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Seismicity of the Arctic in the Early Twentieth Century: Relocation of the 1904–1920 Earthquakes

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Abstract The parameters of earthquake hypocenters in the Arctic at the beginning of the twentieth century, published by researchers in the first half of the twentieth century, are still used today for building maps of epicenters of instrumental earthquakes. However, they are based on bulletins that did not use data from all seismic stations operating during that period, and on approximate ideas about the propagation of seismic waves in the Earth. We relocated earthquakes recorded within the Arctic region beginning from the early twentieth century with a view to creating a relocated catalog. For the relocation, we collected all available seismic bulletins from the global network using data acquired for the International Seismological Centre–Global Earthquake Model (ISC-GEM) catalog, the EuroSeismos project, the Geophysical Survey of the Russian Academy of Sciences, and the Russian State Library. The relocation was performed using a modified method of generalized beamforming and the ak135 velocity model. The relocation procedure was applied to 18 of 25 earthquakes in the Arctic region. The new coordinates of some earthquakes turned out to be significantly different from those that were determined previously. As a result, this may have a significant impact on the final seismic hazard assessment of the territory of the Severnaya Zemlya and Franz Josef Land archipelagoes, which are characterized by weak seismicity. Most of the relocated earthquake epicenters are confined to major seismic zones in the Arctic, namely, mid-ocean ridges, the Svalbard Archipelago, and the Laptev Sea shelf. One earthquake, that of 14 October 1914 with magnitude M_w(ISC-GEM) $= 6.6$, occurred in the shelf of the Barents Sea in the "continent–ocean" transition zone near the Franz Victoria graben.

Supplemental Content: Tables containing the raw data for the study and figures showing the research results for each earthquake.

Introduction

Seismic hazard research for any area is often based on an earthquake catalog from which seismicity parameters can be calculated. The most significant events are the largest earthquakes; it is these that define the seismic potential of a seismic source zone. Large earthquakes have long recurrence times; hence, the estimation of seismic hazard for an area is based on a composite earthquake catalog that contains both historical and instrumental earthquakes, as well as including data on paleoearthquakes. The information on historical earthquakes for the Arctic region is extremely scanty, whereas the data on paleoearthquakes are practically inaccessible. It follows that the earthquakes that have been recorded during the period of instrumental observation are the most significant.

The development of instrumental observation in Europe in the late nineteenth to early twentieth century, especially because the installation of the Bergen (1904), Abisco (1906), Pulkovo (1906), and Reykjavik (1909) seismic stations enabled the recording of seismic motion from larger earthquakes occurring in the Arctic. The early history of seismometry is described in detail by Lee *et al.* (1988), Ferrari (1990), Avetisov (1996), Schweitzer (2007), and Storchak *et al.* (2015). The lowest magnitude of complete reporting during the earlier stage of instrumental observations for the Arctic, until 1957, was 5.5–6.0 (Avetisov, 1996). First reviews of Arctic seismicity can be found in Tams (1922), Hodgson (1930), Gutenberg and Richter (1941), Emery (1949), and Linden (1959). However, the hypocenter parameters as

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reported by earthquake catalogs published in the early half of the twentieth century, which are still used today, are based on data from bulletins of some of the seismic stations operated at the time and on approximate notions of patterns that govern the propagation of seismic waves in the Earth's interior.

At present, modern projects such as the International Seismological Centre–Global Earthquake Model (ISC-GEM) catalog and the EuroSeismos (ES) project enabled researchers to study bulletins and seismograms from stations that have been operated since the beginning of the instrumental period. This makes it possible to estimate earthquake hypocenter parameters from instrumental data, whereas felt data were not available until recently. Examples are Bungum *et al.* (2009), who refined the hypocenter parameters for the Fennoscandian Oslo Fjord earthquake of 23 October 1904 ($M_s = 5.4$), Nikonov and Chepkunas (2009) who sought to more accurately determine the parameters of the Sysola earthquake of 13 January 1939 in the northern European part of Russia, and Niemz and Amorèse (2016) who did a similar study for the 10 November 1935 earthquake near Montserrat.

A large amount of work was done by collaborators at the ISC (Storchak *et al.*, 2013) to develop the standardized ISC-GEM Global Instrumental Earthquake Catalog (1904–2014). The ISC-GEM catalog is the result of a special effort to adapt and substantially extend and improve currently existing bulletin data for large earthquakes (magnitude 5.5 and above) to serve the requirements of specific user groups who assess and model seismic hazard and risk (Storchak *et al.*, 2013). For earthquakes recorded during 1904–1920, they digitized body-wave arrival times, as well as amplitudes and periods for various phases using a multitude of sources with a view to relocation and magnitude revision using the approaches described in Di Giacomo *et al.* (2015).

However, not all earthquakes that occurred in the Arctic during the early twentieth century are found in the ISC-GEM catalog, with some even absent from the Bulletin of the ISC (2015) and the International Seismological Summary (ISS) Bulletin. This study is a review of all data on earthquakes recorded in the Arctic for the period 1904–1920 using a number of sources. We restricted our study to the earthquakes that occurred before 1920 because errors in determining the hypocenter parameters are more likely due to the small number of actual seismic stations and absence of accurate seismic velocity models at that time. We refined their hypocenter parameters based on the same velocity model, the same location algorithm, and all available station bulletins.

Description of the Dataset and Methods

We used data from Tams (1922), Gutenberg and Richter (1941), Linden (1959), the ISS Bulletin between 1917 and 1920, and the ISC-GEM catalog, to make a preliminary earthquake catalog for the period between 1904 and 1920 for events whose epicenters lie above 70° N (Table 1). The preliminary catalog contains a total of 25 earthquakes, with most of these borrowed from different sources and having different hypocenter parameters (see Ⓔ Fig. S1, available in the supplemental content to this article). Eight earthquakes are present in the ISC-GEM catalog. Nearly all epicenters are in the Eurasian Arctic region. Most epicenters lie at mid-ocean ridges.

For each earthquake, we looked for the times of arrival in the bulletins of the seismic stations that were operated during that time period. Seismic station bulletins were collated using data from the ISC-GEM catalog, the ES project, and the Geophysical Survey of the Russian Academy of Sciences, and the Russian State Library (Fig. 1).

All detected instrumental onset times were compared with the ak135 velocity model (Kennett *et al.*, 1995) to remove those onset times that were inappropriate for *P* and *S* waves and to identify the phase that was defined as the Rayleigh-wave maximum (LRM). This had to be done because of the following three reasons. First, some bulletins report only the arrival times of unidentified seismic phases and the times of the onset of maximum waves. Second, as already mentioned in the work of Abe (1988), and in particular, the work of Bungum *et al.* (2009, p. 2842): "Because of the low sensitivity and limited resolution of the seismographs at these early years of instrumental earthquake observations, many of the reported onsets are related to surface-wave observations and cannot be used for an instrumental location." Third, the timekeeping accuracy was low at that time. In the absence of a centralized worldwide timekeeping service at the beginning of the 1900s, early seismometers were often housed at or in the vicinity of astronomical observatories where the time was regularly determined using meridian transit observations (Storchak *et al.*, 2015).

The amplitudes and respective periods of Rayleigh waves for some earthquakes were used to find M_s magnitudes. The Rayleigh-wave periods were between 10 and 60 s and the epicentral distances were 20°–160°. We used the Prague formula (Vanek *et al.*, 1962):

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

Event Location Algorithm

The new association system (NAS) program (Asming and Prokudina, 2016) performed phase association using a modified form of the known generalized beamforming method (Kvaerna and Ringdal, 1996). NAS makes a grid search in a limited region of time and space around a point of a preliminary event location (prototype event). It takes a circle of a relatively large radius (a value of 1000 km was used in this study) around the preliminary location of the event's epicenter. This circle was considered as the search area for a more precise location. It was covered by a set of overlapping circles of smaller radii, thus forming a grid of round cells. A rating function was computed for each cell of the grid, estimating the

Table 1
Seismic Catalog of Earthquakes in an Area of the Arctic Region from the Early Twentieth Century to 1920

			Hypocenter				
Number	Date (yyyy/mm/dd)	Origin Time (hh:mm:ss.s)	φ (°)	λ (°)	h (km)	Magnitude	Source of the Hypocenter
1	1904/10/09	13:52:00.0	73.5	−5.6			Tams (1922)
2	1906/03/19	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 catalog
3	1908/07/08	12:50:00.0	82.9	−5.4			Tams (1922)
4	1908/10/14	14:56:00.0	81.5	28.7		M_s(PAS) = 6.6, **M** = 6.25, M_w(ISC-GEM) = 6.61	Tams (1922)
		14:56:18.0	82.0	30.0	35		Gutenberg and Richter (1941)
		14:56:22.0	81.5	16.0			Linden (1959)
		14:56:14.4	82.64	23.62	10		ISC-GEM catalog
5	1909/04/10	18:46:54.0	77.5	128.0	35	**M**(GUTE) = 6.6, M_s(PAS) = 6.6, **M** = 6.5, M_w(ISC-GEM) = 6.71	Gutenberg and Richter (1941)
		18:46:58.0	78.0	128.0			Linden (1959)
		18:46:54.3	78.54	129.16	10		ISC-GEM catalog
6	1911/12/04	14:39:00.0	79.0	26.2			Tams (1922)
7	1912/01/25	01:37:00.0	79.9	2.6			Tams (1922)
8	1912/02/19	10:32:56.0	71.0	−158.6		**M** = 5.0	Linden (1959)
9	1912/04/13	02:40:00.0	86.4	94.6		M_s(PAS) = 5.6, **M** = 5.0	Tams (1922)
		02:39:42.0	80.0	100.0	35		Gutenberg and Richter (1941)
		02:39:36.0	78.9	107.9			Linden (1959)
10	1914/06/07	16:24:00.0	73.0	119.0		**M** = 5.25	Linden (1959)
11	1914/11/04	12:54:00.0	73.5	−3.0		**M** = 5.5	Tams (1922)
		12:52:55.0	74.0	−2.0			Linden (1959)
12	1914/11/05	08:00:40.0	75.5	5.0		**M** = 5.5	Linden (1959)
13	1915/06/01	14:43:54.0	78.5	8.0	35	**M**(GUTE) = 6.6, M_s(PAS) = 6.8, **M** = 5.75, M_w(ISC-GEM) = 6.54	Gutenberg and Richter (1941)
		14:43:45.0	77.0	7.0			International Seismological Summary (ISS)
		14:43:00.0	82.0	8.0			Tams (1922)
		14:43:57.0	78.5	10.0			Linden (1959)
		14:44:03.3	77.30	9.09	10		ISC-GEM catalog
14	1915/06/02	23:24:04.0	77.5	2.0		**M** = 4.5	Linden (1959)
15	1915/09/16	10:21:44.0	80.0	−8.0		**M** = 4.5	Linden (1959)
16	1915/09/30	14:31:20.0	77.0	12.0		**M** = 4.5	Linden (1959)
17	1916/05/11	03:05:00.0	79.0	−2.0		**M** = 4.25	Bulletin of the seismic station "Pulkovo" (PUL)
		03:05:52.0	79.4	−1.0			Linden (1959)
18	1916/12/06	22:17:00.0	81.0	61.4		M_s(PAS) = 5.8, **M** = 5.25, M_w(ISC-GEM) = 5.75	Tams (1922)
		22:17:12.0	87.0	48.0	35		Gutenberg and Richter (1941)
		22:17:05.0	88.0	40.0			Linden (1959)
		22:17:14.0	87.20	44.86	10		ISC-GEM catalog
19	1917/05/14	06:57:00.0	72.0	−2.8			ISS
		06:57:00.0	74.8	−6.7			Tams (1922)
20	1917/08/21	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 catalog
21	1918/01/27	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	1918/10/20	05:44:55.0	72.0	−2.8			ISS
23	1918/11/30	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 catalog
24	1919/02/02	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 catalog
25	1919/09/12	14:26:37.0	72.0	−2.8			ISS

PAS is the code of the seismological agency on the basis of the California Institute of Technology. GUTE means the magnitude value of Gutenberg and Richter (1941). GEM, Global Earthquake Model; ISC, International Seismological Centre.

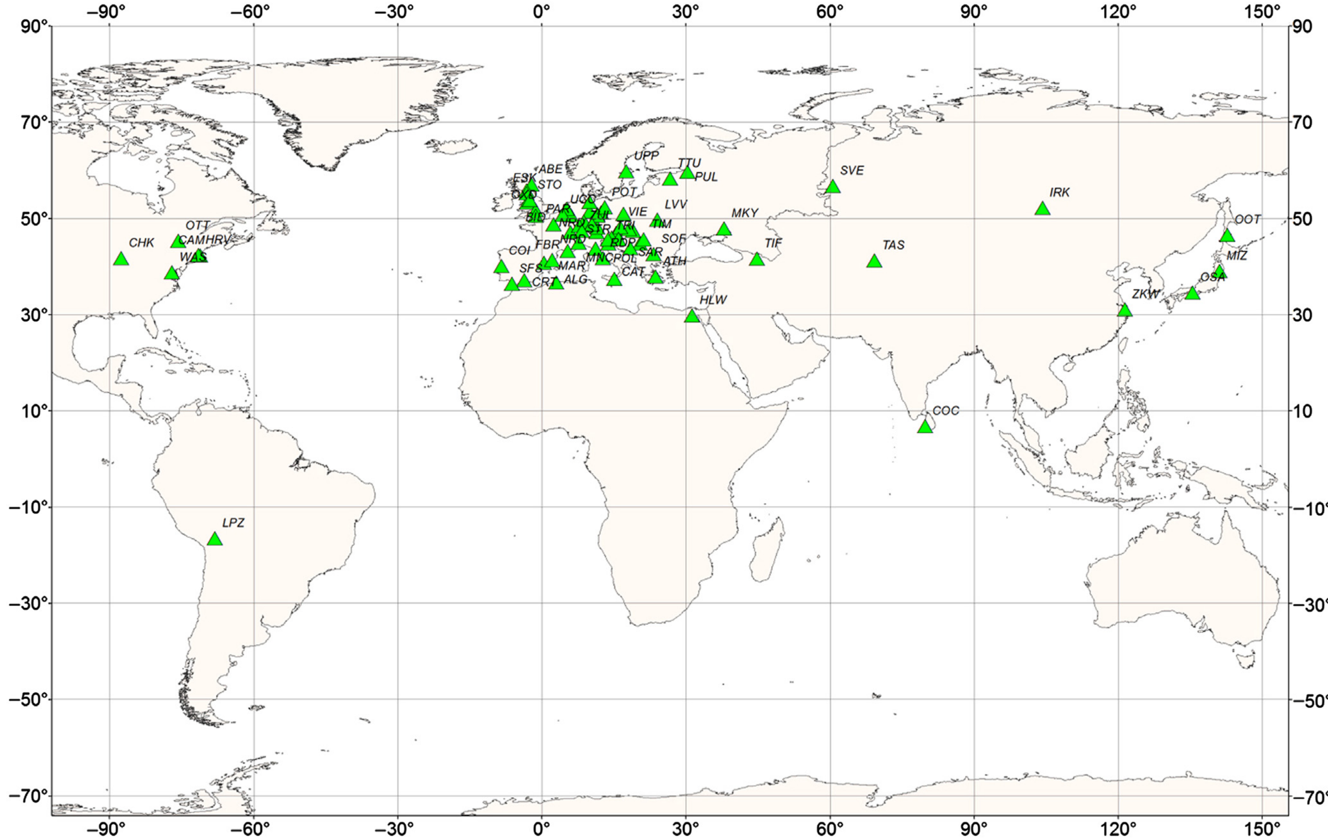

Figure 1. Map of the seismic stations used in the relocation procedure. The color version of this figure is available only in the electronic edition.

hypothesis that the event occurred in a particular cell. The grid was diminished several times. Each time 75% of the cells with the smallest ratings were excluded and each remaining cell was divided into four smaller ones, keeping the same total number of cells. The ratings were then recalculated.

The grid search was performed several times with different fixed depths. Finally, the cell with the maximal rating was selected. In the next step, the phases obtained for the cell were used to improve the location by minimizing the residual of origin time estimation. During this step, the confidence region was estimated depending on the expected errors (uncertainties) of the onset time measurements and the uncertainties of travel velocities.

The onset picking errors (Δt_{onset}) were taken to be $\Delta t_p = \Delta t_s = 3$ s. That is reasonable for old seismograms. The velocity uncertainties were taken to be $\Delta V_P = \Delta V_S = 0.15$ km/s. For the relocation, the ak135 velocity model was used (Kennett *et al.*, 1995). Verification of the modified method was performed using data on four nuclear explosions that occurred in the area of the Novaya Zemlya Archipelago and in the north of the European part of Russia (Morozov *et al.*, 2018).

It is impossible to compute the focal depths reliably because of the lack of P and S measurements at very close stations as well as the absence of teleseismic phases. For this reason, the epicenters were located using a fixed depth for each earthquake. Because the magnitudes were high, the respective rupture zones cannot have been shallower than some definite depths ($H_{\min}$). We found the lowest possible depth of focus for an earthquake from its magnitude using the relation from (Bune and Gorshkov, 1977):

$$M \leq 3.3 \log h + 3.1. \qquad (2)$$

All depths are depths beneath the seafloor.

Discussion of Results

The instrumental period for the Arctic region started with the recording of the 9 October 1904 earthquake. Many large earthquakes were recorded during the first two decades of the twentieth century (Fig. 2; Table 2). These are important both for understanding the general patterns of seismicity in the Arctic and for the assessment of earthquake hazard. The seismic stations of the worldwide network recorded earthquakes of magnitudes equal to or larger than 6.0 in the Arctic region during the period between 1904 and 1911. Since 1912, it became possible to record 5.0+ earthquakes.

Detailed analyses of the source and data for each earthquake listed in Table 1 are available in the Ⓔ supplemental

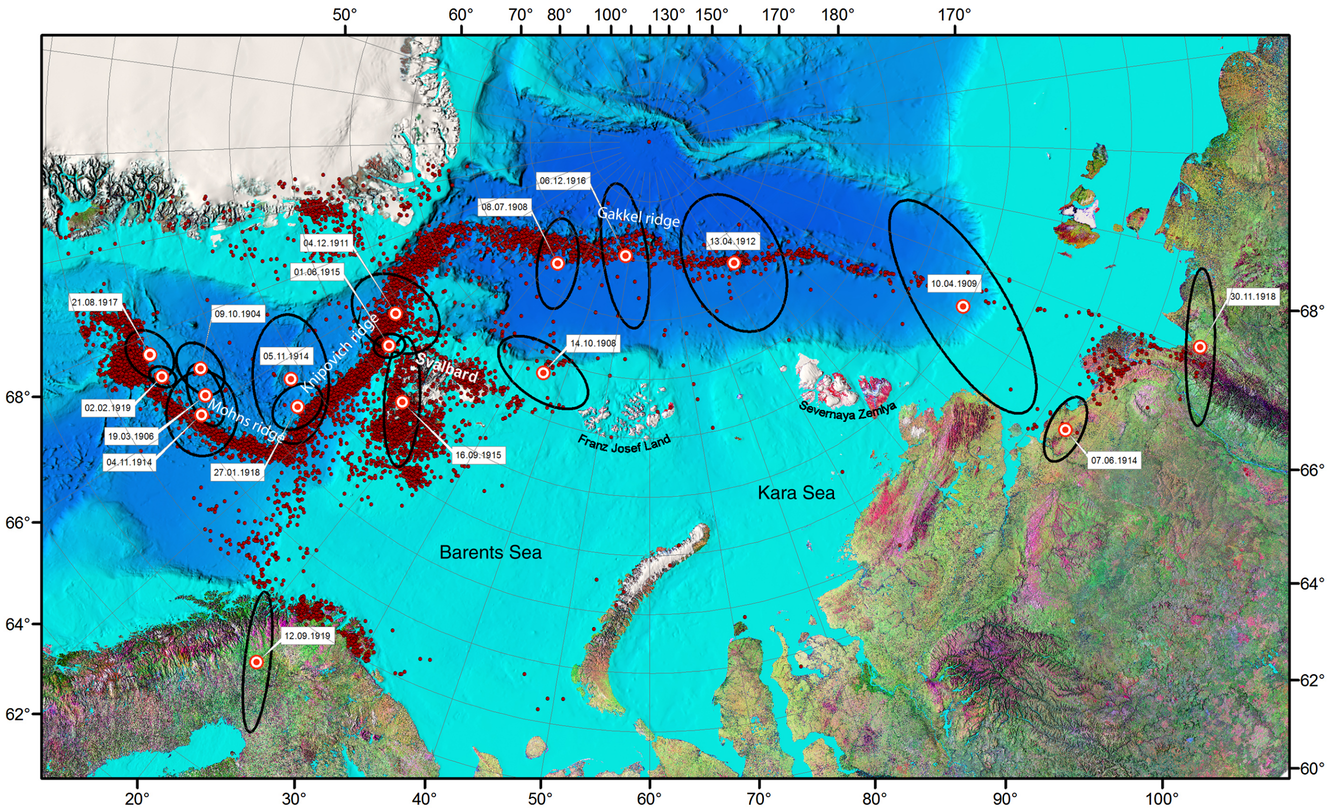

Figure 2. Map showing the relocated epicenters of earthquakes of the Arctic in the early twentieth century. Symbols: a circle with a dot represents the new coordinates and error ellipse; the circles indicate the epicenters of earthquakes recorded in the Arctic (north of 70° N) for the period from 2000 to 2016 according to the International Seismological Centre (ISC, 2015). The color version of this figure is available only in the electronic edition.

content to this article. Our relocation resulted in large error ellipses for most earthquakes owing to the narrow azimuthal coverage and the great epicentral distances for the seismic stations, which is characteristic of the Arctic region during that time period. Figure 3 shows the number of stations, azimuthal gap, and secondary azimuthal gap for two earthquakes of the same magnitude that occurred in the same area: 2 February 1919 and 21 May 2000. Figure 3a,b illustrates the best case in terms of the number of stations and azimuth coverage among all earthquakes examined from 1904 to 1920. For the remaining earthquakes, the number of seismic stations is significantly less, and the azimuth gap is greater. However, large error ellipses do not prevent us from ascribing the epicenters to definite seismic zones. Most of the earthquakes are confined to major Arctic seismic zones, which include mid-ocean ridges, the Svalbard Archipelago, and the Laptev Sea shelf (Fig. 2; Table 2).

However, there was a single "unusual" earthquake that occurred on 14 October 1908, whose magnitude was M_{w}(ISC-GEM) $= 6.6$ (Fig. 4). This earthquake occurred in the shelf of the Barents Sea in the continent–ocean transition zone northwest of Franz Joseph Land (Figs. 2 and 4). Because the error ellipse partly covers the area of the Franz Victoria graben we can assume that the event occurred in this area because, first, the ellipse does not include other significant seismic zones in the Barents-Kara area, that is, the Gakkel and Knipovich mid-ocean ridges and the Svalbard Archipelago. Second, large earthquakes were recorded during the instrumental period in the Franz Victoria graben region (Table 3). Modern studies of low-magnitude seismicity in the "continent–ocean" transition zone corroborate seismic activity in the Franz Victoria graben (Morozov *et al.*, 2015; Antonovskaya *et al.*, 2018). The prevailing geodynamic factor responsible for the occurrence of weak earthquakes is likely the isostatic compensation of avalanche sedimentation in the continent–ocean transition zone (Zaionchek *et al.*, 2010).

A reverse situation concerns the earthquake of 13 April 1912, with magnitude $M_{\mathrm{s}} = 5.1$ (Fig. 5). According to Tams (1922), Gutenberg and Richter (1941), and Linden (1959), the epicenter of the earthquake was in the Severnaya Zemlya Archipelago. However, as a result of the relocation, it was found that the epicenter was to the north in the area of the Gakkel ridge. It is possible that the earthquake took place exactly in the area of the Gakkel Ridge because during the entire instrumental period strong earthquakes from the region of the Severnaya Zemlya Archipelago were not recorded (Morozov *et al.*, 2018).

We have not succeeded in finding onset times in available bulletins of seismic stations for 7 of 23 earthquakes.

Table 2
Catalog of Relocated Earthquakes in an Area of the Arctic Region

			Hypocenter						Error Ellipse				
Number	Date (yyyy/mm/dd)	Time (hh:mm:ss.s)	φ (°)	λ (°)	h (km)	N_{st}/N_{def}	Gap (°)	Range of Epicentral Distances (km)	AzMajor	Rminor	Rmajor	Magnitude	Note
1	1904/10/09	13.52:00.5	73.12	−4.24	10f	8/13	239	1743–5011	80	73.3	107.9	$M_s = 7.3–7.6$	Approximate determination of the M_s
2	1906/03/19	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	1908/07/08	12.50:02.8	84.87	22.61	10f	12/18	244	2950–5231	150	75.9	169.9	$M_s = 6.3$	
4	1908/10/14	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	1909/04/10	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	1911/12/04	14.38:47.9	79.70	3.48	8f	8/15	325	2336–3592	70	133.1	177.8	$M_s = 5.8–6.0$	Approximate determination of the M_s
7	1912/01/25	—	—	—	—	2/3	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
8	1912/02/19	—	—	—	—	3/6	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
9	1912/04/13	02.39:45.9	85.05	94.93	5f	6/8	325	3127–4460	10	181.0	270.3	$M_s = 5.1$	
10	1914/06/07	16.24:02.5	73.03	116.29	10f	8/13	253	2359–5155	80	63.4	129.7	$M_s = 6.3$	
11	1914/11/04	12.54:14.7	72.42	0.22	5f	7/11	307	2269–4063	120	130.9	157.6	$M_s = 5.0$	
12	1914/11/05	08.00:38.3	75.54	2.63	5f	4/5	233	2453–4831	120	141.2	241.3	$\mathbf{M} = 5.25$	
13	1915/06/01	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	1915/06/02	—	—	—	—	2/4	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
15	1915/09/16	10.22:07.0	77.91	15.78	4f	3/4	238	2453–4831	140	67.1	244.8	$\mathbf{M} = 4.5$	Poor determination
16	1915/09/30	—	—	—	—	1/1	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
17	1916/05/11	—	—	—	—	1/2	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
18	1916/12/06	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	1917/05/14	—	—	—	—	1/2	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
20	1917/08/21	10.44:09.1	71.83	−8.07	7f	8/11	271	1722–3400	70	75.2	102.4	M_w(ISC) = 5.67	
21	1918/01/27	02.50:40.4	75.18	6.10	6f	8/10	302	1777–3283	0	74.5	102.1	$M_s = 5.4$	
22	1918/10/20	—	—	—	—	3/4	—	—	—	—	—	—	The relocation procedure was not carried out, not enough data
23	1918/11/30	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	1919/02/02	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	1919/09/12	14.26:32.9	68.02	22.06	5f	4/5	242	1865–7532	150	47.8	263.7	—	Not relevant to the study area

The letter “f” after the “h” values denote the value of the depth is fixed. ISC, International Seismological Centre.

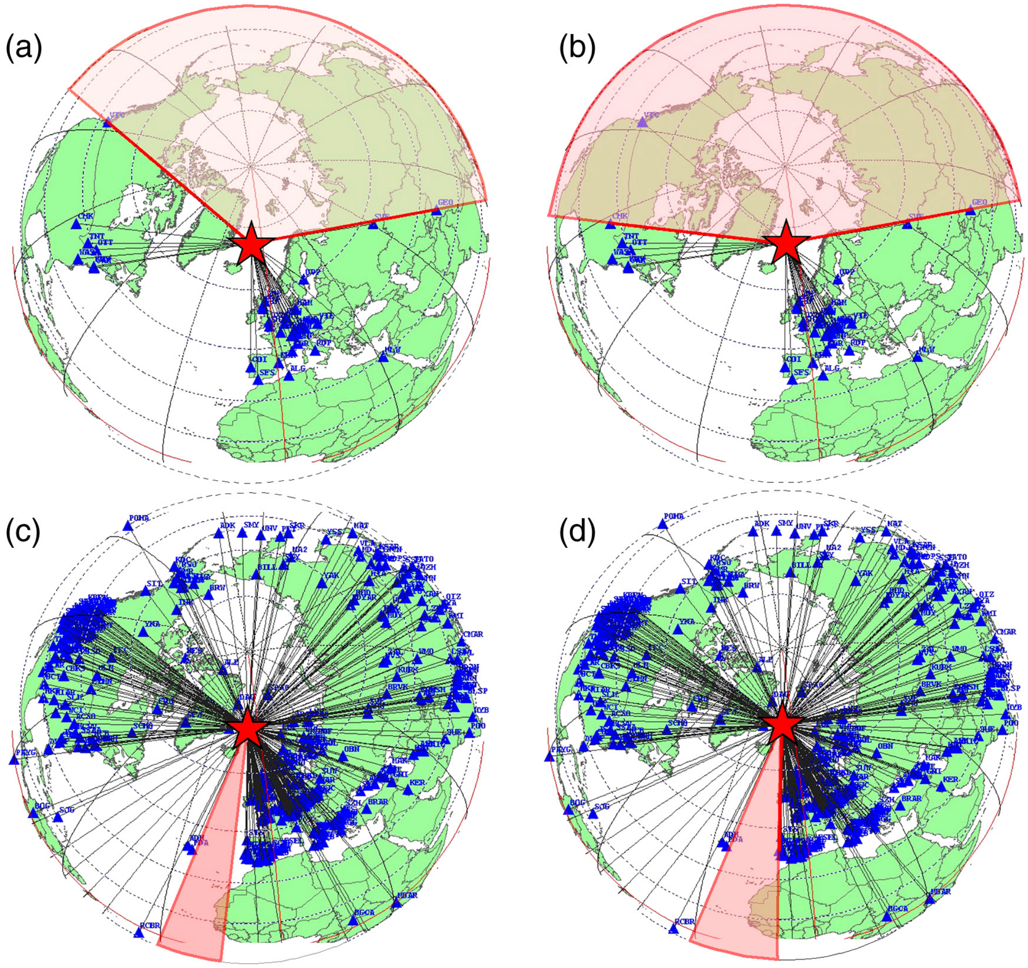

Figure 3. Number of stations, azimuthal gap, and secondary azimuthal gap for the earthquakes of (a,b) 2 February 1919 and (c,d) 21 May 2000. The shaded areas show (a,c) the azimuthal gap and (b,d) the secondary azimuthal gap. The color version of this figure is available only in the electronic edition.

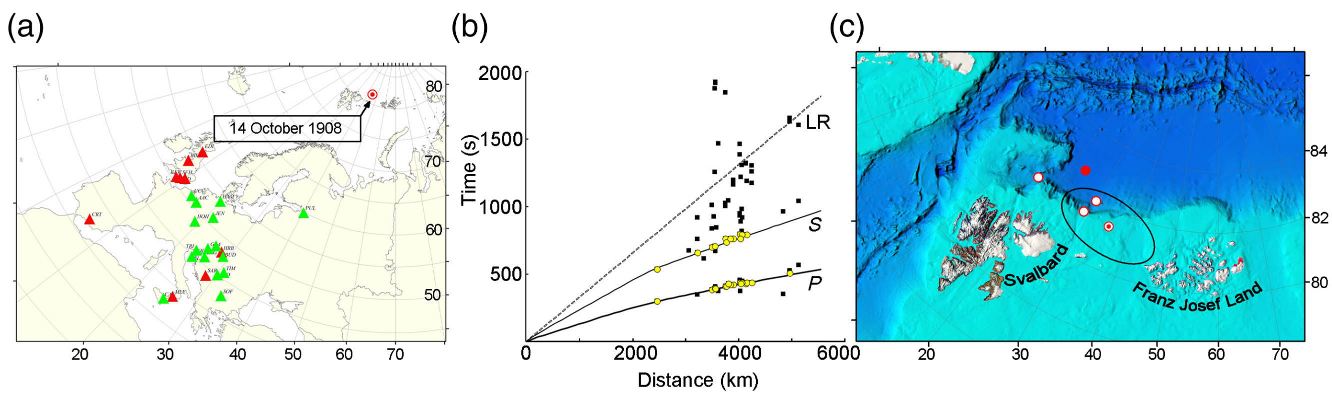

Figure 4. (a) The map of the seismic stations that recorded the earthquake of 14 October 1908. The circled dot marks the relocated epicenter, green triangles show the stations used for the location, and red triangles mark the stations for which onsets were rejected due to possible large timing errors or misinterpretation. (b) All available onset times for the earthquake. The theoretical (ak135 velocity model) *P*-wave travel time is plotted with a thick line, *S* with a thin line, and the surface wave with a dashed line. The onsets used for location are shown as hollow circles and rejected onsets are marked as black squares. (c) The relocated epicenter of the earthquake. The solid circle indicates the position of the epicenter in the ISC–Global Earthquake Model catalog, the hollow circles indicate the position of another coordinate from Table 1, and the circled dot marks the new position. The error ellipse is plotted with a black line. LR, Rayleigh-wave. The color version of this figure is available only in the electronic edition.

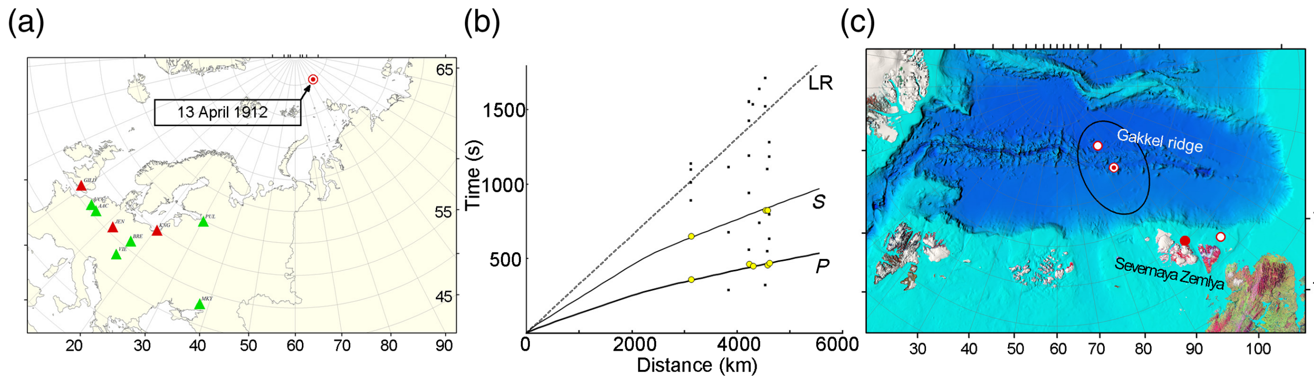

Figure 5. (a) The map of the seismic stations that recorded the earthquake of 13 April 1912. The circled dot marks the relocated epicenter, green triangles show the stations used for the location, and red triangles mark the stations for which onsets were rejected due to possible large timing errors or misinterpretation. (b) All available onset times for the earthquake. The theoretical (ak135 velocity model) *P*-wave travel time is plotted with a thick line, *S* with a thin line, and the surface wave with a dashed line. The onsets used for location are shown as hollow circles and rejected onsets are marked as black squares. (c) The relocated epicenter of the earthquake. The solid circle indicates the position of the epicenter by Gutenberg and Richter (1941), the hollow circles indicate the position of other coordinates from Table 1, and the circled dot marks the new position. The error ellipse is plotted with a black line. The color version of this figure is available only in the electronic edition.

Table 3
Seismic Catalog of Earthquakes in an Area of the Franz Victoria Graben

Number	Date (yyyy/mm/dd)	Origin Time (hh:mm:ss.s)	Hypocenter φ (°)	λ (°)	h (km)	Magnitude	Source of the Hypocenter (ISC, 2015)
1	1948/02/18	20:29:47.0	82.50	41.50	—	**M** = 6.5 by Linden (1959)	ISC Bulletin
2	1948/09/26	05:51:12.0	82.50	41.50	—	—	ISC Bulletin
3	1948/11/22	23:32:48.0	82.50	41.50	—	—	ISC Bulletin
4	1967/03/13	21:44:07.7	82.23	39.60	33.0f	m_b(ISC) = 4.3	ISC-EHB Bulletin
5	1967/03/14	07:50:14.9	82.38	39.10	13.0f	m_b(ISC) = 4.7	ISC-EHB Bulletin
6	1975/06/25	10:14:57.6	82.35	38.72	33.0f	m_b(ISC) = 4.6	Reviewed ISC Bulletin (Prime hypocenters)

The letter "f" after the "*h*" values denote the value of the depth is fixed. EHB, Engdahl–van der Hilst–Buland; ISC, International Seismological Centre.

Therefore, it remains an unresolved issue whether these earthquakes actually occurred in the Arctic region. These earthquakes call for more study involving an analysis of actual records rather than bulletins.

Conclusions

We relocated earthquakes recorded within the Arctic region from 1904 through 1920 with a view to creating a relocated catalog. For the relocation, we collected all available seismic bulletins from the global network. The relocation was performed using a modified method of generalized beamforming and the ak135 velocity model. The relocation procedure was applied to 18 of 25 earthquakes in the Arctic region.

We hope that the present results improve knowledge of seismic activity in the Arctic. Registration of each earthquake from the Arctic at the beginning of the twentieth century was unique because information on historical earthquakes for the Arctic region is extremely scanty, whereas data on paleoearthquakes are practically inaccessible. It follows that the earthquakes recorded during the period of instrumental observation are the most significant.

Data and Resources

Seismic station bulletins of the International Seismological Centre–Global Earthquake Model (ISC-GEM) catalog are available from http://storing.ingv.it/bulletins/ISC-GEM/ (last accessed December 2018) and the EuroSeismos (ES) project are available from http://storing.ingv.it/es_web/ (last accessed December 2018). Bulletins of the Soviet seismic stations were collected using listings from the Geophysical Survey of Russian Academy of Sciences (RAS) (http://www.ceme.gsras.ru/new/eng/ssd_news.htm, last accessed March 2018) and from the Russian State Library (https://www.rsl.ru/en, last accessed March 2018). International Seismological Summary (ISS) Bulletins between 1917 and 1919 are available from http://storing.ingv.it/ISS/index.html (last accessed December 2018).

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