ISSN 0747-9239, Seismic Instruments, 2022, Vol. 58, No. 1, pp. 32–44. © Allerton Press, Inc., 2022.
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Relocation of Early Instrumental Earthquakes in the Arctic

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Received August 17, 2021; revised September 19, 2021; accepted September 20, 2021

Abstract—The source parameters of earthquakes in the Arctic during the entire instrumental period were calculated using a small number of stations, which in addition were remote from each other. Furthermore, during the 20th century, the source parameters of Arctic earthquakes were most often calculated from bulletin data from only part of the seismic stations operating at that time, using outdated velocity models and localization algorithms. The present article describes an approach that has already been successfully used by the authors to refine the source parameters of early instrumental earthquakes in the Arctic. The approach uses all currently available archives of bulletins and seismograms from the seismic stations that operated in the early 20th century; it also employs the modern *ak*135 velocity model and an improved localization algorithm implemented in the NAS program. We have relocated the epicenters of earthquakes recorded within the Arctic in the early 20th century and compiled an updated catalog of relocated seismic events. The relocation procedure was applied to 18 out of 25 earthquakes in the Arctic. The new coordinates of some earthquakes appeared to significantly differ from the previously determined ones. As a result, this may significantly affect the ultimate seismic hazard assessment of such areas as Severnaya Zemlya and Franz Josef Land, which are characterized by weak seismicity. Most of the relocated earthquake epicenters are confined to the main seismically active zones of the Arctic, namely, mid-ocean ridges, the Svalbard archipelago, and the Laptev Sea shelf.

Keywords: seismicity of the Arctic, early instrumental earthquakes, refinement of the source parameters

DOI: 10.3103/S0747923922010066

INTRODUCTION

During the entire instrumental period, the vast region of the Arctic has been covered by stationary seismic observations very inhomogeneously and poorly; the reasons are not only the complex geographic and climatic conditions, but also historical and economic circumstances. Moreover, instrumental observations were developed slowly throughout the 20th century, as well as inhomogeneously in both space and time (Fig. 1).

As noted in (Avetisov, 1996), until the late 20th century, the seismic network that operated in the Arctic was sufficient to carry out general monitoring of the seismic regime in the Arctic on the whole and to accumulate data on the already known peculiarities of this regime; however, it was not completely inapplicable to perform detailed studies of the most interesting and important, from the scientific and applied viewpoints, node elements of seismically active zones. The representative magnitude, which had been estimated at 5.5–6.0 at the first stage of instrumental observations (up until 1957), had decreased to 3.9–4.0 by the late 1980s (Avetisov, 1996).

The development of instrumental observations in Europe in the late 19th–early 20th centuries allowed the first earthquake in the Arctic region (to the north of 70° N) to be recorded instrumentally as early as October 9, 1904, especially after the commissiong of the new seismic station in Bergen in Norway in 1904, followed by those in Vassijaure (Sweden, 1906), Pulkovo (Russia, 1906), and Reykjavik (Iceland, 1909) (Tams, 1922). The first studies to generalize seismicity in the Arctic can be found in the publications by Tams (1922), Hodgson (1929), Gutenberg and Richter (1941), Emery (1949), and Linden (1959). However, the source parameters of earthquakes in the seismic catalogs, provided by these early researchers in the first half of the 20th century and in use even today, had been based, most often, on data (seismic bulletins) only from part of the seismic stations in operation that time, under now obsolete assumptions and ideas about

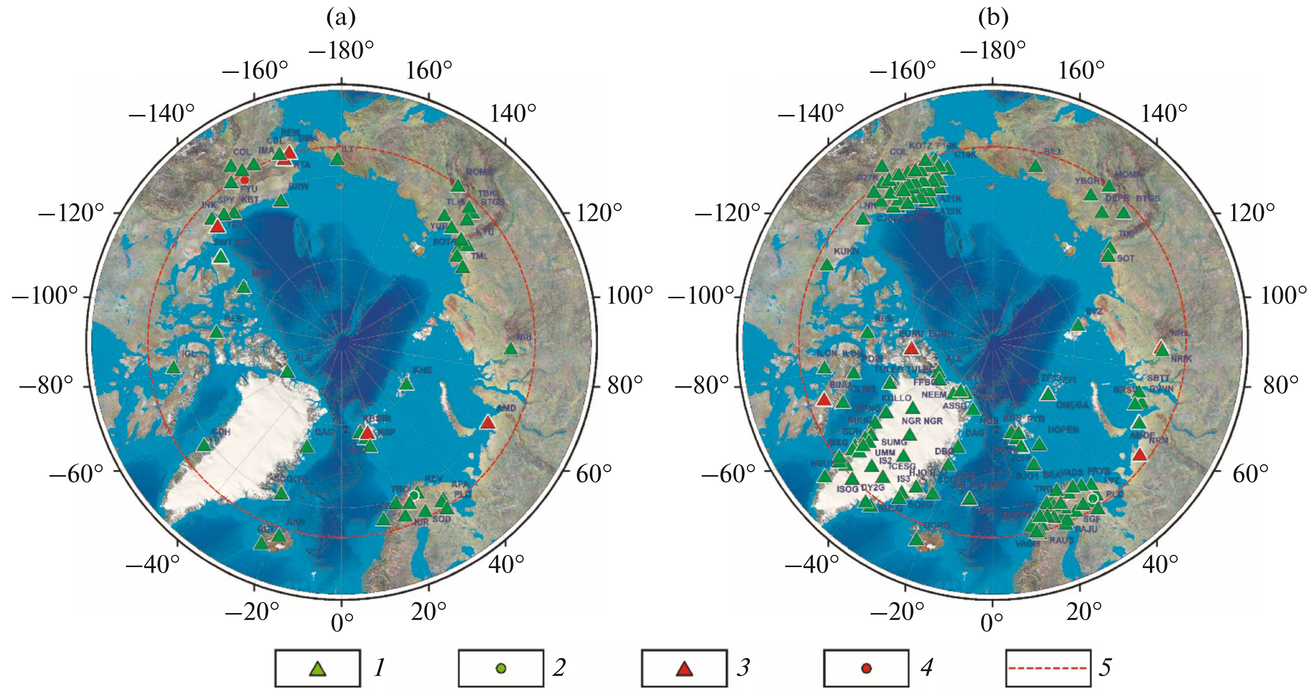

Fig. 1. Seismic stations that operated in Arctic in periods (a) since 1980 until 1990 and (b) since 2010 until 2020: (*1*) seismic stations; (*2*) seismic arrays operated continuously through indicated period; (*3*) stations removed from operation during indicated period; (*4*) seismic arrays removed from operation during indicated period; (*5*) Arctic Circle.

the regularities of seismic wave propagation in the Earth's interior.

Studies aimed at refining and clarifying the source parameters for earthquakes that occurred in the past are very common in seismology. Parameters are usually refined after a certain time period, more precisely, when some new instrumental data can be employed, and/or refined velocity models, novel methodical approaches, and computational algorithms are developed. As an example, below we present a few more or less recent studies in this field: (1) Bungum et al. (2009) refined the parameters of the Oslo fjord earthquake (October 23, 1904; $M_S = 5.4$); (2) Nikonov and Chepkunas (2009), the Sysolsk earthquake (January 13, 1939, East European Plate); (3) Niemz and Amorèse (2016), the Montserrat earthquake (November 10, 1935, Lesser Antilles); (4) Amorèse et al. (2020) calculated the source parameters of two earthquakes, 1926 and 1927, in the western English Channel; (5) Malovichko et al. (2020) refined the parameters of the 1917 Bilimbai earthquake, which is the strongest seismic event in the Ural region.

The necessity of conducting studies on refining the parameters of earthquakes that occurred in the Arctic during the early instrumental period is spurred by the general problem of seismic hazard assessment. Seismic hazard studies for any region are based on a seismic catalog whose data are used to calculate the seismic regime parameters. The strongest earthquakes with long recurrence intervals are the most important events in these catalogs; therefore, seismic hazard assessment for a region is preceded by compilation of a combined catalog of earthquakes that occurred during both the historical and instrumental periods, and data on paleoearthquakes are also employed. However, there are no data on historical and paleoearthquakes for the Arctic, so the data on earthquakes recorded during the historical period are of great value.

The present article describes an approach that has already been successfully applied by us when refining the source parameters of earthquakes of the early instrumental period in the Arctic.

METHODOLOGICAL BASIS OF STUDIES ON REFINING THE SOURCE PARAMETERS FOR EARTHQUAKES OF THE EARLY INSTRUMENTAL PERIOD

It is known that the conditions necessary for earthquake source parameters to be reliably calculated include the number of seismic stations and their azimuthal coverage of the source, as well as the use of a modern, updated velocity model and the modern localization algorithm. The source parameters for the Arctic earthquakes were determined with a small

Table 1. Methodical basis for works on relocating earthquakes in Arctic

Initial data	Bulletins and seismograms from seismic stations operated in first half of 20th century: (1) Archives of ISC-GEM, Euro Seismos, and IASPEI projects (2) GS RAS archive (3) International Seismological Centre database (4) Holdings of Russian State Library (5) Archive of Dr. J. Schweitzer, University of Oslo (6) Dissertation archive consisting of station bulletins of early 20th century and data on respective stations All data are available on https://disk.yandex.ru/d/JxAPERVZDg3Pkg
Location algorithm	Location algorithm of NAS program (Asming and Prokudina, 2016; Fedorov et al., 2019), which implements an enhanced version of the generalized beam forming method (Ringdal and Kværna, 1989)
Velocity models	For seismic stations at teleseismic distances, *ak*135 model (Kennett et al., 1995; Kennett, 2005)
Magnitude estimate	For earthquakes that occurred in early 20th century, magnitude M_S was calculated (Vanek et al., 1962): $M_S = \log\left(\frac{A}{T}\right)_{\max} + 1.66\log\Delta + 3.3$

number of seismic stations employed throughout the entire instrumental period, and these stations have been located quite far from the epicenters. In addition, not all seismic bulletins from the stations that operated in different periods have been available to researchers.

There have been a number of successfully completed scientific projects aimed at acquiring and storing historical seismograms and bulletins from the stations that operated for some time during the early instrumental period, in particular, (1) the Historical Seismogram Filming Project (Lee et al., 1988), supported by UNESCO; (2) the USGS WWFC Pilot Scanning Project (Alejandro et al., 2019); (3) Euro Seismos (ES) (Michelini et al., 2005); and (4) International Seismological Centre-Global Earthquake Model (ISC-GEM) (Storchak et al., 2014); owing to the data acquired in these projects, as well as open access to the archives of the Geophysical Survey of the Russian Academy of Sciences (GS RAS), it is possible to analyze data from bulletins and seismograms corresponding to the first half of the 20th century. As a result, when refining the source parameters of Arctic earthquakes that occurred in the first half of the 20th century, we can employ the results of the mentioned sources, which represent the most complete instrumental datasets on earthquakes of the early instrumental period (Table 1).

The scientific knowledge about the patterns of seismic wave propagation in the solid Earth has gradually evolved throughout the 20th century, and so to the velocity models applied when localizing earthquake epicenters, of which the earliest was that by R. Oldham (1900) and the most recent and currently used is the *ak*135 model (Kennett et al., 1995; Kennett, 2005). Since the parameters of earthquake hypocenters were calculated using different velocity models during the 20th century, in our study on refining the source parameters of Arctic earthquakes that occurred in the early instrumental period, we use the currently valid *ak*135 model.

In order to refine the parameters of hypocenters, we used the algorithm of the New Association System (NAS) program (Asming and Prokudina, 2016, Fedorov et al., 2019), which is, in fact, an enhanced implementation of the generalized beam-forming method (Ringdal and Kværna, 1989). The algorithm of the NAS program has a number of advantages, which favor the refinement of source parameters of earthquakes on the basis of bulletins from seismic stations operated in the beginning of the 20th century. First, this algorithm ignores erroneous arrival times of seismic phases due to operator error or hardware malfunction. Second, the bulletins of that time often only indicated the arrival times, without phase identification, and in such cases the algorithm identifies phases from the arrival times.

In the NAS program we set the initial spatiotemporal point corresponding to the approximate location of the earthquake's epicenter and its approximate time of occurrence. The algorithm preforms association and refinement of coordinates and time in the vicinity of this initial point. The program chooses a large radius circle around the initial point, and seeks for the more exact location within the limits of this circle (for refinement of the source parameters for earthquakes of the early 20th century, we set the radius to be 500 km). The circle is covered with overlapping circles of smaller diameters to form a mesh. For every single circle of smaller diameter, rating function $R(c,t)$ is calculated to assess and assign a rating for the hypothesis about occurrence of an earthquake within cell c at the time moment t. The mesh is reduced several times: at each iteration, three-fourths of all cells with the smallest ratings are excluded from the mesh, and every remaining cell is subdivided into four of smaller size; ratings are recalculated for all these new smaller cells. Such a search is performed for the set of fixed depths (in the the present study, the depth ranged from 0 to 100 km, with a 5-km step). At the end of the first stage, the cell with the maximum rating was assigned as the preliminary location of the earthquake. Then, at the second stage, the location is refined by minimizing the estimated residuals of the origin time from these found times and their weights; then, confidence intervals are constructed (error ellipses). In order to calculate the confidence intervals, in addition to the data on the known phases and station coordinates, one needs estimates of the errors of velocity model Δv (for which a value of 0.15 km/s is usually assigned) and estimates of arrival measurements Δt (for earthquakes of the early 20th century, this is 2 s) for different wave types.

Earthquake magnitude is one of the fundamental parameters listed in earthquake catalogs. The concept of magnitude was introduced several decades after the first seismometers were designed (Storchak et al., 2013, 2014), and the first definition for earthquake magnitude was proposed by C.F. Richter (1935). This magnitude is indicated as M_L and is calculated from the data acquired by the seismic stations nearest to the source. Later, B. Gutenberg (1945) introduced the scales for magnitudes m_B and M_S, which were calculated from the data acquired by seismic stations at teleseismic distances; as a result, it became possible to calculate magnitudes for earthquakes that occurred in remote areas and in areas with no seismic stations. Note that the formulas proposed by Gutenberg to calculate magnitudes have been modified, and, today, M_S is estimated using the amplitudes and corresponding periods of the surface wave in the range from 10 to 60 s at epicentral distances from 20° to 160° using the formula from (Vanek et al., 1962):

$$M_S = \log\left(\frac{A}{T}\right)_{\max} + 1.66\log\Delta + 3.3. \quad (1)$$

When refining source parameters of the earthquakes that occurred in the Arctic in the first half of the 20th century, we estimated magnitude M_S by formula (1). This type of magnitude is used for seismic hazard assessment in Russia and some post-Soviet countries, and there are many formulas to convert it to the moment magnitude M_W, which is used for seismic hazard assessment outside of Russia. One recent study where the conversion formula was inferred is (Di Giacomo et al., 2015).

In this section we described the approach we employed when refining source parameters for Arctic earthquakes of the early instrumental period in order to obtain the most reliable values. This approach is based on the use of (i) all available data and bulletins from the seismic stations operated in that period, (ii) the modern, updated velocity model *ak*135, and (iii) the enhanced location algorithm implemented in the NAS program.

A STUDY OF SEISMICITY OF THE ARCTIC IN THE EARLY 20TH CENTURY

It was noted in (Avetisov, 1996) that the first publications on seismicity in the Arctic and Subarctic regions concerned the particular, strongest earthquakes, for which instrumental data were obtained. The summary by classic seismologist John Milne, which was presented at the August 1907 session of the British Seismological Association, only three epicenters within the Arctic were mentioned among 474 listed epicenters; remarkably, these three earthquakes were located in the vicinity of Jan Mayen Island. The two earthquakes in Iceland, which occurred on January 22, 1910 and on May 6, 1912, were considered by B.B. Golitsyn in 1911 and by I.I. Vilipp in 1913, respectively (Avetisov, 1996).

One of the first works generalizing seismicity in the Arctic was published by E. Tams (1922). Here, this author had provided the results of processing of the data on earthquakes for the period since 1916 until 1921 to supplement the same results for the period of 1904–1915 given in his previous publication (Tams, 1921); thus, he compiled the refined catalog that included 26 earthquakes. Locations were determined from first arrivals of *P*-waves at seismic stations, with the location error being indicated. The values of maximum amplitudes and the respective periods were also indicated. Owing to this, magnitude M_S was calculated later for some earthquakes (Morozov et al., 2019a, 2019b). The presence of the seismically active zone was noted in (Tams, 1922): this zone extends between Greenland and Scandinavia, crossing Iceland, Jan Mayen Island, and Svalbard.

The coordinates of five earthquakes in the Laptev Sea region, which occurred in the period since 1909 until 1925, were provided in (Tams, 1927). These epicenters were indicated on the map of Siberia by V.A. Obruchev; however, their tectonic origin was not considered.

E.A. Hodgson (1929) generalized the data of seismological observations at the Ottawa station for the period of 1911–1927 and at the Oxford station for the period of 1913–1925, employing the data from *Shide Circulars* (bulletins) by John Milne (*Shide*..., 1900–1912) for the period since 1899 until 1906, in order to analyze distribution of earthquakes in the Arctic. Hodgson noted the following seismically active areas:

Iceland, Jan Mayen Island, Lena River mouth (here, two earthquakes that occurred on May 30, 1923, with a time difference of 9 h), and McKenzie River mouth.

The analysis of the first recorded Arctic earthquakes allowed N.V. Raiko and N.A. Linden (1935) to show the presence of the seismic belt in the Arctic, stretched from Iceland, through Jan Mayen Island area, and reaching the northern coasts of the Asian continent. In addition, N. Heck (1938) compiled the first map of the Arctic seismically active belt. Later researchers refined and supplemented the data on earthquakes within this seismically active belt (Gutenberg and Richter, 1941; Linden, 1959); as a result, in the 1960s B.C. Heezen and M. Ewing (1961), as well as L.R. Sykes (1965), confined the earthquake belt in the Arctic to the mid-ocean ridge located within the Eurasian subbasin. The information about the types of instrumentation used at the stations in the early 20th century, together with the standard values of permanent seismographs, are given in (*Bulletin*..., 1931; Kirnos et al., 1961).

The first aggregated bulletins and catalogs of earthquakes recorded by the worldwide seismic network had begun to be issued from around the turn of the centuries, namely:

(1) Shide Circulars (1899–1912);

(2) Bulletins of the International Seismological Association (ISA, today known as IASPEI, 1895–1897, 1903–1908);

(3) Bulletins of the Permanent Central Seismic Commission, Russian Imperial Academy of Sciences (1902–1907, 1911–1912);

(4) British Association for the Advancement of Science (BAAS, 1913–1918);

(5) International Seismological Summary (1918–1963);

(6) Aggregated quarterly bulletin of the teleseismic network (1928–1939);

(7) Bulletins of the Bureau Central International de Seismologie (BCIS, 1930–1971).

All these bulletins are one of the most important information sources for studying and generalizing the data on seismicity in different regions of the world, including the Arctic. The data on Arctic earthquakes, with their source parameters indicated, can also be found in (Tams, 1922; Gutenberg and Richter, 1941; Linden, 1959; *Novyi*..., 1977).

Relocation has already been performed for the certain number of earthquakes in the framework of compiling the unified ISC-GEM catalog for the period since 1904 until 2014 (Storchak et al., 2013, 2014). Nevertheless, certain earthquakes that occurred in the Arctic in the early 20th century have not been included to the ISC-GEM catalog and other catalogs used in present: as will be shown below, they appeared to be "forgotten," i.e., not mentioned in the modern earthquake catalogs.

RELOCATION OF ARCTIC EARTHQUAKES OF THE EARLY 20TH CENTURY

We performed relocation of the epicenters of earthquakes that occurred in the Arctic (to the north of 70° N) in the early 20th century (Morozov et al., 2019b). Based on the analysis of the sources mentioned in the previous section, we compiled the preliminary aggregated earthquake catalog for the period of 1904–1920. This catalog included 25 earthquakes, most of which were already represented in various sources, but with different source parameters. Some earthquakes were represented in the only data source and did not appear in later catalogs (Table 2). These are the earthquakes that can be called forgotten.

We searched for the arrival times for each earthquake in the seismic bulletins for the stations that operated in that period. For this purpose, we found the bulletins of the respective seismic stations based on the sources from Table 1. Figure 2 shows the seismic stations in operation as of 1920. The bulletins of these stations were analyzed to find arrivals from the earthquakes in the Arctic. Based on amplitudes and periods of surface wave (data from bulletins), we calculated the values of magnitude M_S.

As was mentioned, 25 strong earthquakes were recorded during the first two decades of the 20th century in the Arctic, and these seismic events are of great importance not only for understanding the general regularities of regional seismicity, but also for the purposes of seismic hazard assessment (Fig. 3). In the period since 1904 until 1911, global seismic stations recorded the earthquakes with magnitudes 6.0 and higher; after 1912, they recorded the earthquakes with magnitudes 5.0 and higher (Table 3).

After the relocation procedure, error ellipses of most earthquakes have large areas because of a narrow azimuthal range and remoteness of seismic stations, which is quite typical of the Arctic in that time. Nevertheless, the most part of error ellipse does not exclude the possibility to unambiguously refer these epicenters to certain seismically active zones. Most earthquakes coincided to the main seismically active zones of the Arctic, namely, mid-ocean ridges, Svalbard, and the Laptev Sea shelf (Fig. 3).

The first arrivals were not revealed among the available seismic bulletins for 7 out of 25 earthquakes (in Table 3 they are commented as "No relocation was performed..."); hence, the problem whether these earthquakes that occurred in the Arctic or not remains

Table 2. Aggregated catalog of recorded earthquakes in Arctic for period since 1904 until 1920

No.	Date (dd.mm.yyyy)	Time	Hypocenter			Magnitude	Data source
			φ, ° N	λ,°	h, km		
1	09.10.1904	13:52:00.0	73.5	–5.6			(Tams, 1922)
2	19.03.1906	07:57:00.0	73.8	9.1			(Tams, 1922)
		07:56:59.9	71.71	–6.14	15	M_W (ISC-GEM) = 6.26	ISC-GEM
3	08.07.1908	12:50:00.0	82.9	–5.4			(Tams, 1922)
4	14.10.1908	14:56:00.0	81.5	28.7		M_S (PAS) = 6.6	(Tams, 1922)
		14:56:18.0	82.0	30.0	35	M = 6.25	(Gutenberg and Richter, 1941)
		14:56:22.0	81.5	16.0		M_W (ISC-GEM) = 6.61	(Linden, 1959)
		14:56:14.4	82.64	23.62	10		ISC-GEM
5	10.04.1909	18:46:54.0	77.5	128.0	35	M (GUTE) = 6.6	(Gutenberg and Richter, 1941)
		18:46:58.0	78.0	128.0		M_S (PAS) = 6.6	(Linden, 1959)
		18:46:54.3	78.54	129.16	10	M = 6.5 M_W (ISC-GEM) = 6.71	ISC-GEM
6	04.12.1911	14:39:00.0	79.0	26.2			(Tams, 1922)
7	25.01.1912	01:37:00.0	79.9	2.6			(Tams, 1922)
8	19.02.1912	10:32:56.0	71.0	–158.6		M = 5.0	(Linden, 1959)
9	13.04.1912	02:40:00.0	86.4	94.6		M_S (PAS) = 5.6	(Tams, 1922)
		02:39:42.0	80.0	100.0	35	M = 5.0	(Gutenberg and Richter, 1941)
		02:39:36.0	78.9	107.9			(Linden, 1959)
10	07.06.1914	16:24:00.0	73.0	119.0		M = 5.25	(Linden, 1959)
11	04.11.1914	12:54:00.0	73.5	–3.0		M = 5.5	(Tams, 1922)
		12:52:55.0	74.0	–2.0			(Linden, 1959)
12	05.11.1914	08:00:40.0	75.5	5.0		M = 5.5	(Linden, 1959)
13	01.06.1915	14:43:54.0	78.5	8.0	35	M (GUTE) = 6.6	(Gutenberg and Richter, 1941)
		14:43:45.0	77.0	7.0		M_S (PAS) = 6.8	ISS
		14:43:00.0	82.0	8.0		M = 5.75	(Tams, 1922)
		14:43:57.0	78.5	10.0		M_W (ISC-GEM) = 6.54	(Linden, 1959)
		14:44:03.3	77.30	9.09	10		ISC-GEM
14	02.06.1915	23:24:04.0	77.5	2.0		M = 4.5	(Linden, 1959)
15	16.09.1915	10:21:44.0	80.0	–8.0		M = 4.5	(Linden, 1959)
16	30.09.1915	14:31:20.0	77.0	12.0		M = 4.5	(Linden, 1959)
17	11.05.1916	03:05:00.0	79.0	–2.0		M = 4.25	Bulletin of PUL station
		03:05:52.0	79.4	–1.0			(Linden, 1959)
18	06.12.1916	22:17:00.0	81.0	61.4		M_S (PAS) = 5.8	(Tams, 1922)
		22:17:12.0	87.0	48.0	35	M = 5.25	(Gutenberg and Richter, 1941)
		22:17:05.0	88.0	40.0		M_W (ISC-GEM) = 5.75	(Linden, 1959)
		22:17:14.0	87.20	44.86	10		ISC-GEM
19	14.05.1917	06:57:00.0	72.0	–2.8			ISS
		06:57:00.0	74.8	–6.7			(Tams, 1922)

Table 2. (Contd.)

No.	Date (dd.mm.yyyy)	Time	Hypocenter			Magnitude	Data source
			φ, ° N	λ,°	*h*, km		
20	21.08.1917	10:44:10.0	72.0	–2.8		$M = 5.0$ M_W(ISC-GEM) = 5.67	ISS
		10:43:00.0	76.1	–7.8			(Tams, 1922)
		10:44:13.0	71.4	–7.8			(Linden, 1959)
		10:44:21.4	71.43	–3.50	10		ISC-GEM
21	27.01.1918	02:51:00.0	64.8	35.3		$M = 4.25$	ISS
		02:51:00.0	73.2	12.2			(Tams, 1922)
		02:51:07.0	72.7	7.8			(Linden, 1959)
22	20.10.1918	05:44:55.0	72.0	–2.8			ISS
23	30.11.1918	06:48:40.0	71.0	132.0		M_S (PAS) = 6.2 $M = 6.0$ M_S (ISC) = 6.4 M_W (ISC-GEM) = 6.52	(Gutenberg and Richter, 1941)
		06:48:38.0	71.2	134.0			(Linden, 1959)
		06:48:47.0	70.56	130.44	15		ISC-GEM
24	02.02.1919	20:02:50.0	72.0	–2.8		$M = 5.5$ M_W (ISC-GEM) = 6.07	ISS
		20:02:00.0	72.0	–18.5			(Tams, 1922)
		20:02:57.0	72.0	–8.0			(Linden, 1959)
		20:03:05.2	71.58	–5.05	10		ISC-GEM
25	12.09.1919	14:26:37.0	72.0	–2.8			ISS

ISC-GEM means unified ISC-GEM catalog; PAS, California Institute of Technology; GUTE, (Gutenberg and Richter, 1941); ISS, International Seismological Summary.

unresolved. These seismic events require a more thorough study employing the analysis of the respective seismograms recorded by seismic stations, rather than station bulletins.

Among the rest 18 earthquakes, for which relocation was performed, the earthquake of October 14, 1908 should be distinguished: this earthquake with M_W(ISC) = 6.6 occurred on the Barents Sea shelf, to the northwest of Franz Josef Land, in the "continent–ocean" transition zone (Fig. 4). Since the error ellipse partially covers the area of the Franz–Victoria trench (graben), we can suppose that this earthquake occurred exactly here because of the following. First, the error ellipse does not cover other seismically active zones within the Barents–Kara region (mid-ocean ridges and Svalbard); second, strong earthquakes have been recorded within the limits of this graben during the instrumental period (Avetisov, 1996; Morozov et al., 2019a); and third, the modern studies of weak seismicity of the "continent–ocean" transition zone support the seismic activity of the Franz–Victoria graben (Morozov et al., 2015).

Notably, the opposite situation is seen in case of the M_S = 5.1 earthquake of April 13, 1912. According to (Tams, 1922; Gutenberg and Richter, 1941; Linden, 1959), its epicenter was located in the area of Severnaya Zemlya archipelago. However, after relocation it appeared to be further north, in the area of the mid-ocean Gakkel Ridge (Fig. 5). It is very likely that this earthquake occurred exactly within the Gakkel Ridge and not in the vicinity of Severnaya Zemlya, because no strong earthquakes have been recorded in this area throughout the entire instrumental period.

Thus, generalization of the data on earthquakes that occurred in the early 20th century in the Arctic, together with their relocation, has allowed us to reveal so called forgotten strong earthquakes that have not been mentioned in the modern catalogs, and, as a result, to compile the aggregated and refined earthquake catalog. Some earthquakes after relocation appeared to be hosted within seismically active regions of the Arctic different from those initially determined—and this may affect the ultimate seismic hazard assessment for some areas within the Arctic, in particular, Severnaya Zemlya and Franz Josef Land. All this indicates that the studies on relocation and refinement of source parameters of the earthquakes that occurred in the early instrumental period are still topical.

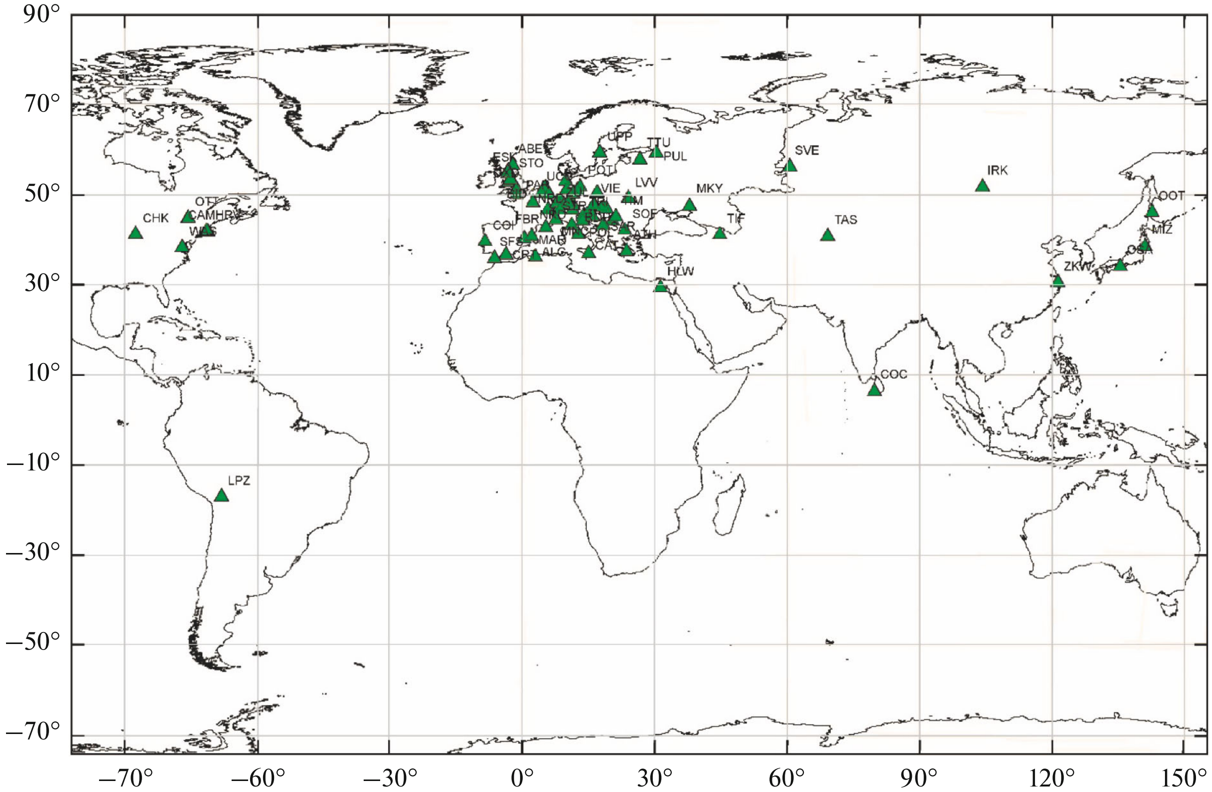

Fig. 2. Map of seismic stations, data from which were used to relocate earthquake epicenters.

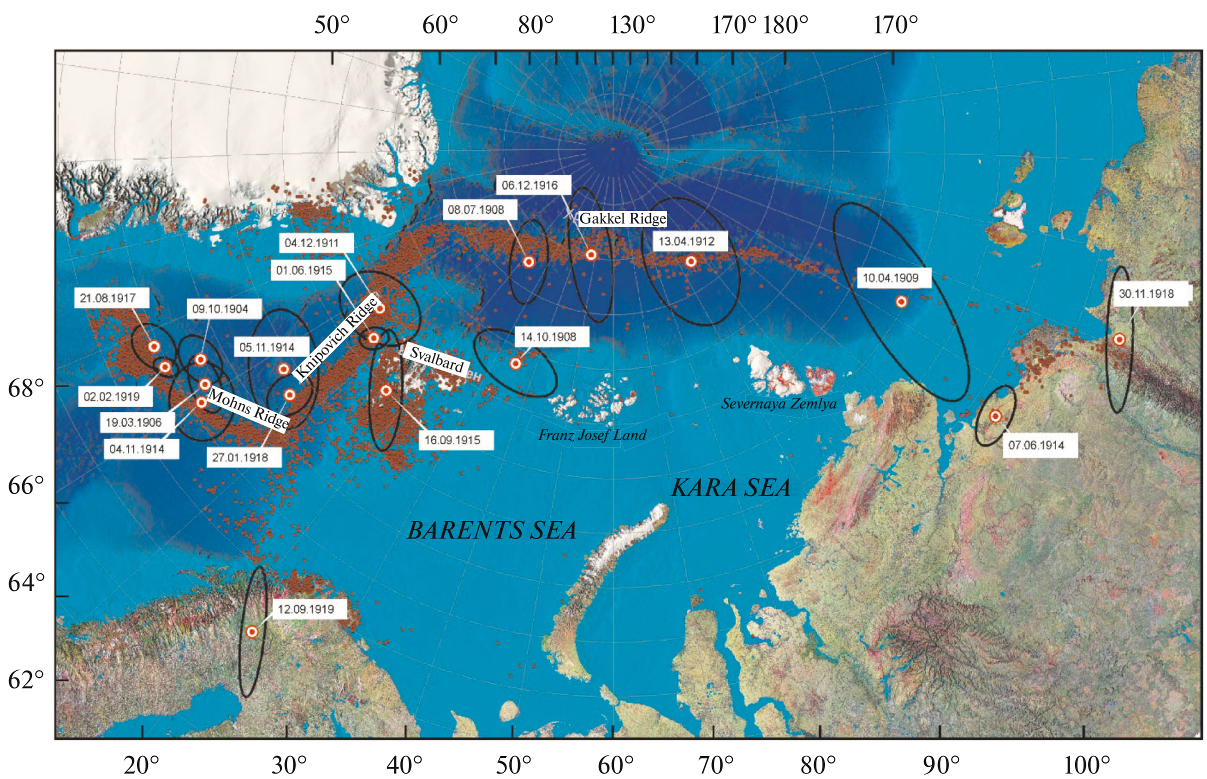

Fig. 3. Map showing relocated epicenters of Arctic earthquakes that occurred period since 1904 until 1920. Red circles with dots denote epicenters of earthquakes that occurred in Arctic (to north of 70° N) in 2000–2016, according to ISC data (International..., 2020).

Table 3. Catalog of relocated earthquakes in Arctic for period since 1904 until 1920

No.	Date (dd.mm.yyyy)	Time	Hypocenter			N_{st}/N_{phase}	Shadow zone, deg	Range of epicentral distances, km	Error ellipse			Magnitude	Comments
			φ, ° N	λ,°	*h*, km				AZ_{major}	R_{minor}	R_{major}		
1	09.10.1904	13:52:00.5	73.12	−4.24	17f	8/13	239	1743–5011	80	73.3	107.9	M_S = 7.3–7.6	Lack of data to reliably determine M_S
2	19.03.1906	07:56:47.5	73.85	−1.33	9f	14/23	244	1982–4928	100	59.2	120.5	M_W(ISC) = 6.26	
3	08.07.1908	12:50:02.8	84.87	22.61	10f	12/18	244	2950–5231	150	75.9	169.9	M_S = 6.3	Lack of data to reliably determine M_S
4	14.10.1908	14:56:24.1	81.44	34.93	12f	17/26	329	2419–4271	100	100.7	193.0	M_W(ISC) = 6.61	
5	10.04.1909	18:47:02.2	78.12	123.01	13f	11/18	343	3600–5396	30	156.0	456.6	M_W(ISC) = 6.71	
6	04.12.1911	14:38:47.9	79.70	3.48	8f	8/15	325	2336–3592	70	133.1	177.8	M_S = 5.8–6.0	Lack of data to reliably determine M_S
7	25.01.1912	–	–	–	–	2/3	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
8	19.02.1912	–	–	–	–	3/6	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
9	13.04.1912	02:39:45.9	85.05	94.93	5f	6/8	325	3127–4460	10	181.0	270.3	M_S = 5.1	
10	07.06.1914	16:24:02.5	73.03	116.29	10f	8/13	253	2359–5155	80	63.4	129.7	M_S = 6.3	
11	04.11.1914	12:54:14.7	72.42	0.22	5f	7/11	307	2269–4063	120	130.9	157.6	M_S = 5.0	
12	05.11.1914	08:00:38.3	75.54	2.63	5f	4/5	233	2453–4831	120	141.2	241.3	*M* = 5.25	
13	01.06.1915	14:43:51.2	78.88	7.45	12f	16/28	155	2228–5026	30	44.3	59.3	M_W(ISC) = 6.54	
14	02.06.1915	–	–	–	–	2/4	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
15	16.09.1915	10:22:07.0	77.91	15.78	4f	3/4	238	2453–4831	140	67.1	244.8	*M* = 4.5	Lack of data for finding a reliable solution
16	30.09.1915	–	–	–	–	1/1	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
17	11.05.1916	–	–	–	–	2/4	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
18	06.12.1916	22:17:17.2	86.09	47.69	7f	6/8	229	2787–6062	160	83.5	273.7	M_W(ISC) = 5.75	
19	14.05.1917	–	–	–	–	1/2	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
20	21.08.1917	10:44:09.1	71.83	−8.07	7f	7/11	271	1722–3400	70	75.2	102.4	M_W(ISC) = 5.67	
21	27.01.1918	02:50:40.4	75.18	6.10	6f	8/10	302	1777–3283	0	74.5	102.1	M_S = 5.4	
22	20.10.1918	–	–	–	–	3/4	–	–	–	–	–	–	No relocation is performed due to insufficiency of data
23	30.11.1918	06:48:44.5	70.38	130.80	11f	9/12	197	3492–6309	70	52.7	288.7	M_W(ISC) = 6.52	
24	02.02.1919	20:03:00.4	71.88	−5.42	8f	23/36	166	1666–5214	50	35.7	52.3	M_W(ISC) = 6.07	
25	12.09.1919	14:26:32.9	68.02	22.06	5f	4/5	242	1865–7532	150	47.8	263.7	–	Beyond study area

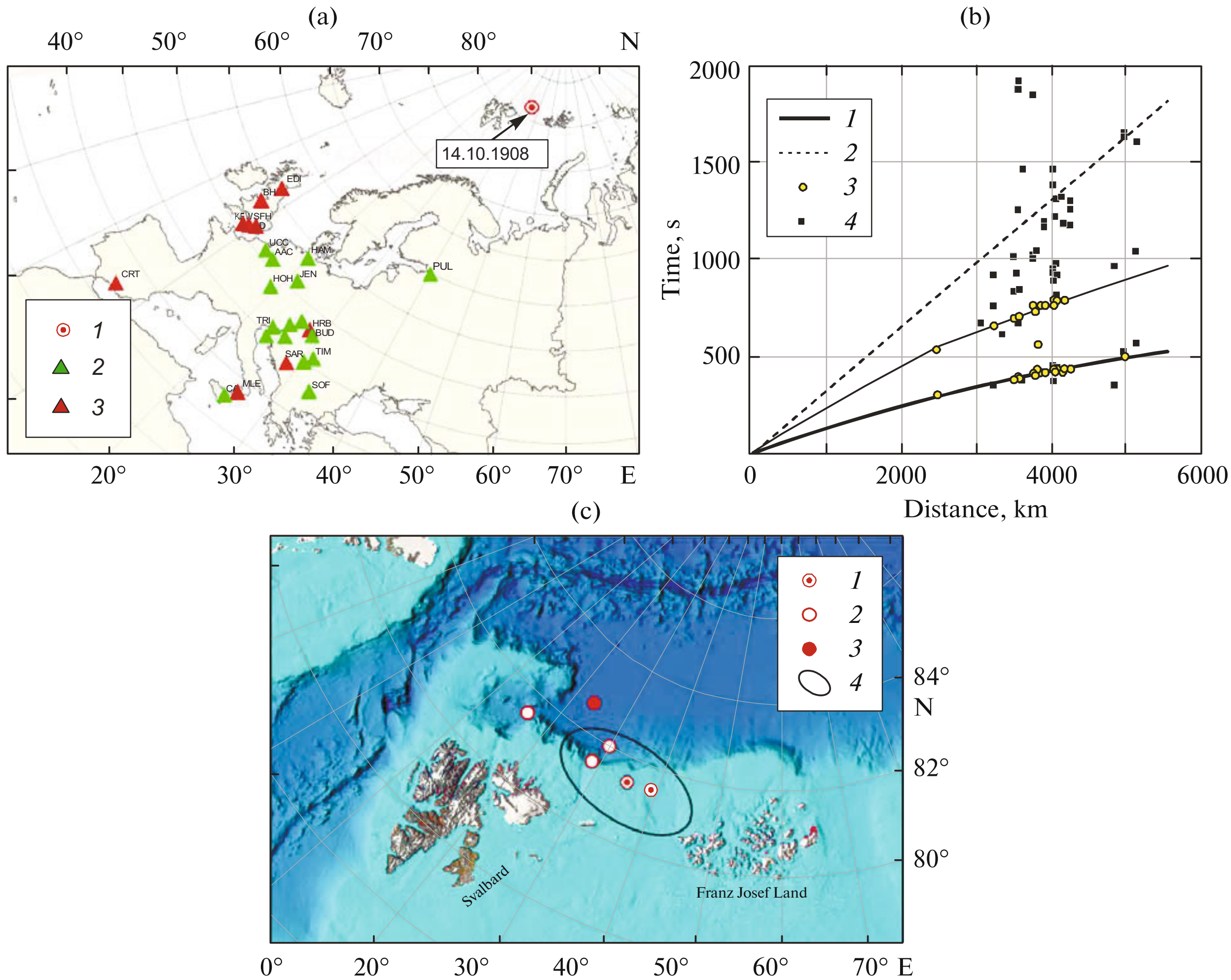

Fig. 4. Earthquake of October 14, 1908. (a) Epicenter and seismic stations recorded this earthquake: (*1*) relocated epicenter; (*2*) stations, arrival times from which were used to relocate epicenter; (*3*) stations, arrival times from which were not considered. (b) All arrival times available in bulletins for this earthquake: (*1*, *2*) theoretical travel times by *ak*135 velocity model: (*1*) *P*- and *S*-waves, (*2*) surface wave; (*3*) arrival times used to relocate epicenter; (*4*) arrival times which were not considered. (c) Map showing (*1*) relocated earthquake epicenter, (*2*) epicenters after (Tams, 1922; Gutenberg and Richter, 1941; Linden, 1959), (*3*) epicenter from ISC-GEM catalog, and (*4*) error ellipse.

CONCLUSIONS

In the present work we have followed the approach that was successfully applied before to relocate earthquake epicenters and refine the source parameters of the earthquakes that occurred in the Arctic in the early instrumental period, providing another case of its successful application. The approach is based on the use of all currently available archives of bulletins and seismograms from the seismic stations operated in the early 20th century and also on the employment of the modern *ak*135 velocity model and the enhanced location algorithm implemented in the NAS program. The necessity of conducting these studies is caused by the fact that the parameters of Arctic earthquakes that occurred in the 20th century were most often determined from the data of bulletins acquired from only a part of really operating stations, not to mention the use of outdated velocity models and location algorithms.

The provided examples of relocating the epicenters of earthquakes that occurred in the early 20th century show that the epicenters of some earthquakes were erroneously referred to the areas that are presently not considered as seismically active. Such errors may affect the ultimate seismic hazard assessment for some areas within the Arctic.

ACKNOWLEDGMENTS

We are grateful to Dr. A.A. Nikonov (Schmidt Institute of Physics of the Earth, Russian Academy of Sciences)

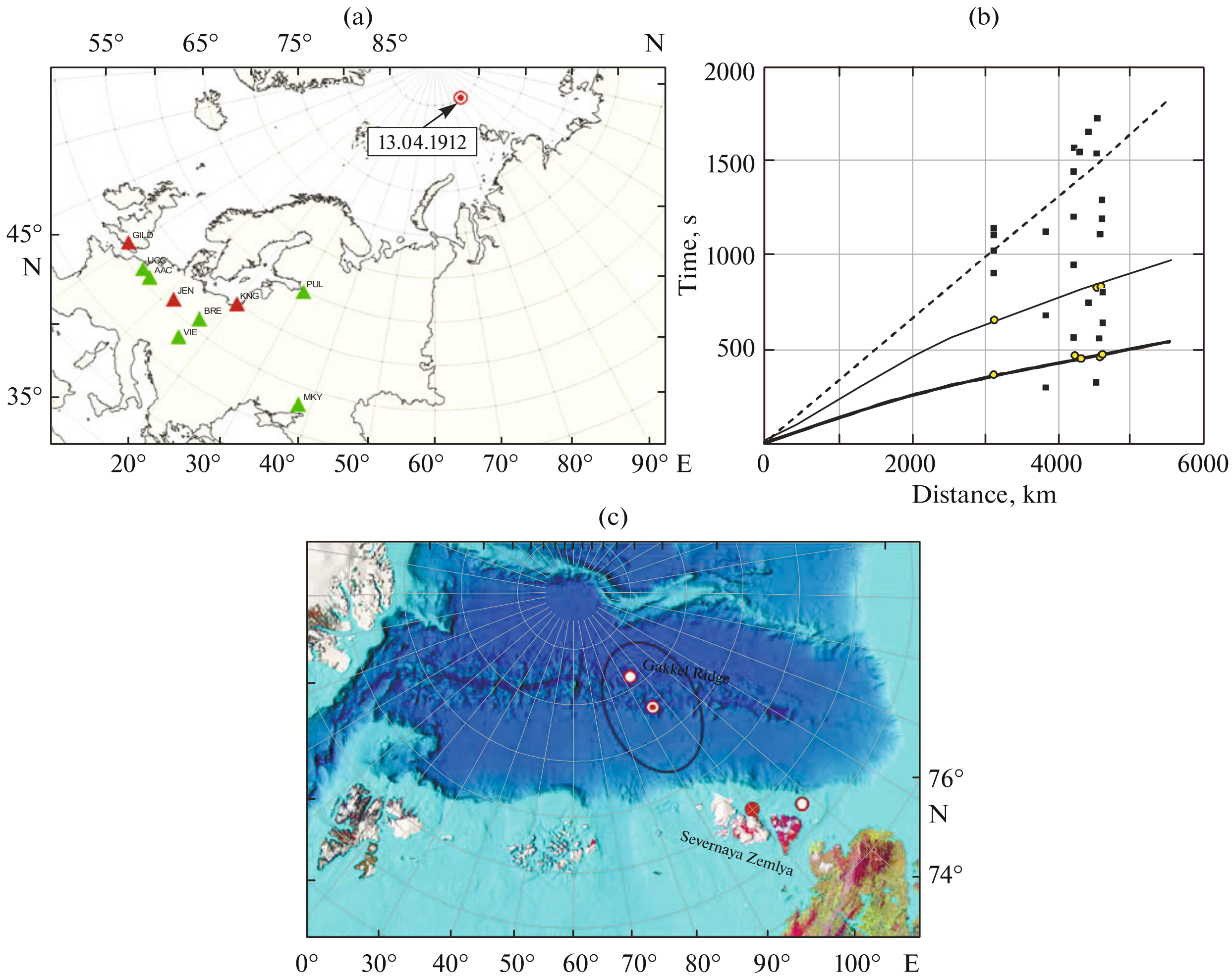

Fig. 5. Earthquake of April 13, 1912: (a) epicenter and seismic stations recorded this earthquake; (b) all arrival times available from bulletins; (c) position of relocated earthquake epicenter. Arbitrary notes are same as Fig. 4.

whose advice, recommendations, and questions motivated us to conduct the present study.

FUNDING

The research was supported by the research projects for the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences (no. AAAA-A19-119072590031-6), and Laverov Federal Center for Integrated Arctic Research, Ural Branch of the Russian Academy of Sciences (no. FUUW-2022-0036).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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Translated by N. Astafiev