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The anomalous structure of Knipovich Ridge

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Abstract. The study of bathymetric, single-channel seismic and CDP profiling data, and modern seismicity for the Knipovich Ridge reveals its discordance with respect to the surrounding structural grain, suggesting that it is a recent, superimposed feature. The available geological and geophysical data constrain the inception of the Knipovich Ridge as an oceanic rift to the Miocene. The trend of lineaments, emphasized by the deep structure and present-day seafloor topography on the west flank of the ridge and along its crest, most likely reflects a stress field geometry and a dynamic pattern of tectonic movements dissimilar to the modern structural plan. From the degree of development of structural features of the Knipovich Ridge and from the changes in the mode of its tectonic evolution, which are atypical of mid-oceanic ridges, it is an oceanic rift that is still, structurally, in its formative phase.

Introduction

The Knipovich Ridge and surrounding area has long been a focus of interdisciplinary and specialized surveys performed by international marine expeditions. The global scientific community has sound reasons for scrutinizing this region because the Svalbard Archipelago and its adjacent Norwegian-Greenland Basin are key features to unraveling the tectonics and evolution of the western Arctic sector and the development of structural links between the North Atlantic and Arctic Ocean in Late Cenozoic time. Most researchers admit a spreading origin for the Knipovich Ridge in the Norwegian-Greenland Basin. The presence of a well-developed rift valley, modern seismicity beneath the ridge, and its sign-variable magnetic field, all seem to suggest that it is a regular segment of the global mid-oceanic ridge system. Many anomalous features of this structure, however, do not fit in the traditional concepts and remain as yet to be elucidated.

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Data

Our study draws on single- and multichannel seismic surveys performed by the Marine Arctic Geological Exploration Expedition (MAGE), Murmansk [*Baturin,* 1990, 1992, 1993; *Baturin and Nechkhaev,* 1989; *Shkarubo,* 1996, 1999], and seismic data of Bergen University, Norwegian Petroleum Directorate, and Federal Geological Service of Germany (BGR, Hanover) [*Eiken,* 1994; *Faleide et al.,* 1996; *Gabrielsen et al.,* 1990; *Hinz and Schluter,* 1978] (Figure 1). We analyzed bathymetric maps [*Cherkis and Vogt,* 1994; *Crane et al.,* 1995; *Matishov,* 1984; *Naryshkin,* 1998; *Ohta,* 1982], seafloor sampling data [*Neumann and Schilling,* 1984], and deep-sea drilling [*Talwani and Udintsev,* 1976; *Thiede et al.,* 1995] and structural drilling data from the western Barents margin [*Eidvin et al.,* 1993; *Saettem et al.,* 1994]. Besides, we used the published magnetic and gravity anomaly maps [*Faleide et al.,* 1984; *Olesen et al.,* 1997].

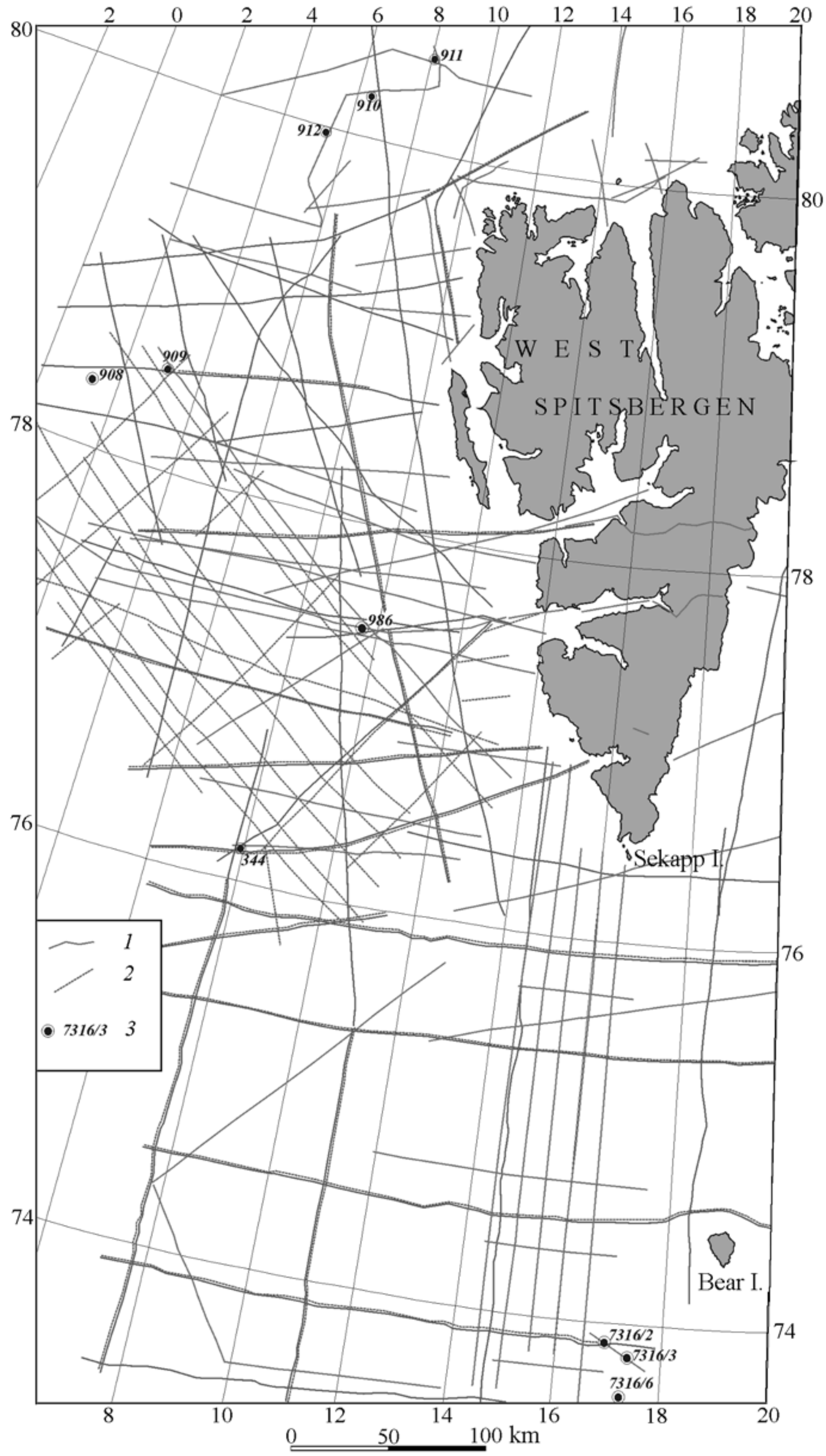

Figure 1. Location of single- and multichannel seismic lines used in this work. 1 – seismic lines, 2 – MAGE seismic lines, 3 – ODP and NDP holes.

Approaches used

Proposed is an integrated analysis of a broad spectrum of geological and geophysical data, both new and published. We constructed a bathymetric index map summarizing the available bathymetric schemes and maps at various scales. These maps were updated using single-channel seismic profiles shot between 1986 and 1990 by the Marine Arctic Geological Exploration Expedition. For the northern segment of the Knipovich Ridge (76° to 79°N), which has the most detailed seismic coverage, a large scale bathymetric map was constructed. The area south of 76°N (Figure 2) received a more sketchy bathymetric imaging. The lineament analysis of these maps along with seismic materials provided the basis for outlining neotectonic displacements in the crestal zone of the Knipovich Ridge.

Then, a seismostratigraphic analysis of multichannel seismic profiles was performed. In order to refine the structural pattern of sedimentary cover in the Norwegian-Greenland deep-sea basin with due regard for seismostratigraphic schemes of various workers [*Baturin,* 1986, 1992; *Faleide et al.,* 1996; *Hinz and Schluter,* 1978; *Savostin and Baturin,* 1986; *Shkarubo,* 1999], seismic horizons were correlated. In contrast to previous studies, our stratigraphic tie of key reflectors is based, among other things, on deep-sea drilling data from the Fram Straight.

In the crestal zone of the Knipovich Ridge, distinctive for its heterogeneous structure, and in which reflectors are hard to trace continuously, sedimentary cover was subdivided by means of identifying the "structural styles" of individual stratigraphic assemblages. In small isolated basins, seismostratigraphic assemblages were established on the basis of a number of distinctive features, such as seismic signature carrying indirect information on the sedimentary facies, degree and style of deformation in sedimentary piles, and relations among stratigraphic assemblages and between these assemblages and acoustic basement. The use of such methodological approaches is justified by the lack of direct geological observations in the numerous isolated basins and ponds, on terraces, etc., whose sedimentary cover requires dating prerequisite to paleotectonic reconstructions.

Paleogeographic evolution of the Norwegian-Greenland Sea

Deep-sea drilling in the southern Norwegian-Greenland Sea (Vöring Plateau, Lofoten and Norwegian basins, Icelandic Plateau) [*Talwani and Udintsev,* 1976] has elucidated the main evolutionary phases of the oceanic basin. In a number of localities, the Paleocene-Eocene sedimentary cover was laid down in shallow-water environments, and it is only the Miocene and Pliocene to Quaternary strata, unconformably overlying this cover, that can be labeled with confidence as bathyal. The marked hiatuses displayed by the sequences penetrated by deep-sea drilling led some workers to infer that, over some part of the present-day Norwegian-Greenland Sea, Early Oligocene to Middle Eocene times were characterized by uplifting and even by continental environments [*Rudich,* 1983].

According to the plate tectonics, the southern part of the Norwegian-Greenland Sea was incepted in the epoch of M24 magnetic anomaly (56–58 Ma) [*Talwani and Eldholm,* 1977]. However, the presence of chemially anomalous basalts and the temporal mismatch between the cored basalts and magnetic anomalies called for tectonic models other than plate-tectonic ones [*Rudich,* 1983; *Udintsev,* 1982]. These models invoke taphrogeny, flood magmatism, oceanization, and rifting as leading ocean-forming processes. Besides, the mid-oceanic ridges were assumed to have formed at a concluding phase of formation of the Norwegian-Greenland oceanic basin [*Rudich,* 1983].

Sediments deposited in the system of oceanic margin basins rimming the continental shelves are chiefly Cenozoic in age. Note also that the sharp thickening of Upper Cretaceous strata on the western Barents margin [*Gabrielsen et al.,* 1990] and on the Vöring Plateau [*Sigmond,* 1992] toward the modern oceanic basin suggests a pre-Cenozoic inception age for the system of oceanic margin basins located south of the Senja Fracture Zone. The dikes and sills recovered by deep-sea drilling from oceanic basement sections alongside volcanics and postdating the overlying sediments [*Talwani and Udintsev,* 1976] testify to magmatism that continued. Relationships like this are characteristic of the transitional zone between the continent and the Norwegian-Greenland Sea basins, in which sedimentary sequences grade into lavas and tuffs pertaining to oceanic crust [*Klitin,* 1983, 1988]. Such structures, detected by seismic surveys on the east Greenland margin, are termed "pseudo-scarps" [*Larsen,* 1990].

Even more topical to the matter in question are results from Holes 908 and 909 in the Fram Strait, located immediately northwest of the Knipovich Ridge [*Thiede et al.,* 1995] (Figure 3). These data point to an enclosed character of the marine basin that existed there in Oligocene time. The study of skeleton habits of the silicoflagellates Cannopilus hemispaericus, Dictyocha bryonalis, Distephanus crux, and D. paulii indicates a very limited influence of surface water from the North Atlantic [*Locker,* 1996]. The similarity of these species to the assemblages from Western Siberia and the Urals suggests possible paleogeographic links with eastern regions via the Arctic Basin or the Barents Sea.

The Paleogene diatom assemblages from Hole 908, located northwest of the Knipovich Ridge, on the aseismic Hovgaard Ridge, display epiphytic forms indicative of low-salinity neritic and nearshore environments. Further evidence for nearshore paleoenvironment is furnished by the finds of epipelic (growing on soft sediment) and epipsammic (growing on sandy bottom) epibenthic diatom taxocoenoses. This conclusion draws on the analysis of modern habitats of the genera Paralia, Diploneis, Cocconeis, Grammatophora, Rhaphoneis, etc. [*Scherer and Koç,* 1996]. The Paleogene diatom assemblages from Hole 908 also indicate a great sedimentation rate in a shelf environment in water depths of a few hundred meters. Rather common are finds of freshwater diatoms representative of paralic swamps and marshes (acidophilic diatoms of the genera Eunotia and Pinnularia) [*Scherer and Koç,* 1996]. Some of the forms

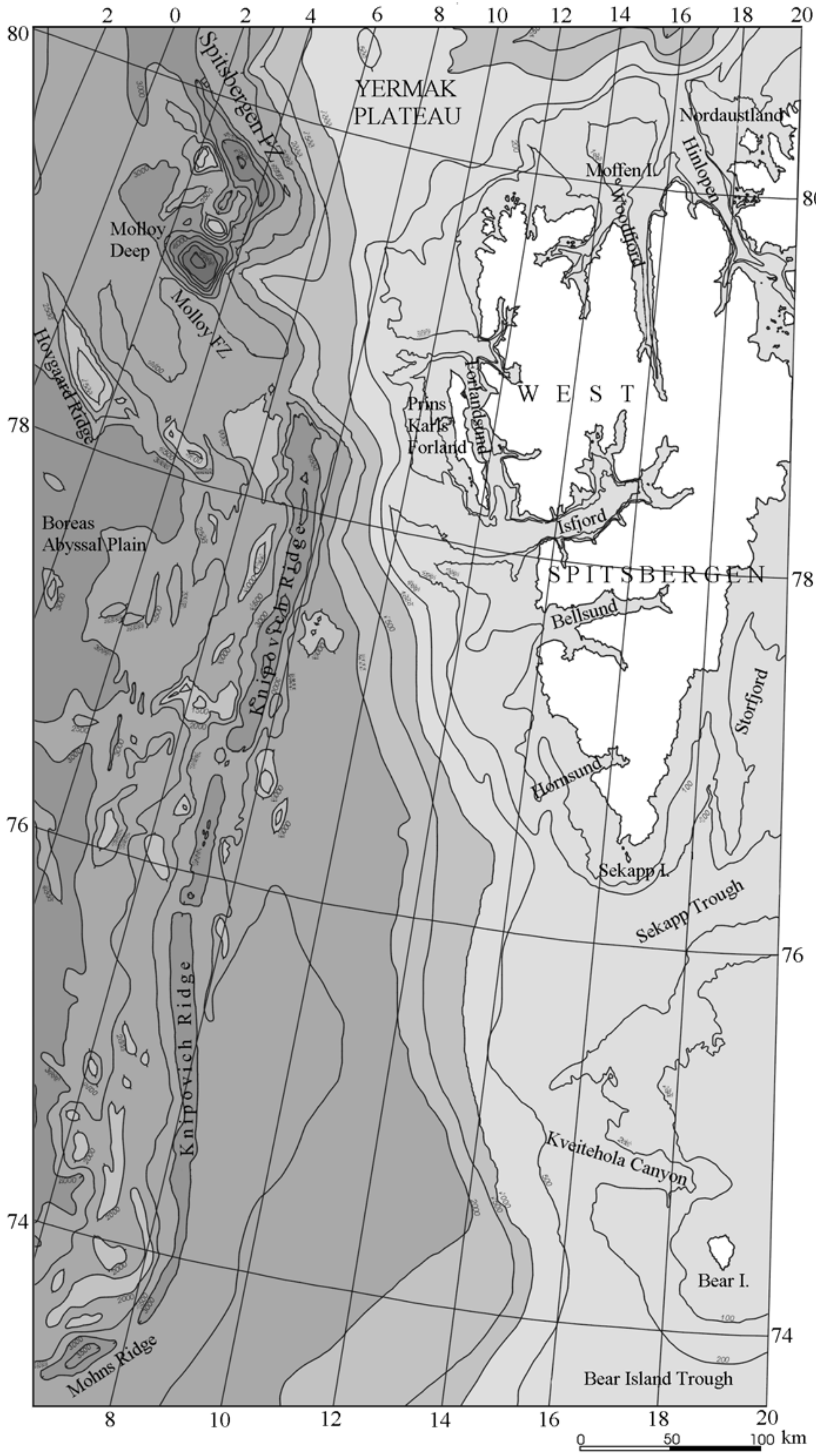

Figure 2. Bathymetric scheme of the northeastern Norwegian-Greenland Sea (from [*Cherkis and Vogt,* 1994; *Crane et al.,* 1995; *Ohta,* 1982] and MAGE (Marine Arctic Geological Exploration Expedition) single-channel seismic lines; see Figure 2 for line locations).

encountered in Hole 908 have been reported from Western Siberian Oligocene strata, in which they are also suggestive of a low-salinity habitat in a nearshore setting. The benthic foraminiferal assemblages from Paleogene sediments in the northern Norwegian-Greenland Basin point to a somewhat deeper shelf environment [*Ostermann and Spiegler,* 1996]. During Miocene time, the Fram Strait was distinguished by great depositional rates, and it was an isolated, relatively deep-water basin, as suggested by the studies of agglutinated benthic foraminifers. This sedimentation environment favored a longer lasting preservation of agglutinated benthic foraminifer assemblages than in the North Atlantic, where they disappeared much earlier [*Ostermann and Spiegler,* 1996]. The fact that the bottom water was isolated from the rest of the North Atlantic is further supported by the absence of calcareous faunas from Hole 909.

The above circumstances imply an isolated nature for the northern Norwegian-Greenland Sea and an unusually dynamic formation mode of the deep-sea basin, with great subsidence rates in Miocene and, especially, Pliocene to Quaternary times.

Discussion

Structure of the oceanic basin. In order to identify the structural and genetic type of the Knipovich Ridge and reconstruct the tectonic and geodynamic processes responsible for the present-day morphostructure of the crestal zone and rift valley of the ridge, one should primarily consider the general architecture of the deep in the northern Norwegian-Greenland Basin.

The plate tectonic formation model for the Norwegian-Greenland Basin [*Talwani and Eldholm,* 1977] proposes that its northern part began to open at 36 Ma (M13 magnetic anomaly), as the North American and Eurasian plates split up giving rise to an oceanic rift. This tectonic scenario implies that the Oligocene deposits, coeval to the initial phase of the oceanic basin opening, must be confined to oceanic margin basins at the opposite continental margins, and their overlying Pliocene to Quaternary strata must be spread more widely, reaching as far as the ridge zone.

Sediment distribution in the oceanic deep of the Norwegian-Greenland Basin is controlled by the topography of heterogeneous acoustic basement (Figure 4), which, on the basis of its geological and geophysical characteristics, can be subdivided into the oceanic basaltic basement that includes the axial zone of the Knipovich Ridge, an abyssal step, and destroyed continental substrate (Figure 5). Seismic data suggest a transitional zone between the continental and oceanic basements [*Shkarubo,* 1996]. Within the oceanic deep, acoustic basement surface subsides generally west and east from the Knipovich Ridge. The most rugged basement topography is recorded in the area of continental crust destruction and in the neotectonically active zone along the crest of the ridge. West of the Knipovich Ridge, on the Boreas Abyssal Plain, basement surface is cut into minor ridges. The elongate ridges and intervening depressions run at an angle to the ridge's strike. East of the ridge, tectonic relief is leveled off completely by sedimentary cover, and the slope base displays a modern accumulative topography.

The outline of the deep-sea basin is marked by the faulted continental-slope flexure zone, in which continental basement is cut by a system of listric faults and is overlain by a sedimentary wedge. Near the continental slope break and further outboard, the structure of sedimentary cover on the continental margin exhibits elongate, en echelon oceanic margin basins.

The distributional pattern and seismic signature of rock assemblages in the Norwegian-Greenland Sea basin suggest a dramatic change in depositional environment at the Miocene /Pliocene boundary.

Rift valley. The rift valley of the Knipovich Ridge trends roughly N-S and is V-shaped over a great length (Figure 6). Slope angles on the western and eastern walls change along the strike of the rift valley. The rift valley displays numerous elevations, formed mostly by active undersea volcanoes with lava flows, recorded by sonar surveys [*Crane et al.,* 1995]. The rift-valley walls are modified by terraces emphasizing the block-faulted fabric of the ridge's crestal zone. These step faults displace basaltic basement and its entire overlying sedimentary cover, suggesting a comparatively recent age for the extensional dislocations. Rather frequently, the fault scarps are spaced at 500-m intervals. On both the eastern and western walls of the rift valley, seismic sequences thin out in a westerly direction. This might point to sediments "overflowing" from the Svalbard margin across the locus of the present-day rift valley. It is also conceivable that the depression on the site of the modern rift valley was much shallower while the sediments were deposited, and the subsequent seafloor sagging and rifting caused strong displacements in sedimentary cover.

The chain of the highest summits in the crestal zone of the ridge is associated with M3 magnetic anomaly. The axial anomaly is well-developed in the northern segment of the Knipovich Ridge alone. The Knipovich Ridge volcanic rocks are relatively enriched in Na, Si, and K and depleted in Fe [*Neumann and Schilling,* 1984; *Sushchevskaya et al.,* 1997]. In the rift valley, a present-day hydrothermal activity is documented [*Poroshina et al.,* 1998].

Sediment distribution in the crestal zone. Deep-sea drilling Holes 908 and 909 on the Greenland-Spitsbergen Sill enabled a stratigraphic tie of the seismic horizons. A detailed analysis of seismic data reveals a broad distribution of the Oligocene assemblage, traceable as far as the crestal zone of the Knipovich Ridge (Figure 7). Apparently, this sedimentary assemblage, the oldest recovered by drilling in the Norwegian-Greenland Sea [*Thiede et al.,* 1995], is preserved fragmentarily in oceanic basement lows, in which the Oligocene assemblage is unconformably overlain by Neogene strata. The unconformity surface, suggestive of block uplifting, is recorded by numerous seismic profiles in the ridge's axial zone (Figures 8, 9). This nondeposition event is also documented at Hole 908 on the Hovgaard Ridge, on which Miocene to Early Pliocene strata are missing [*Thiede et al.,* 1995].

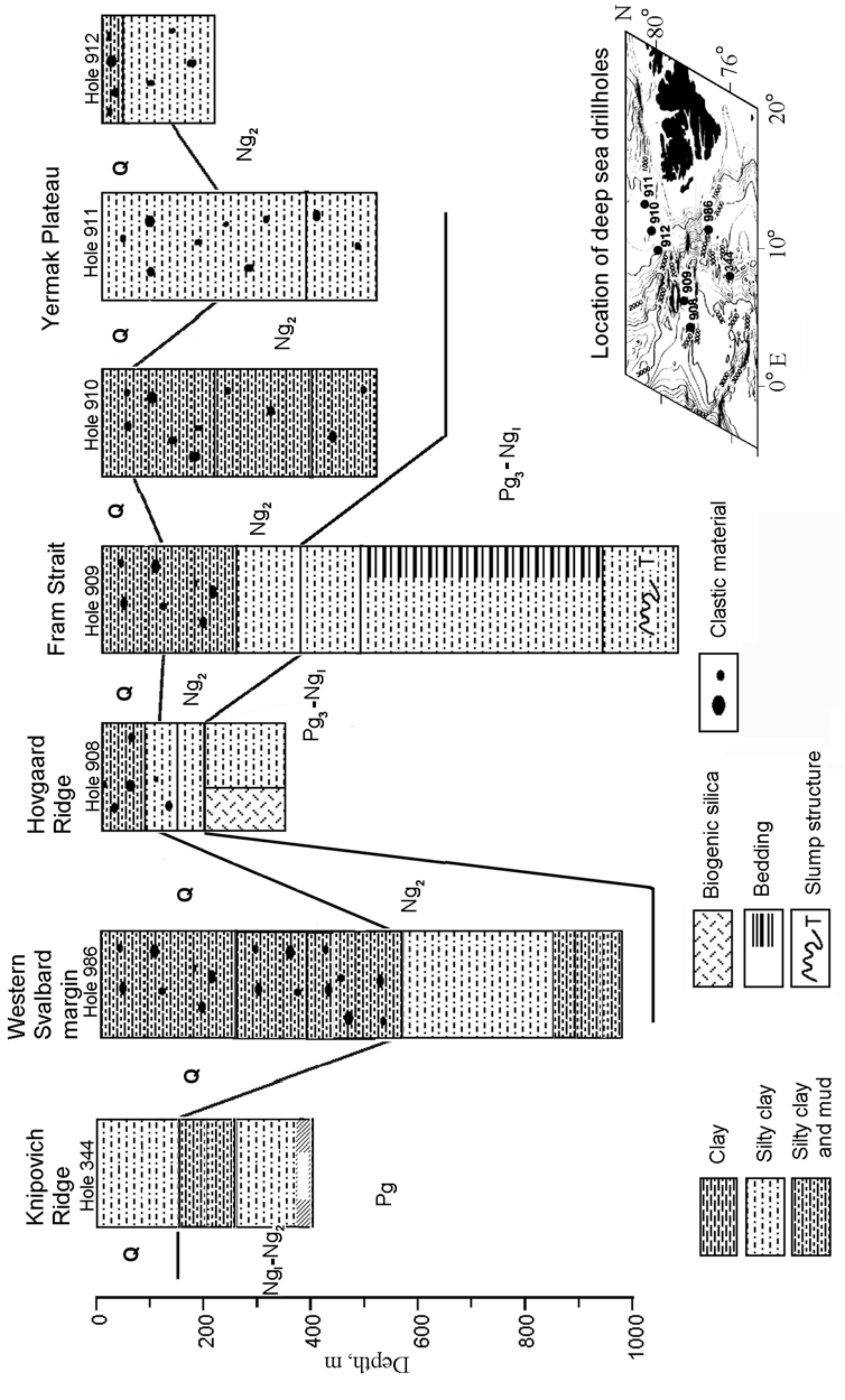

Figure 3. Correlation of deep sea drillholes [*Talwani and Udintsev*, 1976; *Thiede et al.*, 1995].

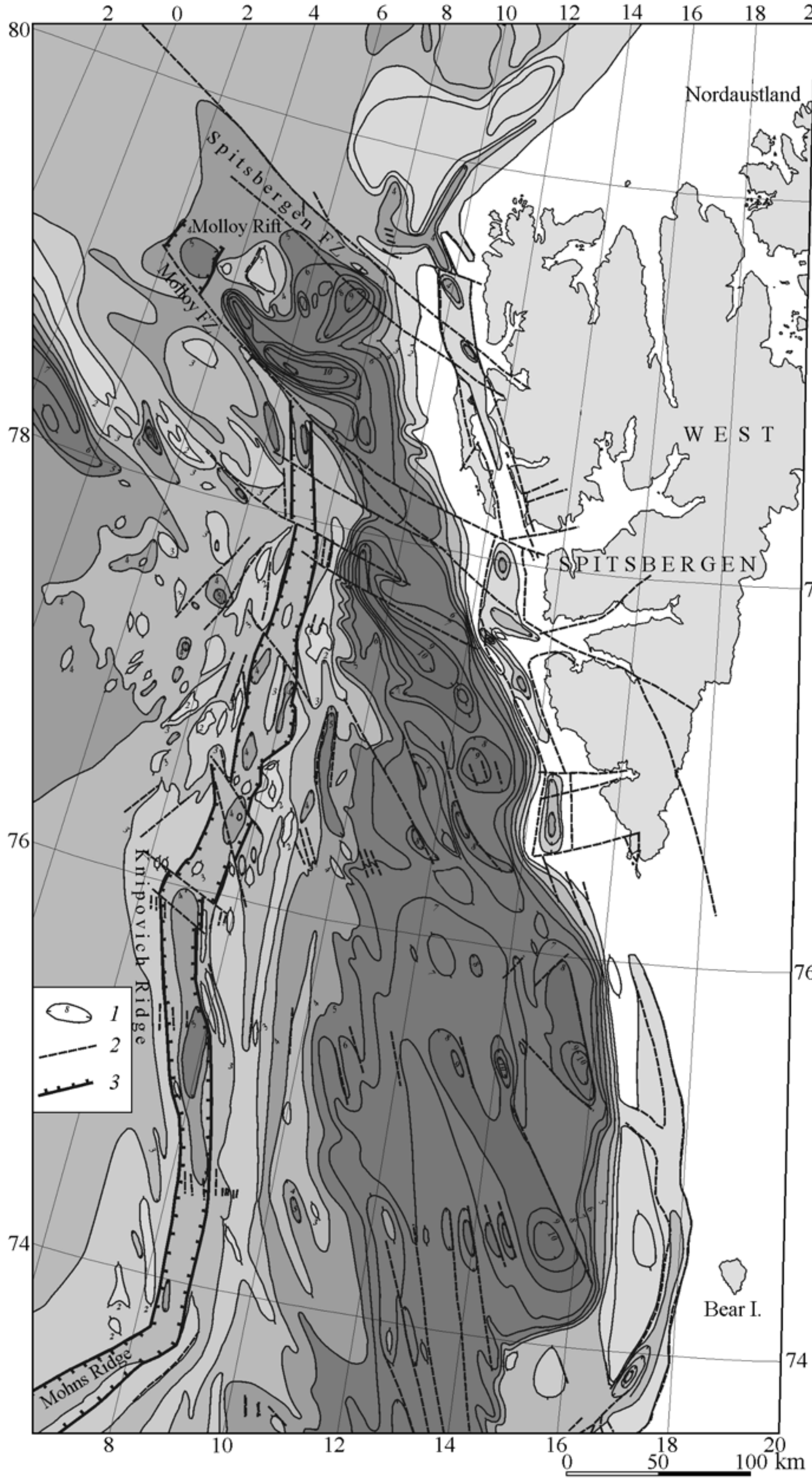

Figure 4. Depth to acoustic basement. 1 – contours in kilometers , 2 – fault, 3 – fault bounding rift valley.

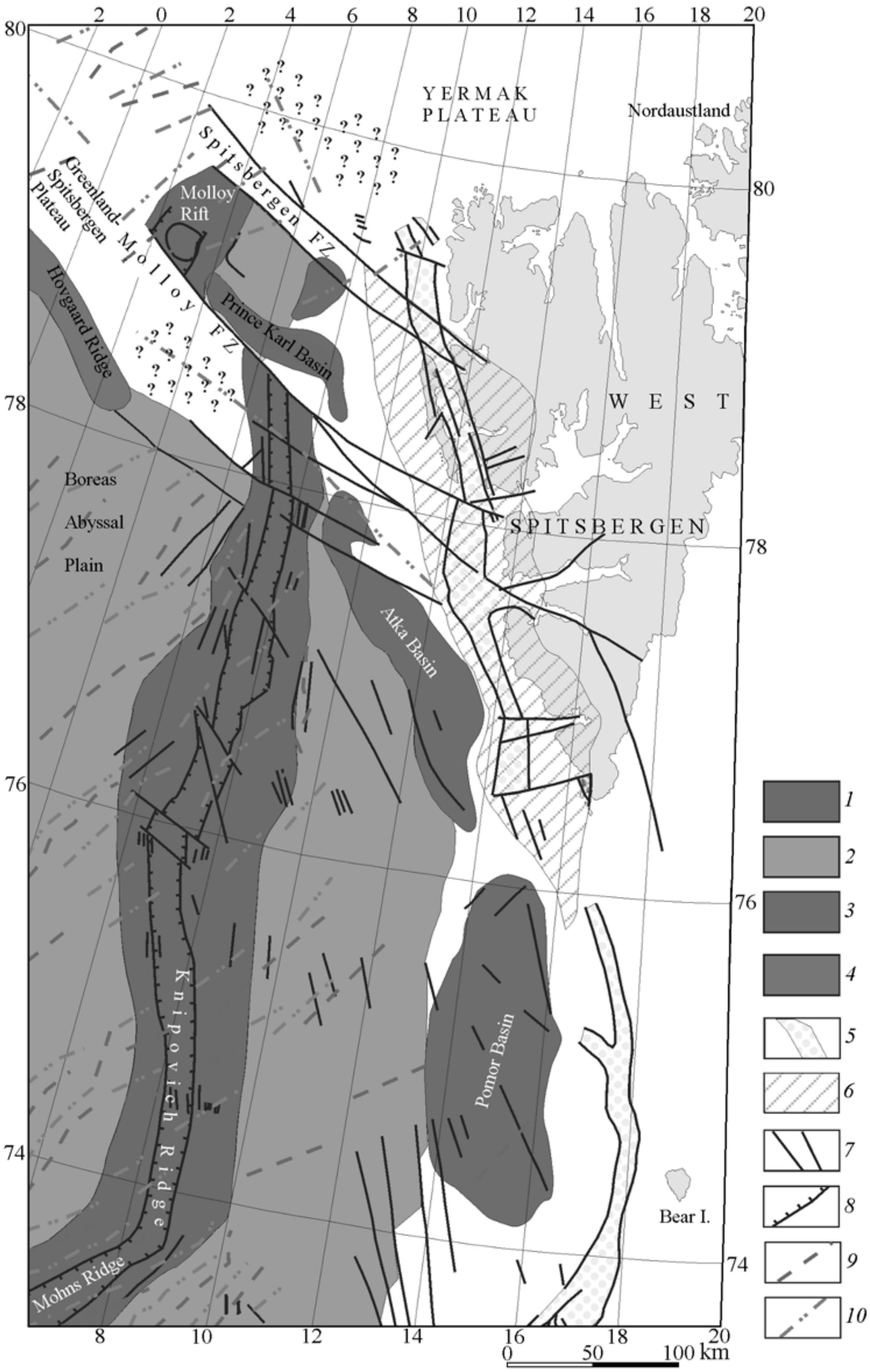

Figure 5. Tectonic features of the northeastern Norwegian-Greenland Sea. 1 – neotectonic reactivation zone of the Knipovich Ridge, 2 – region of oceanic crust, 3 – oceanic margin basins, 4 – aseismic Hovgaard Ridge, 5 – Forlandsund-Bellsund system of graben-like troughs, 6 – western Svalbard fold-and-thrust belt, 7 – faults, 8 – faults bounding rift valleys, 9 – axis of magnetic high [*Olesen et al.,* 1997], 10 – axis of magnetic low [*Olesen et al.,* 1997].

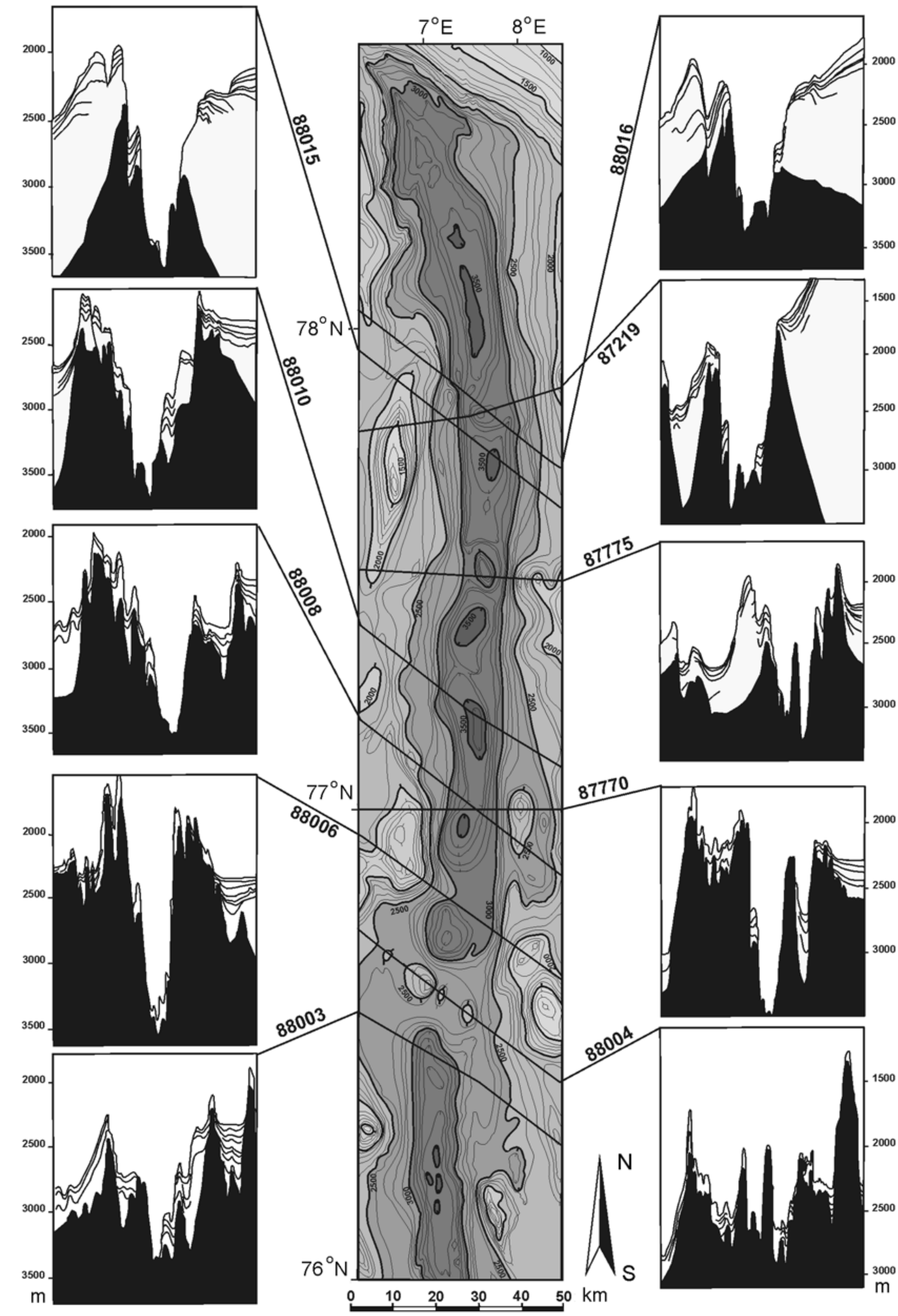

Figure 6. Bathymetric map of the rift valley of the Knipovich Ridge and transverse MAGE seismic profiles, vertical scale exaggerated.

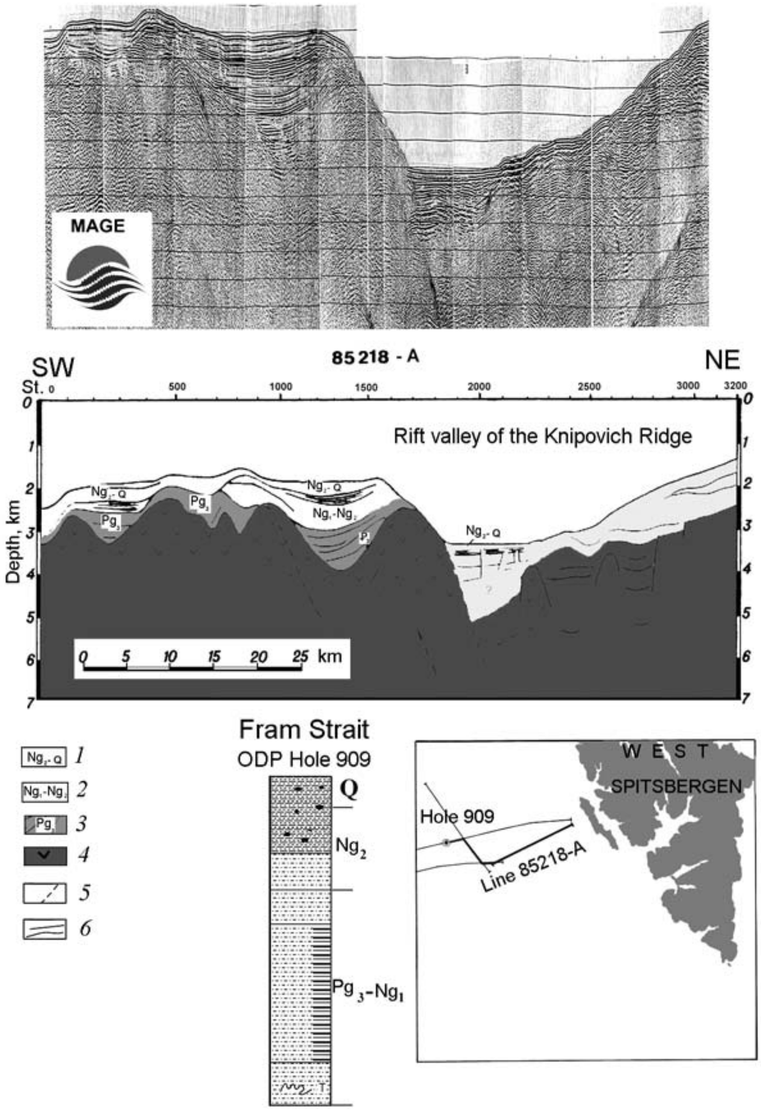

Figure 7. Interpretive scheme of seismic line 85218-A across the northernmost Knipovich Ridge near the offset of its axis by the Molloy Fracture Zone. Seismostratigraphic units are tied to deep-sea drilling Hole 909 and MAGE seismic grid. 1 – Pliocene to Quaternary sediments, 2 – Miocene to Pliocene sediments, 3 – Oligocene rocks, 4 – oceanic basaltic basement, 5 – fault.

Geodynamic setting of the ridge. The gap in stratigraphic record at the ridge axis due to nondeposition or erosion suggests uplifting of this seafloor region. Judging from the seismically portrayed syndepositional deformations in sedimentary cover, such as horizons that "ride up" and sedimentary assemblages that pinch out toward basement highs, it was in pre-Late Miocene time that this area was involved in uplifting. To a first approximation, the uplifting was comparable in magnitude to the elevation, as great as 0.5 to 1.0 km, of the ridge crestal zone above the contiguous Boreas Abyssal Plain. Simultaneously, the chain of the highest volcanic summits took shape, which makes up the modern submarine ridge and bounds the rift valley.

The seismic profiles across the rift valley on the southern Knipovich Ridge testify to cyclicity of the extensional processes (Figures 10, 11). Sedimentary sequences on the rift shoulders, as thick as several hundred meters, are cut by a system of listric faults whose tectonic impact dates to a single event of neotectonic reactivation. The geodynamic environment in the area of the ridge must have involved protracted phases of tectonic quiescence, long enough for considerable sediment thicknesses to have accumulated, and intervening brief pulses of reactivated tectonism.

The magnitude of post-Oligocene horizontal extension in

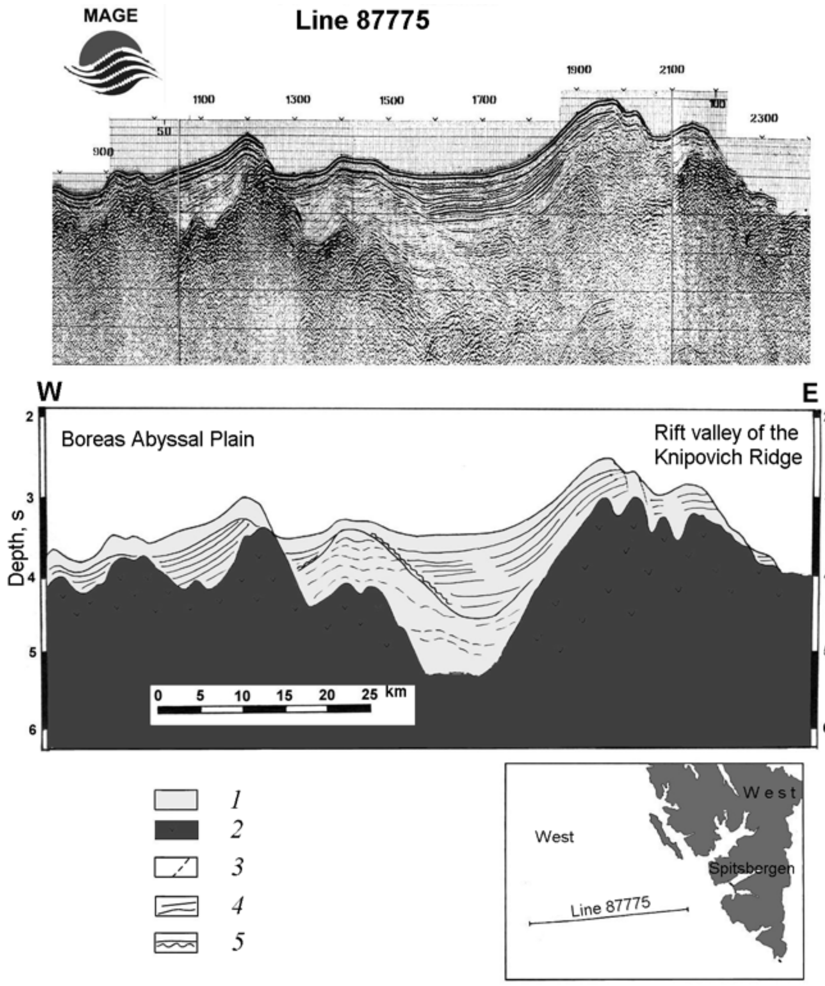

Figure 8. Interpretive scheme of seismic line 87775 across the northern Knipovich Ridge. Half graben west of the rift valley displays a thick (up to 2 km) sedimentary assemblage subdivided into two seismic sequences separated by unconformity, as inferred from seismic signature and velocity parameters. 1 – Sedimentary rocks, 2 – Oceanic basaltic basement, 3 – Fault, 4 – Selected reflectors, 5 – Unconformity.

the northern part of the Knipovich Ridge can be quantified approximately by adding up horizontal plane projections of the areas devoid of Oligocene rocks, which corresponds roughly to the rift valley width (ca. 20 km) and to the sum total of horizontal throw on the normal faults (up to 1.5 km). Structural peculiarities of the crestal zone of the Knipovich Ridge suggest a domal uplift and its subsequent splitting as a leading formative mechanism.

Earthquake epicenters beneath the Knipovich Ridge are distributed unevenly (Figure 12). They are denser in some localities within the rift valley and laterally sparse in others [*Avetisov,* 1996, 1998; *Avetisov et al.,* 1999; *Sigmond,* 1992]. Some distance north of 76°N, the crestal zone is traversed obliquely by a NNW-SSE trending graben, which is completely leveled off by sediments outside the rift valley. To the graben, some earthquake epicenters are confined [*Avetisov,* 1998] whose focal mechanisms point out a normal fault regime directed WSW-ENE, i.e., orthogonally to the principal extensional direction for the Knipovich Ridge, WNW-ESE. The Norwegian researchers [*Eiken,* 1994] have mapped a triple junction of the rift valley with a minor graben at ca. 77°N. Taken together, these data are indicative of variously oriented tensile stresses within the ridge.

The trend of lineaments, which is expressed topographically and emphasized by the structural features of basaltic basement, reflects both parallel extensional features and discordant structural elements, such as faults and volcanic (extrusive) topographic forms. The fault pattern on the western flank apparently mimics an older one, which is discernible in

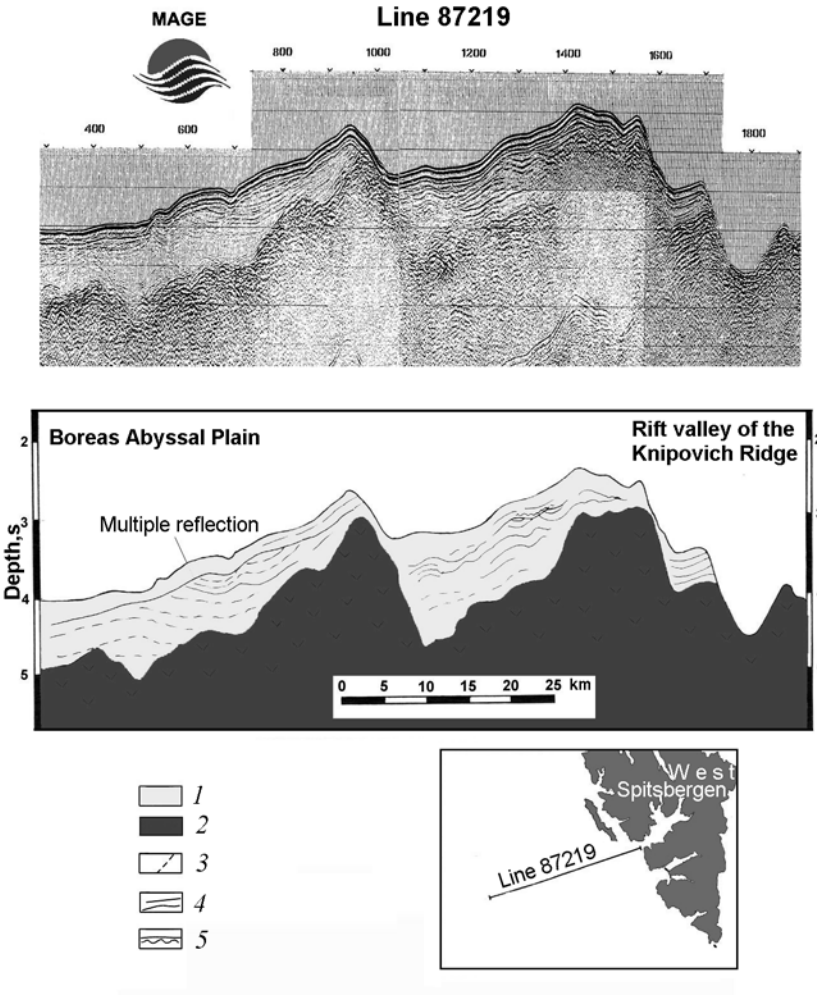

Figure 9. Interpretive scheme of seismic line 87219 across the Knipovich Ridge near 78°N. 1 – Sedimentary rocks, 2 – Oceanic basaltic basement, 3 – Fault, 4 – Selected reflectors, 5 – Unconformity.

the magnetic anomaly fabric [*Olesen et al.,* 1997] and trends NE-SW.

Transverse faults. The existing geodynamic models, drawing on the interpretation of magnetic lineations, seismic data, and bathymetry [*Baturin,* 1990; *Ohta,* 1982; *Shkarubo,* 1996, 1999; *Talwani and Eldholm,* 1977], invoke numerous ridge-axis offsets by transverse faults. More detailed bathymetric constructions (Figure 6), however, do not support any considerable amount of strike slip across the crestal zone or rift valley of the ridge. A comparison of bathymetric maps and a magnetic anomaly map [*Olesen et al.,* 1997] provides a strong proof for the modern rift valley to be discordant to the trend of magnetic lineations. It thus can be inferred that the modern rift valley of the Knipovich Ridge formed due to an eastward jump of the spreading axis that occurred in Late Miocene time, with the new spreading axis tending to be as rectilinear as possible. Basalts dredged on the Knipovich Ridge exhibit MORB-like geochemical fingerprints, none of the samples displaying features characteristic of fracture-zone basalts [*Neumann and Schilling,* 1984; *Sushchevskaya et al.,* 1997]. Among the ridges and fracture zones of the Norwegian-Greenland Sea, the Knipovich Ridge is distinctive for its having the weakest seismicity, whereas transform faults are noted for highly recurrent strong earthquakes [*Avetisov,* 1998]. At the same time, our analysis of seismic profile 89239 (Figure 13), which runs longitudinally through the crestal zone and rift valley of the ridge from 73 to 77°N, reveals a dense network of minor and major faults imparting to this area a "keyboard" structure. It is a matter of discussion whether these faults are transform or not and how great the amount of strike slip on them is, but future detailed studies will doubtless provide exhaustive solutions to these riddles.

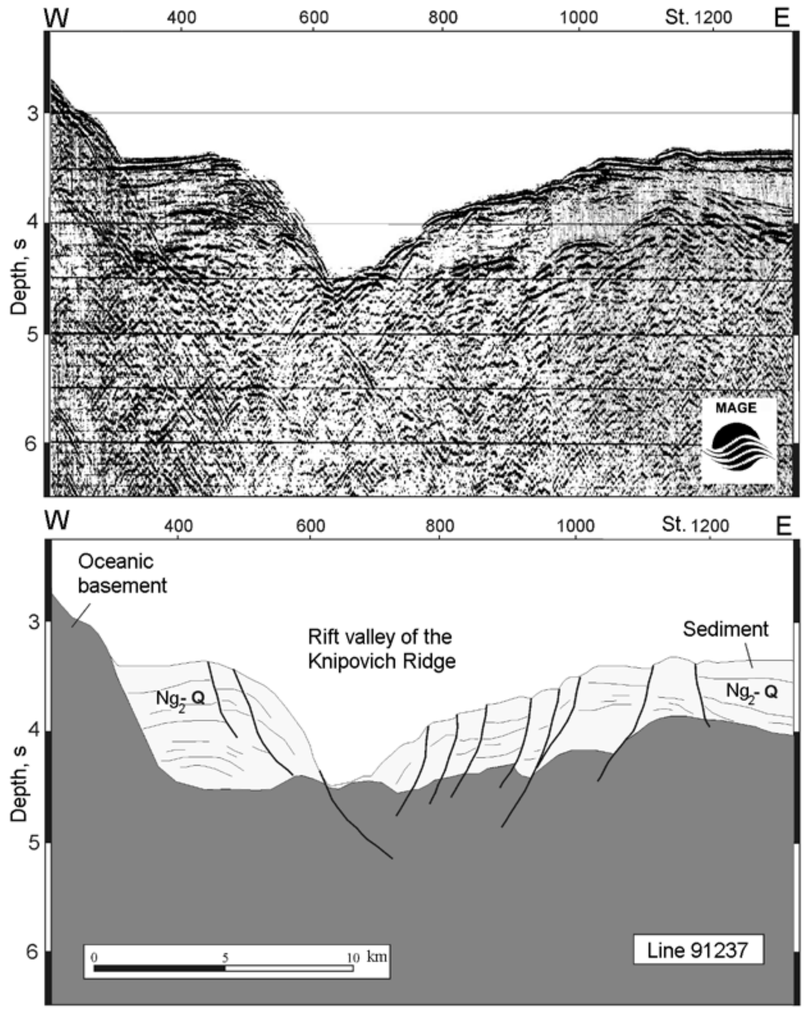

Figure 10. Interpretive scheme of seismic line 91237 across the rift valley of the Knipovich Ridge south of 74°N. Listric faults dislocating the sedimentary sequence in the rift valley testify to cyclicity of extension.

Conclusions

Our detailed study of bathymetry, single- and multichannel seismic profiles, and modern seismicity for the Knipovich Ridge reveals its discordant attitude with respect to the surrounding features and points to its genesis due to recent, superimposed tectonic processes. Although currently the Knipovich Ridge is an active spreading center with a conspicuous rift valley, numerous active submarine volcanoes, hydrothermal manifestations, and a modern seismicity, it exhibits no constant addition of new seafloor. The extension processes are cyclic, with pulses of dramatically intensified tectonic and magmatic activity alternating with protracted quiescent periods. No synchroneity exists between the extension pulses that occur in various segments of the ridges rift zone and which involve normal or listric faulting and emplacement of basaltic extrusions.

The Knipovich Ridge took shape in the deep eastern part of the Norwegian-Greenland Basin in the immediate vicinity of the western Svalbard margin in Miocene time. This corollary is based on our analysis of seismic sections correlated with faunally characterized stratigraphies at deep sea drilling sites.

The above suggests that the Knipovich Ridge has features that are not normal in typical mid-oceanic ridges. Rather, this is a young oceanic rift that came into being in Miocene time but, thus far, has not fully developed as a mid-oceanic ridge structurally.

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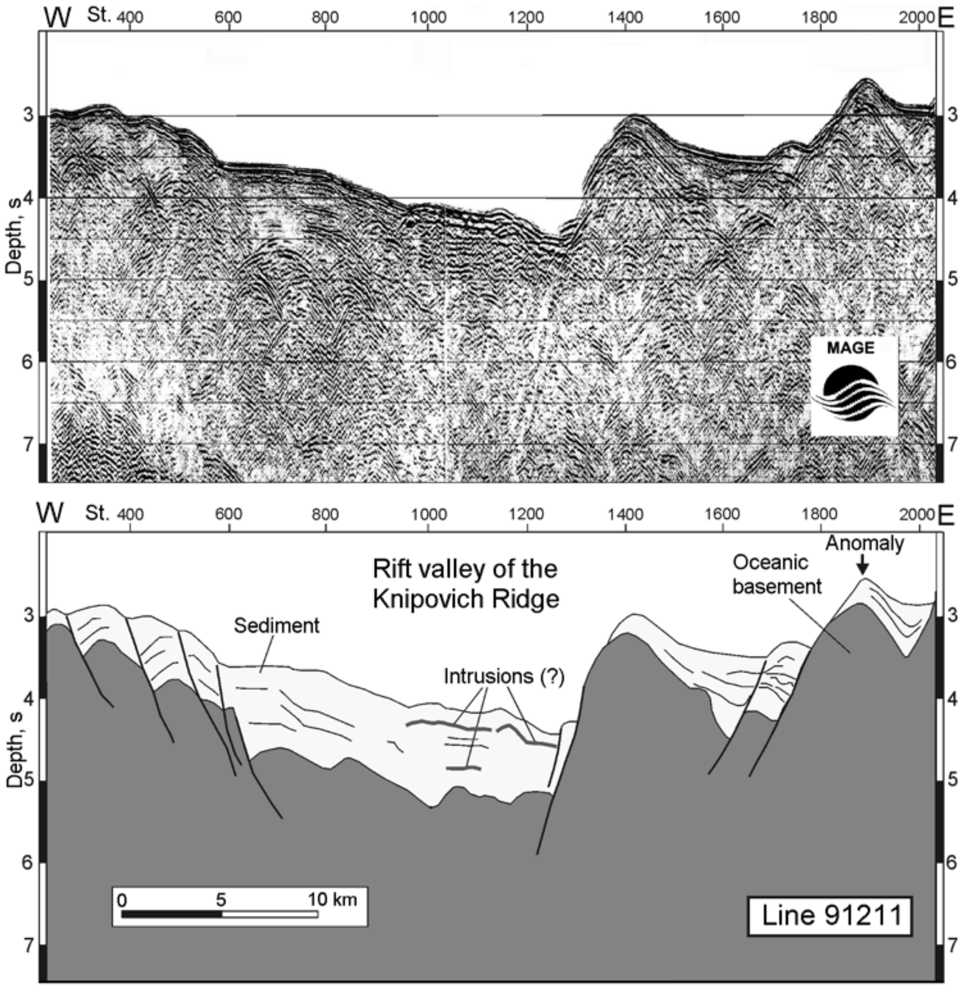

Figure 11. Interpretive scheme of seismic line 91211.

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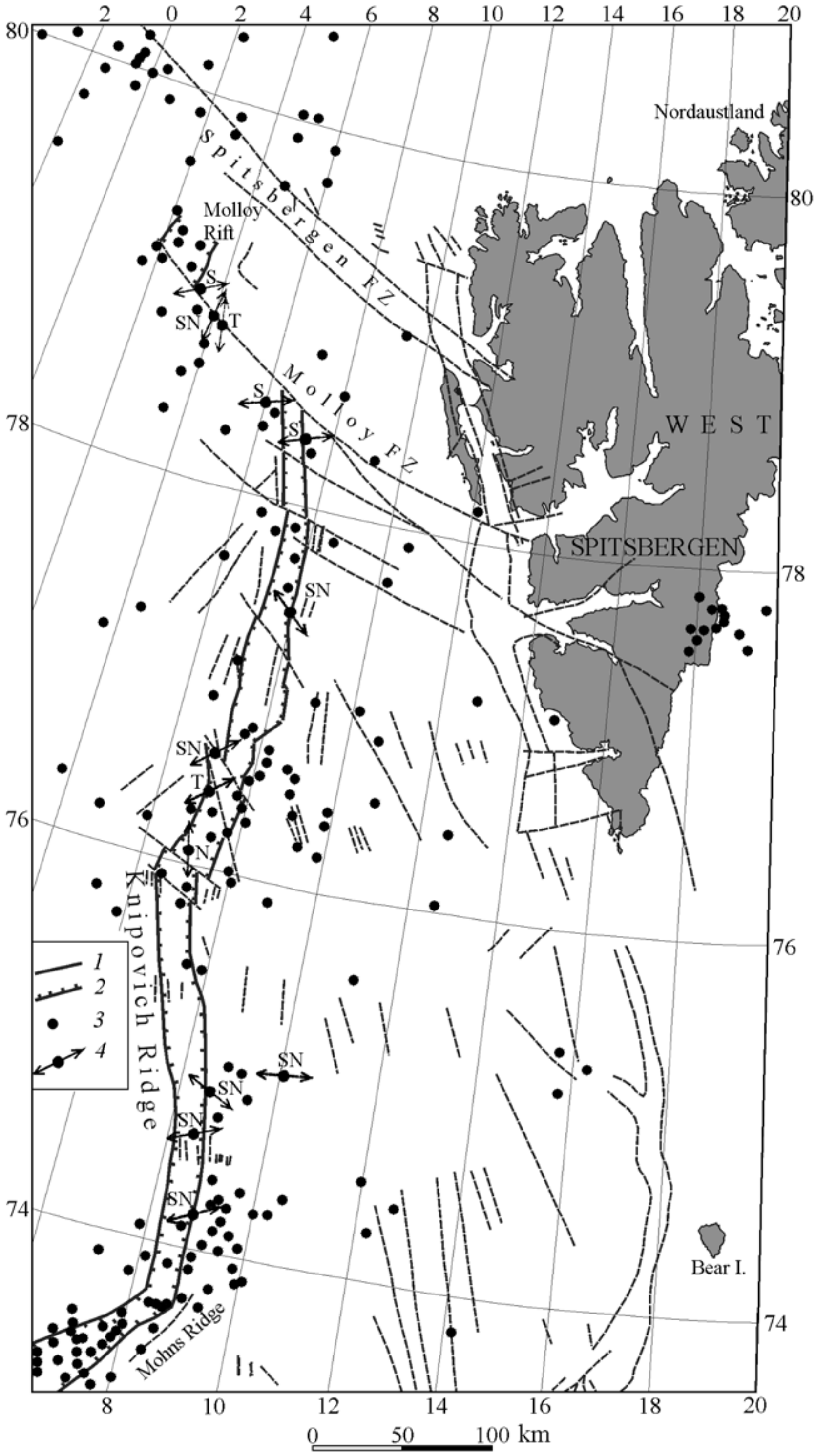

Figure 12. Principal faults and earthquake epicenters. 1 – Fault, 2 – Fault bounding rift valley, 3 – Earthquake epicenter [*Sigmond*, 1972], 4 – Focal mechanism [*Avetisov*, 1996]: N – normal fault; S – strike-slip fault; NS – transtensional fault; T – thrust.

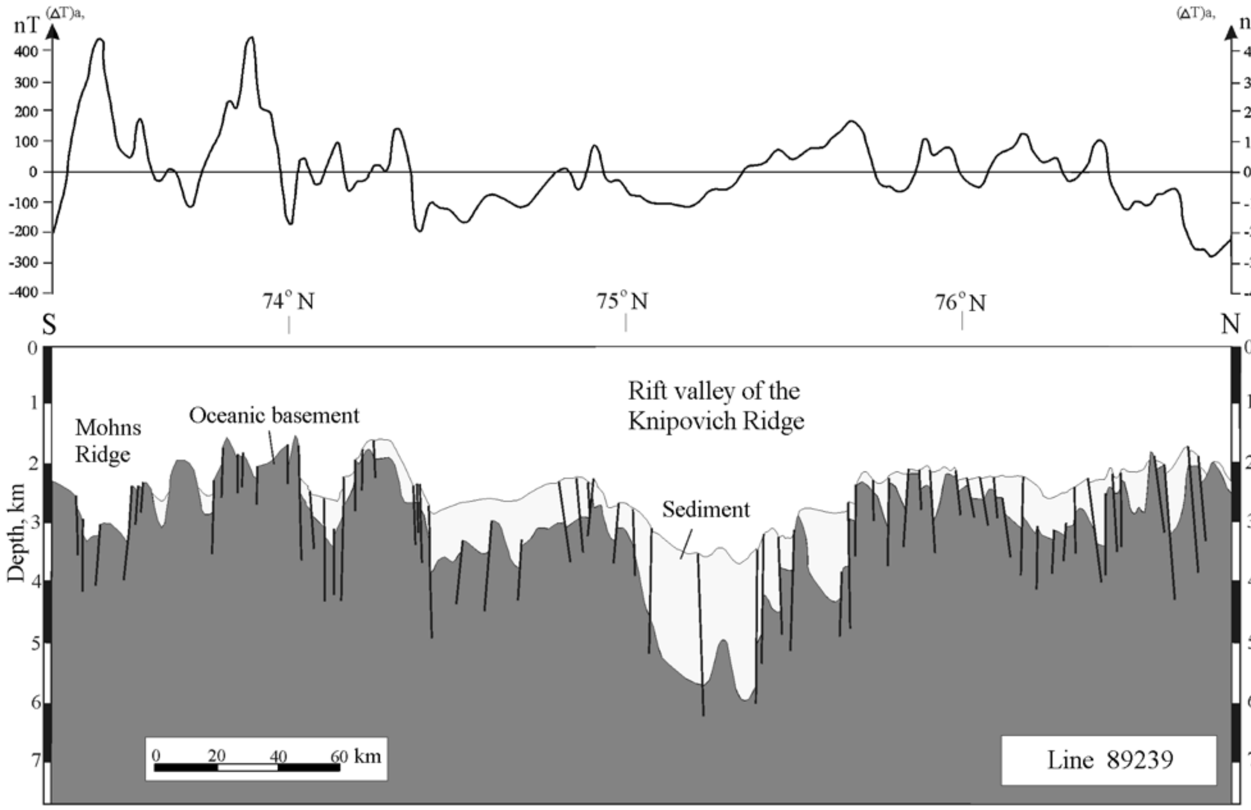

Figure 13. Interpretive scheme of seismic line 89239 imaging small-scale segmentation of crestal zone of the Knipovich Ridge.

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