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GEOLOGY

Abnormal Heat Flow and the Trough's Nature in the Northern Svalbard Plate

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The Svalbard continental margin, which embraces the shelf, continental slope, and the northeast islands of Spitsbergen (Svalbard), makes up the northwestern part of a larger structural tectonic zone, the Barents Sea continental margin. Exploration of this region is providing very interesting information for better understanding of the relations of tectonic processes in the continental and oceanic lithosphere.

Information on the tectonics and geodynamics of this region was mainly provided by geothermal data. In 2007, in the course of an expedition aboard R/V *Akademik Nikolai Strakhov*, a geothermal survey was conducted in two areas and in districts of the Barents Sea shelf not investigated earlier: west of Franz-Josef Land (the FJL area) and east of the Spitsbergen northeast land (the Spitsbergen area).

The expedition was supported by the Norwegian Petroleum Management, the Program of the Presidium of the Russian Academy of Sciences (RAS) (program "Fundamental Problems of Oceanology" (project "Comparative Study of the Evolution and Recent Structure of Continental Margins of Eastern Atlantic and Arctic Regions") and the program of the Division of Earth Sciences, RAS, "History of Formation of the Arctic Ocean Basin and the Regime of Recent Natural Processes in the Arctic," and by the Russian Foundation for Basic Research, project no. 05-05-00016.

In 1976 during the 23rd voyage of R/V *Akademik Kurchatov*, geothermal work was carried out for the first time on the Barents Sea shelf along the profile in the Rybachii Peninsula, FJL [1]. The devices applied at that time (single-channel autonomous thermal probe (PTG)) could not register some important parameters such as the bottom water temperature, the probe tilt, and the form of thermogram. When this device was used, the relative errors in measurements amounted to 30–40%.

In the 1980s, when ocean drilling was developing in the Arctic regions, the first reliable estimations of heat flow were obtained from thermal logging data in the Barents and Kara seas [2]. Later, these data were made more precise [3]. In the same years, researchers from the Geological Institute (Kola Science Center, Russian Academy of Sciences) measured heat flow in the southern and central parts of the Barents Sea using the double-channel autonomous TGCP probe. Area observations went parallel with regime observations of the sea bottom temperature at several reference sites in the southern and eastern parts of the Barents Sea. This allowed the evaluation of the deep component of the heat flow with a specially developed algorithm [3] and recording of the quantitative account of the effect of periodic fluctuations of the bottom temperature.

The analysis of available borehole and probe measurements suggests that there is a tendency towards increasing of heat flow in the northeasterly and northwesterly directions (Fig. 1). In the zone of the Kola microplate and the Baltic shield convergence, the mean value of heat flow is 54 mW/m^2, while in the region of the North Barents basin and Central Barents rise, it is 70 mW/m^2. This trend of the heat flow might be due to the influence of tectonic processes going on in the Earth's crust of the Barents Sea plate, whose rejuvenation is recorded in the northerly direction. Previously, the authors proposed that this phenomenon was interrelated with the development of rifting [4].

During the voyage, work was done using the updated modification of the well-known series of GEOS geothermal probes approbated with GEOS-M probe. The probe is intended for automated high-precision measurements of the temperature of bottom sediments; the temperature gradient at four measuring bases; the heat conduction of sediments at the same bases; hydrostatic pressure (at depth); water temperature; the probe tilt (angle of deviation from the vertical line); and, on the basis of the obtained data, definition of the deep heat flow of the Earth across the water area.

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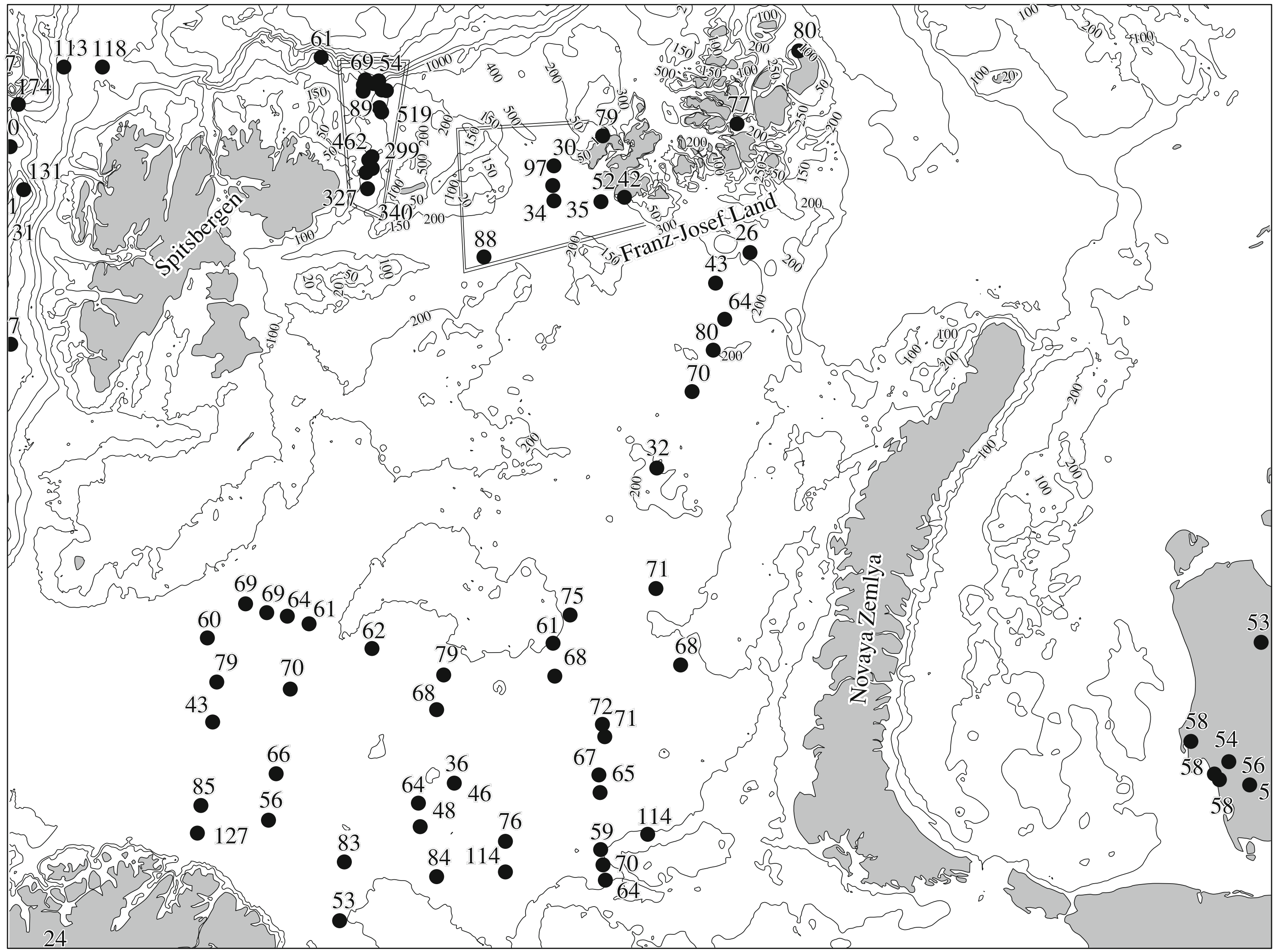

Fig. 1. Geometrically studied heat flow (the values are in mW/m^2) in the Barents Sea region (the working areas of voyage 25 are contoured).

Moreover, the probe allows vertical temperature sounding of the water stratum. The measurement process is cable-controlled, and the information gained accumulates in the surface-ship computer.

Seven measurements of heat flow (Table 1) and temperature in the water stratum were performed in the FJL area. As a result of the measurement of temperature in the water stratum, a stratum with negative temperatures was identified in the 30–80 m depth interval and an isometric zone, at depths more than 370–380 m (Fig. 2). Thus, the minimum depth (~370 m) at which the heat flow can be measured was defined, as at lesser depths it could not be done because of the "nonisothermal" character of the bottom water stratum. In view of this, only at limited number of areas could the heat flow be measured at a depth of 370 m and more (Fig. 3). At the majority of sites, it could not be calculated but involved the temperature readings in the lowest bases of the probe.

In the 3D block diagram showing the temperature distribution in the water stratum of the area (Fig. 2), in the 30–100 m interval, a water stratum with negative temperature was observed. A lens of relatively high water temperature (to 1.9°C) is observed in the southeastern zone of the area. Such a temperature regime must be provided by a supply of warmer and denser water from the Atlantic Ocean, which has a distinct stratification under the influence of cold and lighter Arctic water.

Table 1. Results of heat flow measurements in the FJL area

Station N	Coordinates		Depth, m	HF, mW/m^2
	N	E		
2501	79.3463	38.1587	314	88
2502	80.0112	48.3466	375	42
2503	80.0083	46.581	402	52
2505	80.2472	43.0693	400	97
2506	80.5039	43.3696	530	30
2507	80.2472	43.0693	550	34
2509	80.067	43.1672	390	35

In general, the area exhibits the background values of the heat flow (Table 1). However, we observe two high values (88 and 97 mW/m^2) along the northeast trend line belonging to the Franz–Victoria Strait, as well as reduced values of heat flow (30–35 mW/m^2) north and south of that line.

Such variations of the heat flow, when the difference between values on a small area may be twofold, are characteristic of regions with developed evaporate

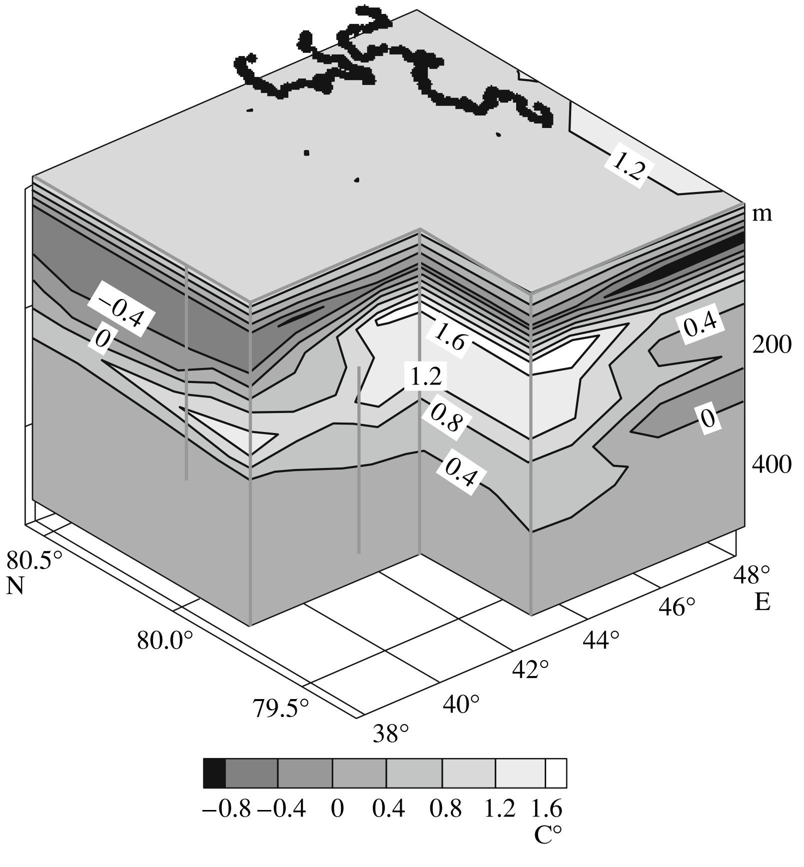

Fig. 2. 3D-block-diagram showing distribution of water temperature in the FJL area.

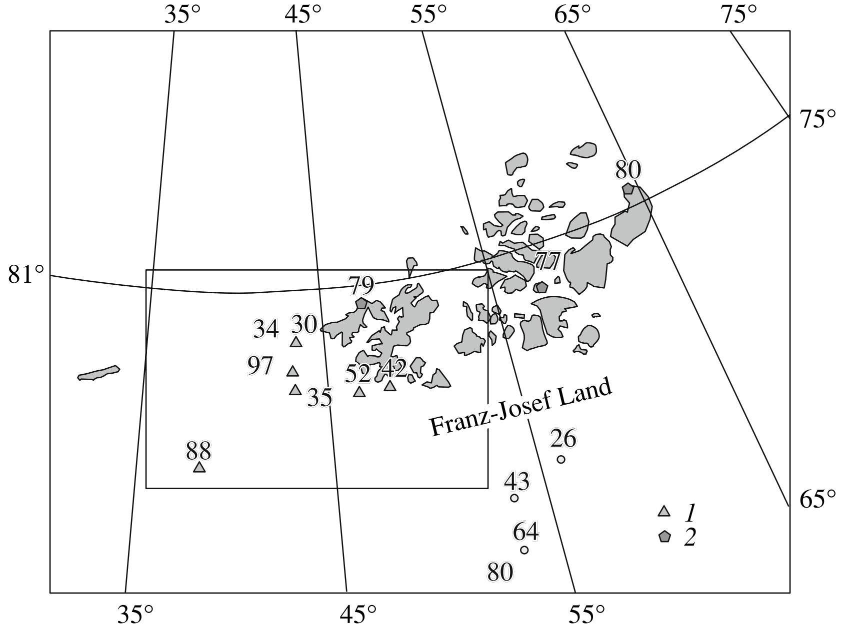

Fig. 3. Heat flow measurements performed in the FJL area (*1*). Three values of heat flow (*2*) obtained during thermal logging in boreholes (from west to east): Nagursk (Land of Alexandra Island), Heisa (Heisa Island), and Severnaya (Graham-Bell Island). The heat flow values are given in mW/m^2.

basins under the conditions of crust destruction. In western FJL, namely in the Alexander Rise, volcanics with an absolute age of 116 ± 5 Ma are contoured with a magnetic anomaly up to 600 nT [5]. This allowed the proposition of a model of break-up of the continental crust in this part of the archipelago [6]. The break-up stage is associated with the process of generation of saliferous beds [7]. Evaporites are identified in the sections of the oceanic mantle in marginal perioceanic basins of the Atlantic region [8]. A system of grabens filled with evaporate sediments are generated on the destructive continental crust. This may be illustrated by salt-generating basins of the West African (the Canary basin) and North American (Newfoundland) passive margins [8, 9].

On the FJL continental slope, in the zone of depressions of the British Channel and the Cambridge Strait, local minima of the gravitational field in the Fye reduction were revealed, which V.V. Verba associated with saliferous diapirs. Later this hypothesis was confirmed by the results of density modeling [5].

The heat conduction of rock salt is very high. It is 3–3.5 times as high as that of host terrigenous rocks. Such a sharp difference in heat conduction, as well as steep angles of the inclination of boundaries separating the mediums, provides redistribution of the deep heat flow.

The effect of redistribution of the deep flow of energy within structural thermophysical heterogeneities might also be observed in the FJL area. At the stations elevated values of the heat flow could be measured above the apical part of domes, whereas somewhat reduced values were measured above the interdome zones.

This is one of possible models that could explain the variations of the heat flow, though to confirm it, results of seismic profiling are needed.

The object to be studied at the Spitsbergen area was the Orel trough, which extends from the King Carl archipelago in the south to the border of the continental slope of the Nansen Basin in the north. In different literature sources, the name of the trough varies. In [10] the structure is called the “Orel graben.” It is also mentioned under the name of “Storoya trough,” named after Storoya Island situated nearby [11]. The trough is a narrow, topographically pronounced, NS trending depression. The walls of the depression are up to 400 m high, and the bottom lies at a depth of 470–520 m; its depth further increases towards the continental slope. The trend of the trench is traced for nearly 200 km, its width being only 50 km.

The temperature distribution in the water stratum is completely analogous to that in the FJL area.

The tectonic nature of this structure was not at all clear, and the literature provides only some scattered information about it.

Twenty measurements of the heat flow have been performed (Table 2) in the trough and its continuation within the continental slope, and their results have caused, without exaggeration, a great sensation. The heat flow was from 300 to 520 mW/m^2, that is 10 times as high as the level of the background heat flow in the Barents Sea. The ideal way of the temperature registration of the gage temperature in the ground provided reliable results.

Abnormally high heat flow is characteristic of the entire Orel trough and its continuation on the continental slope, up to the 1200 m isobath (Fig. 4). Reduced heat flow was recorded only at great depths, though at a depth from 1400 to 1870 m, elevated values were obtained relative to the background ones, 89 and 90 mW/m^2.

Extrapolation of temperatures to the lower space shows that the solidus temperatures might occur at a depth of 4.0–4.5 km beneath the bottom. This means that the break-up of the continental crust has affected its entire thickness and penetrated into the basement (maybe even into lower layers of the sedimentary cover) of hot mantle (?) matter. The absence of signs of the convective discharge of deep thermal mass flow on the floor is due to the high rate of accumulation of terrigenous and moraine material, which screen the appearance of zones of fluid discharge into the bottom layer. To find out the extent of removal of deep-seated material, hydrochemical sampling of bottom layers is to be carried out so as to analyze the indicators of the mantle thermal mass transfer (^{3}He/^{4}He and others).

The morphology of the trough and geothermal data obtained on this structure for the first time suggest that the Orel trough is of tectonic origin. This is, most likely, a rift affecting Earth's crust through its entire thickness and now passes an active phase of development.

However, the obtained data will be more remarkable if we take up the more general problem of the break-up of the Barents Sea continental crust against the background of other phenomena related to this problem.

A system of trenches (troughs), pronounced in the seafloor topography, developed at the northern border of the Barents Sea shelf. They are NS oriented, orthogonal to the shelf margin, and open in the direction of the continental slope. In addition to the Orel trough, there are the Voronin, Svyataya Anna, and Franz-Victoria troughs, as well as some smaller structures: the British Channel in the Franz Josef Land and Hinlopen in Spitsbergen. In recent years, these troughs are regarded to be of tectonic origin and even referred to as "grabens" or "rifts" [11, 12].

Among the mentioned large depression structures, the Orel trench occupies the westernmost position, and by its morphological characteristics, it is similar to NS trending structures, similar to those in the Spitsbergen islands. In Western Spitsbergen Island, this is a system of fjords: Bock-fjord, Wood-fjord, and Wejde-fjord, and the aforementioned Hinlopen Strait.

The recorded structures, situated orthogonally to the northern border of the Barents Sea shelf, are oriented parallel to the continental slope west of Spitsbergen and parallel as well to the Knippovich Oceanic Ridge, i.e., to structures opening the given sector of the Northern Atlantic region. This structural plan suggests a geodynamic relationship between oceanic (Knippovich Ridge) and continental (Spitsbergen) structures.

Table 2. Results of heat flow measurements in the Spitsbergen area

Station N	Coordinates		Depth, m	HF, mW/m^2
	N	E		
2523	80.0604	29.3266	330	340
2525	80.0642	29.337	330	338
2526	80.3177	29.4437	440	299
2527	80.409	29.309	430	484
2529	80.4194	29.0828	530	462
2530	80.4456	29.2863	485	438
2531	80.4657	29.2331	465	407
2535	80.2788	29.2516	410	327
2537	81.3974	27.5607	2330	54
2539	81.1018	29.0919	340	474
2541	81.0538	29.3096	310	519
2543	81.325	29.395	1185	118
2544	81.319	29.21	1010	122
2545	81.3221	29.0358	1010	107
2547	81.4142	28.5693	2530	53
2548	81.3908	28.1994	2250	77
2549	81.3944	27.455	2280	69
2550	81.3501	27.4793	1870	89
2551	81.314	27.4789	1400	90
2552	81.2616	27.4984	770	326

Young Spitsbergen volcanoes favor a better understanding of the recent tectonic activity of NS trending trenches (grabens) and fault systems bordering on them. Volcanic mechanisms of this age are concentrated in the northwestern islands, in the vicinity of the Bock-fjord and Wood-fjord bays.

The data of [13] suggest that outflow products are represented by lava and pyroclastic subalkaline olivine basalt. The isotopic age of ancient eruptions is dated within an interval from 2.7 ± 1 to 2.0 ± 1 Ma. The latest eruptions are quite recent; by geological data (volcanic material in marine terraces) their age is dated as 10 ka. The time of the two latest volcanism episodes, which occurred in the Neopleistocene–Holocene, was given in [14]; the second took place in the Sverre volcano region and was dated as Middle Holocene. Recent hydrothermal activity observed in these regions involves two groups of now active thermal springs with an appreciable impurity of mantle helium, identified by O.M. Prasolov and I.L. Kamenskii [15] and by B.G. Polyak (oral communication).

Noteworthy are the following characteristics of volcanism: (a) assignment of volcanic and hydrothermal activity to NS trending fault zones; (b) presence of

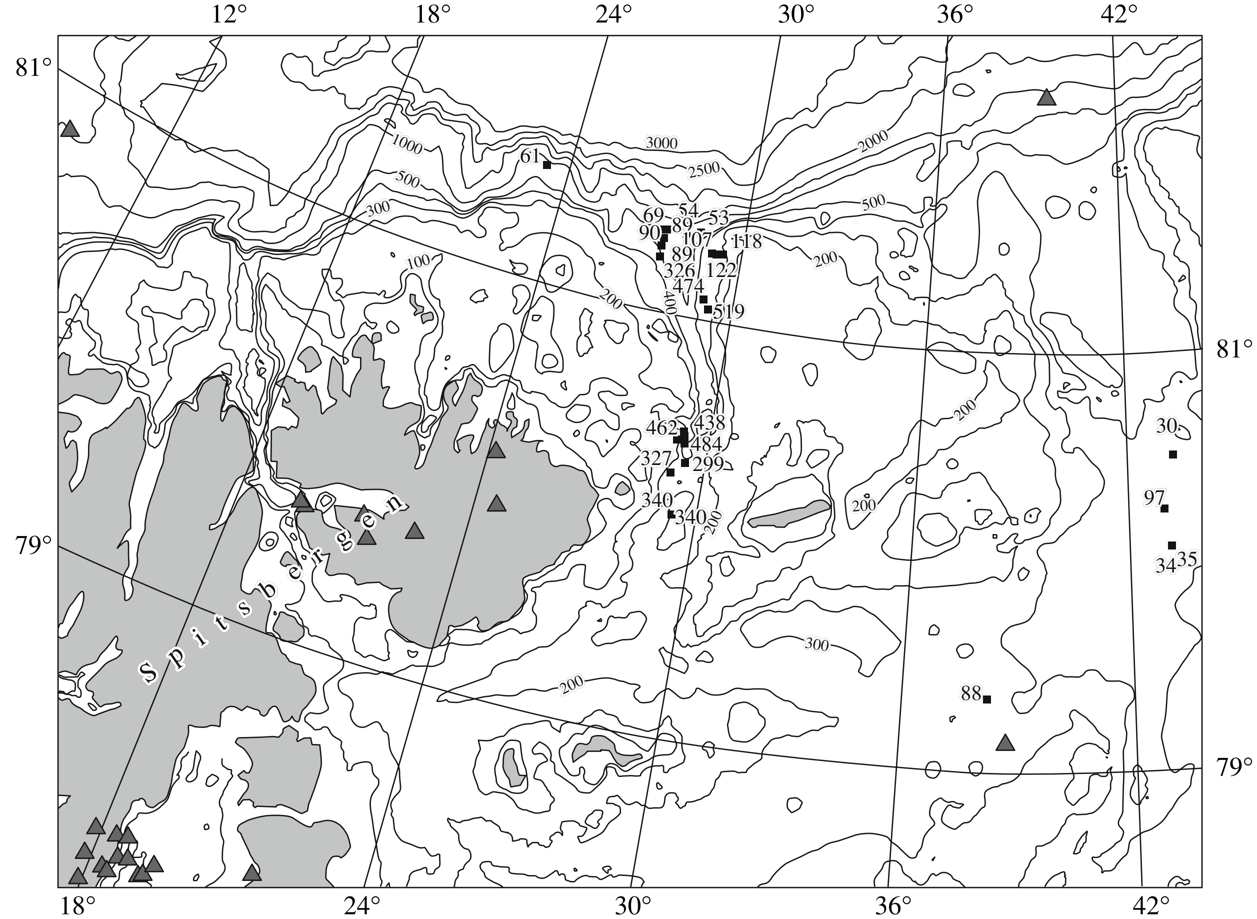

Fig. 4. Location of heat flow measurement stations in the Spitsbergen area and heat flow values (mW/m^2).

xenoliths in igneous material that indicate high scope of the processes; (c) persistent alteration of the composition: increasing alkalinity in the northern direction and rejuvenation of the volcanism age in the same direction; this is regarded as a consequence of a more general process, i.e., the opening of the Norwegian–Greenland basin and the Arctic Ocean Basin [13]. North of Spitsbergen, the Ermak plateau displays abnormal values of heat flow (110–125 mW/m^2), and there are signs of the existence of submarine volcanoes. Provided these data are confirmed, we shall get a picture analogous to that in the Orel trench, which shows similar tendencies in the development of these structures.

Therefore, the considered trench or trough structures have a number of features in common. These data in combination allow us to develop a generalized structural model with features of rift-type structures (morphology of trenches, structure of on-land grabens, Quaternary (including Holocene) volcanism, thermal activity, hydrothermal discharge, Alpine dissected topography), i.e., characters typical of the process of recent break up of the continental crust. Previously, recent break-up of the continental crust was also put forward, but the available quantitative data were not sufficient to prove it. The discovered abnormally high heat flow in the Orel trough has supplied the necessary data.

We have discovered the recent activity of western troughs (the Orel trough and Spitsbergen graben–fjords); we cannot state the same for eastern troughs (the Franz–Victoria trough and others). Their tectonic origin is quite evident, but the peak of activity occurred in the late Mesozoic [5, 6], and at present, in addition to the relaxation of the Cretaceous thermal activity, they might serve as channels for sedimentary material transport.

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