago is assumed (LMA C6–C5E) [15, 16].

This is explained by the asymmetric opening of this segment of the Knipovich Ridge, when the half-rate in the eastward direction for the time interval of ~18–0 Ma averaged ~7.1 mm/year, which is the generally accepted value for the Knipovich Ridge, and in the west, ~5.9 mm/year [15].

For this segment, there are significant contradictions when comparing the provisions of the LMA and TLMA. In the eastern part, the position of LMA C5 and C5C on DL-4 corresponds well to TLMA, which does not allow us to consider that the half-rate disclosure of the Knipovich Ridge is slowing down. The position of DL-4 in comparison with the other DLs shows that in the western part for LMA C5 and C5C, there is a significant shift towards Greenland, which means that the half-rate of opening within this segment is exceeded compared to the other segments of the Knipovich Ridge.

Structure of the Knipovich Ridge

According to bathymetric data, the Knipovich Ridge is characterized by short segmentation [2, 5, 7, 13]. In the rift valley of the ridge, which is intersected by DL-4, there is a clearly defined neovolcanic ridge, ~20 km long with a maximum elevation in the central part with respect to the bottom of the rift valley, which is ~450 m (Fig. 1).

The highest-amplitude local AMF (LMA C1n) is located exactly above this section of the rift valley of the Knipovich Ridge, reaching values of ~780 nT (Fig. 1b). The DL-4 DL crosses clearly defined segments of the LMA in the anomalous magnetic field, which are particularly well-defined on the western flank of the Knipovich Ridge.

The direction and extent of these LMA segments coincide with linear elevations of the relief orthogonal to the direction of opening of the Knipovich Ridge. The comparison of the data confirms the long-lived nature of segmentation of this short magmatic segment. Traces of long-lived segmentation are clearly distinguished in the AMF as positive and negative LMAs parallel to the DL.

In the eastern part, above DL-3, a shift in the position of identified LMAs C5 and C5C is observed [15] (Fig. 1b). Between DL-3 and DL-4 in the AMF, we can clearly see a chain of negative elongated local AMFs, parallel to the DL, which map the fault and the southern boundary of the magmatic segment. Traces of this fault are visible in the western direction in the interruption of the LMA in the proposed paleosegment C6 (~20 Ma)–C5E (~18 Ma)–C6 (~20 Ma) [15].

The existence of the paleosegment contradicts the theoretical calculations. The period of its formation is limited to 2 Ma with a half-rate of paleosegment opening of ~13 mm/year, which is almost twice the average half-rate of opening of the Knipovich Ridge [15]. On the continuation of DL-4, the distance between LMA C6 with respect to the position of the supposed paleoaxis (LMA C5E) is ~46.5 km.

The modern scale of geomagnetic field reversals determines the age of Chron C6no as ~19.53 Ma, while the age of Chron C5Eny is ~18.01 Ma; i.e., the half-rates of opening in the supposed paleosegment should be even higher, possibly ~15.3 mm/year. In this case, the eastern paleoaxis of LMA C6 on DL-4 corresponds to the position of a TLMA, as well as LMA 5C. This means that there is an additional unaccounted for area of oceanic crust between these LMAs.

This scenario of the openinf of this segment of Knipovich Ridge [15] seems unlikely to us; therefore, in our study, the idea of continuous opening of the southern and central parts of the Knipovich ridge is adopted within the last ~20 Ma without significant jumps, which is confirmed by theoretical calculations [18].

On the eastern flank of the Knipovich Ridge, between the magnetometric COB [15, 16] and the 400 m isobath, there is a series of local LMAs, some of which are identified as LMA-6 [18], coinciding with the position of the TLMA (Fig. 1). The differences in the position of the LMA and TLMA may be caused by geological features of the structure of the eastern flank of the Knipovich Ridge. Significant volumes of sedimentary cover (for some areas ~60% of the total thickness) in the deep-sea basin located between the Knipovich Ridge and western margin of the Barents Sea consist of glacial–marine deposits with an age of <2.7 Ma, the thickness of which can reach several kilometers, indicating intensive erosion of sedimentary rocks from the shelf [23, 32, 33].

Based on the results of studying deep-sea drilling wells and seismic data, stages of intensive glacial–marine sedimentation have been identified, associated with expansion/or reduction of ice sheets that existed over a significant area of the Barents Sea and the archipelagos located within its boundaries [23, 27, 32].

In the sedimentary strata of most of the Barents Sea, including Franz Josef Land and Svalbard, Lower Cretaceous magmatic bodies of mafic composition have been mapped according to geological and geophysical data [8, 35]. In areas with a near-surface or surface position, magmatic bodies are high in magmatic magnetic field amplitude. Intensive glacial erosion of the Barents affected not only sedimentary rocks, but also the near-surface parts of magmatic bodies. Magnetic minerals entered the deep-sea basin adjacent to the west of the continental margin of the Barents Sea, which led to some weakening of expression of the AMF and partial loss of its linearity in areas with maximum deepening of the oceanic basement and volumes of glacial–marine sediments.

On the eastern flank of the Knipovich Ridge, based on the results of gravimagnetic modeling along the lines of deep seismic profiles, the entire area from the magnetometric COB to the continental margin is referred to as a wide continent–ocean transition zone [15, 16]. Gravimetric modeling was previously performed for deep seismic profiles, the results of which relate the entire area from the Knipovich Ridge to the western continental margin of the Barents Sea to oceanic crust [12].

We believe that the discrepancy in the results is due to the use in [16] of the initial model, which differs somewhat from the generally accepted approaches. In particular, in gravity modeling of oceanic regions and continent–ocean transition zones, the layered nature of the mantle density is taken into account due to its thermal expansion [12], but in the original model [16] all differences in mantle density are reduced only to vertical—oceanic—blocks and the continent–ocean transition zone. The density characteristics of oceanic crust (2.7–2.95 g/cm^3), the lower part of the crust in the continent–ocean transition zone (2.8–2.97 g/cm^3) and the lower part of the continental crust (2.88–3.09 g/cm^3) almost coincide [16]. We adhere to the definition of COB based on gravimetric and seismic data [1, 12, 14, 18, 28, 33, 36].

Development of the Northern Segment of the Knipovich Ridge

The north of the Knipovich Ridge shows the maximum disproportion of the position of the modern divergent boundary within the Norwegian–Greenland basin (Fig. 1). In the north, the ridge is bounded by the Molloy fracture zone, which records a direction of opening completely consistent with the DL. The center of the rift valley along the Molloy fault is located at a distance of ~65 km from the edge of the shelf of Svalbard, while the distance to the edge of the eastern shelf of Greenland is ~325 km (Fig. 1a).

Within the northern part of the Knipovich Ridge we have identified two segments. The center of the southern segment corresponds to the center of DL-6. In the rift valley of the Knipovich Ridge, DL-6 is crossed by a pronounced neovolcanic ridge with a length of ~16 km and a maximum elevation of up to ~600 m in the central part of the ridge with respect to the bottom of the rift valley (Fig. 1a). Above this section of the rift valley is the second most intense high-amplitude local AMF (LMA C1n), reaching values of ~760 nT (Fig. 1b).

DL-6 intersects the LMA segments (C2A, C5, C5A [18]) that are well expressed in the anomalous magnetic field. The direction and extent of these LMA segments coincide with the linear elevations of the relief recorded in the bathymetric data, located orthogonally to the opening direction. This confirms the long-lived nature of the segmentation of this short magmatic segment.

The following patterns are observed within the segment and its surroundings: one-dimensionality. In the Borea Basin, a series of local anomalies (LAs) of the AMF with maximum values of ~160–460 nT are recorded, which are interpreted as magmatic intrusive formations formed during the final stage of rifting and the initial stage of spreading [18]. Within the southeastern part of the ridge In the Hovgaard, which is a continental fragment of the continental margin of the Barents Sea, a contrasting LA of the AMF with maximum values of ~500 nT [18] is distinguished (Fig. 1b).

Chron C6no (~19.5 Ma) is close to the foot of the Hovgaard Ridge, and its mirror position (DL-6) is located near the LA of the AMF, which is also interpreted as a "signal" from intrusive objects [4, 16].

This identity of the LA of the AMF on both sides of the divergent boundary suggests intense magmatism during the initial stage of the ridge's detachment. Hovgaard from the continental margin.

Earlier, a deep seismic profile, which clearly records the compliance of the provisions, was not used within the COB of Chrons C5An.2no (~12.5 Ma) and COB on DL-7 [18, 36]; therefore the allocation of COB adopted by us has differences (Figs. 1a, 2).

Above and below DL-6, the linearity of the AMF is clearly recorded, reflecting the faults that bound this segment of the modern position of the Knipovich Ridge. In the west, the segment abuts the eastern part of the continental Hovgaard Ridge (Chron C6no). In the east, the distance from the position of Chron C6no (~19.5 Ma) to the inferred continuation of the COB, taking into account preservation of the DL-6 direction, is ~127.5 km (Fig. 2). This suggests two stages of development for this segment with a jump in the opening axis ~19.5 Ma ago (or slightly earlier), although uncertainty remains in understanding the mechanism of disclosure.

From Chron C13n (~33.5 Ma), the rate of opening of the Fram Strait has been approximately constant [18]. If we assume that the paleoaxis of opening was on the western flank and is mapped by the well-defined LMA 5E (according to [16]) or C7 (C7n.1n, 24.04 Ma), (according to [18]), then this means that on the eastern flank, it is necessary to use the half-rate of opening, which along DL-6 is ~7.1 mm/year (the distance between Chrons C6no is ~282 km). In this case, detachment of the Hovgaard Ridge from the continental margin of the Barents Sea should have occurred ~37.5 Ma ago, which is early for detachment of the Hovgaard Ridge from the continental margin.

If we consider the scenario of the existence of a paleoaxis of opening on the eastern flank, then it is necessary to use the total rate of opening. In this scenario, the theoretical age of formation of the oceanic crust between the eastern position of Chron C6no (~19.5 Ma) and the COB is ~9 Ma; i.e., detachment of the Hovgaard Ridge from the continental margin of the Barents Sea occurred ~28.5 Ma ago, which corresponds to the proposed age of the final stage of rifting between the Yermak Plateau and the Morris Jesup Rise [3].

Existing seismic data do not establish the presence of a paleorift in the considered region. It is possible that this area is a local pull-apart type. Then the age of ~28.5 Ma can be taken as the beginning of the impulse of magmatic activation, evidenced by local anomalies of the magmatic magnetic field. We believe that the activation caused a local uplift, as the results of drilling the deepwater well ODP908 on the Hovgaard Ridge establishes a sedimentary hiatus boundary in the period ~25–6.7 Ma ago, which suggests its subaerial position [25].

The development of the northernmost segment, continuing to the Molloy transform fault, followed

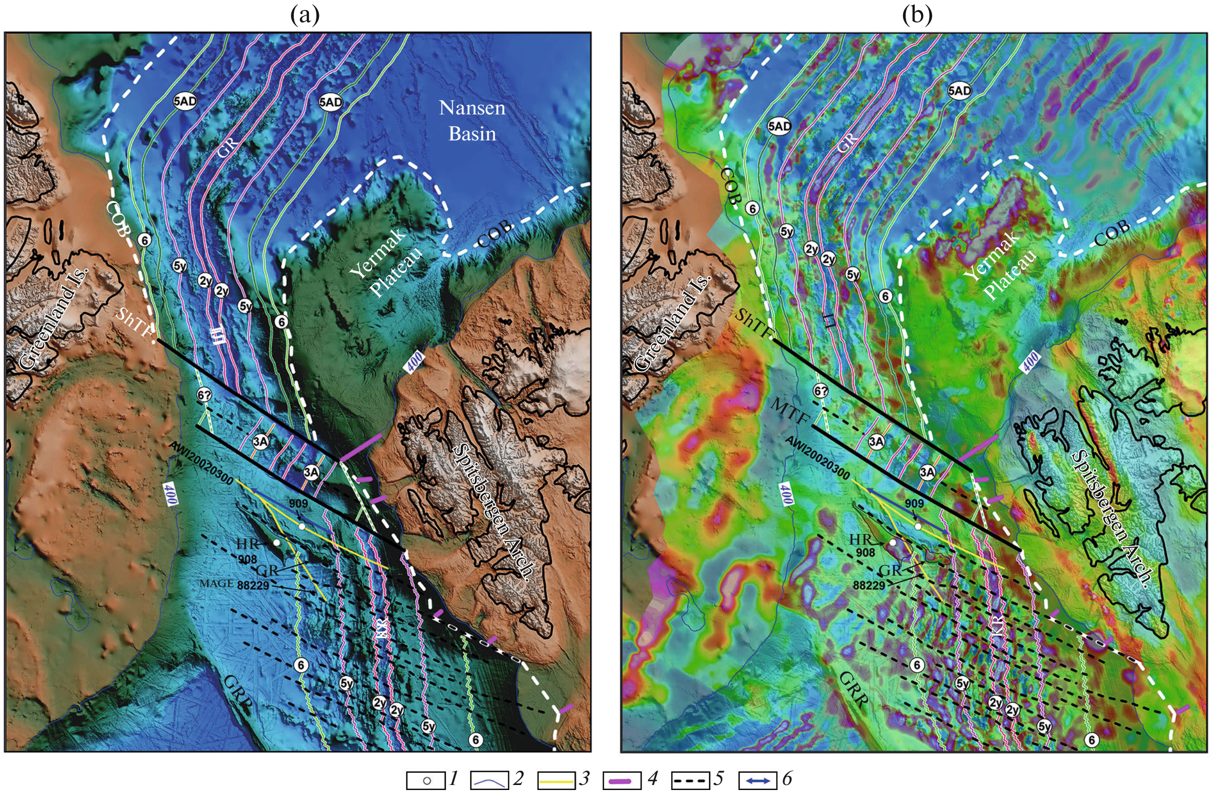

Fig. 2. Theoretical position of axis of linear magnetic anomalies (according to data from [1, 12, 14, 16, 19, 22, 24, 27, 33, 36]. (a) Pseudoshadow representation of IBCAO v.4 digital elevation model with Greenland ice sheet removed (according to [22]); (b) anomalous magnetic field (according to [15], with changes) superimposed on a pseudoshadow representation of IBCAO v.4 digital elevation model with Greenland ice sheet removed (according to [22]). Notation: CMB, central Molloy Basin; WMB, western Molloy Basin; NWMB, northwestern Molloy Basin; COB, inferred position of continent–ocean boundary; GR, Gakkel Ridge; KR, Knipovich Ridge; LT, Lena Trough; HR, Hovgaard Ridge; MH, Mt. Hovgaard; GR, Greenland Ridge; SPZ, Spitsbergen fracture zone; MFZ, Molloy fracture zone; HFZ, Hornsund fracture fone. Shown (Arabic numerals in circles): theoretical position of axis of linear magnetic anomalies (Chron, Ma): 2y, (2ny, ~1.8); 3A, (3An.2no, ~6.7); 5y, (5n.1ny, ~9.8); 5AD, (5ADno, ~14.6); 6, (6no, ~19.5). *1*, Position of wells ODP 908 and ODP 909; *2*, 400 m isobath; *3–5*, position of: *3,* CDP reflection profiles (AWI20020300, MAGE 88229); *4*, continent–ocean transition zones according to deep seismic exploration data; *5*, inferred faults mapped using bathymetric and magnetometric data; *6*, direction and width of opening of central Molloy basin during period of Chron (Ma): C6no (~19.5), C5n.1ny (~9.8).

a different scenario (Fig. 1, Fig. 2). In this segment, two sub-segments can be distinguished, the center of one of which approximately corresponds to DL-7 and is bounded from above by a clear linear negative anomaly of the AMF, parallel to the DL (Figs. 1a, 2a). The center of the second highlighted sub-segment roughly corresponds to DL-8.

On the western flank, the segment is bounded by Chron C5n.1ny (~9.8 Ma), roughly corresponding to the position of the eastern foot of Mt. Hovgaard, and in the east by Chron C5An.2no (~12.5 Ma), which falls on the COB. According to [16, 18], Mt. Hovgaard has oceanic crust, which contradicts remote method data (Figs. 1a, 1b).

Minimum depths to the summit of Mt. Hovgaard and summit of the Hovgaard Ridge coincide: ~1275 and 1274 m; the minimum depth of the Svyatogor Rise with oceanic crust, located to the northeast towards the Knipovich Ridge, is ~1500 m. The most intense LA of the AMF with a maximum value of ~1600 nT in the entire Fram Strait is located above the western part of Mt. Hovgaard, which exceeds the maximum AMF peaks (Fig. 1b):

— by approximately two times over the rift valley of the Knipovich Ridge (~760 and 780 nT);

— by more than three times over the Hovgaard Ridge (~500 nT);

— by ~2.5–10 times over intrusions in deep-sea basins and continental slopes (~160–640 nT).

With such intensity, the assumption of an oceanic spreading origin of Mt. Hovgaard is unlikely, since the amplitude of the AMF over nearby LMAs C5, 5A, 5E (according to [18]) is only 230, 180, and 150 nT.

Mt. Hovgaard, as well as the Horvgard Ridge, is considered by us to be a continental fragment of the Barents Sea margin. When reconstructing the age of Chron C5n.1ny (~9.8 Ma), the position of the opening

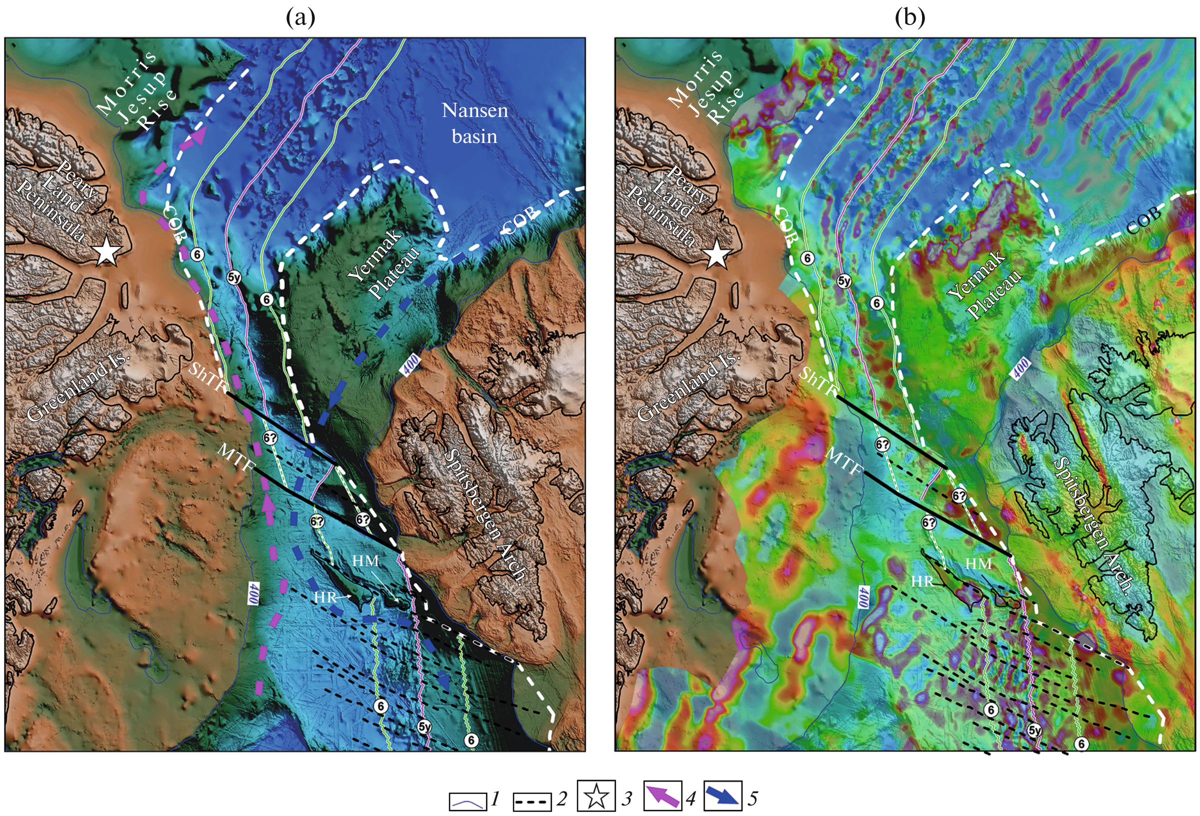

Fig. 3. Plate tectonic reconstruction with age of ~9.8 Ma (C5n.1ny). (a) Pseudoshadow representation of IBCAO v.4 digital elevation model with Greenland ice sheet removed (according to [22]); (b) anomalous magnetic field (according to [15], modified) superimposed on a pseudoshadow representation of IBCAO v.4 digital elevation model with Greenland ice sheet removed (according to [22]). Notation: HR, Hovgaard Ridge, MH, Hovgaard Mountain, SFZ, Spitsbergen fracture zone; MFZ, Molloy fracture zone; COB, continent–ocean boundary (according to [18] modified); theoretical position of axis of linear magnetic anomaly 6 (6no, ~19.5 Ma); theoretical position of spreading axis at Chron 5y (5n.1ny, ~9.8 Ma); *1*, 400 m isobath; *2*, position of inferred faults mapped from bathymetric and magnetometric data; *3*, deposits of Cape Copenhagen Formation; *4*–*5*, expected position and direction of currents: *4*, warm; *5*, cold.

axis almost completely coincides with the eastern foot of Mt. Hovgaard, but between the opening axis and inferred position of the COB, there remains a section oceanic crust between Chrons C5n.1ny–C5An.2no (~9.8–12.5 Ma) (Figs. 1a, 1b, 3a, 3b).

Since there is no such section of oceanic crust in the western part (coincidence of the foot of Mt. Hovgaard and TLMA C5n.1ny), the time interval between the Chrons (2.7 Ma) should be divided by 2, i.e., the theoretical age of detachment of Mt. Hovgaard from the continental margin occurred ~11.2 Ma ago, and in the subsegment located above, ~9.8 Ma ago (Figs. 3a, 3b).

The western extension of the subsegment is the Molloy Basin, within which are well ODP908 (Fig. 1) and seismic profile AWI20020300 (Fig. 4a).

The completed reinterpretation of the borehole core and seismic data allowed us to significantly clarify the geological history of sedimentation in the Molloy Basin [19]. A sharp change in the nature of sedimentation with increased deposition of coarse-grained material and enrichment of kaolinite with a fine fraction occurred ~10.8 ± 0.9 Ma ago [19], which corresponds to the theoretical age we obtained for the beginning of formation of the northernmost segment of the Knipovich Ridge and detachment of Mt. Hovgaard from the continental margin. This assumption is also confirmed by the nature of the seismic record, since the point of overlap of the MB09 horizon (~CDP 3500) corresponds to the position of TLMA C5n.1ny (~9.8 Ma), while the northern segment developed according to a tectonic scenario, as evidenced by the low-amplitude AMF (Figs. 1b, 2b, 4a).

Formation of the Molloy Basin

Opening of the northern segment of the Knipovich Ridge, which began more than ~10 Ma ago, formed the Molloy Basin. In the well ODP908 below the MB09 boundary, in the depth range 923.4–1061.80 m (hereinafter, from the seabed surface), landslide structures with intermittent and inclined internal seismic reflections were discovered [19]. Well ODP908 did not reach the basement surface, but seismic data at a depth

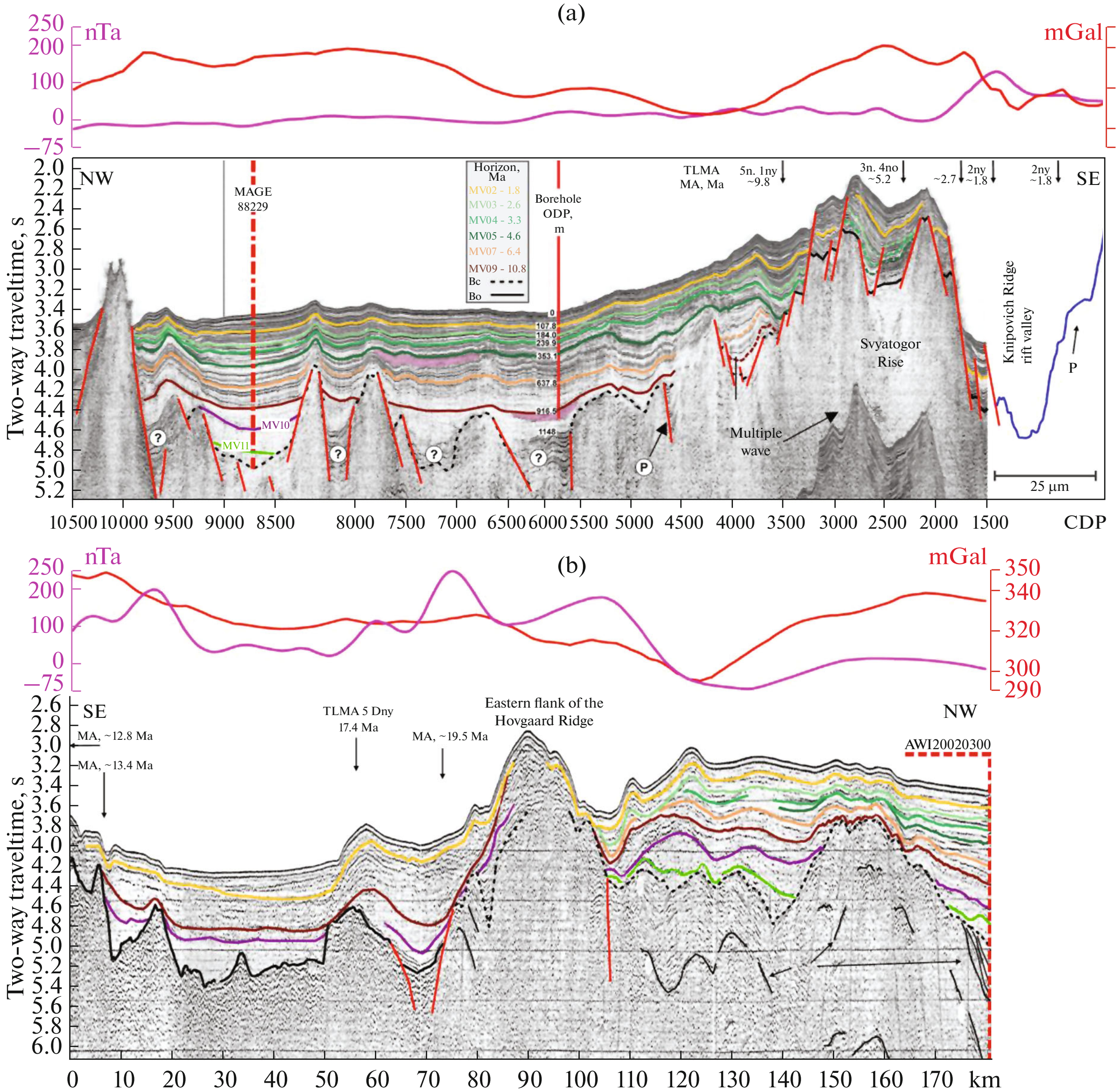

Fig. 4. Interpretation of seismic time sections. Curves (lines) show: anomalous magnetic field (red) (after [15], modified); Bouguer gravity anomalies (purple), extracted from matrices of values (according to [11]). See Fig. 2 for position of profiles. (a) Seismic profile AWI20020300 (according to [19], modified); (b) seismic profile MAGE88229. Seismic horizons MB02–MB09 are indicated (after [19], modified): R, relief of bottom of rift valley of Knipovich Ridge extracted from matrix of values of IBCAO v.4 relief model [22]; TLMA, theoretical axis of linear magnetic anomalies; TA, theoretical age of oceanic crust; Bc, position acoustic "continental" basement; Bo, position of "oceanic" basement; CR, contrast reflections below surface of acoustic "continental" basement.

of ~1228 m clearly recorded a contrasting boundary, below which the presence of layered deposits is assumed, which may be associated with ancient lithified deposits filling basement lows, or with lava flows, or with the presence of free gas [19, 36]. When extrapolating sedimentation rates from the deepest dated intervals of the section, the age of the top (~1228 m) of this layered sequence is assumed to be 14.7 ± 1.3 Ma [19].

Similar contrasting reflections in the very bottom of the section are also distinguished in other areas of the seismic profile west of the position of well ODP908 and are characteristic of local areas of intermontane basins (Fig. 4a).

A characteristic feature of the seismic recording is the contrasting relief of the surface of the acoustic basement (AB), which is also reflected in the relief. Highs in the acoustic basement are local narrow ridges of northwestern extension, the direction of which corresponds to the general direction of the Lena Trough (Figs. 2a, 5).

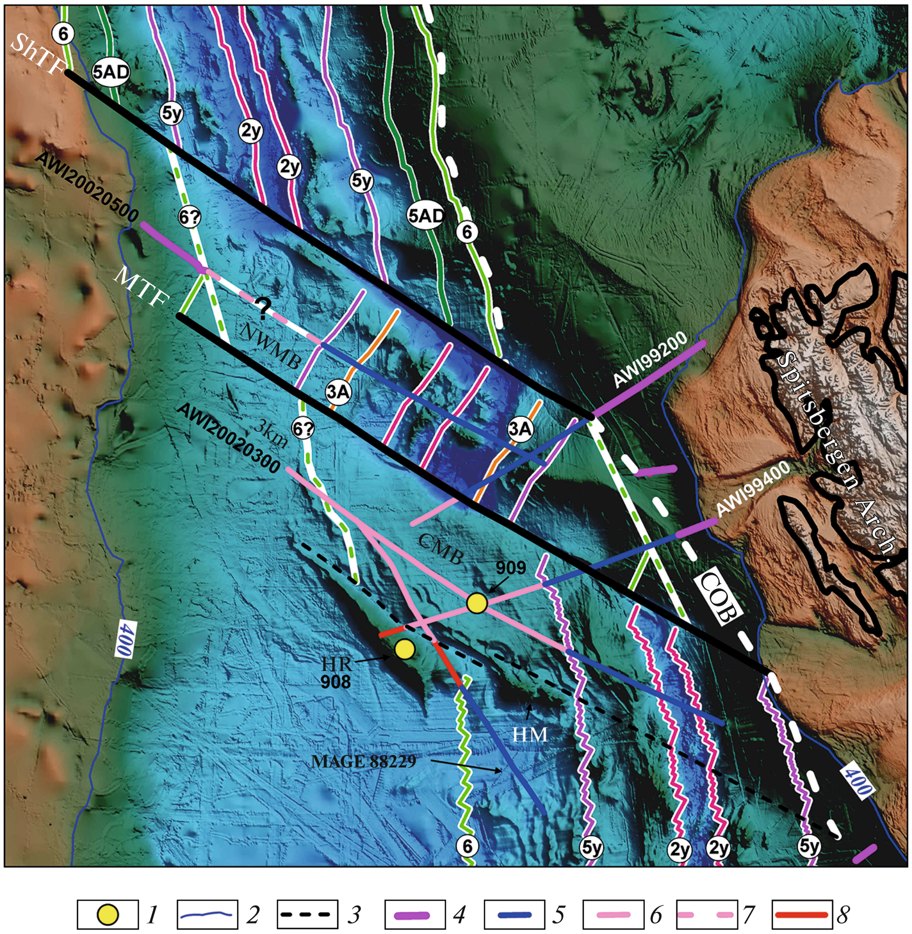

Fig. 5. Comparison of results of seismic data interpretation by crust type in central Fram Strait (AWI99200 and AWI99400 [14], AWI20020300 [19], AWI20020500 [17], modified). IBCAO v.4 digital elevation model with Greenland ice sheet removed was used as basis (according to [22]). Notation: CMB, central Molloy Basin; WMB, western Molloy Basin; NWMB, northwestern Molloy Basin; COB, inferred position of continent–ocean boundary; HR, Hovgaard Ridge; MH, Mt. Hovgaard; SFZ, Spitsbergen fracture zone; MFZ, Molloy fracture zone; COB, continent–ocean boundary (according to [18], modified). Theoretical position of axis of linear magnetic anomalies (Ma) is indicated (Arabic numerals in circles): 2y, (2ny, ~1.8); 3A, (3An.2no, ~6.7); 5y, (5n.1ny, ~9.8); 5AD, (5ADno, ~14.6); 6, (6no, ~19.5). *1*, Position of wells ODP 908 and ODP 909 (according to [19, 24]); *2*, 400 m isobath; *3*, inferred position of fault separating northern segment from southern segment Knipovich Ridge–Molloy Basin; *3–5*, types of crust along lines of seismic profiles: *3*, continent–ocean transition zone; *4*, continental; *5*, oceanic; *6*, intensively stretched crust of West Spitsbergen fold belt; *7*, inferred intensely stretched crust of West Spitsbergen fold belt; *8*, continental fragment of Hovgaard Ridge.

In the western part, the AWI profile between CDP8500–9000 intersects with the MAGE-88229 profile (Fig. 4b).

The basement high identified on the AWI profile east of CDP8500 can be traced on profile MAGE-88229 in the ~110–170 km interval. In the seismic record of profile MAGE-88229, some patterns are observed below the boundary of the acoustic basement.

The section of the profile southeast of the Hovgaard Ridge is considered to have an oceanic basement, characterized by contrasting reflections. North of the Hovgaard Ridge, reflections from the acoustic basement are not very contrasting, but below, local areas of contrasting reflections are clearly distinguished. During the initial phase of detachment in the northeast, the Greenland Plate came into contact with the Eurasian Plate at an acute angle and transform movement occurred here.

As a result of this transform movement in the contact zone of the plates along the western coast of Svalbard, the Cenozoic fold–thrust belt occurred [20]. Precambrian basement rocks and steeply dipping Late Paleozoic–Mesozoic sedimentary rocks were folded and thrust over each other. The lower part of the section on profile MAGE-88229 may reflect fragments of the West Spitsbergen fold belt, and in the northwestern part of the profile, steeply dipping reflections below the surface of the acoustic basement are identical to steeply dipping Late Paleozoic–Mesozoic sedimentary rocks.

In the northeastern part, the AWI profile intersects another narrow local ridge with a summit protruding from the sedimentary cover in the area of CDP1000;

this local ridge is connected in an en echelon manner to the Hovgaard Ridge in the south (Figs. 2a, 4a).

The distance from this local ridge along the direction of the DL of opening to the position of TLMA C5n.1ny clearly corresponds to the theoretical distance that should have formed during the period of opening in the interval of Chrons C6no (~19.5 Ma)–C5n.1ny (~9.8 Ma). The central Molloy Basin may be a very extended part of the West Spitsbergen fold belt, and narrow local ridges within its boundaries are fragments of the steeply dipping Precambrian basement, on which Upper Paleozoic–Mesozoic sedimentary rocks have been preserved.

As the Molloy Basin opened, the isolated tectonic plates of the fold belt, originally located almost vertically, slid down and tended to a horizontal position, thereby filling the resulting space.

Along the AWI profile line above the Svyatogor Rise, elevated values of the Bouguer gravity field anomaly (BGFA) are observed, which decrease towards the western part of the Molloy Basin (Fig. 4a).

The minimum BGFA values are located west of the supposed end of the oceanic crust region (Chron C5n.1ny, ~9.8 Ma), after which a smooth increase in the BGFA values occurs. A similar situation is also observed for the MAGE-88229 profile. There is a tendency for the AGBP field to decrease over the oceanic basement towards the western part of the Molloy Basin, the minimum is recorded in the region of ~123 km of the profile, and after that an increase in the AGBP occurs.

Absence of local anomaly over the continental Ridge Hovgaard shows its isostatic compensation, which distinguishes it from oceanic uplifts (e.g., the Svyatogor Rise (Fig. 4a)), over which characteristic positive anomalies are observed. The average gravity field levels along seismic profiles over the proposed oceanic and reduced continental crustal areas are approximately the same, which does not allow us to confirm the assumption of a continental basement for the central Molloy Basin.

However, seismic data from deep methods can serve as evidence for greatly thinned continental crust. On seismic profile AWI99400, the section of crust before intersection with the position of the TLMA (Chron C5n.1ny, ~9.8 Ma) is interpreted as a section of oceanic crust with an average crustal thickness of 3.5–4 km and longitudinal wave velocities of 5.8–6.6 km/s [14].

In the Molloy Basin, the crustal thickness increases by 1.5–2 times, and in the upper part, the longitudinal wave velocities are 3.6–5 km/s, which is identical to those observed further for the Hovgaard Ridge, where the crustal thickness doubles: 10–12 km.

A similar pattern is observed for northern deep profile AWI99200, along which the thickness of the crust after crossing the Molloy Basin increases by approximately three times up to 10–10.5 km, but the longitudinal wave velocities remain high: 6.6–6.75 km/s [14]. The increased velocities in the crust can be explained by the fact that during the formation of the West Spitsbergen fold–thrust belt, Mesozoic terrigenous deposits could have been heavily eroded, and the underlying Paleozoic carbonate rocks, like the Precambrian basement, are quite dense, suggesting high velocities.

The geographical delineation of the Molloy Basin varies, so we propose dividing the basin into several parts. The area under discussion, which we define as the central Molloy Basin, is bounded in the south by the Hovgaard Ridge and Mt. Hovgaard, and in the north by the Molloy fracture zone. In the west, the central Molloy Basin is bounded by a local ridge, which is intersected by the AWI profile in the area of CDP1000 and in the east by the western foot of the basement high of the Svyatogor Rise, which corresponds to the position of TLMA C5n.1ny (~9.8 Ma).

It was assumed that the Molloy Basin began to open ~20–21 Ma ago [16], but, according to our data, its opening began earlier, ~28.5 Ma ago, synchronously with the beginning of detachment of the Hovgaard Ridge from the continental margin of the Barents Sea. This resulted in strong stretching of the fractured continental crust and formation of the western Molloy Basin, located west of the central part of the basin to the northeastern continental margin of Greenland (Fig. 5).

When tracing horizons from the AWI profile to profile MAGE-88229, only horizons clearly distinguished on the MAGE-88229 profile remained; therefore, there are gaps in identification of horizons (MB01, MB06, MB08) compared to [19]. We have identified two additional horizons, MB10 and MB11, in the lower part of the sedimentary section. The MB09 boundary (~10.8 ± 0.9 Ma) is confidently traced on the MAGE-88229 profile (Fig. 4b).

For the local ridge segment between ~150–165 km, the MB09 horizon almost completely overlaps the surface of the acoustic basement and shows traces of erosion. We believe that this area was located in shallow-water or subaerial conditions. North and south of this area below the MB09 boundary, two reflectors, MB10 and MB11, are clearly distinguished, which are distinguished on the AWI profile by low-contrast chains of local reflections. At the intersection point of the profiles they are located at similar time marks (Figs. 4a, 4b).

Based on the nature of the seismic record after the onset of extension in the Molloy Basin ~19.5 Ma ago, some sections of local ridges were in subaerial conditions and sedimentation occurred within interridge basins. It is possible that the MB10 horizon corresponds to the top of the contrasting AWI reflections identified below the bottom of the wellbore.

The theoretical age of oceanic crust in the southeastern part of profile MAGE-88229 is ~19.5–12.8 Ma. The point of overlap of the lower identified horizon MB10 in the sedimentary cover is located on the oceanic basement with a theoretical age of ~13.5 Ma, which is close to the value of 14.7 ± 1.3 Ma obtained for the AWI profile.

On profile MAGE-88229, the lower recorded horizon in the sedimentary cover above the AF is MB11; i.e., its age can be taken as younger than ~19.5 Ma.

The opening axis jumped from the central Molloy Basin to the east about 10 Ma ago and the opening of the northern segment of the Knipovich Ridge began. Based on the data obtained from the study of the ODP909 well core, a threefold increase in sedimentation rates was established, which amounted to >16 cm/ka in the period ~6.4–4.6 Ma ago [19]. When considering the northern segment between the Molloy and Spitsbergen fracture zones, the Molloy Basin is bounded by TLMA 3An.2no (~6.7 Ma); i.e., the age of the increase in sedimentation rates in the Molloy Basin coincides with the beginning of formation of the pull-apart basin (Molloy Basin (Figs. 2a, 2b)).

According to the study of the ODP908 well core in the ~6.7–4.6 Ma interval, there was continuous subsidence of the Hovgaard Ridge, which was previously in shallow-water or subaerial conditions, associated with the widening and, possibly, deepening of the central part of the Fram Strait [25] (Figs. 1a, 1b, 2a, 2b). The ~6.4–4.6 Ma interval is characterized by a high smectite content in sediments and higher amounts of igneous material in coarse-grained sediments [19]. High-amplitude positive linear anomalies of the AMF over Mt. Hovgaard and the Hovgaard Ridge suggest intense magmatism during the initial stage of their detachment from the continental margin of the Barents Sea.

On profile MAGE-88229, the upper part of the section of the eastern part of the Hovgaard Ridge contains contrasting reflections that can be interpreted as igneous intrusions that formed during the initial stage of detachment of the Hovgaard Ridge, which began ~28.5 Ma ago (Fig. 4b).

There are no positive linear anomalies of the AMF above this area, which may be due to the following reasons. The period of ~23.3–31.0 Ma (Chrons C7–C12) is characterized by frequent magnetic field reversals, so magmatic intrusions formed during this interval may have multidirectional magnetization, leading to superposition of AMFs from local objects and the absence of contrasting LAs. Precambrian basement rocks, which are part of the West Spitsbergen fold belt, contain magnetic minerals, which are clearly recorded in the magnetic field (Figs. 1b, 2b).

In addition, Triassic deposits of West Spitsbergen host Lower Cretaceous sills and dikes [8, 35]. If we assume that the western part of the Molloy Basin is an extended section of the West Spitsbergen fold belt, then the source of magmatic material in coarse-grained deposits of intermontane basins (well ODP909) could have been local ridges.

On profile MAGE-88229 for a ~148–162-km-long section of the local, wedging out of the MB05 horizon (4.6 Ma) has been established; above, the MB04 horizon (3.3 Ma) is continuously traced (Fig. 4b).

This may indicate local erosion of rocks, which could have been caused by the location of this area above sea level. If we accept the viewpoint about the appearance of ice in the Fram Strait starting from ~10.8 ± 0.9 Ma ago [19], then the erosion of rocks could have been caused by glacial erosion, or both factors at once.

The timing of the onset of opening of the segment between the Molloy and Spitsbergen fracture zones is controversial and debated by researchers in the region. In the northern part of the eastern flank of the Knipovich Ridge, the position of TLMA C5n.1ny (~9.8 Ma) clearly corresponds to the COB, but on the southern eastern flank between TLMA C6no (~19.5 Ma) and the COB, there is a section of oceanic crust (Figs. 2a, 2b).

Continuous tracing of the COB from Greenland is complicated by the lack of deep seismic data in the area and, as analysis of the position of the COB in the area of the western edge of the Barents Sea has shown, the gravimetric COB may differ from the seismic COB (Fig. 1a).

According to CMP reflection seismic, the beginning of a sharp rise in the acoustic basement surface towards the continental margin is interpreted as a COB, which coincides with the position of TLMA C6no (~19.5 Ma) [17] (Fig. 5).

Closer to the Molloy Basin up to the position of TLMA C5n.1ny (~9.8 Ma), the surface of the acoustic basement is at a depth of ~4.7 km on average, which is significantly deeper than in the central Molloy Basin, but its indentation with amplitudes of up to 1 km is observed, visually similar to the central Molloy Basin (Figs. 4a, 4b).

In the area of TLMA C5n.1ny (~9.8 Ma), the surface of the acoustic basement rises sharply and its new average depth is ~3 km. The area between the Molloy and Spitsbergen fracture zones, localized in the eastern part between TLMA C5n.1ny (~9.8 Ma) – C6no (~19.5 Ma), is interpreted as an area similar in structure and formation time to the central Molloy Basin, and it can be attributed to a separate structural unit: the northwestern Molloy Basin (Fig. 5).

DISCUSSION

The opening of the segment—the future Molloy Basin—began ~28.5 Ma ago in its eastern part synchronously with the beginning of detachment of the Hovgaard Ridge from the continental margin of the Barents Sea, the formation of the western part of the Molloy Basin, and beginning of opening between the Yermak Plateau and Morris Jesup Rise (Figs. 2a, 2b).

In the ~19.5–9.8 Ma interval, extension of the opening axis coincided with the axis of segments located to the south and north (central Molloy Basin and Lena Trough), and the northwestern part of the Molloy Basin was formed. About 9.8 Ma ago (C5n.1ny), just like in the central Molloy Basin, a jump in the opening axis to the east occurred and the axis occupied its present position.

We believe that the opening scenario was more complex and that another transform fault existed between the Molloy and Spitsbergen fracture zones during the period ~28.5–10 Ma [6].

Theoretical calculations confirm the beginning of opening of the Lena Trough during TLMA C6no chron (~19.5 Ma), except for the northern section, where this occurred a bit earlier, as well as formation of a narrow oceanic passage connecting the Norwegian–Greenland and Eurasian basins in the Early Miocene ~20–15 Ma ago [18] (Figs. 2a, 2b).

Towards the spreading center from TLMA C6no (~19.5 Ma) between the Yermak Plateau and Morris Jesup Rise, an LMA is clearly recorded, fragmentarily traced in the Lena Trough, which corresponds to TLAM 5ADno (~14.6 Ma) (Fig. 2b).

The opening of the oceanic passage led to the beginning of deep-sea exchange of water between the North Atlantic and Arctic oceans, although there is some uncertainty. If the original Lena Trough was covered by terrigenous sediments or had not sufficiently subsided, then this would have prevented deep-water circulation and stable water exchange could have begun only in the Late Miocene during formation of chron C5n.1ny (~9.8 Ma) [18].

According to the theoretical calculations obtained, the northernmost segment of the Knipovich Ridge began to open only ~9.8 Ma ago, simultaneously with the jump of the opening axis in the connecting segment between the Molloy and Spitsbergen fracture zones (Figs. 4a, 4b).

Mt. Hovgaard adjoined the continental margin of the Barents Sea, the Hovgaard Ridge was in subaerial conditions, and the Molloy Basin was a shallow-water area [19, 25] with narrow local continental ridges located within the basin with peaks protruding above sea level. This means that an ocean current (or currents) must have passed between the Hovgaard Ridge and continental margin of Greenland, since the western Molloy Basin began to open no later than ~28.5 Ma ago.

Due to the oblique opening of the Fram Strait between Svalbard and Greenland, the minimum width and depth of the passage sufficient for the beginning of full-fledged circulation of water masses has been determined ambiguously. Theoretical calculations suggest a minimum sufficient distance of 50 km [21].

In the northern segment of the Knipovich Ridge, the shortest distance from the eastern foot of Mt. Hovgaard to the COB (between chrons C5n.1ny, ~9.8 Ma) is ~115 km; i.e., theoretically, for formation of oceanic crust 50 km wide, ~4.3 Ma are required, so deep-sea circulation could have begun ~5.5 Ma ago.

However, the northern segment of the Knipovich Ridge adjoins with a system of fracture zones with significant displacement and in the west the ridge it is bounded by continental fragments: Mt. Howard and the Hovgaard Ridge. According to our calculations, the Hovgaard Ridge detached from the continental margin ~28.5 Ma ago, began to subside ~6.7 Ma ago, and reached depths >1000 m below sea level ~4.7 Ma ago [25]. If we consider Mt. Hovgaard an analogue of a smaller ridge, then, having begun to separate ~10 Ma ago, Mt. Hovgaard could have reached modern depths much later than ~4.7 Ma ago and it initially served as an additional complicating factor for the appearance of water circulation through the northern segment of the Knipovich Ridge.

An indirect confirmation is the change in water circulation that occurred ~2.6 Ma ago, which corresponds to the lower boundary of the appearance of the glacial–marine sediments in the northern part of the Norwegian–Greenland Basin and in the Eurasian Basin [3, 18].

On profile MAGE-88229 at 112 and 123 km in the upper part of the seismic section, two local ridges are clearly distinguished, which began to form ~2.6 Ma ago, since erosion of the underlying deposits and absence of inheritance of the horizon shape from the underlying forms of sediment relief are observed (Fig. 4b).

These two rises are clearly distinguished in the bathymetric data as narrow, elongated elevations of the bottom relief, located parallel to the north of the northeastern foot of the Hovgaard Ridge (Fig. 2a).

The southern rise starts from the northwestern foot of Mt. Hovgaard and extends northwest, crossing the MAGE-88229 profile; the second rise is located somewhat to the north. Clearly, ~2.6 Ma ago, a local intensive current formed between Mt. Hovgaard and the Hovgaard Ridge, which may indirectly indicate the beginning of passage of the current or a branch thereof through the northern segment of the Knipovich Ridge.

The coast of the Peary Land Peninsula in northeast Greenland hosts sedimentary deposits of the Cape Copenhagen Formation (Fig. 3a). Ancient DNA samples have been isolated from sedimentary horizons dated by magnetostratigraphic data to ~2 Ma ago, which are attributed to more than 100 different plant and animal species, including mastodons and ancient reindeer species [24]. This indicates that temperatures in the polar desert environment of the area in the Late Pliocene and Early Pleistocene were 11–19°C warmer than today, and the presence of DNA from green algae and the marine family Limulidae (various species of fish and crustaceans such as horseshoe crabs) suggests that the waters surrounding northeastern Greenland were much warmer [24]. The only modern Atlantic representative of the horseshoe crab is the population *Limulus polyphemus*, which lives in warm shallow-water conditions along the eastern coast of North

America and does not extend north of 45° N, indicating warmer surface water conditions (mean temperature 8°C) during the Early Pleistocene off the coast of Peary Land [24].

The source of heat that preserved biodiversity in polar desert and polar night conditions is the most interesting for research. In the modern Fram Strait, the cold East Greenland Current runs along the eastern coast of Greenland, and on the opposite side is the warm West Spitsbergen Current [19].

Presumably, in the Late Miocene (~9.8 Ma), when the opening axis in the central part of the Fram Strait jumped to the east and spreading began in the northern segment of the Knipovich Ridge, a warm current passed along the eastern coast of Greenland (Fig. 3a).

The cold countercurrent passed along the northern margin of the Barents Sea and in the central Fram Strait, west of the continental fragments located in subaerial or shallow-water conditions: the Hovgaard Ridge and local ridges within the Molloy Basin. The intensity of currents and their passage within the North Atlantic is complex, as the modern warm West Spitsbergen Current does not provide the high biodiversity that it did ~2 Ma ago for the northeastern coast of Greenland.

It is possible that the change in the direction of currents occurred ~1.8 Ma ago as a result of sufficient opening of the northern segment of the Knipovich Ridge and beginning of passage of an intense current over it. Indirect confirmation of this can be the obvious change in the sedimentation conditions in the rift valley of the ridge, in the central part of which, as follows from bathymetric and seismic data, the sedimentary cover is extremely thin and has developed sporadically.

On the western wall of the rift valley of the Knipovich Ridge, a fairly thick (~600 m) sedimentary layer formed in a short period of time ~2.7–1.8 Ma ago, which coincides with the interval of formation of the lower strata of glacial–marine sediments [25] (Fig. 4a). Earlier, ~1.8 Ma ago, cycles of formation of similar deposits occurred repeatedly between the Knipovich Ridges and western and northwestern margins of the Barents Sea [25, 32], but in the rift valley, the deposits are extremely thin [9, 29]; i.e., after ~1.8 Ma, the warm West Spitsbergen Current could have occupied its current position in the Fram Strait.

CONCLUSIONS

1. The opening of the Fram Strait occurred according to a complex and multistage scenario and was governed by the directions of movement of the North American and Eurasian plates, which determined the long-lived nature of medium- and short-scale segmentation.

2. In the Early Miocene (~19.5 Ma), the Lena Trough began to form—the narrowest segment of the Fram Strait.

3. In the Early and Late Miocene (~19.5–9.8 Ma), opening of the central part of the Fram Strait led to to the formation of the central and northwestern parts of the Molloy Basin, the basement of which consists of stretched blocks of the West Spitsbergen fold–thrust belt.

4. In the Late Miocene (~9.8 Ma) in the central part of the strait, the opening axis jumped to the east in the segments between the Molloy and Spitsbergen fracture zones, and spreading began in the northern segment of the Knipovich Ridge. This event is correlated with a change in sedimentation rates in the central Molloy Basin.

5. In the Late Miocene (~6.7 Ma), the Molloy Basin began to open, which coincides with the beginning of continuous subsidence of the Hovgaard Ridge, which prior to this event was in shallow-water or subaerial conditions and a threefold increase in sedimentation rates occurred in the central Molloy Basin.

6. In the Late Miocene (~9.8 Ma), deep-sea water exchange between the North Atlantic and Arctic oceans should have occurred west of fragments of the continental margin of the Barents Sea: the Hovgaard Ridge and Mt. Hovgaard, as well as local ridges within the Molloy Basin, located in subaerial or shallow-water conditions.

7. In the Late Miocene–Early Pleistocene (~9.8–1.8 Ma), a warm current from the North Atlantic could have passed along the eastern continental margin of Greenland, which even at its peak intensity provided heat to support the existence of biological diversity in polar desert and polar night conditions in north-northeast Greenland and shallow sea areas adjacent to its coast.

ABBREVIATIONS AND NOTATION

AMF	anomalous magnetic field
AB	acoustic basement
BAGF	Bouguer gravity field anomaly
COB	Continent–ocean boundary
LA	local anomaly
DL	drift line
LMA	linear magnetic anomaly
TLMA	theoretical axis of linear magnetic anomalies
MBE	multibeam echosounding
DEM	digital elevation model

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. D. G. Baturin and S. A. Nechkhaev, “The deep structure of Spitsbergen marginal plateau, NE-Greenland Sea,” Dokl. Akad. Nauk SSSR **306** (4), 925–930 (1989).
2. E. A. Gusev and S. I. Shkarubo, “The anomalous structure of Knipovich Ridge,” Russ. J. Earth Sci. **3** (2), 145–161 (2001). https://doi.org/10.2205/2001ES000056
3. A. V. Zayonchek, S. Yu. Sokolov, and A. V. Solov’ev, “The pre-Quaternary evolution of the Eurasia Basin: The results of interpretation of seismic profile ARC1407A,” Geotectonics **57**, 693–725 (2023). https://doi.org/10.31857/S0016853X23060085
4. G. S. Kazanin, G. A. Tarasov, T. Ya. Fedukhina, V. V. Shlykova, and G. G. Matishov, “The West Spitsbergen continental margin: The geological structure and petroleum resource potential,” Dokl. Earth Sci. **460** (1), 22–27 (2015). https://doi.org/10.7868/S086956521502019X
5. A. V. Kokhan, E. P. Dubinin, A. L. Grokhol’skii, and A. S. Abramova, “Kinematics and characteristic features of the morphostructural segmentation of the Knipovich Ridge,” Oceanology **52**, 688–699 (2012).
6. S. Yu. Sokolov, “Tectonic evolution of the Knipovich Ridge based on the anomalous magnetic field,” Dokl. Earth Sci. **437** (1), 343–348 (2011).
7. A. A. Peive and N. P. Chamov, “Basic tectonic features of the Knipovich Ridge (North Atlantic) and its neotectonic evolution,” Geotectonics **42** (1), 31–47 (2008).
8. E. V. Shipilov, “Basalt magmatism and the problem of gas content in the East Barents Sea basin,” Arktika: Ekol. Ekon. **30** (2), 94–106 (2018). https://doi.org/10.25283/2223-4594-2018-2-94-106
9. I. M. H. Amundsen, M. Blinova, B. O. Hjelstuen, R. Mjelde, and H. Haflidason, “The Cenozoic western Svalbard margin: Sediment geometry and sedimentary processes in an area of ultraslow oceanic spreading,” Mar. Geophys. Res **32** (4), 441–453 (2011). https://doi.org/10.1007/s11001-011-9127-z
10. J. Backman, M. Jakobsson, M. Frank, F. Sangiorgi, H. Brinkhuis, C. Stickley, M. O' Regan, R. Lovlie, H. Palike, D. Spofforth, J. Gattacecca, K. Moran, J. King, C. Heil, “Age model and core-seismic integration for the Cenozoic ACEX sediments from the Lomonosov Ridge,” Paleoceanography **23**, 1–15 (2008). https://doi.org/10.1029/2007PA001476
11. G. Balmino, N. Vales, S. Bonvalot, and A. Briais, “Spherical harmonic modeling to ultra-high degree of Bouguer and isostatic anomalies,” J. Geodes. July 2012 **86** (7), pp. 499–520. https://doi.org/10.1007/s00190-011-0533-4
12. A. Breivik, R. Mjelde, P. Grogan, H. Shimamura, Y. Murai, and Y. Nishimura, “Crustal structure and transform margin development south of Svalbard based on ocean bottom seismometer data,” Tectonophysics **369**, 37–70 (2003). https://doi.org/10.1016/S0040-1951(03)00131-8
13. K. Crane, S. Doss, P. Vogt, E. Sundvor, I. P. Cherkashov, and J. Devorah, “The role of the Spitsbergen shear zone in determining morphology, sedimentation and evolution of the Knipovich Ridge,” Mar. Geophys. Res **22**, 153–205 (2001). https://doi.org/10.1023/A:1012288309435
14. W. Czuba, O. Ritzmann, Y. Nishimura, M. Grad, R. Mjelde, A. Guterch, and W. Jokat, “Crustal structure of the continent–ocean transition zone along two deep seismic transects in north–western Spitsbergen,” Polish Polar Res. **25** (3–4), 205–221 (2004).
15. M.-A. Dumais, L. Gernigon, O. Olesen, S. E. Johansen, and M. Bronner, “New interpretation of the spreading evolution of the Knipovich Ridge derived from aeromagnetic data,” Geophys. J. Int. **224**, 1422–1428 (2021). https://doi.org/10.1093/gji/ggaa527
16. M.-A. Dumais, L. Gernigon, O. Olesen, A. Lim, S. E. Johansen, and M. Brönner, “Crustal and Thermal Heterogeneities across the Fram Strait and the Svalbard Margin,” Tectonics **41**, e2022TC007302 (2022). https://doi.org/10.1029/2022TC007302
17. B. Ehlers and W. Jokat, “Subsidence and crustal roughness of ultra-slow spreading ridges in the northern North Atlantic and the Arctic Ocean,” Geophys. J. Int. **177** (2), 451–462 (2009). https://doi.org/10.1016/j.tecto.2015.12.002
18. Ø. Engen, J. I. Faleide, and T. K. Dyreng, “Opening of the Fram Strait gateway: A review of plate tectonic constraints,” Tectonophysics **450**, 51–69 (2008). https://doi.org/10.1016/j.tecto.2008.01.002
19. J. Gruetzner, J. Matthiessen, W. H. Geissler, A. C. Gebhardt, and M. Schreck, “A revised core-seismic integration in the Molloy Basin (ODP Site 909): Implications for the history of ice rafting and ocean circulation in the Atlantic–Arctic gateway,” Global Planet. Change **215**, Art. 103876 (2022). https://doi.org/10.1016/j.gloplacha.2022.103876
20. W. B. Harland, *The Geology of Svalbard*, Ed. by W. B. Harland (Geol. Soc. London, UK, 1998, Geol. Surv. Mem., Is. 17).
21. M. Jakobsson, J. Backman, B. Rudels, J. Nycander, M. Frank, L. Mayer, W. Jokat, F. Sangiorgi, M. O’Regan, H. Brinkhuis, J. King, and K. Moran, “The early Miocene onset of a ventilated circulation regime in the Arctic Ocean,” Nature **447**, 986–990 (2007). https://doi.org/https://doi:10.1038/nature05924
22. M. Jakobsson, L. A. Mayer, C. Bringensparr, et al., “The International Bathymetric Chart of the Arctic

Ocean. Version 4.0," Sci. Data **176** (7) (2020). https://doi.org/10.1038/s41597-020-0520-9

23. J. I. Faleide, A. Solheim, A. Fiedler, B. O. Hjelstuen, E. S. Andersen, and K. Vanneste, "Late Cenozoic evolution of the western Barents Sea—Svalbard continental margin," Global Planet. Change **12**, 53–74 (1996). https://doi.org/10.1016/0921-8181(95)00012-7

24. K. H. Kjær, M. W. Pedersen, B. De Sanctis, B. De Cahsan, T. S. Korneliussen, C. S. Michelsen, K. K. Sand, S. Jelavić, A. H. Ruter, A. M. A. Schmidt, K. K. Kjeldsen, A. S. Tesakov, Ian Snowball, J. C. Gosse, I. G. Alsos, Y. Wang, C. Dockter, M. Rasmussen, M. E. Jørgensen, B. Skadhauge, A. Prohaska, J. Å. Kristensen, M. Bjerager, M. E. Allentoft, E. Coissac, PhyloNorway Consortium, A. Rouillard, A. Simakova, A. Fernandez-Guerra, C. Bowler, M. Macias-Fauria, L. Vinner, J. J. Welch, A. J. Hidy, M. Sikora, M. J. Collins, R. Durbin, N. K. Larsen, and E. Willerslev, "A 2-million-year-old ecosystem in Greenland uncovered by environmental DNA," Nature **612**, 283–296 (2022). https://doi.org/10.1038/s41586-022-05453-y

25. J. Knies, R. Mattingsdal, K. Fabian, K. Grøsfjeld, S. Baranwal, K. Husum, S. De Schepper, C. Vogt, N. Andersen, J. Matthiessen, K. Andreassen, W. Jokat, S.-I. Nam, and C. Gaina, "Effect of early Pliocene uplift on late Pliocene cooling in the Arctic—Atlantic gateway," Earth Planet. Sci. Lett. **387**, 132–144 (2014). https://doi.org/10.1016/j.epsl.2013.11.007

26. J. Knies and C. Gaina, "Middle Miocene ice sheet expansion in the Arctic: Views from the Barents Sea," Geochem. Geophys. Geosyst. **9** (2), Q02015 (2008). https://doi.org/10.1029/2007GC001824

27. J. Knies, J. Matthiessen, C. Vogt, J. S. Laberg, B. O. Hjelstuen, M. Smelror, E. Larsen, K. Andreassen, T. Eidvin, and T. O. Vorren, "The Plio-Pleistocene glaciation of the Barents Sea—Svalbard region: a new model based on revised chronostratigraphy," Quat. Sci. Rev. **28** (9), 812–829 (2009). https://doi.org/10.1016/j.quascirev.2008.12.002

28. L. Krysiński, M. Grad, R. Mjelde, W. Czuba, and A. Guterch, "Seismic and density structure of the lithosphere—asthenosphere system along transect Knipovich Ridge—Spitsbergen—Barents Sea – geological and petrophysical implications," Polish Polar Res. **34** (2), 111–138 (2013). https://doi.org/10.2478/popore—2013—0011

29. T. Kvarven, B. O. Hjelstuen, and R. Mjelde, "Tectonic and sedimentary processes along the ultraslow Knipovich spreading ridge," Mar. Geophys. Res. **35**, 89–103 (2014). https://doi.org/10.1007/s11001-014-9212-1

30. S. Merkouriev and C. DeMets, "High-resolution Quaternary and Neogene reconstructions of Eurasia—North America plate motion," Geophys. J. Int. **198**, 366–384 (2014). https://doi.org/10.1093/gji/ggu142

31. A. M. Myhre, J. Thiede, J. V. Firth, G. L. Johnson, W. F. Ruddiman, "Ocean Drilling Program," in *Proceedings ODP* (College Station, Texas A&M Univ., USA, 1995, Initial Rep. No. 151).

32. A. P. E. Lasabuda, N. S. Johansen, J. S. Laberg, J. I. Faleide, K. Senger, T. A. Rydningen, and A. Hanssen, "Cenozoic uplift and erosion of the Norwegian Barents Shelf – A review," Earth-Sci. Rev. **217**, 1–35 (2021). https://doi.org/10.1016/j.earscirev.2021.103609

33. A. Libak, C. H. Eide, R. Mjelde, H. Keers, and E. R. Flüh, "From pull-apart basins to ultraslow spreading: Results from the western Barents Sea Margin," Tectonophysics **514–517**, 44–61 (2012). https://doi.org/10.1016/j.tecto.2011.09.020

34. J. Ogg, "Geomagnetic polarity time scale," *The Geologic Time Scale—2020*, Ed. by F. M. Gradstein, J. G. Ogg, M. D. Schmitz, and G. M. Ogg (Elsevier Sci., Oxford. UK, 2020, Ch. 5), pp. 159–192.

35. S. Polteau, B. W. Hendriks, S. Planke, M. Ganerod, F. Corfu, J. I. Faleide, I. Midtkandal, H. S. Svensen, and R. Myklebust, "The Early Morgan Cretaceous Barents Sea sill complex: Distribution, ^{40}Ar/^{39}Ar geochronology, and implications for carbon gas formation," Palaeogeogr., Palaeoclimatol., Palaeoecol. **441**, 83–95 (2016). https://doi.org/10.1016/j.palaeo.2015.07.007

36. O. Ritzmann, W. Jokat, R. Mjelde, and H. Shimamura "Crustal structure between the Knipovich Ridge and the Van Mijenfjorden (Svalbard)," Mar. Geophys. Res. **23**, 379–401 (2002). https://doi.org/10.1023/B:MARI.0000018168.89762.a4

37. P. R. Vogt, "Geophysical and geochemical signatures and plate tectonics," in *The Nordic Seas*, Ed. by B. G. Hurdle (Springer, NY, USA, 1986), pp. 413–662.

38. P. R. Vogt, P. T. Taylor, L. C. Kovacs, and G. L. Johnson, "Detailed aeromagnetic investigation of the Arctic Basin," J. Geophys. Res. **84** (B3), 1071–1089 (1979).

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