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Recent Geodynamics and Seismicity of the European Arctic

*Evgeniy Rogozhin, Galina Antonovskaya, Irina Basakina
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Abstract

The recent seismicity and heat flow density are indicators of geodynamic processes. For the European Arctic, the information of recent earthquakes were generalized and compiled on the general seismic catalog for 1998–2017 based on the new seismic data from stations opened in the region from 2011 to 2016. The general database of the heat flow from different data sources is compiled to obtain its spatial distribution for the European Arctic region. The relationships of heat flow values and seismic activity are discussed for this region, and combined geological and geophysical lithosphere cross sections are made in the latitudinal and meridional directions. The most geodynamic active structures and zones of tectonic stress concentration are distinguished; there are Gakkel Ridge and the Svalbard anticline in the Barents Sea region. Weak seismic events were recorded in the Novaya Zemlya region that reflect manifestations of recent tectonic activity.

Keywords: sea geotectonics, seismic activity, heat flow, deep structure, earthquake catalog, seismic stations

1. Introduction

The European sector of the Arctic region is an element of a geodynamic system that includes the ancient Eurasian continent and intensely developing younger Arctic Ocean. Seismic, gravity and geothermal fields establish a structural-density inhomogeneity of the crystalline basement and sedimentary cover, show the nature of the heterogeneous blocks compound of Earth's crust, etc. Deep crustal processes are marked by heat flow and peculiarities of stress-strain state reflected in parameters of the seismic regime. The great volume of collected geological and geophysical data has revealed complex and spatially heterogeneous structures of the Earth's crust and upper mantle in this region [1–8]. The peculiarities of lithosphere forms the causes in changes in thickness and “disappearance” of granitic-gneissic layer beneath deep basins; all of this is still disputable [3, 8].

Significantly, to date, the methodology of seismotectonic formation and its relationship with geodynamics that are investigated are not enough. Small attention is paid to the study of the relationship of weak seismicity and the deep structure, the definition of suture form zones of the crystalline basement, and the connection on structural places, primarily in the sedimentary cover.

The European sector of the Arctic region is considered aseismic; however, the number of seismic events recorded here in the period of 1998–2017 with respect to

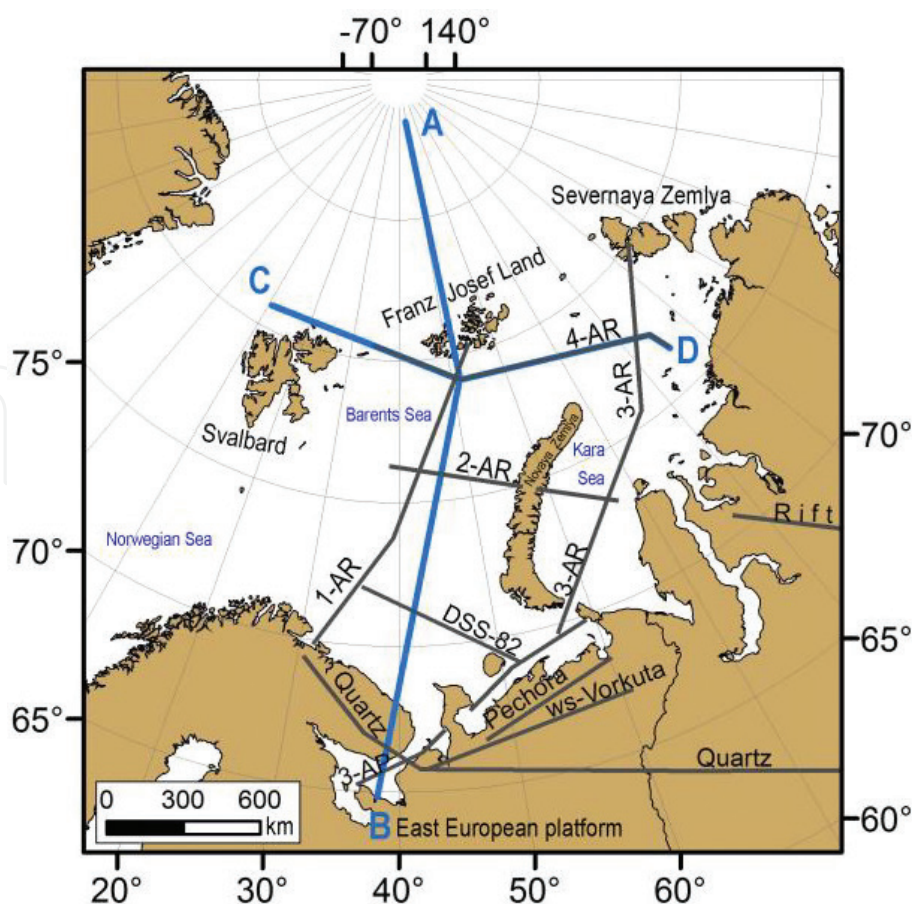


Figure 1.

Scheme showing locations of profiles A–B and C–D, geotraverses, and deep seismic profiles in water area (1-AR, 2-AR, 3-AR, 4-AR, DSS-82) and on land (Kvarts, Pechora, Rift, SW Vorkuta) in studied region.

improvements of Arctic seismic networks suggests a need for revision. The contemporary seismicity and heat flow density are indicators of geodynamic processes [9]. Joint analysis of these fields will allow a better understanding of the regional geodynamics, and such analysis is the aim of this study.

For this, a unified seismic catalog based on data from seismic networks that monitor the studied region was compiled; we generalized data of deep geological and geophysical cross sections of the crust and upper mantle along geotraverses [10–13] (**Figure 1**) and employed data on the spatial heat flow distribution [14–17]. Based on an analysis of the geological and geophysical data, we summarized the cross sections along the A–B and C–D profiles, which reflect the main structural features of the lithosphere in the region and make it possible to consider the relationship between the seismicity, heat flow density, and tectonics.

2. Relationship between the seismicity of the European Arctic and structural-tectonic elements of the lithosphere

Instrumental observations of the seismicity in the European Arctic are carried out by a number of seismic services and networks, but the Norwegian seismological center NORSAR (<http://www.norsardata.no>), the Arkhangelsk seismic network of N. Laverov Federal Center for Integrated Arctic Research (<http://www.fdsn.org/networks/detail/AH/>), and the Kola Branch of the Geophysical service of RAS (<http://www.krsc.ru>) make the greatest contribution.

Each seismological service has its own high-priority zones and shadow zones where earthquakes are being recorded [18]. Combining efforts in seismological

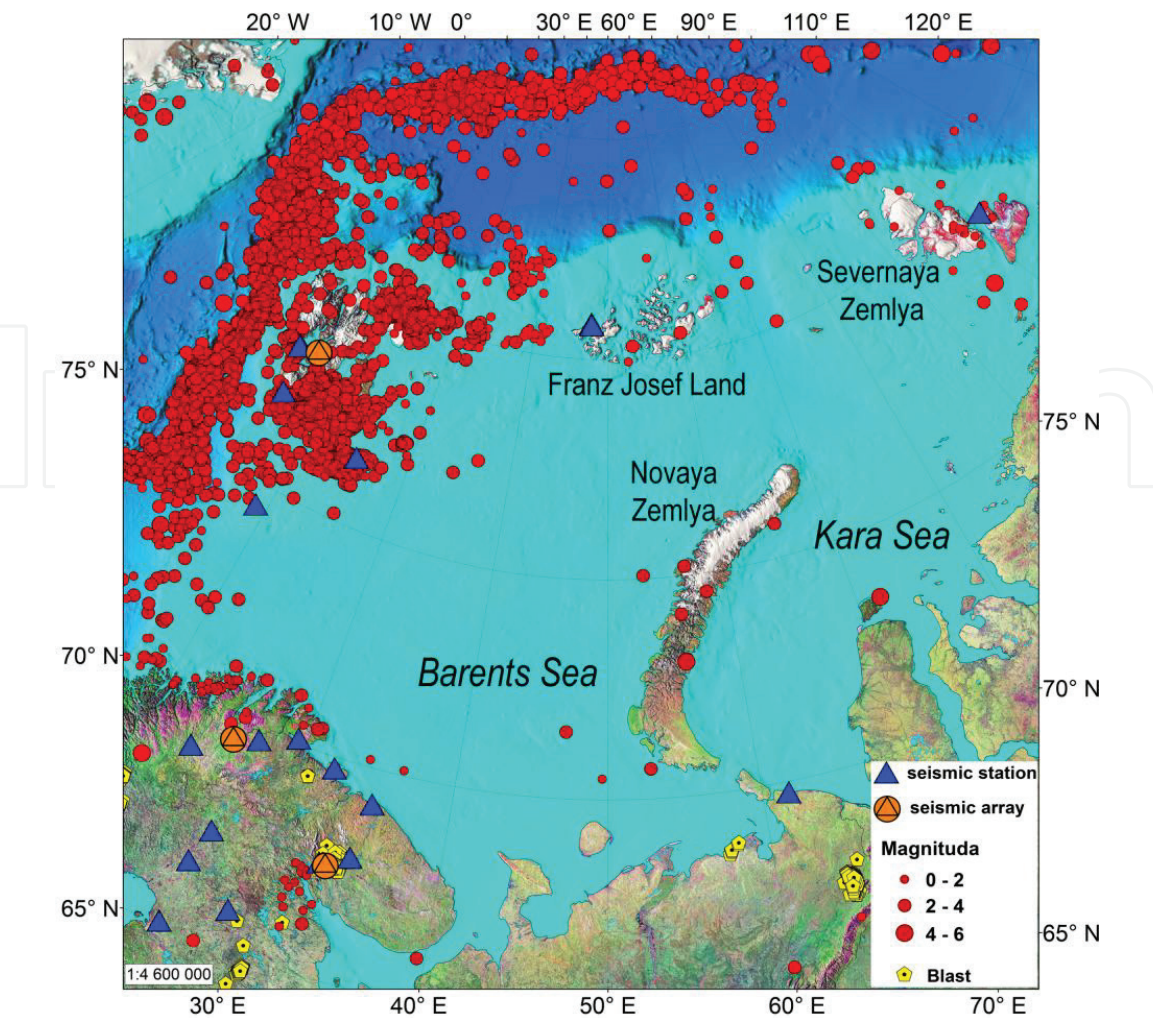


Figure 2.
Results of the unified seismic catalog which makes use of stations in Fennoscandia, Spitsbergen, Franz Josef Land, Severnaya Zemlya archipelago, north of the Russian Platform, and the Kola Peninsula. The figure covers seismic events (red dots) for 1998–2017. For Novaya Zemlya we collected information from 1986. Some additional stations which provide minor contributions to this unified catalog are not shown on the map.

monitoring of the Arctic region can help to increase the accuracy in locating epicenters and estimating their energy. Obviously, an urgent problem is the expansion of seismic networks in the Russian sector of the Arctic region, where seismological observations are insufficient compared to foreign ones. The coverage density of seismic stations in the European Arctic is shown in **Figure 2**. The opening of several new seismic stations in the Russian Arctic recently allows to cover the European Arctic territory at large, but the number of stations is still small. The seismic stations installed on the Franz Josef Land (ZFI and OMEGA) and Severnaya Zemlya (SVZ) archipelagos make a special contribution to the European Arctic monitoring, allowing to investigate the seismicity of the Gakkel Ridge (central and eastern parts) and the Arctic shelf.

Assessment of the seismic situation in the region is additionally complicated by the fact that the data in catalogs of different seismological services and networks are not unified, the quantity and quality of the initial data greatly vary, and different processing methods have been used for them. The parameters of the same earthquakes often vary in different information sources. The seismic data were generalized to increase the quality of earthquake location in the European Arctic [9]. For each network the zones of responsibility (priority) were determined where epicentral parameters are determined with minimal errors (**Figure 2**). For example, zones of responsibility of the NORSAR network are the Mona and Knipovich ridges and Svalbard, whereas those of the Arkhangelsk seismic network are the Gakkel

Basic data							Alternative data				
Date	Origin time	Lat	Lon	MI	Region	Data source	Origin time	Lat	Lon	MI	Data source
08.10.2013	01:39:58.9	74.29	15.23	4.3	Mohns Ridge	NORSAR	01:40:00.0	74.44	15.30	-	ASN
08.10.2013	09:10:26.0	84.06	4.51	3.3	Gakkel Ridge	ASN	-	-	-	-	-
09.10.2013	03:32:57.0	73.17	7.31	3.0	Mohns Ridge	NORSAR	-	-	-	-	-
09.10.2013	06:13:55.0	81.42	-1.63	3.6	Knipovich region	ASN	-	-	-	-	-
16.10.2013	16:33:09.0	79.14	4.19	3.5	Knipovich region	ASN	-	-	-	-	-
18.10.2013	02:05:18.5	84.56	12.47	-	Gakkel Ridge	ASN	-	-	-	-	-
20.10.2013	16:49:53.8	72.33	2.73	3.4	Mohns Ridge	NORSAR	-	-	-	-	-
21.10.2013	19:04:49.8	86.28	49.91	3.3	Gakkel Ridge	ASN	-	-	-	-	-
22.10.2013	22:45:10.9	73.53	8.47	3.4	Mohns Ridge	NORSAR	-	-	-	-	-
23.10.2013	10:31:04.8	77.76	8.56	3.7	Knipovich region	NORSAR	10:31:08.9	77.78	8.99	3.9	ASN
23.10.2013	14:17:00.0	85.25	26.91	3.0	Gakkel Ridge	ASN	-	-	-	-	-
24.10.2013	09:51:00.8	77.92	8.50	2.2	Knipovich region	NORSAR	09:51:01.0	77.88	8.58	3.2	ASN
24.10.2013	23:46:07.0	85.01	12.02	3.4	Gakkel Ridge	ASN	-	-	-	-	-
25.10.2013	22:48:21.7	76.60	9.08	2.6	Knipovich region	NORSAR	22:48:21.0	76.77	7.79	-	ASN
25.10.2013	01:25:56.0	80.33	40.06	1.9	Franz-Victoria Graben	ASN	-	-	-	-	-

Note: ASN, Arkhangelsk seismic network; MI, local magnitude.

Table 1.
Example of the unified seismic catalog.

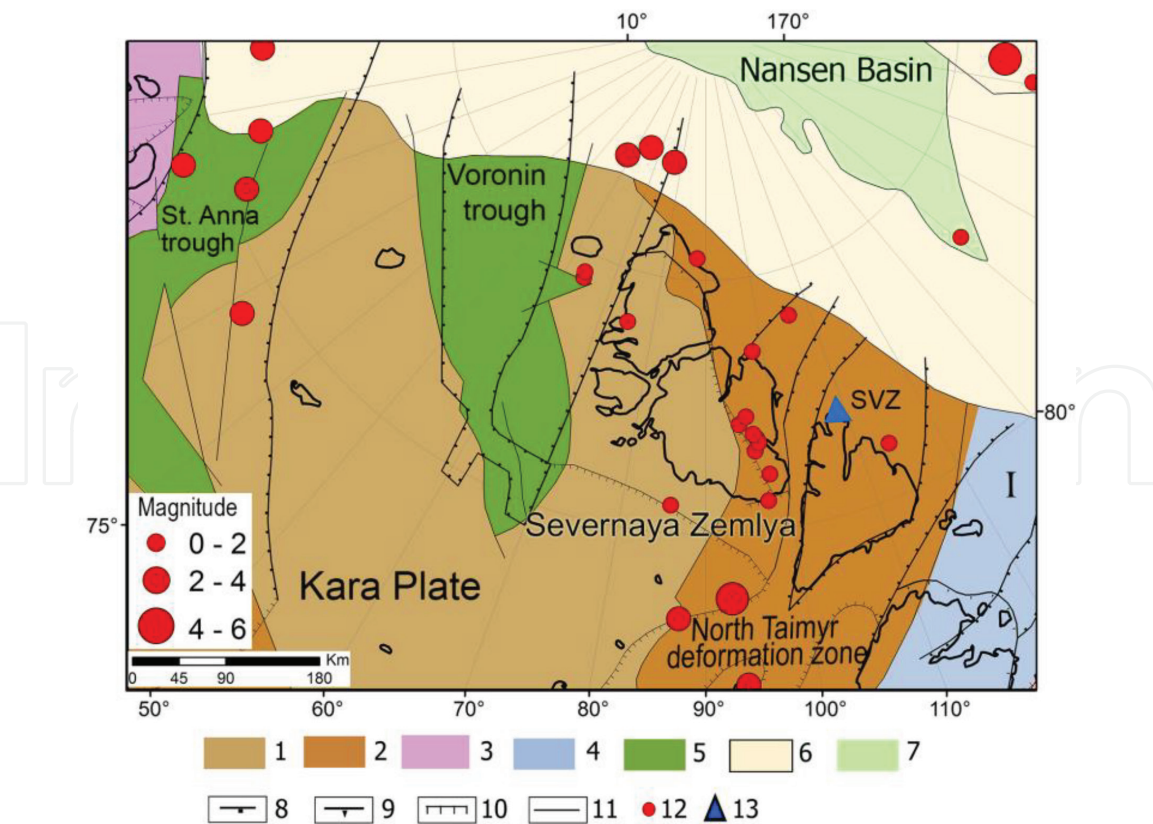


Figure 3. Spatial distribution of seismic events in the Severnaya Zemlya archipelago region on the map of main neotectonic and geomorphological elements of the Arctic by [21]. Lithospheric plates: (1) with late Precambrian basement, (2) with late Precambrian basement that was subjected to Hercynian tectonic deformations, (3) with Grenvillian basement, (4) Neoproterozoic Taimyr accretionary belt, (5) troughs with suboceanic type crust, (6) continental slope, and (7) oceanic crust. Neotectonic faults: (8) normal faults, (9) thrusts, (10) undetermined type, (11) structures boundaries, (12) earthquakes, and (13) seismic stations. I, Taimyr accretion belt.

Ridge, Franz Josef Land, Severnaya Zemlya, and Novaya Zemlya archipelagos. The unified seismic catalog for 1998–2017 contains data on earthquakes in the European sector of the Arctic region north of 70°N, recorded by at least three seismic stations. An excerpt from the unified catalog is presented in **Table 1**.

The unified seismic catalog consists of two parts: (a) primary epicentral parameters (basic data in **Table 1**) calculated for earthquakes according to priority zones and (b) alternative versions of the earthquake parameters (alternative data in **Table 1**). There are a number of earthquakes whose parameters were calculated only by the network. According to the catalog, earthquakes in the European Arctic range from 0.9 to 6.2 in magnitude, and the representative magnitude is 2.9.

The difficulty is that the predominant numbers of earthquakes are recorded by single station only and they cannot be included in the seismic catalog (about 20% of the total number) due to the poor quality of their processing. For example, the spatial distribution of earthquakes (red circles) recorded by the SVZ station during 2017 and processed using wave forms from other seismic stations installed in the Arctic region is shown in **Figure 3**, in which the earthquake processing results recorded by the SVZ station only are presented also. Location of earthquake epicenters is reliant on the hodograph type which is absent for the central part of the Arctic Ocean; as a result, we use the NOES [19] or BARENTS [20] regional hodographs. As a result, we can determine the most likely areas of their location roughly. However, even at the first approach, these epicenters are confined to the eastern part of Gakkel Ridge, the boundary of the

Kara plate, and fall into the zone of the North Taimyr deformation associated with tectonic fault. Seismicity around Severnaya Zemlya to all appearance is consequence of rifting processes emerging in the central seismically active zone of the Laptev Sea.

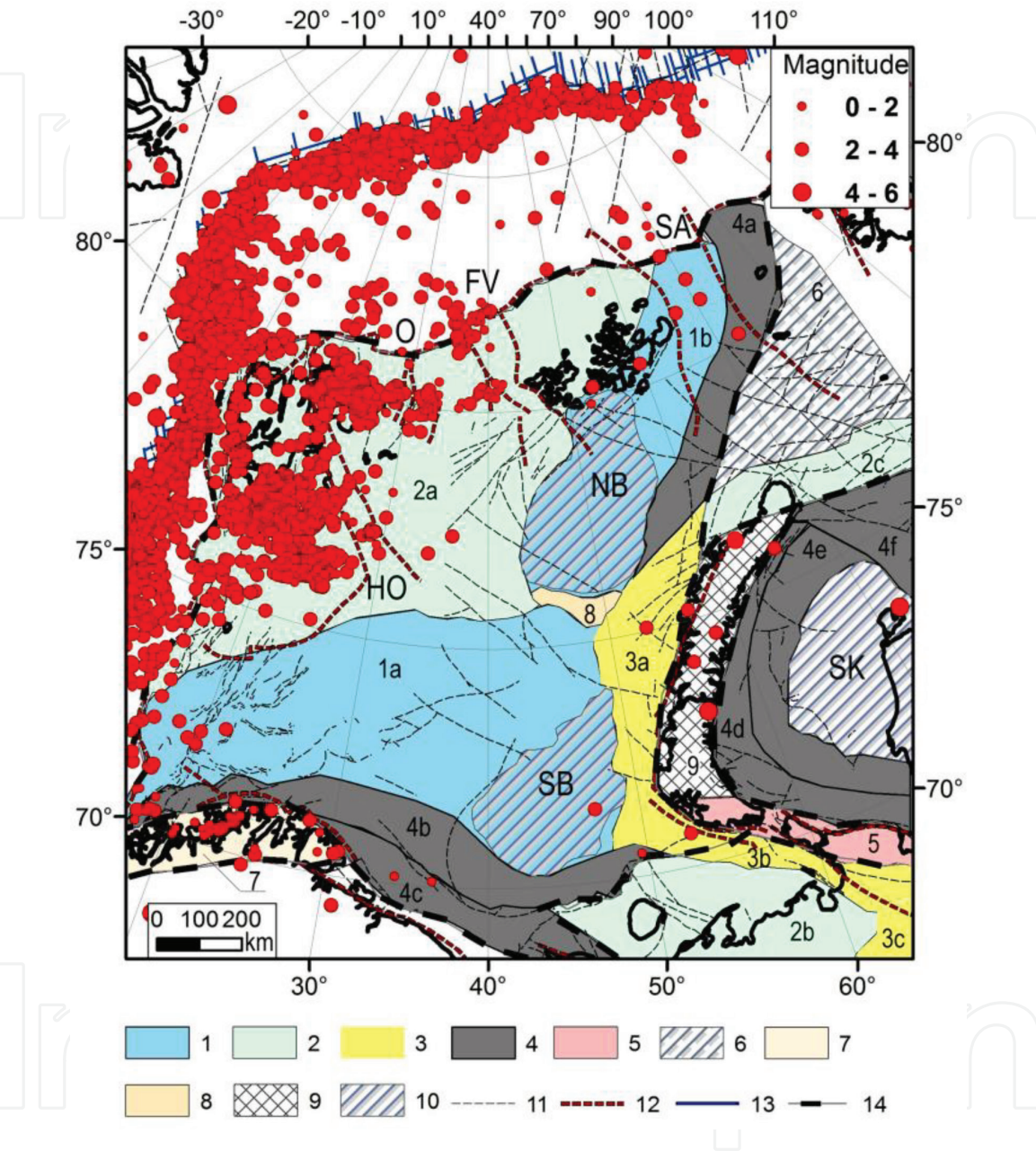


Figure 4. Contemporary seismicity in map showing main structural-tectonic elements in Barents Sea region (with data from [13, 22]). The figure covers seismic events (red dots) for 1998–2017, and for Novaya Zemlya we collected information from 1986. Notation: SA, St. Anna trough; HO, Hipopen-Olga trench; FV, Franz-Victoria trough; O, Orly trough. (1) basins: (a) central Barents and (b) north Barents. (2) Cratonic massifs: (a) Svalbard antecline, (b) Pechora plate, and (c) north Siberian threshold. (3) marginal troughs: (a) Sedov trough, (b) Korotaiikha Basin, and (c) Kos'yu-Rogovskaya Basin. (4) slopes of deep basins: (a) east Barents step zone, (b) south Barents step zone, (c) kola monocline, (d) East Novaya Zemlya monocline, (e) East Novaya Zemlya step zone, and (f) north Siberian step zone. (5) Baikalian folding: Pai-Khoy range. (6) North Kara syncline. (7) Caledonian folding structures of Scandinavian peninsula. (8) Luninskaya saddle. (9) early Cimmerian folding of Novaya Zemlya. (10) deep basins (SB, south Barents; NB, north Barents; SK, South Kara). (11) boundaries of near-shelf and unclassified faults. (12) largest faults, strike-slips, and thrusts. (13) active spreading center. (14) superorder structures.

Let us compare the spatial distribution of earthquakes from the unified seismic catalog and the positions of the main structural-tectonic elements in the Barents Sea region [13, 22]. By all data generalizing, we can reveal the following geodynamical peculiarities of this region (**Figure 4**):

1. Seismic activation of the arch-block ascent of Svalbard, Franz Josef Land, and the Belyi Rise was caused by tectonic stresses for which tensional and shortening morphostructures form [2, 6].
2. Extension of the continental shelf margin and its elongation in the Franz Victoria, St. Anna, and Orly toughs [2, 6], and probably isostatic compensation of rapid sedimentation at the offshore boundary, is reflected as weak seismicity within the ML magnitude range of 0.6–4.9.
3. Particular weak earthquakes were revealed in the boundaries of tectonic structures in the Central Barents Basin (Norwegian shelf) and in the Caledonian fold zone of the Scandinavian Peninsula.

4. Singular seismic event was recorded on the slopes of deep basins, namely, in the eastern Barents and southern Barents step zones:

- i. January 23, 2012, $t_0 = 09:52:55.0$, lat 80.11, lon 72.71, ML = 2.7.
- ii. November 10, 2002, $t_0 = 11:04:41.7$, lat 70.47, lon 49.62, ML = 2.0.

In addition, two earthquakes were recorded in the Kola monocline:

- i. November 5, 2002, $t_0 = 07:31:16.22$, lat 70.17, lon 34.25, ML = 1.6.
- ii. November 2, 2000, $t_0 = 08:14:24.61$, lat 70.12, lon 36.56, ML = 1.1.

5. Seismic activity was recorded in the marginal eastern part of the Barents Sea plate, in the Novaya Zemlya fold zone, and in the Sedov Trough [23, 24]. As an example, here are two seismic events that occurred on Novaya Zemlya:

- i. October 11, 2010, $t_0 = 22:48:29$, lat 76.18, lon 63.94, ML = 4.49.
- ii. March 4, 2014, $t_0 = 04:42:36$, lat 74.72, lon 56.72, ML = 3.3.

We also note the event recorded in the South Barents Basin in November 11, 2009 ($t_0 = 04:18:20.2$, lat 71.52, lon 47.06, ML = 3.2) [24]. The geological feature of the event epicenter is the big thickness of the sedimentary cover (15–20 km), which makes it unique and requires additional geophysical studies of the area.

Thus, the earthquake distribution reflects the impact of the spreading processes and transforms movements and the result of tectonic stress fields generated directly in the marginal parts of the Barents Sea plate, with singular events being recorded in its central part. The maximum cluster of earthquakes is located along the central axis of mid-ocean ridges (MOR).

3. Correlation between heat flow, seismicity, and deep structure

The time of thermal relaxation of the Earth ($\sim 1.5 \times 10^9$ years) makes it possible to consider the Earth's thermal component as constant [25]. There are two main heat sources: that supplied from the mantle ($\sim 60\%$) and that formed by radioactive

decay in crustal rocks (~40%). In the sedimentary cover, the majority of radioactive elements are hosted in clay rocks, whereas intrusive bodies are the local heat sources. Based on the data from different sources [14–17], we compiled a database of heat flow values. The summary data on seismicity and heat flow within the distinguished tectonic structures (cratonic and oceanic) of the studied region are presented in **Table 2**.

The seismic activity correlates with heat flow values in middle ocean ridge (MOR) areas. In the northern East European Craton, there was no clear relationship between these parameters, except for the North Barents Rise. Let us consider

Structures		Earthquakes			Average heat flow, mW/m ²
Superorder structures	First and second orders	Number	ML _{max}	ML _{av}	
Barents plate	Central Barents Basin (1a)	23	3.6	2.48	60–70
	North Barents Basin (1b)	3	2.7	2.4	60–80
	North Barents Rise (2a) Orly trough (exclusion)	1758	5.9	2.5	60–80, 100–300
	Sedov trough (3a)	2	2.3	2.25	50–80
	East Barents step zone (4a)	1	2.7	2.7	70
	Luninskaya saddle (8)	-	-	-	70
	South Barents step zone (4b)	9	3.7	2.37	60–70
	Kola monocline (4c)	2	1.6	1.35	50–60
Timan-Pechora plate	Pechora plate (2b)	-	-	-	40–50
	Korotaikha Basin (3b)	-	-	-	40
	Kos'yu-Rogovskaya Basin (3c)	-	-	-	30–40
	Timan Range (5a)	-	-	-	50
West Siberian plate	East Novaya Zemlya monocline (4d)	-	-	-	60
	East Novaya Zemlya step zone (4e)	-	-	-	60
	North Siberian step zone (4f)	-	-	-	60
Novaya Zemlya microplate	Early Cimmerian folding of Novaya Zemlya (9)	5	4.5	3.24	60
	Pai-Khoy Range (5b)	-	-	-	60
North Kara plate	North Siberian threshold (2c)	-	-	-	60–70
	North Kara syncline (6)	-	-	-	70
Baltic Shield	Caledonian folding structures of Scandinavian Peninsula (7)	33	2.8	1.9	40–50
Eurasian and North Atlantic Basins	Nansen Basin	135	4.3	2.5	60–80
	MOR	3224	6.6	2.83	>100

Table 2.
Seismicity parameters and heat flow in distinguished tectonic structures of studied region of the Arctic.

the distribution of these parameters in more detail, with knowledge about the structure of the lithosphere along the composite geological and geophysical cross sections (**Figure 1**).

Profile A–B (**Figure 5**) crosses such morphostructures as the MOR (Gakkel Ridge), the abyssal plain (Nansen Basin), the Barents Sea shelf, the eastern Baltic Shield, the White Sea shelf, and the continental rise of the East European Craton. To construct the model for the lithosphere structure on P-wave velocities, we used data from deep geological and geophysical cross sections along such profiles as Kvarts, 1-AR, 2-AR, 3-AR, 4-AR, DSS-82, etc. [10–13, 26].

Profile C–D (**Figure 6**) crosses such morphostructures as the Svalbard antecline, North Barents Basin, North Kara syncline, and the Taimyr-Severnaya Zemlya fold system. The majority of it is overlapped by the 4-AR deep seismic profile (seismic reflection CMP method) [2, 11, 13].

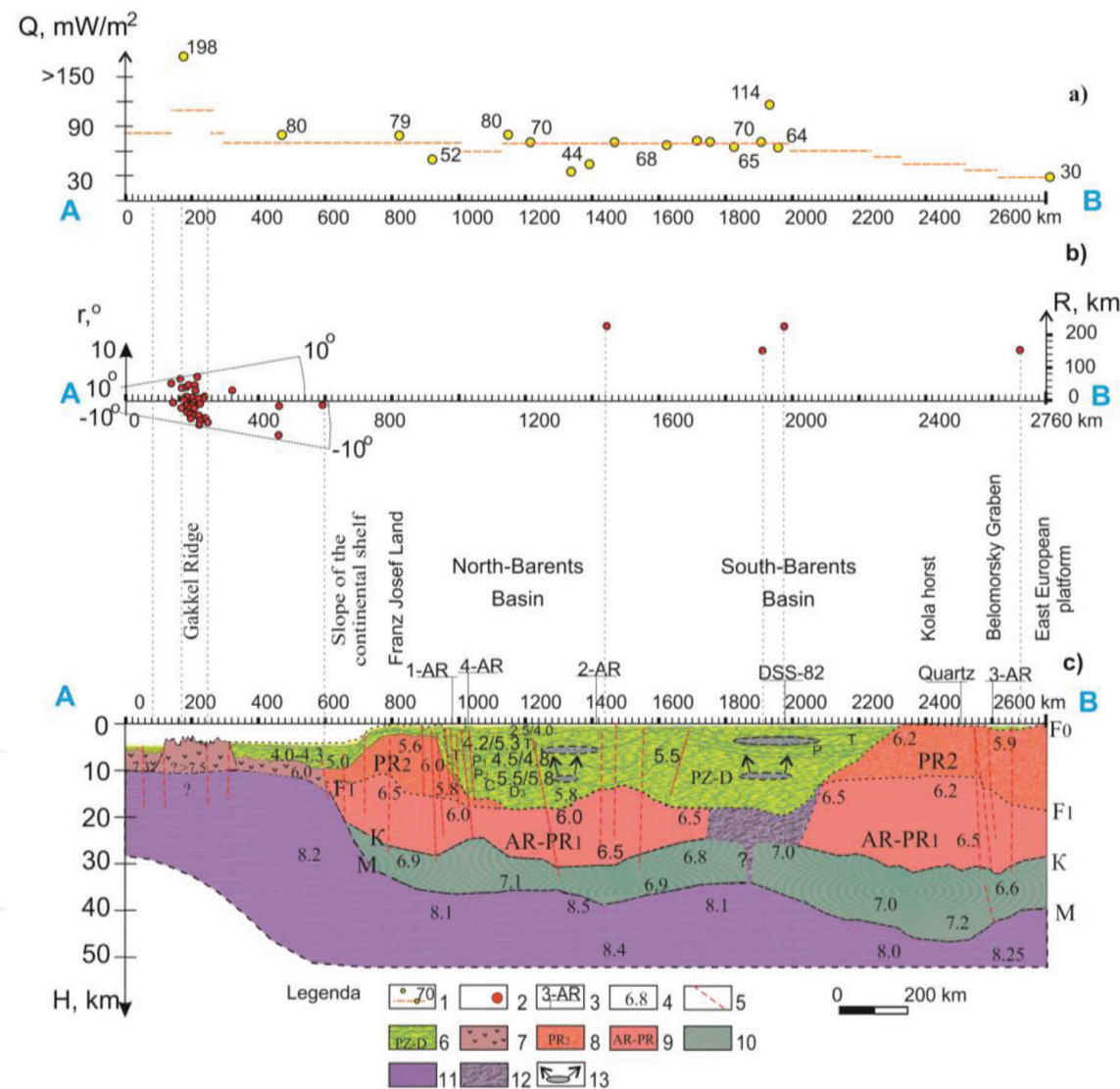


Figure 5. Distribution of heat flow (I) and seismicity (II) and geological and geophysical cross section along profile A–B (III) (with data from [10, 13, 26]). Notation: M, Moho; K, middle boundary in crust; F0, top of upper Proterozoic basement; and F1, top of Archean-Proterozoic crust (PR1-AR). Arbitrary notes: (1) heat flow values (including averaged ones) along profile, mW/m^2 , (2) epicenters of earthquakes in 1995–2015, (3) crossing points of geotraverses, (4) P-wave velocities, (5) faults, (6) sedimentary cover and its age, (7) acoustic basement of oceanic crust, (8) upper Proterozoic basement (PR2), (9) upper sialic part of consolidated crust (PR1-AR), (10) basite part of consolidated crust, (11) upper mantle, (12) basite massifs, and (13) fluid-saturated decompacted zones in sedimentary cover where hydrocarbon generation is possible.

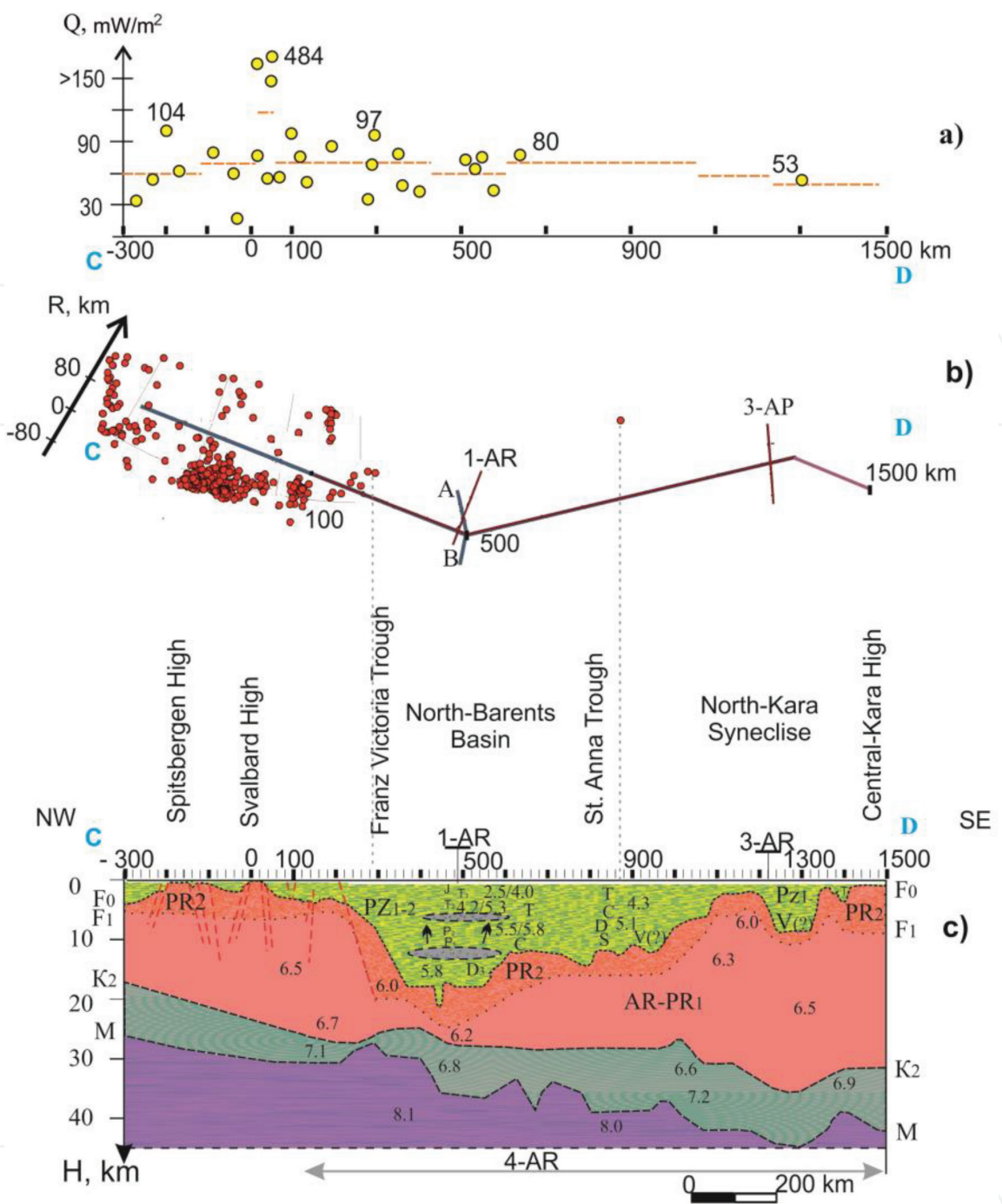


Figure 6. Distribution of heat flow (I) and seismicity (II) and geological and geophysical cross section along profile C-D (III) (with data from [10, 13, 26]). Notations are shown in Figure 5.

The heat flow values and earthquake epicenters are drawn along the composite lithosphere cross sections. Below are the results of comparison of the geological and geophysical fields.

3.1 Profile A–B

The oceanic lithosphere is sharply distinguishable from the continental crust, and the oceanic Moho is located at a depth of 12–13 km (Figure 5). The seismic velocities in the upper oceanic crust are from 4.5 to 6 km/s, whereas they are from 6.8 to 7.3 km/s in the lower part. The rift valley of the Gakkel Ridge is formed by rocks from the oceanic basement, which supposedly had velocities of more than 7.5 km/s [26]. In the sedimentary cover above the basement of the oceanic crust, we can distinguish several stratigraphic complexes, whose thicknesses increase toward

the Barents-Kara continental margin. In the Nansen Basin, the Moho was acoustically detected at 10–12 km depth [26].

Seismic activity has been recorded in the zone where the continental and oceanic lithosphere joins. Single seismic events in this area are supposedly caused by the removal of sedimentary masses from the continent [2] or by transform fault activity. The lithosphere is the continental type. The surface of the mantle (P-wave velocities from 8.0 to 8.5 km/s) is at 34–36 km in the Barents Sea Basin, 35–40 km in the Kola monocline, and 44–46 km in the Baltic Shield. The consolidated crust can be roughly subdivided into two layers. The upper one has velocities of 5.6–6.5 km/s and the lower 6.6–7.2 km/s. The thickness of the upper layer of the consolidated crust changes from 8 km in the basin to 15–25 km in the areas of the Voronin, Albanov, and Fedynsky rises, as well as beneath the Baltic Shield [8]. The thickness of the basite part of the consolidated crust in this area ranges from 10 to 20 km in the zone of the rise, whereas it thins to 5–16 km in the sinking zone [10, 11].

For the oceanic lithosphere with thinned crust, heat flow increases to 200 mW/m², and seismic activity is higher, especially in the Gakkel Ridge area. In the Nansen Basin, where single earthquakes have been recorded closer to the transform zones, the heat flow values are 98 mW/m². Toward the ledge of the continental shelf, the average heat flow decreases to 70 mW/m².

Based on the seismic data, the upper layer of the consolidated crust beneath the South Barents Basin contains local velocity inhomogeneities. It is assumed that the upper crust contains abundant plateau basalts and is close to oceanic crust in its physical properties. Such thinning and transformation of the continental crust, coupled with its sinking, were probably caused by phase transitions of rocks [1, 27]. **Figures 5 and 6** schematically show fluid-saturated decompaction zones in the sedimentary cover, where subsequent generation of hydrocarbons is possible. In the North Barents Basin, the lower crustal layer contains high-velocity inhomogeneities with values of 7.1 km/s. According to [1, 28], their compactions were the result of gradual metamorphic transition of gabbroids to eclogite.

In the Barents Sea Basin, singular earthquakes have been recorded in zones where rock transformation takes place (**Figure 4**). These areas are remarkable for higher heat flow values (60–80 mW/m²). The last zone along profile A–B is a thick mantle-crustal structure; it is thermally cold (heat flow values from 30 to 50 mW/m²) and has a thin, up to wedging, sedimentary layer in the southwestern part of the continental rise of the East European Craton. It can be assumed that this structure limits shortening from the Middle Arctic Ridge and tectonic deformations from the fold units of the Polar Urals, Novaya Zemlya, Taimyr Peninsula, and Caledonides of the North Atlantic, which is manifested as single relatively weak earthquakes at the boundaries of large tectonic structures [29].

3.2 Profile C–D

High seismic activity has been recorded in the area of collisional dislocations at the Svalbard plate margin (**Figure 6**). Heat flow values of about 80 mW/m² exceed the mean ones for the Barents Sea Rise, and in the area of Orly Trough, they reach peak values of ≈ 500 mW/m². The slow and gentle downwarping of this part of the Barents Sea plate to an almost horizontal plane resulted in the formation of the North Kara Basin [6].

Seismic data suggest that the crust is continental type, which is supported by low seismic wave velocities (5.6–6.0 km/s) in the granitic-gneissic layer. According to [8, 11], thinning of the crust and the influence of small flows of deep mantle fluids (compared to those that affected the South Barents Basin) gave rise

to slow eclogitization in the lower crust. This is supported by the mean heat flow (about 70 mW/m²), with an anomalous increase up to 97 mW/m². In the eastern part of profile C–D, there are only singular instances of heat flow data, and these are 50 mW/m² on average.

Seismic activity manifests itself in most of profile C–D, although it decreases moving from the junction zone between the Svalbard plate and the MOR. This may be related in part with the absence of permanently operating seismic stations in the Kara Sea region, because the model from [18] suggests that there should be weak seismicity at the junction of the Barents Sea and North Kara plates. The East Barents step zone (**Figure 4**) has the only seismic event recorded (lat 80.11, long 72.71, ML = 2.7), supposedly above the domain of high-velocity inhomogeneities in the lower and upper crusts (**Figure 6**).

4. Conclusion

Comparison of the geological and geophysical fields makes it possible to combine together different indicators of geodynamic processes. We have revealed the relationship between seismicity and deep structure, as well as the correspondence of seismicity to both the most geodynamically active structures and zones of concentrated tectonic stresses. According to the compiled unified catalog, the most geodynamically active area in the Barents Sea region is the Svalbard anticline, where the greatest concentration of tectonic stresses is observed on the MOR side and zones with higher values of heat flow are distinguished (70–80 mW/m² on average).

The recorded single earthquakes in the basins and troughs reflect manifestations of recent tectonic activity in the region, probably as a result of commonly developed high-velocity inhomogeneities in the lower and upper crusts or accumulation and release of stresses in weakened zones. This conclusion is, however, quite conditional because of a small time interval for which seismic data on the Barents Sea region are available. Seismological monitoring is necessary in the future to verify or refute such conclusions.

Manifestations of single earthquakes should be marked as promising areas for searching and prospecting for hydrocarbon fields within the limits of the South and North Barents basins, St. Anna Trough, and western Barents Sea Basin. Our studies supplement existing data on the structure and tectonics of the Barents Sea region.

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Conflict of interest

The authors declare no conflict of interest.

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