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GEOLOGY

# Structure of the Transition Zone between Hovgaard Ridge and Spitsbergen Plateau according to the Data Obtained during Cruise 27 of the RV *Academik Nikolai Strakhov*

**A. V. Zayonchek, S. Yu. Sokolov, A. O. Mazarovich, A. V. Ermakov, A. A. Razumovskii, V. R. Akhmedzyanov, A. A. Barantsev, N. S. Zhuravko, E. A. Moroz, E. A. Sukhikh, M. M. Fedorov, and K. P. Yampol'skii**

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In the framework of the research project of "The International Polar Year" cruise 27 of the RV *Akademik Nikolaj Strakhov* under the leadership of chief scientist A.V. Zayonchek (Geological Institute, Russian Academy of Sciences, Moscow) was organized from August 16 to September 8, 2010, in the Greenland Sea (areas of the Molloy fault zone and Hovgaard Ridge), as well as in the central part of the Orly (Kvitøya) trough (northwest area of the Barents Sea) (Fig. 1). This cruise was aimed to examine the geological structure and evolution of the Norwegian–Greenland Basin in the framework of the Program of the Russian Academy of Sciences no. 20 "Fundamental Problems of Oceanology: Physics, Geology, Biology, Ecology"; the project "Tectonic Setting and Geodynamics of the Outer Zone of the West Arctic Shelf of Eurasia and the Continental Slope in the Cenozoic," which was carried out together with the Norwegian Petroleum Directorate (NPD) (academic advisors are Academician Yu.G. Leonov and H. Brekke).

During the expedition, data about the ocean bottom topography and the upper parts of the sedimentary cover were collected using the RESON sonar system (Denmark), which includes shallow water multibeam echosounders SeaBat-8111 and deep water echosounders SeaBat-7150, as well as the high-frequency sub-bottom EdgeTech-3300 Profiler (United States). The continuous seismic profiling survey during research works was carried out using the SONIC-4M system, developed in the SPE "LENARK" (Russia). During the works, the heat flow values were measured at 20 stations with the geothermal probe GEOS-M (Russia). The total length of the route survey with echo-sounding and high-frequency profiling was 2500 km; together with seismic profiling, it was 1400 km.

Information about the structure of the upper part of the sedimentary cover and the topography in the area studied according to previous expeditions is given in [1–4]. In [5], the results of the seismoacoustic studies of gas hydrates in the west of the Spitsbergen plateau are very important.

Initially, much of the research was planned to be carried out within the Orly (Kvitøya) trough, but due to ice conditions, we were not able to carry them out. Only measurements of heat flow in a ring structure identified earlier were carried out [4]. Later on, works were continued on the slopes of Knipovich Ridge and Hovgaard Ridge and within the Molloy fault zone (Fig. 1). In this work, a short summary of our work is presented.

*Geological Institute, Russian Academy of Sciences, Pyzhevsky per. 7, Moscow, 109017 Russia*
*e-mail: sysokolov@yandex.ru*

## *The Bottom Topography of the Transition Zone between Hovgaard Ridge and the Spitsbergen Plateau*

In the south of the research area (Fig. 2), according to the bathymetric survey, an oval-shaped rise about 17 km in size was identified with a northeastern strike; the difference in height is about 170 m. The transition zone has a junction with the peripheral parts of en echelon rises on Knipovich Ridge. In addition, an underwater trough with depths of up to 25 m was found there.

The Molloy fault zone is a large structure, stretching in the northwesterly direction. Its width is 700 m on average, and it is well manifested throughout at depths of 2600–2650 m. In the middle of the Molloy fault, depths of up to 2986 m were recorded. In plan view the fault zone has a wedgelike shape. In the northwest its width is a few hundred meters. In the southeast it widens to 5–6 km, forming a horsetail

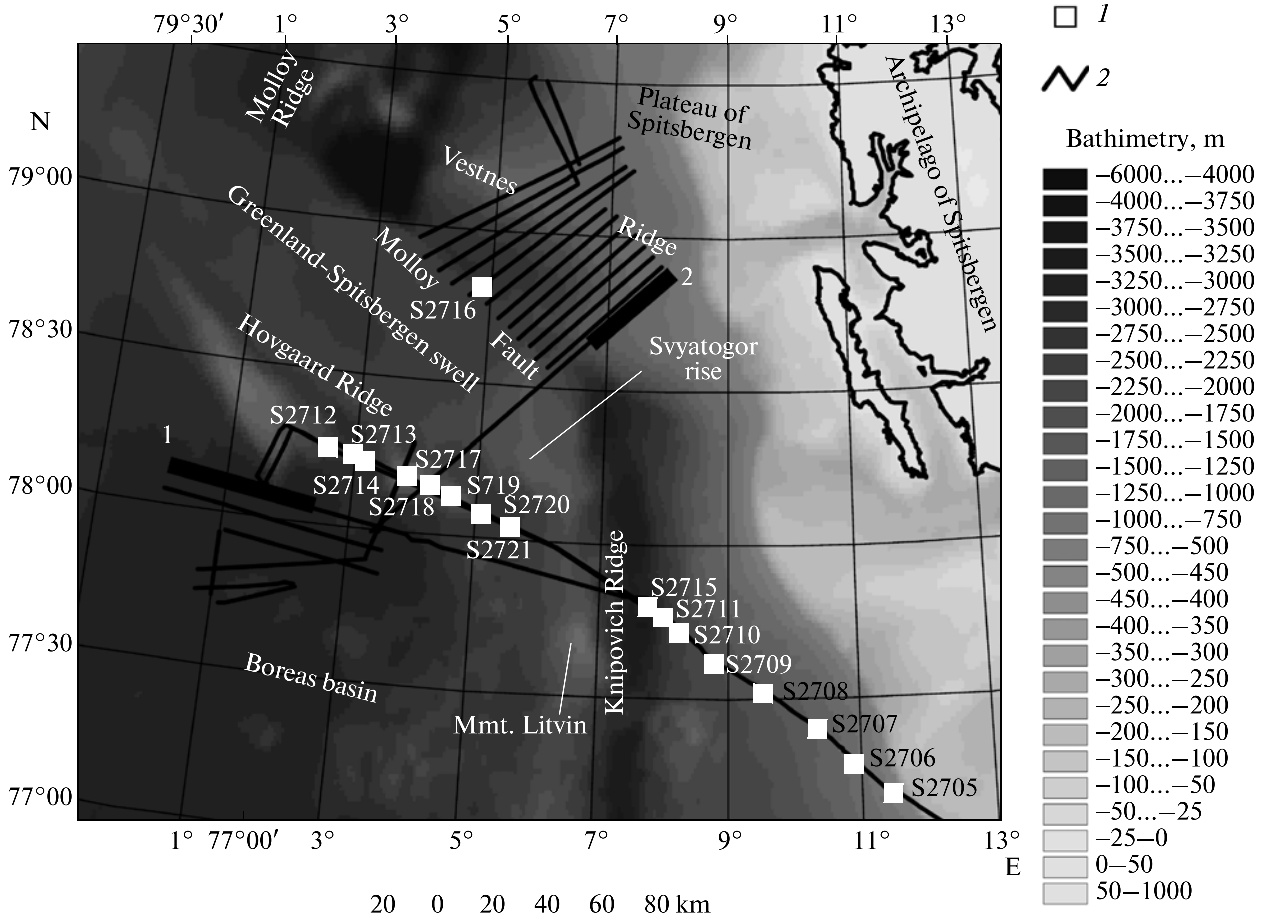


**Fig. 1.** Survey scheme of RV *Akademik Nikolaj Strakhov* 27-th cruise. The locality of sections fragments used in this paper are shown by thick lines (1, 2). In legend: *1*—heatflow stations, *2*—tracklines of seismic profiling.

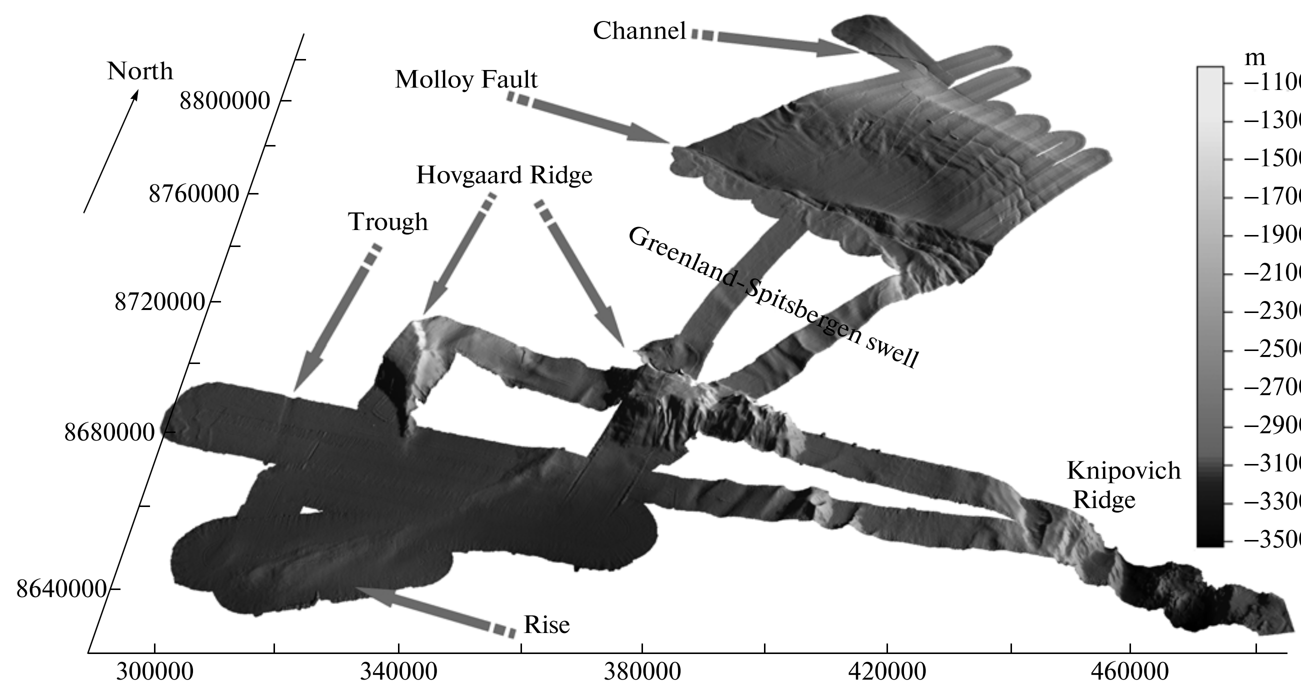


**Fig. 2.** 3D shaded-relief image of the bathymetric survey obtained during cruise 27 onboard the RV *Akademik Nikolaj Strakhov* on flanks of the Molloy Fault. Metres in UTM32 projection are given along horizontal axis.

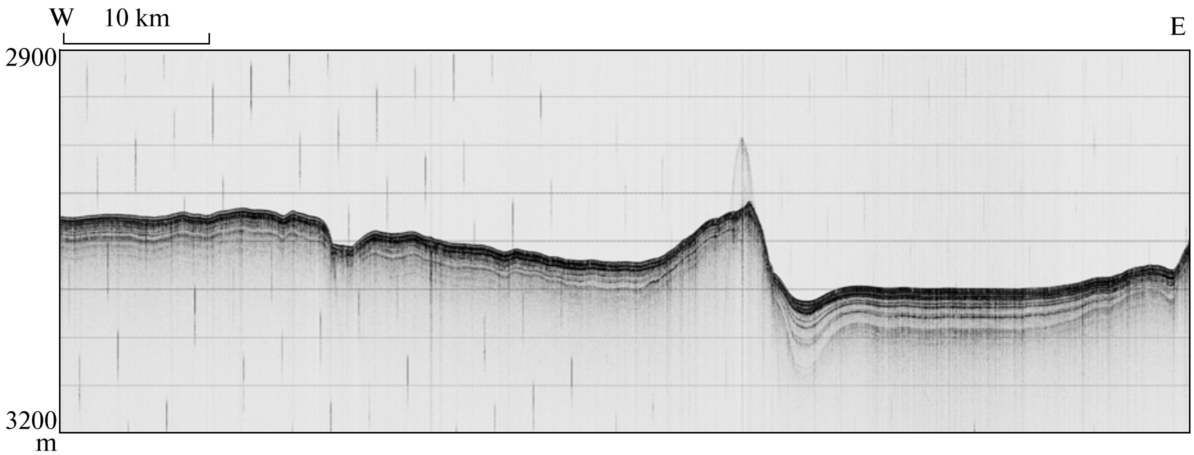


**Fig. 3.** The fragment of the S27-P2-01 section obtained using the EdgeTech-3300 profilograph (line 1 in Fig. 1).

structure feathering the fault structure by echeloned fault scarps in the bottom topography.

In the northern part of this area, an underwater channel was found (Fig. 2), which begins at a depth of 1600 m and cuts through the continental slope, turning a bit to the northwest. The channel depth is about 60 m; a width is 450–500 m.

Hovgaard Ridge stretches to the southwest from the transition zone, and it lies subparallel to the Molloy fault zone. It bounds the abyssal basin Boreas in the southwest, and the Greenland–Spitsbergen swell in the northeast (Fig. 2). The ridge stretches about 155 km and consists of two segments of (northwest and southeast) northwest stretch, separated by the depression of the northeast stretch with a width from 10 to 20 km. The first segment resembles an arrowhead, stretching about 100 km to the northwest. The width of the rise in the southeast is about 30 km; in the northwest, it is about 5 km.

The northern slopes of the Greenland Spitsbergen threshold are complicated by numerous landslide bodies.

### *The High-Frequency Profiling Data*

The profile S27-P2-01 (no. 1 in Figs. 1, 3) crossed the southern branches of the southeast and northwest segments of Hovgaard Ridge, as well as the northeastern part of the Borrey basin. The upper part of the sedimentary cover with a thickness of about 30 meters is represented by a well-stratified sequence, which, according to the data obtained from hole 908A, is made of the subhorizontal Quaternary clay strata. In the central part of the basin, the thickness of the lower parts of the sequence studied increases from 8–10 m (northwestern branches of the near-rift mountains of Knipovich Ridge) up to 20 m.

A characteristic structural feature of the area is the consedimentational depression (Fig. 3) of the northeast strike. The depression stretches along the southeast area of the northwestern segment of Hovgaard Ridge. Towards the abyssal Borrey basin it narrows, which allows us to associate its formation with the modern movements of Hovgaard Ridge.

The second feature of the area studied is considered to be the submeridional extension structure identified earlier [6] (Fig. 2, the western part).

In the bottom relief it occurs as a trough structure (Fig. 3, the western part), which looks like a graben structure on the sections. At the end of the profile, horst structures appear. It is obvious that the entire area of Hovgaard Ridge is subjected to modern movements of different direction. The geodynamic reasons for these movements require a comprehensive regional analysis. Two profiles that crossed the southeast segment of Hovgaard Ridge confirm all the above-mentioned features. Both profiles were made actually at the same place. The asymmetry of the ridge and the difference in the depths of the Borreas basin and Greenland–Spitsbergen swell (about 500 m) are clearly visible.

In the area of the Molloy fault, a complex survey of the upper part of the section was conducted. This allowed us to establish that the entire research area is characterized by a higher modern mobility, resulting in numerous faults and flexures within the uppermost part of the sedimentary cover, deposited under the conditions of an unconsolidated oceanic substrate and avalanche sedimentation. According to the seismic profiling data, all the western flanks of Knipovich Ridge at distances up to 180 km are complicated by tectonic deformations, resulting in the folding and formation of unconformities at the top of the sedimentary sequence. These unconformities are manifested at the continuation of the southern branch of Hovgaard Ridge.

The upper part of the section is mostly an acoustically transparent sedimentary stratum with the thickness ranging from 800 to 1100 meters and containing

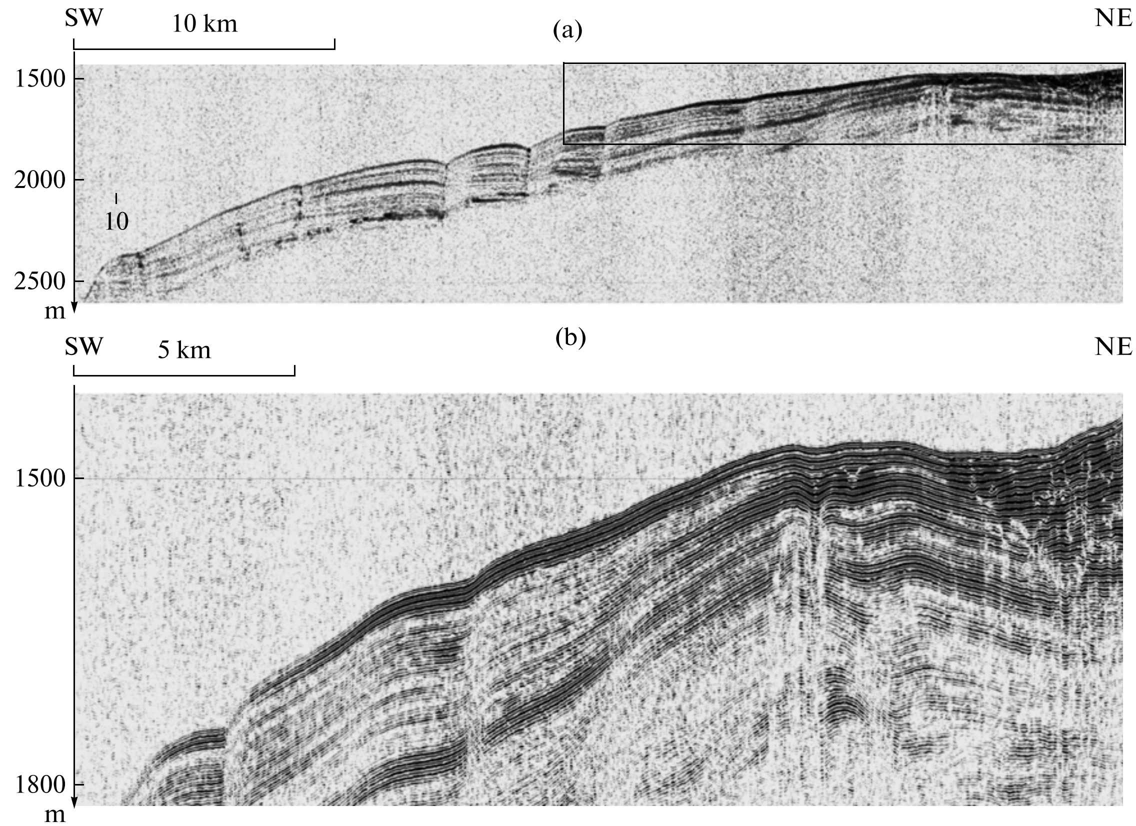


**Fig. 4.** The fragment of the S27-P3-01 section obtained using the SONIK-4M complex (a) and its scaled-up northern part (b) (line 2 in Fig. 1).

high-amplitude reflectors in the 200-m upper part of the sequence. Their configurations are characterized by unconformities, folds, and acoustic lightness of records above the highs of the acoustic basement.

The occurrence of the detailed stratification in the upper part of the section at this distance from the ridge axis can be explained by the weakening of the flow of turbidite deposits and (or) the appearance of alternative source areas.

The structure of the upper part of the sedimentary sequence of Hovgaard Ridge is a subhorizontal acoustic basement of Late Oligocene–Early Miocene age [1]. The basement is likely of sedimentary origin. The basement is dislocated by faults with an amplitude of 15–20 m and overlain by a Pliocene–Quaternary acoustically transparent sedimentary cover.

The Greenland–Spitsbergen swell contains a bottom-simulated reflector (BSR), which is an analog of reflectors recorded on the plateau of Spitsbergen to the north of the Molloy fault [5]. The reflectors trap fluid reservoirs below the hydrate. In addition, on the rise a reflector was recorded, which corresponds to the upper boundary of the Late Oligocene–Early Miocene sediments drilled on Hovgaard Ridge.

On the Spitsbergen Plateau, a bottom-simulated reflector was also revealed. It is broken by faults and is represented as seismic anomalies as bright and flat spots (Fig. 4a). In general, the fragmentation of the reflector here is substantially higher than was recorded on the profiles at approximately the same position [5]. In the vicinity of fault zones, the vertical bands of acoustic lightness of records are observed, which are traces of the discharge of fluid reservoirs due to landslides and isostatic compensation of the shelf edge through the layer of gas hydrates located at depths of 250–300 m under the oceanic floor.

It should be noted that the continuous reflector [5] is divided into a series of 4–8 km fragments, below which flat spots are observed. The seismic record in the reflector located above discontinuities is enlightened, which testifies to the fluid discharge through the appearing "windows."

Figure 4b shows a scaled-up northern fragment of the section. It is seen that, in the vertical light field of the acoustic record, a structure formed in the sediment strata at a depth of 40 m, which is similar to a mud volcano, a gas breakthrough, or a buried pockmark, where the breakthrough of fluids isolated from sediments took place. Next to this structure, small tectonic dislocations in the sedimentary cover with an amplitude of a few meters were observed, which are associated with the compression conditions.

Geothermic data

| Number of station | Date | Time (Moscow) | North Latitude, °N | East Longitude, °E | Depth, m | Temperature Gradient, mK/m | Heat Conductivity, W/(m K) | HF, mW/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| S2701 | 24.08.2010 | 0:30 | 80.469738° | 29.852777° | 390 | 170 | 1.00 | 170 |
| S2702 | 24.08.2010 | 1:40 | 80.469633 | 29.874777 | 438 | 216 | 0.94 | 203 |
| S2703 | 24.08.2010 | 2:30 | 80.466482 | 29.877982 | 440 | 205 | 0.95 | 195 |
| S2704 | 24.08.2010 | 5:10 | 80.443050 | 29.536460 | 357 | 327 | 1.15 | 376 |
| S2705 | 26.08.2010 | 8:40 | 77.184820 | 11.517363 | 573 | 162 | 1.25 | 202 |
| S2706 | 26.08.2010 | 10:13 | 77.284130 | 10.954982 | 1093 | 103 | 1.03 | 106 |
| S2707 | 26.08.2010 | 12:10 | 77.399610 | 10.391253 | 1422 | 124 | 0.88 | 109 |
| S2708 | 26.08.2010 | 14:25 | 77.514667 | 9.609100 | 1750 | 163 | 0.81 | 132 |
| S2709 | 26.08.2010 | 16:45 | 77.615903 | 8.843482 | 2066 | 203 | 0.93 | 189 |
| S2710 | 26.08.2010 | 18:45 | 77.719012 | 8.312362 | 2190 | 183 | 1.04 | 190 |
| S2711 | 26.08.2010 | 20:50 | 77.766315 | 8.059135 | 2620 | 204 | 1.00 | 204 |
| S2712 | 27.08.2010 | 20:17 | 78.254367 | 2.597370 | 2615 | 65 | 1.08 | 70 |
| S2713 | 27.08.2010 | 23:15 | 78.241467 | 2.985917 | 2690 | 77 | 0.98 | 75 |
| S2714 | 28.08.2010 | 1:18 | 78.218217 | 3.241550 | 2772 | 66 | 1.04 | 69 |
| S2715 | 28.08.2010 | 13:00 | 77.798517 | 7.795950 | 3320 | 401 | 0.75 | 301 |
| S2716 | 02.09.2010 | 8:00 | 78.788667 | 5.155250 | 2640 | 152 | 0.96 | 146 |
| S2717 | 04.09.2010 | 12:00 | 78.189233 | 3.881211 | 1270 | 111 | 1.4 | 156 |
| S2718 | 04.09.2010 | 14:25 | 78.164383 | 4.314533 | 1975 | 93 | 1.12 | 104 |
| S2719 | 04.09.2010 | 16:00 | 78.127517 | 4.627633 | 1550 | 49 | 1.21 | 59 |
| S2720 | 04.09.2010 | 19:10 | 78.076733 | 5.143500 | 2670 | 102 | 0.94 | 96 |
| S2721 | 04.09.2010 | 21:00 | 78.047300 | 5.592800 | 2584 | 128 | 1.03 | 132 |

To the north of the zone of tectonic dislocations, a "flat" spot with a very intense reflection energy and inclined lightness zones are observed, which may be associated with the feathering dislocations of the vertical fault structure, located in the continuation of Knipovich Ridge.

In addition, along Vestnes Ridge thrusts are observed. This testifies to the complex pattern of discharge of tectonic stresses within the Molloy fault zone. These thrusts begin to manifest themselves along the near-fault depression with a depth of 2986 m, which is located hypsometrically below the fault trough and the near-fault ridge.

On the profiles, stepped landslide bodies with a height difference of up to 400 m from one body to another are observed near the Molloy basin.

### *The Heat Flow*

Almost all the measurements made during cruise 27 are considered to be conditioned; the shape of the thermograms in the soil surface is linear for most stations. The thermal flow value at station S2716 within the Molloy fault zone is correlated with the data obtained by Norwegian researchers [8].

The heat flow increases regularly near the southeast side of the rift valley of Knipovich Ridge as the age of the oceanic crust becomes younger towards the spreading axis; the maximum value was recorded in the valley at the point S2715 (table).

On the western flank of Knipovich Ridge, the heat flow values decrease with distance from the ridge and reach the value of 60–80 mW/m$^2$. This corresponds to the background values for abyssal basins of the World Ocean.

The measurements of heat flow were carried out also in the northwest of the Barents Sea within the Orly (Kvitøya) Trough. Thermograms obtained at the stations S2701–S2705 show the bending in the upper part, which can be connected, probably, with the variability of temperature at the water–soil boundary. According to these thermograms, the heat flow (HF) was calculated for the values of lower parts.

Measurements at the stations of S2701–S2703 within the ring structure of the eastern part of the Orly (Kvitøya) trough and at station S2704 in the southern part of the trough confirmed the conclusion made in [7] that the HF high values are due to modern destruction of the continental crust in this region.

Thus, the bathymetric survey data show that to the northeast of the Molloy fault there is a near-fault depression with depths higher than in the fault trough. The northern slope of this depression is dislocated by numerous landslide bodies. The conjunction zone of the fault with Knipovich Ridge has a horsetail structure.

The high-frequency profiling data show that the research area has a high mobility, either in the south in the Borrey basin or in the north on the slope of the plateau of Spitsbergen. As a result of our research work, grabens, consedimentational depressions, faults, and flexures were identified. Seismoacoustic data also show an intensive mobility within the research area, which is clearly manifested as dislocations of unconsolidated sediments on the movable substrate.

To the south of the Molloy fault, a pseudobottom reflector was revealed. To the north, it is very fragmented and the fluid breakthrough through the ruptures of the reflector takes place. The geothermal data obtained confirm that the anomalous formation of the Orly (Kvitøya) trough is connected with the destruction of the continental margin, and the occurrence of a normal pattern of an increase in heat flow values towards Knipovich Ridge axis with a decrease to background oceanic values at the western flank.

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