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ORIGINAL ARTICLE

Seismicityof the Novaya Zemlya archipelago: relocated event catalog from 1974 to 2014

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Abstract We have relocated seismic events registered in the area of the Novaya Zemlya Archipelago, which are not identified as nuclear explosions but are probably of tectonic nature. For the relocation, we collected all available seismic bulletins and waveform data. The location was performed by applying a modified method of generalized beamforming. Verification of the modified method and selection of the travel time model were performed using data on two Novaya Zemlya nuclear explosions that occurred on 02.11.1974 and 24.10.1990. The modified method and the BARENTS travel time model provide sufficient accuracy for event location in the region. The relocation procedure was applied for 9 seismic events registered in the area of the Novaya Zemlya Archipelago. As a result, the new coordinates of the five events turned out to be significantly different from those that were defined previously.

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1 Introduction

The Novaya Zemlya Archipelago is the largest in the Russian Arctic and is located in the eastern part of the Barents Sea (Fig. 1). It includes two large islands, Severniy and Yuzhniy, which are separated by the narrow Matochkin Shar Strait (2–3 km) and numerous of smaller islands. A Soviet nuclear test site was operated on the archipelago until 1990. At Novaya Zemlya, a total of 130 tests were carried out high in the atmosphere, at low levels above water, at the water/air interface, below water, and underground (Khalturin et al. 2005).

Novaya Zemlya is characterized by low seismicity, and most of the detected seismic events from the region resulted from nuclear tests. There are significant difficulties in the seismic monitoring of the Novaya Zemlya Archipelago. Widely spaced seismic stations cannot register small-magnitude earthquakes, and poor station coverage makes it difficult to determine earthquake hypocenters and focal mechanisms accurately. According to the studies Assinovskaya (1994) and Avetisov (1996), the completeness threshold of earthquakes for the Barents Sea region and, in particular, the Novaya Zemlya Archipelago in the period 1971–1980 was m_b = 4.3–4.6, and in the period 1981–1990 was m_b = 3.9–4.2. As a result, understanding of the archipelago's seismic activity is based on 18 seismic events

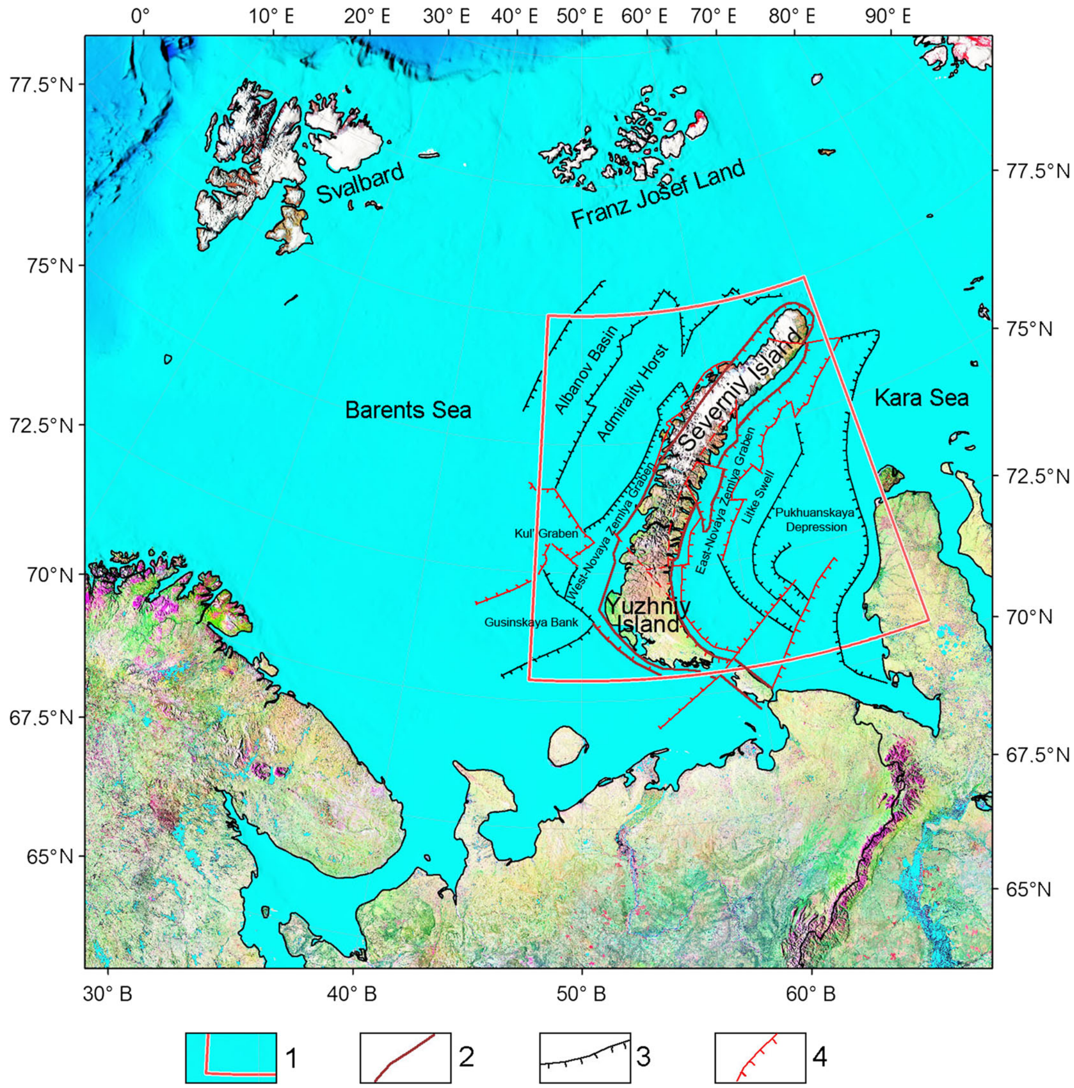

Fig. 1 Map showing the location of the Novaya Zemlya Archipelago, the neotectonic structures and active faults (Atlas 2004), combined with a bathymetric data (www.ngdc.noaa.gov): *1* boundaries of the study area; *2* main neotectonic faults; *3* borders of neotectonic structures; *4* dislocation with a break of continuity

that are not identified as nuclear explosions but are probably tectonic in nature (Table 1).

Two new seismic stations were installed in the region between 2010 and 2011. The AMD station (69.76°N/61.68°E) was placed in the settlement of Amderma on the coast of the Kara Sea, and the ZFI station (80.81°N/47.66°E) was installed on Alexandra Land Island in the Franz Josef Land Archipelago (Morozov and Konechnaya 2013). The ZFI and AMD seismic stations belong to the Arkhangelsk seismic network (AH network). The threshold of earthquakes for the Barents Sea region and, in particular, the Novaya Zemlya Archipelago is now 2.7 (Morozov and Konechnaya 2013). Only two earthquakes have occurred after the installation of the stations, one on 11.10.2010 at 22:48:27.8 (m_b(ISC) = 4.7) and one on 04.03.2014 at 04:42:36.0 (M_L(AH) = 3.3). The uncommon occurrence of tectonic activity requires a detailed survey for each earthquake detected. A list of seismic stations and their parameters is presented in Table 2 and in Fig. 2.

Worldwide, seismic events are preliminarilylocated immediately after their occurrence. A common practice in seismology is a posterior reprocessing of the events

Table 1 Combined seismic catalog of events in an area of the Novaya Zemlya Archipelago and adjacent territories over the instrumental observation period

No	Date dd/mm/yyyy	Origin time hh/mm/ss.0	Hypocenter			Magnitude				Source of the hypocenter
			φ,°	λ,°	h, km	Mb (ISC)/MS (ISC)	mb (EIDC)/md (NEIC)	mb (NAO)/ML (NAO)	ML (HEL)/ML (AH)	
1	12.12.1974	21:19:46.4	71.96	49.53	0f	4.4/–				Reviewed ISC Bulletin (Prime hypocentres)
2	15.11.1978	08:30:04.9	72.57	52.84	0f			4.3/–		Reviewed ISC Bulletin (Prime hypocentres)
3	01.08.1986	13:56:37.0	72.93	56.06	0f	4.8/3.7	–/4.7	4.5/–		ISC-EHB Bulletin
4	31.12.1992	09:29:24.0	73.61	55.18	0f			2.7/–		(Ringdal 1997)
5	13.06.1995	19:22:37.9	75.26	56.88	0f			3.5/–		(Ringdal 1997)
6	13.01.1996	17:17:23	75.13	56.73	0f			2.4/–		(Ringdal 1997)
7	16.08.1997	02:10:59.2	72.62	56.94	10.0f		3.9/3.2	3.5/–	3.8	Reviewed ISC Bulletin (Prime hypocentres)
8	23.02.2002	01:21:12.2	74.27	55.83	10.0f	3.0/–		–/3.0	3.1/–	Reviewed ISC Bulletin (Prime hypocentres)
9	10.11.2002	11:04:41.5	70.40	48.64	10.0f			–/2.0	2.4/–	Institute of Seismology (University of Helsinki)
10	08.10.2003	23:07:19.7	75.64	62.89	-			–/2.6		NORSAR
11	05.03.2006	23:17:35.7	76.80	64.30	0f			–/2.7		NORSAR
12	14.03.2006	20:57:02.4	75.07	53.06	-			–/2.2		NORSAR
13	30.03.2006	10:46:02.4	70.89	51.01	0			–/2.3	2.6/–	Reviewed ISC Bulletin (Prime hypocentres)
14	26.06.2007	03:19:19.4	73.39	53.39	-			–/2.8		NORSAR
15	11.11.2009	04:18:20.2	71.42	47.07	10.0f				3.2/–	Institute of Seismology (University of Helsinki)
16	11.06.2010	16:46:25.6	70.81	49.42	0					Kola Regional Seismic Centre
17	11.10.2010	22:48:28.8	76.30	64.27	19.4	4.7/3.5	/4.8			Reviewed ISC Bulletin (Prime hypocentres)
18	04.03.2014	04:42:36.0	74.72	56.72	5.0f				–/3.3	Arkhangelsk seismic network

Table 2 Parameters of seismic stations

Station			Latitude (°)	Longitude (°)	Elevation/ depth, m	Start	Instrument	Status
Code	Network	Name, country						
AMDE	AH	Amderma, Arkhangel'skaya Oblast', Russia	69.761	61.678	48	2010	CMG-40T	open
APA (APZ9)	KOGSR	Apatity, Russia	67.569	33.405	182	1956 2010	- Guralp-3ESP	open
APA0	KOGSR	Apatity Array Site A0, Russia	67.606	32.992	200	1992 2009	S-500 OYO GS1	open
ARA0	NO	ARCESS Array Site A0, Norway	69.535	25.506	403	1990	CMG 3T, GS-13	open
ARU	II	Arti, Russia	56.429	58.562	260	1976 1999	- Streckeisen STS-1/BB Seismometer	open
BGF	LDG	Bois d'Agland, France	46.558	2.846	390	1980	ZM-500 and HM-500 short-period seismometers	open
BILL	IU	Bilibino, Russia	68.039	166.271	299	1995	Streckeisen STS-1 Seismometer	open
BMO	US	Blue Mountains Array, U.S.A.	44.853	−117.306	1154	1962 2004	- STS2-I	open
BRG	SX	Berggiesshubel, Germany	50.873	13.943	36	1972	-	open
CLL	GR	Collm, Germany	51.308	13.003	230	1939	-	open
COL	-	College Outpost, U.S.A.	64.900	−147.793	320	1954	-	closed
CVF	RD	Calvi, France. Replaced by PGF (Pioggiola)	42.568	8.869	530	1975 2013	- Streckeisen STS-2 seismometer	open
CYP	PD	Chylin, Poland	51.293	23.300	100	1981	-	closed
DAG	GE	DanmarksHavn, Greenland	76.771	−18.655	30	1972	STS-2	open
DMN	-	Daman, Nepal	27.609	85.106	2225	1980	-	open
EKA	CTBT	Eskdalemuir, United Kingdom	55.333	−3.159	263	1962	-	open
ELT	ASGSR	Eltsovka, Russia	53.261	86.239	235	1960	-	open
FIA0 (FINES)	HE	FINESS Array Site A0, Finland	61.444	26.077	156	1992	Geotech S-13,Earthdata PS6–24	open
GBA	-	Gauribidanur Array, India	13.604	77.436	686	1965	-	open
HEF	HE	Hetta, Finland	68.408	23.660	380	2007	STS-2, Earthdata PS6–24	open
HFS	UP	Hagfors, Sweden	60.134	13.695	296	1969	STS-1	open
HOPEN	NS	Hopen, Svalbard,Norway	76.510	25.010	25	2004	-	open
INK	CN	Inuvik, Canada	68.307	−133.525	44	1969 1994 2007	- Guralp CMG3T_NSN/CNSN GD1 digitizer Guralp CMG3T_120sec/CNSN GD2_v21 digitizer	open

Table 2 (continued)

Station Code	Network	Name, country	Latitude (°)	Longitude (°)	Elevation/depth, m	Start	Instrument	Status
JOF	HE	Joensuu, Finland	62.918	31.312	180	1981	STS-2, Earthdata PS6–24	open
KAF	HE	Kangasniemi, Finland	62.113	26.306	195	1977	STS-2, Earthdata PS6–24	open
KBA	OE	Koelnbreinsperre, Austria	47.078	13.345	1721	1981 1997	- Streckeisen STS-2G3/Quanterra Qx80 19920812 (new)	open
KBS	GE	Kingsbay, Norway	78.926	11.942	74	1999	Streckeisen STS-1/BB Seismometer	open
KEF	HE	Keuruu, Finland	62.166	24.866	215	1977	STS-2, Earthdata PS6-24	open
KEV	HE	Kevo, Finland	69.755	27.007	80	1964	Guralp CMG-3T/Quanterra/ ED PS6-24	open
KHC	CZ	KasperskeHory, Czech Republic	49.131	13.578	695	1960 1973 1995	- STS-2 STS-2,short-period/Earth	open
KIF	HE	Kilpisjarvi, Finland	69.004	20.802	0	2002	STS-2, Earthdata PS6-24	open
KIR	UP	Kiruna, Sweden	67.840	20.417	390	1951	-	-
KJF	HE	Kajaani, Finland	64.199	27.715	160	1970	-	closed
KJN	HE	Kajaani, Finland	64.085	27.711	250	1961 1990	- Geotech S-13, DAS98	closed reopened
KKN	-	Kakani, Nepal	27.790	85.280	1920	1980	-	open
KRV	AB	Ganja, Azerbaijan	40.628	46.310	532	1950	-	open
KSP	PD	Ksiaz, Poland	50.843	16.293	353	1971	-	open
KTK1	NS	Kautokeino, Norway	69.011	23.237	340	1989	-	open
KU4	HE	Liikasenvaara, Finland	66.365	29.579	290	2004	STS-2, Earthdata PS6-24	open
LAO	US	LASA Array, U.S.A.	46.689	−106.223	902	1966 2004	- STS2-I	open
LBF	FR	Les Buteaux, France	46.984	3.977	715	1964	-	open
LIC	CTBTO	Lamto, Ivory Coast	6.224	−5.028	105	1965	-	open
LOR	RD	Lormes, France	47.268	3.859	520	1963 2013	- Streckeisen STS-2 seismometer	open
LPG	LDG	La Plagne, France	45.498	6.751	2570	1985	ZM-500 and HM-500 short-period seismometers	open
LVZ	II	Lovozero, Russia	67.898	34.651	630	1992	Streckeisen STS-1 Seismometer, Geotech GS-13 Seismometer	open
MBC	CN	Mold Bay, Canada	76.242	−119.360	15	1960	-	closed
MFF	RD	Saint Martin du Fouilloux, France	46.602	−0.146	270	1971	-	open

Table 2 (continued)

Station			Latitude (°)	Longitude (°)	Elevation/ depth, m	Start	Instrument	Status
Code	Network	Name, country						
MKAR (MKAZ)	IU	Makanchi Array Beam Reference Point, Kazakhstan	46.794	82.290	615	2011 2001	Streckeisen STS-2 seismometer Streckeisen STS-2 Standard-gain	open
MLR	RO, GE, CTBT	MunteleRosu, Romania	45.491	25.945	1360	1974	-	open
MSF	FN	Maaselka, Finland	65.911	29.040	365	1999 2000	Streckeisen STS-2 seismometer Streckeisen STS-2	open
NAO	NO	NORSAR Subarray 1A Beam Reference Point	60.824	10.832	379	1971	CMG-3T	open
NB2 (NOA)	NO	NORSAR Subarray 2B Beam Reference Point, Norway	61.040	11.215	717	1971	CMG-3T	open
NC2	NO	NORSAR Subarray 2C Beam Reference Point, Norway	61.281	10.835	847	1971	CMG-3T	open
NC4	NO	NORSAR Subarray 4C Beam Reference Point, Norway	61.079	11.719	522	1971	CMG-3T	open
NRA0	NO	NORESS Array Site A0, Norway	60.735	11.541	302	1985	GS-13	open
NRI	-	Noril'sk, Russia	69.430	88.083	44	1964	-	
NRS	DK	Narsarsuaq, Greenland	61.160	−45.419	65.9	2000	Streckeisen STS-2 G3/Nanometrics HRD24, Streckeisen STS-2G3/ Quanterra 330 Linear Phase Co	open
NUR	HE	Nurmijarvi, Finland	60.509	24.649	102	1957	-	-
NVS	ASGSR	Novosibirsk, Russia	54.841	83.234	150	1965	-	open
OBN	II	Obninsk, Russia	55.114	36.569	160	1964	Guralp CMG-3T Seismometer	open
PKI	-	Pulchoki, Nepal	27.571	85.409	2758	1978	-	open
PRU	CZ	Pruhonice, Czech Republic	49.988	14.542	302	1957 2010	- STS2	open
PUL	GE	Pulkovo, Russia	59.773	30.322	89	1906	STS-2	open
RNF	FN	Rovaniemi, Finland	66.609	26.014	198	2007	Streckeisen STS-2	open
SBF	LDG	Sospel, France	43.863	7.435	848	1985	ZM-500 and HM-500 short-period seismometers	open
SGF	FN	Sodankyla, Finland	67.442	26.526	180	2000	Streckeisen STS-2	open
SMF	LDG	Signal de Mont, France	46.645	3.841	459	1976	ZM-500 and HM-500 short-period seismometers	open
SOD	SGO	Sodankyla, Finland	67.371	26.629	181	1987	-	closed
SPA0	NO	Spitsbergen Array Site A0	78.177	16.370	323	1992	Guralp-BB	open

Table 2 (continued)

Station			Latitude (°)	Longitude (°)	Elevation/ depth, m	Start	Instrument	Status
Code	Network	Name, country						
(SPITS)								
SSF	LDG	Saint Saulge, France	47.062	3.506	355	1967	ZM-500 and HM-500 short-period seismometers	open
SUF	HE	Sumiainen, Finland	62.719	26.151	185	1979	STS-2/Earthdata PS6-24	open
SVE	OBGSR.	Sverdlovsk, Russia	56.827	60.637	275	1906	-	open
TCF	LDG	Toulx Ste. Croix, France	46.288	2.210	593	1965	ZM-500 and HM-500 short-period seismometers	open
TIK	IU	Tiksi, Russia	71.633	128.867	41	1956	Streckeisen STS-1/BB Seismometer	closed
TIXI	IU	Tiksi, Russia	71.649	128.867	50	1995	Streckeisen STS-1 Seismometer	open
TRO	NS	Tromso, Norway	69.633	18.928	15	1960	-	open
TUP	BAGSR	Tupik, Russia	54.425	119.954	650	1961	-	open
UME	UP	Umea, Sweden	63.815	20.237	16	1960	-	closed
UPP	UP	Uppsala, Sweden	59.858	17.627	14	1904	-	open
UZH	-	Uzhgorod, Ukraine	48.631	22.293	160	1934	DAS-04 SKD	open
VRF	HE	Varrio, Finland	67.748	29.609	350	2007	STS-2, Earthdata PS6-24	open
VRI	RO	Vrincioaia, Romania	45.867	26.728	472	1967	STS-2	open
YKA	CN	Yellowknife Array Beam Reference Point, Canada	62.493	−114.605	197	1966 2013	- Geotech S-13 SP seismometer + YKA pre-amp/Guralp D	open
ZFI2	AH	Zemlya Franca-Iocifa, Arkhangel'skaya Oblast', Russia	80.809	47.655	18	2011 2015	CMG-40T CMG-6TD	open

"-" Station parameters not known

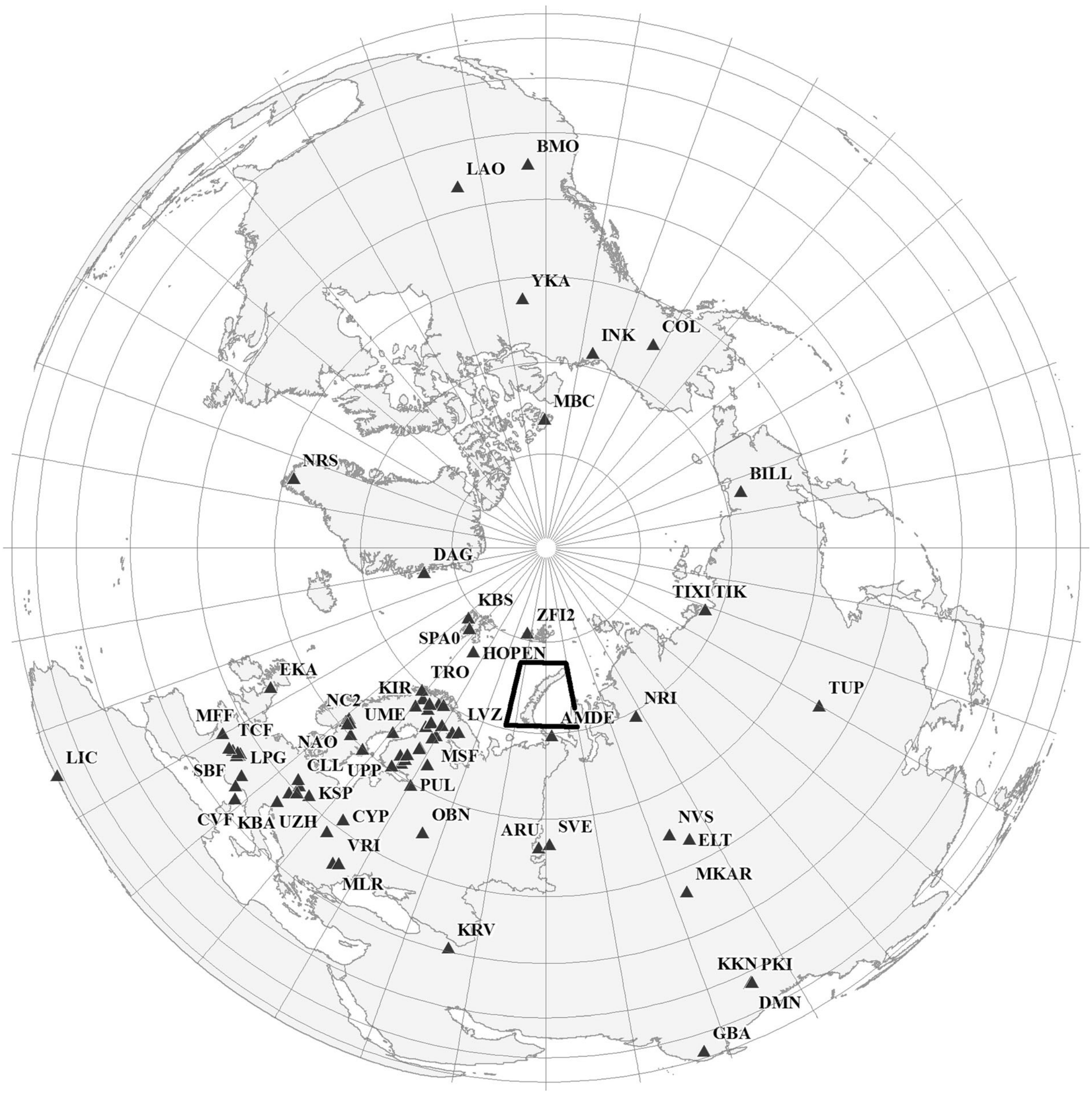

Fig. 2 Location of seismic stations from Table 2

when data of all seismic stations are collected, velocity models are updated, and location techniques are worked out. This article illustrates relocation procedures performed for seismic events registered within the area of the Novaya Zemlya Archipelago, which were not identified as nuclear explosions, but likely of tectonic nature. We have used all available bulletin data for the relocation procedure. For more exact onset determination, waveform data were used for some cases, including data from Soviet and Russian seismic stations.

2 Description of dataset and methods

A catalog of seismic events was created for the Novaya Zemlya Archipelago using the data of International Seismological Centre (ISC; International Seismological Centre 2013), NORSAR (NOA network), Institute of Seismology (University of Helsinki) (ISUH, HEL network), Kola Regional Seismic Center (KOLA network), and the Arkhangelsk seismic network (AH network) (Table 1). The area of interest was limited to the following coordinate ranges: latitude from 70.4°N to 77.5°N and longitude from 47.0°E to 70.0°E.

Nuclear explosions were excluded from the catalogusing the data of Databases of Nuclear Tests (Yang et al. 2003), as well as seismic events that occurred in the area of the nuclear test site, thus considering only seismic events of tectonic origin (Table 1).

Bulletins and waveform data from the Soviet and Russian seismic stations were obtained from the Geophysical Survey (OBN-network) of the Russian Academy of Sciences (RAS), the Kola Regional Seismic Center, and the Arkhangelsk seismic network. Seismic station bulletins from the global network were collated using data from the ISC, NORSAR, and the ISUH. The waveform data were obtained from the GEOPHON Seismological Archive (www.geofon.gfzpotsdam.de/geofon/).

The goal of analyzing the waveform data from seismic events was phase identification. Onset determination was performed using the Windows Seismic Grafer (WSG) program, a joint product from the Geophysical Survey of the RAS and Geotech, a limited liability company (www.ceme.gsras.ru). Seismic event location and depth estimation were carried out using the New Association System (NAS) program, which is a part of the New System for Detection and Location (NSDL) system developed in the Kola branch of the Geophysical Survey of RAS. The software was used to carry out automated seismicity monitoring of any region using an arbitrary network (Asming and Prokudina 2016; Asming et al. 2016). We have relocated only seismic events with at least 8 phases from 4 stations.

2.1 Event location algorithm

The NAS program (Asming and Prokudina 2016; Asming et al. 2016) performs phase association using a modified form of the known generalized beam forming 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 (value of 250 km was used in this study) around the preliminary location of the event's epicenter. This circle is considered as a search area for a more precise location. It is covered by a set of overlapping circles of smaller radii, thus forming a grid of round cells. A rating function R(**c**,**t**) is computed for each cell **c** of the grid, with the hypothesis that the event has occurred in this particular cell at time **t**. To describe this function in more detail, let a phase (P or S) arrived at the i-th seismic station at time $\mathbf{t_i}$. Let $\mathbf{r_{i0}(c)}$ and $\mathbf{r_{i1}(c)}$ be the minimal and maximal distances from the i-th station to the cell **c**. If the event actually occurred in this cell, its origin time has to be within the limits $[t_i - r_{i1}(c)/v, t_i - r_{i0}(c)/v]$, where **v** is the wave's apparent propagation velocity. Thus, following Kvaerna and Ringdal (1996), we can define the total rating function as follows:

$$R(c,t) = \sum_i S\left(t, t_i - r_{i1}(c)/v, t_i - r_{i0}(c)^{i0}/v\right), \tag{1}$$

where $\mathbf{S(t,t_a,t_b)}$ is the step function:

$$S(t, t_a, t_b) = \begin{cases} 1, t\in[t_a, t_b] \\ 0, otherwise \end{cases} \tag{2}$$

It is assumed that each phase that can correspond to an event that occurred in a given cell at a given time makes unit contribution to the rating function for this cell. This would work well if all measurements $\{\mathbf{t_i}\}$ were accurate and the knowledge of **v** was exact. In the present case, we measure onsets with some uncertainty $\mathbf{\Delta t_{onset}}$, and we know the velocity with uncertainty $\mathbf{\Delta v}$. Therefore, the interval for the origin time must be expanded as follows: $[t_i - r_{i1}(c)/v - \Delta t, t_i - r_{i0}(c)/v + \Delta t]$, where $\Delta t = \Delta t_{onset} + r \cdot \Delta v/v^2$.

Instead of $\mathbf{S(t, t_a, t_b)}$, we introduce a trapezoidal-shaped function **T**:

$$T(t, t_a, t_b, \Delta t) = \begin{cases} 1-(t_a - t)/\Delta t, t\in[t_a - \Delta t, t_a] \\ 1, t\in[t_a, t_b] \\ 1-(t - t_b)/\Delta t, t\in[t_b, t_b + \Delta t] \\ 0, otherwise \end{cases} \tag{3}$$

And finally we define the rating function as follows:

$$R(c,t) = \sum_i T(t, t_i - r_{i1}(c)/v, t_i - r_{i0}(c)/v, \Delta t) \tag{4}$$

This is a sum of contributions of all phases that can correspond to an event that occurred in a given cell at a given time. Those phases that belong to the exact time interval $[t_i - r_{i1}(c)/v, t_i - r_{i0}(c)/v]$ add 1 to the sum, whereas the ones that are outside the main interval but may correspond to the event add smaller values.

The rating functions are computed for an interval of possible origin times $\mathbf{[t_0 - \Delta T, t_0 + \Delta T]}$, where $\mathbf{t_0}$ is the preliminary estimation of origin time of the prototype event, $\mathbf{\Delta T}$ is the some large time reserve (30 s value was taken for the events considered in this study). Maximal values of the rating function among the times within the interval are rating estimations for the grid cells. The grid is diminished several times. Each time 75% of the cells with the smallest ratings are excluded and each remaining cell is divided into four smaller ones, to keep the same total cell number. Following, ratings are recalculated.

The grid search is performed several times with different fixed depths (from 0 to 100 km with a step 5 km for the present study). Finally, the cell with the maximal rating is selected. The time $\mathbf{t_0}$ for which the rating function has reached its maximum is considered to be the event's origin time.

A weight is attributed to each phase, which is taken equal to the contribution of the phase to the rating function for an estimated origin time $\mathbf{t_0}$:

$$w_i = T(t_0, t_i - r_{i1}(c)/v, t_i - r_{i0}(c)/v, \Delta t) \quad (5)$$

The phases with non-zero weights are taken into account for the next stage of processing. This approach enables us to screen out phases with non-realistic times. This procedure may be proven useful for processing onsets obtained from old analog seismograms.

In the next step, the phases and the weights are used to improve the location by searching the point where the residual of origin time estimation computed for this point is minimal.

We briefly remind the method. Again, let $\mathbf{t_i}$ be an arrival time of a P or S wave to the i-th station with coordinates $(\boldsymbol{\varphi_i}, \boldsymbol{\lambda_i})$. Suppose that the event coordinates are $(\boldsymbol{\varphi}, \boldsymbol{\lambda}, \mathbf{h})$, where $\boldsymbol{\varphi}$ is the latitude, $\boldsymbol{\lambda}$ is the longitude, and $\mathbf{h}$ is the depth. Origin time estimations are as follows:

$$t_{0i}(\phi, \lambda, h) = t_i - TT(\phi_i, \lambda_i, 0, \phi, \lambda, h) \quad (6)$$

where **TT** is the travel time between two points for this wave type. If $(\boldsymbol{\varphi}, \boldsymbol{\lambda}, \mathbf{h})$ are true coordinates of the event, onsets are measured exactly and **TT** is known, then all $\mathbf{t_{0i}}$ must be the same and equal to the true origin time.

The average origin time estimation is as follows:

$$\overline{t_0}(\varphi, \lambda, h) = \sum_i w_i \cdot t_{0i} / \sum_i w_i, \quad (7)$$

where w_i are the weights of the phases that are calculated during the grid search (Avetisov, 1996).

And its standard deviation is as follows:

$$\sigma(\varphi, \lambda, h) = \sqrt{\sum_i w_i \cdot \left(\overline{t_0} - t_{0i}\right) / \sum_i w_i} \quad (8)$$

To locate the event, we find the point $(\varphi_{event}, \lambda_{event}, h_{event})$ where σ is the minimal:

$$\sigma_{\min} = \min_{(\varphi,\lambda,h)} \sigma(\varphi, \lambda, h), \quad (\varphi_{event}, \lambda_{event}, h_{event}) = Arg \min_{(\varphi,\lambda,h)} \sigma(\varphi, \lambda, h) \quad (9)$$

Usually, for bulletin processing, the coordinates obtained by the minimization differ very slightly from those obtained by the grid search. As a rule, the final point lies within the same cell of the grid where the maximum of the rating function was reached. Thus, it would seem that this step of processing could be omitted. Nevertheless, the function$\sigma(\varphi, \lambda, h)$ appeared to be useful for the estimation of the confidence region.

We estimate the confidence region by solving the inequality (with fixed depth $\mathbf{h_{event}}$):,

$$\sigma(\varphi, \lambda, h_{event}) \leq \sigma_0$$

where $\boldsymbol{\sigma_0}$ is the border value of the standard deviation, depending on the expected errors (uncertainties) of the onset time measurements $\boldsymbol{\Delta t_{onset}}$ and the uncertainties of travel velocities $\boldsymbol{\Delta v}$.

It is estimated for a given set of arrivals $\{t_i\}$ as: (r_i is distance from the i-th station to the event):

$$\Delta t_i = \sqrt{\Delta t_{onset}{}^2 + \left(\frac{r_i \cdot \Delta v}{v^2}\right)^2} (summary\ onset\ time\ uncertainty)$$
$$\sigma_0 = \sqrt{\sum_i (w_i \cdot \Delta t_i)^2 / \sum_i w_i} \quad (10)$$

The region is estimated numerically and is approximated by an ellipse.

To determine the depth range, a similar inequality is solved for $\mathbf{h}$:

$$\min_{(\varphi,\lambda,)} \sigma(\varphi, \lambda, h) < \sigma_0 \quad (11)$$

The onset picking errors (Δt_{onset}) were taken $\Delta t_p = 0.5$ s and $\Delta t_s = 1$ s. That is reasonable for old seismograms. The velocity uncertainties were taken $\Delta v_p = \Delta v_s = 0.15$ km/s.

2.2 Verification of the algorithm, selection of travel time model, location error estimation

Two Novaya Zemlya nuclear explosions (02.11.1974 and 24.10.1990) were chosen for verification of the algorithm, selection of the travel time model, and estimation of the location error (Fig. 3). The last Soviet nuclear test occurred in 1990, and we chose it as a reference because most of the seismic stations that we used in the relocation were already in operation at the time. This explosion is denoted as event GT1 (Yang et al. 2000).

The 1974 explosion (GT5 after Yang et al. 2000) was chosen because it occurred at a significant distance from the 1990 explosion in another area of the nuclear test site (Fig. 3). The parameters of the hypocenters of the 1974 and 1990 explosions were obtained from Yang et al. (2003).

Several 1D velocity models were tested: BARENTS (Kremenetskaya et al. 2001), BAREY, and BAREZ from Schweitzer and Kennett (2007), NORP (Morozov and Vaganova 2011), NOES (Morozov and Vaganova 2017), and NZ2010 (Gibbons et al. 2016). The BARENTS model has been developed for Fennoscandia, the Baltic shield, and adjacent areas. In its upper layers, the model is a simplified average of various models developed for parts of the region. Below the Moho, the model uses the IASPEI91 model layers (Kennett and Engdahl 1991).

The BAREY and BAREZ models were adapted from a model developed by Kremenetskaya et al. (2001) by making minor P-velocity adjustments and varying the V_P/V_S ratio in the upper mantle. The BAREZ model uses a V_P/V_S ratio of 1.73 in the crust and a ratio of 1.72 below the Moho. The BAREY model uses a V_P/V_S ratio of 1.77 in the uppermost mantle (Schweitzer and Kennett 2007).

The NORP model has been developed based on calculation of the crustal velocity structure of two areas of the Russian Plate using receiver functions (Morozov and Vaganova 2011).

The NOES model is based on calculation of the crustal velocity structure for the area of the Franz Josef Land Archipelago using receiver functions (Morozov and Vaganova 2017). The BAREY, BAREZ, NORP, and NOES models were combined with the deep layers of the IASPEI91 model to compute travel times at teleseismic distances.

The NZ2010 model is the modification to BAREY/BAREZ, which appears to give the best fit to the regional arrival times for the purely teleseismic hypocenter and the origin time for the 11 October 2010 event in the Novaya Zemlya Archipelago (Gibbons et al. 2016). The model is identical to BAREY/BAREZ except for a 1.74 V_P/V_S ratio but with a 0.5% increase in P velocities between 41 and 410 km depth.

Seismic station bulletins for the 1974 and 1990 nuclear explosions were collated using data from the ISC and Geophysical Survey of the RAS. All available onsets were collected, and several datasets from stations located at certain distance intervals from the event's location were prepared: 0–10°, 0–15°, 0–20°, 0–30°, and 0–90°. The results are summarized in Fig. 3.

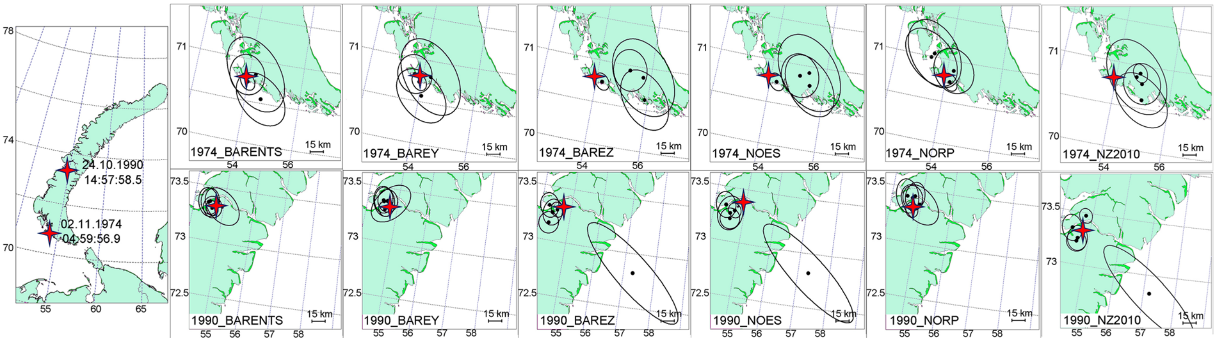

Fig. 3 Checking the efficiency of the modified generalized beamforming and the velocity models using the underground nuclear explosions performed on 02.11.1974 (t0 = 04:59:56.9, mb(IASPEI) = 6.4, GT5) and 24.10.1990(t0 = 14:57:58.3, mb(IASPEI) = 5.7, GT1) (Yang et al. 2003). Maps showing the computed (*circles*) and true (*stars*) epicenters of the underground nuclear explosions

Table 3 Checking the efficiency of the modified generalized beamforming and the BARENTS, BAREY, and NORP velocity models using the underground nuclear explosions performed on 02.11.1974, t_0 = 04:59:56.9, mb(IASPEI) = 6.4 and 24.10.1990, t_0 = 14:57:58.3, mb(IASPEI) = 5.7 (Yang et al. 2003)

Ground truth[a] event: underground nuclear explosions					Result of the relocated procedure											
Date dd/mm/yyyy	Time hh/mm/ss.0	Hypocenter			R^b,°	Nst	Nphases	Time hh/mm/ss.0	Hypocenter			Error ellipse			D[c], km
		φ,°	λ,°	h, km					φ,°	λ,°	h, km	AzMajor,°	Rminor, km	Rmajor, km	
BARENTS model															
02.11.1974	04:59:56.9	70.81	53.91	0	0–90	275	305	5.00:01.3	70.73	53.99	(0) 0–7	140	8.6	12.5	9.4
					0–30	65	86	5.00:00.5	70.81	53.93	(0) 0–11	150	23.3	27.3	0.7
					0–20	12	19	4.59:55.5	70.55	54.58	(0) 0–75	130	26.7	40.9	38.0
					0–15	8	14	4.59:56.8	70.83	54.24	(0) 0–99	140	33.0	54.4	12.3
24.10.1990	14:57:58.5	73.33	54.76	0	0–90	518	534	14.58:03.0	73.30	54.63	(0) 0–8	150	6.3	7.9	5.3
					0–30	74	85	14.58:02.2	73.36	54.53	(0) 0–7	170	9.7	13.4	8.1
					0–20	24	31	14.58:01.1	73.31	54.64	(0) 0–8	160	9.7	11.1	4.4
					0–15	10	14	14.58:01.5	73.35	54.48	(0) 0–16	160	10.4	14.9	9.2
					0–10	4	7	14.58:01.2	73.33	54.95	(0) 0–100	130	14.2	22.2	6.1
BAREY model															
02.11.1974	04.59:56.9	70.81	53.91	0	0–90	275	305	5.00:00.8	70.73	53.91	(0) 0–6	140	8.6	12.4	8.9
					0–30	65	86	5.00:00.5	70.81	53.70	(0) 0–10	150	22.6	26.0	7.7
					0–20	12	19	4.59:56.7	70.57	54.08	(0) 0–99	130	26.7	40.9	27.4
					0–15	8	14	4.59:59.2	70.81	54.29	(33) 0–99	140	33.6	55.1	13.9
24.10.1990	14.57:58.5	73.33	54.76	0	0–90	518	534	14.58:02.4	73.30	54.61	(0) 0–8	150	6.2	7.9	5.8
					0–30	74	85	14.58:01.4	73.38	54.52	(0) 0–8	170	9.6	13.4	9.5
					0–20	24	31	14.58:00.4	73.38	54.65	(0) 0–9	160	10.2	11.8	6.6
					0–15	10	14	14.58:00.6	73.37	54.54	(0)	160	10.8	15.7	8.3

Table 3 (continued)

Ground truth[a] event: underground nuclear explosions					Result of the relocated procedure										
Date dd/mm/yyyy	Time hh/mm/ss.0	Hypocenter			R^b,°	Nst	Nphases	Time hh/mm/ss.0	Hypocenter			Error ellipse			D[c], km
		φ,°	λ,°	h, km					φ,°	λ,°	h, km	AzMajor,°	Rminor, km	Rmajor, km	
					0–10	4	7	14.58:00.4	73.36	54.77	0–28 (0) 0–100	130	14.8	23.7	3.4
NORP model															
02.11.1974	04.59:56.9	70.81	53.91	0	0–90	276	306	5.00:02.5	70.74	54.17	(0) 0–4	140	8.6	12.9	12.3
					0–30	65	86	5.00:01.4	70.88	54.24	(0) 0–13	140	25.3	31.4	14.3
					0–20	12	18	5.00:04.2	70.99	53.33	(0) 0–54	130	27.1	44.3	29.1
					0–15	8	14	5.00:03.2	71.04	53.42	(0) 0–76	140	30.8	48.8	31.2
24.10.1990	14.57:58.5	73.33	54.76	0	0–90	517	530	14.58:04.3	73.30	54.73	(0) 0–11	160	6.3	7.9	3.5
					0–30	71	79	14.58:03.6	73.43	54.76	(0) 0–11	0	10.1	14.4	11.1
					0–20	21	26	14.58:03.8	73.41	54.69	(0) 0–23	160	10.2	13.0	9.2
					0–15	10	14	14.58:03.4	73.42	54.51	(0) 0–27	160	11.5	17.8	12.8
					0–10	4	7	14.58:04.1	73.36	54.96	(0) 0–100	130	15.3	24.2	7.2

[a] GT categories. GTX refers to events with location accuracy better than X km (Yang et al. 2000)

[b] Epicentral distances

[c] The distance between the calculated and truth coordinates

The BARENTS, BAREY, and NORP models showed sufficient location accuracy for all the datasets. The focal depth was estimated to be equal to zero for all of these variants. We chose the BARENTS model for the relocation because the distance between each obtained location and the true coordinates for this model were slightly smaller than for the other models (Table 3).

Thus, the application of the algorithm implemented in the NAS program together with the BARENTS model gives the most accurate parameters of hypocenters. This allows us to apply the algorithm and model to relocate seismic events registered in the area of the Novaya Zemlya Archipelago.

3 Discussion of results

3.1 12.12.1974 seismic event

According to the Reviewed ISC Bulletin, the seismic event occurred on December 12, 1974, in an area of the Barents Sea 70 km to the west of Yuzhniy Island, which is part of the Novaya Zemlya Archipelago (Table 1). The event was registered at the seismic stations of the ISUH, Hagfors Observatory (National Defense Research Institute, HFS2 network), and Large Aperture Seismic Array (LAO network). The Reviewed ISC Bulletin includes the hypocenter calculated based on the following: $N_{stations}$ = 14, gap = 220°.

For this seismic event, additional bulletins from the SVE, APA, ARU, and OBNSoviet stations (Table 4) were collected and analyzed. Seismic phases were identified from the bulletins of the APA and ARU stations. The relocation procedure was performed based on the following: $N_{stations}$ = 16; N_{phases} = 23; gap = 167° (Table 4). The epicentral distances varied from 790 to 7020 km.

According to the new location of the 1974 seismic event, the epicenter is shifted 200 km (Fig. 4) to the south-east with respect to the initial coordinates. It is located in the south part of Yuzhniy Island in the Novaya Zemlya Archipelago on the shore of the Barents Sea in the vicinity of the nuclear test site. This could imply a possible anthropogenic nature of the seismic event. The range of possible depths varies from 0 to 40 km. The area of the error ellipse is 1507 km^2. The size of the ellipse can be explained by the wide azimuthal gap and the wide range of epicentral distances (Fig. 4, Table 13).

3.2 15.11.1978 seismic event

According to the Reviewed ISC Bulletin, the seismic event on November 15, 1978 occurred in the north-western part of Yuzhniy Island in the Novaya Zemlya Archipelago by the shore of the Barents Sea. NORSAR and Hagfors Observatory registered the event. The Reviewed ISC Bulletin reports a hypocenter that was calculated based on the following: $N_{stations}$ = 6, gap = 336° (Table 1).

In this case, the bulletins of the PUL, APA, ARU, OBN, and MOS Soviet stations were collected and analyzed. However, no seismic phases corresponding to the event were found. As a result, the relocation procedure was performed based on the following parameters: $N_{stations}$ = 6; N_{phases} = 10; gap = 336° (Table 5). The epicentral distances varied from 980 to 2170 km.

According to the new location of the 1978 seismic event, the epicenter is shifted 115 km (Fig. 4) to the north-east with respect to the initial coordinates. The epicenter is located in the southern part of Severniy Island in the area of the Matochkin Shar Strait in the vicinity of the nuclear test site, which could imply a possible anthropogenic nature of the seismic event. It is impossible to compute the focal depth of the event reliably due to the small number of available stations and phases. The area of the error ellipse is 12,866 km^2. The large size of the ellipse can be explained by the wide azimuthal gap and the narrow range of epicentral distances (Fig. 4, Table 13).

3.3 01.08.1986 seismic event

According to the ISC-EHB Bulletin, a seismic event occurred on August 01, 1986, in the north-eastern part of Yuzhniy Island in the vicinity of the Brandta Strait. According to Marshall et al. (1989), the hypocenter of the seismic event is as follows: 13:56:37.8 73.03°N/56.73°E, H = 24 km. In comparison to report by the ISC-EHB Bulletin, the epicenter is shifted 25 km to the north-east into the Kara Sea. The hypocenter in the bulletin enlists was calculated based on the following: $N_{stations}$ = 51, gap = 11° (Table 1).

Bulletins of Soviet stations PUL, APA, ARU, OBN, and MOS were also analyzed for the given seismic event. Seismic phases were found in the bulletins of stations PUL, APA, and OBN (Table 6). The arrival times of seismic phases from the PUL stations were

Table 4 Phase picks for the 12 December 1974

Station Code	Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	ISC	This study
APA	Apatity, Russia	67.569	33.405	7.1	239.6	21:21:34.0	21:23:00.0	−	+
KEV	Kevo, Finland	69.755	27.007	7.7	264.2	21:21:41.0	21:23:22.0	+	+
SOD	Sodankyla, Finland	67.371	26.629	9.2	251.1	21:22:04.0	21:23:54.8	+	+
TRO	Tromso, Norway	69.633	18.928	10.3	271.8	21:22:24.0	−	+	+
KIR	Kiruna, Sweden	67.840	20.417	10.8	261.8	21:22:26.5	21:24:34.0	+	+
KJF	Kajaani, Finland	64.199	27.715	11.2	236.9	21:22:26.0	21:24:33.0	+	+
NUR	Nurmijarvi, Finland	60.509	24.649	15.1	233.2	21:23:16.3	21:26:03.8	+	+
ARU	Arti, Russia	56.429	58.562	16.0	161.6	21:23:00.5	21:25:36.0	−	+
HFS	Hagfors, Sweden	60.134	13.695	18.4	248.4	21:24:02.6	−	+	+
NAO	NORSAR Subarray 1A Beam Reference Point, Norway	60.824	10.832	18.6	253.3	21:24:06.8	−	+	+
CLL	Collm, Germany	51.308	13.003	26.3	237.6	21:25:29.0	−	+	+
BRG	Berggiesshubel, Germany	50.873	13.943	26.4	236.0	21:25:18.0	−	+	+
VRI	Vrincioaia, Romania	45.867	26.728	28.3	214.8	21:25:55.0	−	+	+
MBC	Mold Bay, Canada	76.242	−119.360	31.9	355.0	21:26:14.0	−	+	+
LAO	LASA Array, U.S.A.	46.689	−106.223	60.4	341.0	21:29:58.4	−	+	+
BMO	Blue Mountains Array, U.S.A.	44.853	−117.306	63.1	349.5	21:30:15.7	−	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

not considered in the ISC-EHB Bulletin for the calculation of the hypocenter. Thus, a relocation procedure was conducted based on the following: $N_{stations}$ = 52; N_{phases} = 64; gap = 11° (Table 6). The epicentral distances varied from 1030 to 8430 km.

According to the new location of the 1986 seismic event, the epicenter is shifted 12 km (Fig. 4) to the north with respect to the initial coordinates of the ISC-EHB Bulletin and 23 km to the west compared to the epicenter calculated by Marshall et al. (1989). The epicenter was located within Klokova Bay of Yuzhniy Island. The range of possible depths varies from 0 to 15 km and the area of the error ellipse is 602 km^2. The size of the ellipse can be explained by the narrow azimuthal gap and the wide range of epicentral distances (Fig. 4, Table 13). The initial epicenter from the ISC-EHB Bulletin is located within the error ellipse of the new epicenter. Thus, both solutions are correct.

3.4 13.06.1995 seismic event

NORSAR registered the event on the Novaya Zemlya Archipelago in 1995. According to the research of Ringdal (1997), the epicenter was located within the Glazova Bay in the western part of the Severniy Island (Table 1).

Seismic phases of the 1995 event were registered at the KBS, ARU, and LVZ stations (Table 7). Thus, a relocation procedure was performed based on the following: $N_{stations}$ = 7; N_{phases} = 10; gap = 233°. The epicentral distances varied from 1120 to 3870 km.

According to the new location of the 1995 seismic event, the epicenter is shifted 6 km (Fig. 4) to the southwest with respect to the initial coordinates. It is impossible to compute the focal depth of the event reliably due to the small number of available stations and phases. The area of the error ellipse is 6374 km^2. The large size of the ellipse can be explained by the wide azimuthal gap and the narrow range of epicentral distances (Fig. 4, Table 13). The initial epicenter from Ringdal (1997) is located within the error ellipse of the new epicenter. Thus, both solutions are correct.

3.5 23.02.2002 seismic event

According to the Reviewed ISC Bulletin, the seismic event on February 23, 2002 occurred in the south-

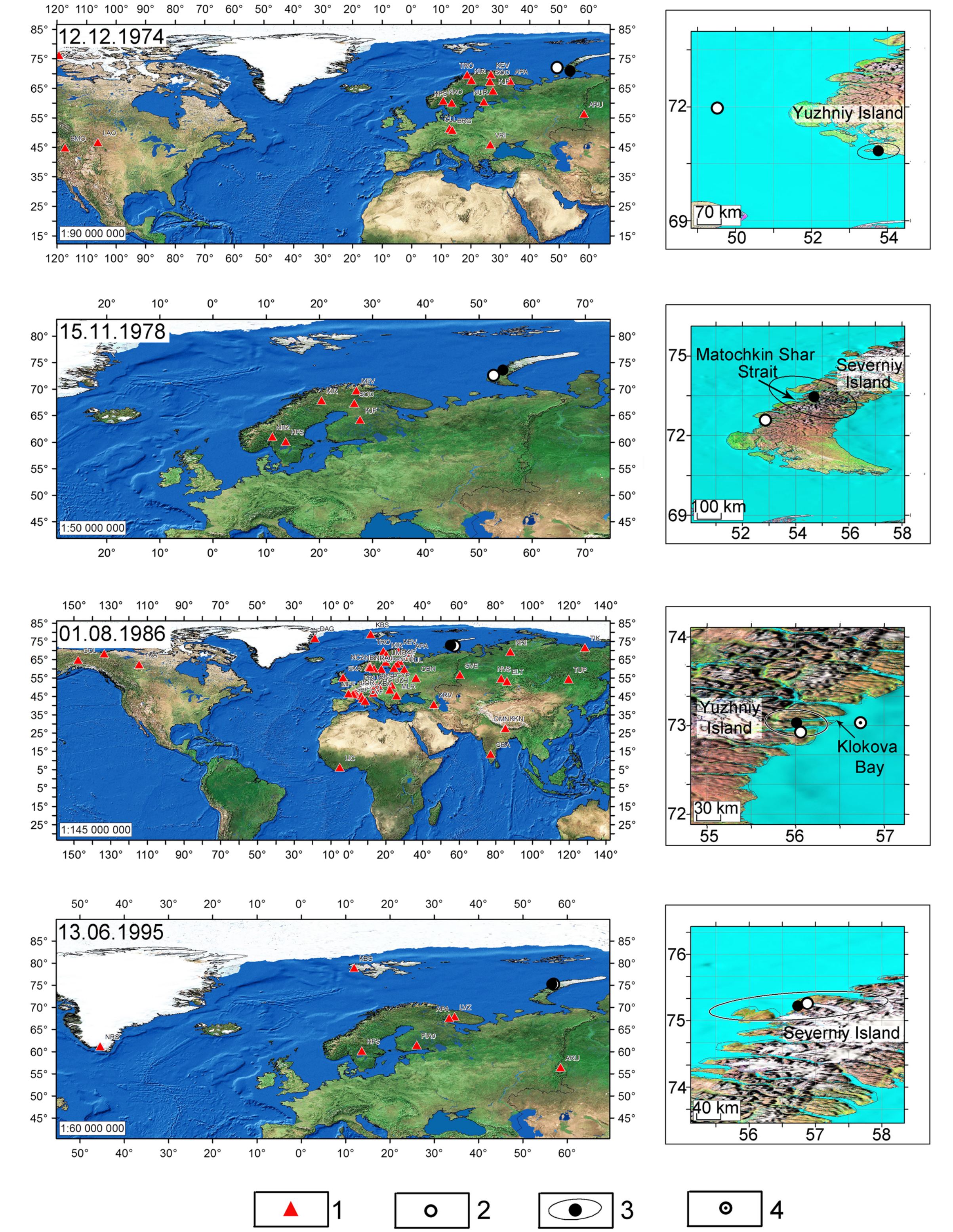

Fig. 4 Maps showing the relocated epicenters of seismic events in the area of the Novaya Zemlya Archipelago: *1* seismic stations; *2* initial coordinates; *3* new coordinates; *4* coordinates according to Marshall et al. (1989) of the 01.08.1986 event

Table 5 Phase picks for the 15 November 1978

Station Code	Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	ISC	This study
KEV	Kevo, Finland	69.755	27.007	8.8	263.9	08:32:16.0	08:33:56.0	+	+
SOD	Sodankyla, Finland	67.371	26.629	10.3	252.7	08:32:38.8	08:34:34.9	+	+
KIR	Kiruna, Sweden	67.840	20.417	11.8	262.6	08:32:56.5	08:35:08.5	+	+
KJF	Kajaani, Finland	64.199	27.715	12.4	240.1	08:33:04.0	08:35:28.0	+	+
NB2	NORSAR Subarray 2B Beam Reference Point, Norway	61.040	11.215	19.5	255.5	08:34:35.9	-	+	+
HFS	Hagfors, Sweden	60.134	13.695	19.5	250.9	08:34:36.7	-	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

western part of the Severniy Island in an area of Yuzhnaya Sul'meneva Bay. The event was registered at the stations of the ISUH, OBN network, International Data Center (IDC), and NORSAR. The Reviewed ISC Bulletin reports the hypocenter based on the following: $N_{stations}$ = 14, gap = 89° (Table 1).

We were unable to find additional seismic phases in the bulletins of Russian stations (Table 8). Therefore, the calculation was based on similar parameters: $N_{stations}$ = 14, N_{phases} = 20, gap = 89°. The epicentral distances varied from 1034 to 3470 km.

According to the new location of the 2002 seismic event, the epicenter is shifted 16.5 km (Fig. 5) to the south-east with respect to the initial coordinates. Thus, the epicenter is located in the southern part of the Severniy Island. The range of possible depths varies from 0 to 39 km. The area of the error ellipse is 905 km^2. The size of the ellipse can be explained by the narrow azimuthal gap and the wide range of epicentral distances (Fig. 5, Table 13). The initial epicenter from the Reviewed ISC Bulletin is located within the error ellipse of the new epicenter. Thus, both solutions are correct.

3.6 10.11.2002 seismic event

The seismic event that occurred on November 10, 2002 was recorded at the seismic stations of the ISUH and NORSAR. According to the data of the ISUH, the epicenter was located in the waters of the Barents Sea, 160 km to the south-west of Yuzhniy Island. The ISUH reports the hypocenter based on the following: $N_{stations}$ = 5, gap = 276°. The minimum epicentral distance is equal to 823 km (Table 1).

Waveform data from the ARU, LVZ, OBN, and PUL Russian stations were analyzed for the event. The seismic phases were identified at the LVZ station (Table 9). Thus, a relocation procedure was performed based on the following: $N_{stations}$ = 6; N_{phases} = 10; gap = 276° (Table 9). The epicentral distances varied from 623 to 1280 km.

The epicenter is shifted 36 km (Fig. 4) to the east with respect to the initial coordinates reported by the ISUH. Thus, the epicenter is located in the Barents Sea 130 km from the shores of Yuzhniy Island. It is impossible to compute the focal depth of the event reliably due to the small number of available stations and phases. The maximum of the rating function is obtained at a depth of 99 km. This focal depth is unlikely for the area. It shows once again that depth estimations can have large uncertainties for events in the region. The area of the error ellipse is 2817 km^2. The size of the ellipse can be explained by the wide azimuthal gap and the narrow range of epicentral distances (Fig. 5, Table 13).

3.7 30.03.2006 seismic event

According to the Reviewed ISC Bulletin, the seismic event on March 30, 2006 occurred in the Barents Sea 60 km from the Yuzhniy Island. The event was registered by the stations of the ISUH and NORSAR. The Reviewed ISC Bulletin lists the hypocenter calculated based on the following parameters: $N_{stations}$ = 14, gap = 267° (Table 1).

The waveform data of the Russian stations ARU, OBN, and PUL were analyzed. However, no seismic phases corresponding to the event were found. Thus, a relocation procedure was performed based on the

Table 6 Phase picks for the 01 August 1986

Station Code	Station Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	ISC	This study
APA	Apatity, Russia	67.569	33.405	9.3	246.1	13:58:51.5	14:00:30.3	+	+
KEV	Kevo, Finland	69.755	27.007	9.7	265.3	13:58:58.2	14:00:45.0	+	+
NRI	Noril'sk, Russia	69.430	88.083	10.9	93.1	13:59:08.5	14:01:11.0	+	+
KBS	Kingsbay, Norway	78.926	11.942	11.9	319.5	13:59:24.2	14:01:32.1	+	+
TRO	Tromso, Norway	69.633	18.928	12.1	272.7	13:59:30.7	13:59:39.8	+	+
KIR	Kiruna, Sweden	67.840	20.417	12.7	264.5	14:00:38.2	14:01:58.8	+	+
KJF	Kajaani, Finland	64.199	27.715	13.3	243.8	13:59:46.0	14:02:11.0	+	+
SUF	Sumiainen, Finland	62.719	26.151	14.9	242.5	14:00:06.7	–	+	+
UME	Umea, Sweden	63.815	20.237	15.7	253.1	14:00:16.5	14:03:03.0	+	+
SVE	Sverdlovsk, Russia	56.827	60.637	16.3	171.0	14:00:30.0	14:03:29.0	+	+
PUL	Pulkovo, Russia	59.773	30.322	16.5	230.6	14:00:27.0	14:03:27.0	–	+
NUR	Nurmijarvi, Finland	60.509	24.649	17.2	240.3	14:00:36.0	14:03:51.0	+	+
DAG	DanmarksHavn, Greenland	76.771	−18.655	18.6	315.9	14:00:58.0	–	+	+
OBN	Obninsk, Russia	55.114	36.569	19.5	214.8	14:01:08.0	14:04:36.0	+	+
UPP	Uppsala, Sweden	59.858	17.627	19.6	248.6	14:01:07.4	–	+	+
NC4	NORSAR Subarray 4C Beam Reference Point, Norway	61.079	11.719	20.3	257.7	14:01:15.6	–	+	+
NC2	NORSAR Subarray 2C Beam Reference Point, Norway	61.281	10.835	20.4	259.0	14:01:16.7	–	+	+
NB2	NORSAR Subarray 2B Beam Reference Point, Norway	61.040	11.215	20.4	258.2	14:01:17.2	–	+	+
HFS	Hagfors, Sweden	60.134	13.695	20.5	253.9	14:01:17.4	–	+	+
NRA0	NORESS Array Site A0, Norway	60.735	11.541	20.6	257.0	14:01:18.9	–	+	+
TIK	Tiksi, Russia	71.633	128.867	21.0	57.8	14:01:22.0	14:05:13.0	+	+
NVS	Novosibirsk, Russia	54.841	83.234	21.4	133.5	14:01:26.0	–	+	+
ELT	Eltsovka, Russia	53.261	86.239	23.6	130.8	14:01:45.0	–	+	+
CYP	Chylin, Poland	51.293	23.300	25.8	231.0	14:02:22.0	–	+	+
KSP	Ksiaz, Poland	50.843	16.293	28.0	239.7	14:02:30.0	–	+	+
BRG	Berggiesshubel, Germany	50.873	13.943	28.5	242.6	14:02:35.0	–	+	+
UZH	Uzhgorod, Ukraine	48.631	22.293	28.6	230.5	14:02:43.0	–	+	+
PRU	Pruhonice, Czech Republic	49.988	14.542	29.1	241.1	14:02:41.5	–	+	+
EKA	Eskdalemuir, United Kingdom	55.333	−3.159	29.4	265.7	14:02:43.0	–	+	+
KHC	KasperskeHory, Czech Republic	49.131	13.578	30.2	241.6	14:02:50.5	–	+	+

Table 6 (continued)

Station		Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	ISC	This study
Code	Name, country								
MLR	MunteleRosu, Romania	45.491	25.945	30.8	223.5	14:02:55.0	–	+	+
TUP	Tupik, Russia	54.425	119.954	31.7	90.7	14:03:03.0	–	+	+
KBA	Koelnbreinsperre, Austria	47.078	13.345	32.2	240.3	14:03:09.2	–	+	+
KRV	Ganja, Azerbaijan	40.628	46.310	32.6	193.0	14:03:01.0	–	+	+
LOR	Lormes, France	47.268	3.859	34.5	251.3	14:03:26.9	–	+	+
LBF	Les Buteaux, France	46.984	3.977	34.8	250.9	14:03:28.7	–	+	+
SSF	Saint Saulge, France	47.062	3.506	34.8	251.5	14:03:29.6	–	+	+
SMF	Signal de Mont, France	46.645	3.841	35.1	250.8	14:03:31.5	–	+	+
LPG	La Plagne, France	45.498	6.751	35.4	246.8	14:03:34.2	–	+	+
BGF	Bois d'Agland, France	46.558	2.846	35.5	251.9	14:03:35.3	–	+	+
TCF	Toulx Ste. Croix, France	46.288	2.210	35.9	252.4	14:03:38.8	–	+	+
MFF	Saint Martin du Fouilloux, France	46.602	−0.146	36.3	255.1	14:03:42.2	–	+	+
SBF	Sospel, France	43.863	7.435	36.7	245.0	14:03:45.6	–	+	+
CVF	Calvi, France	42.568	8.869	37.5	242.0	14:03:53.7	–	+	+
INK	Inuvik, Canada	68.307	−133.525	38.9	5.0	14:04:05.0	–	+	+
COL	College Outpost, U.S.A.	64.900	−147.793	41.5	15.0	14:04:25.0	–	+	+
YKA	Yellowknife Array Beam Reference Point, Canada	62.493	−114.605	44.7	354.0	14:04:48.3	–	+	+
KKN	Kakani, Nepal	27.790	85.280	47.9	144.0	14:05:16.0	–	+	+
DMN	Daman, Nepal	27.609	85.106	48.0	144.0	14:05:17.2	–	+	+
PKI	Pulchoki, Nepal	27.571	85.409	48.1	144.0	14:05:18.5	–	+	+
GBA	Gauribidanur Array, India	13.604	77.436	60.7	156.0	14:06:50.0	–	+	+
LIC	Lamto, Ivory Coast	6.224	−5.028	75.8	244.0	14:08:23.5	–	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

Table 7 Phase picks for the 13 June 1995

Station Code	Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	(Ringdal, 1997)	This study
LVZ	Lovozero, Russia	67.898	34.651	10.1	234.6	19:24:59.5	19:26:45.3	–	+
KBS	Kingsbay, Norway	78.926	11.942	10.4	311.1	19:25:05.3	19:26:56.1	–	+
APA	Apatity, Russia	67.569	33.405	10.6	235.8	19:27:02.3		+	+
FIA0	FINESS Array Site A0, Finland	61.444	26.077	17.5	234.7	19:26:36.7		+	+
ARU	Arti, Russia	56.429	58.562	18.9	177.1	19:26:54.3	19:30:16.4	–	+
HFS	Hagfors, Sweden	60.134	13.695	21.4	249.1	19:27:28.9		+	+
NRS	Narsarsuaq, Greenland	61.160	−45.419	34.8	304.4	19:27:28.7		+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

following: $N_{stations}$ = 14; N_{phases} = 20; gap = 267° (Table 10). The epicentral distances varied from 712 to 1523 km.

According to the new location of the 2006 seismic event, the epicenter is shifted 73 km (Fig. 4) to the south-east with respect to the initial coordinates. The epicenter is located in the Barents Sea 25 km from the southern part of Yuzhniy Island. It is impossible to compute the focal depth of the event reliably due to the small number of available stations and phases. The maximum of the rating function is obtained at a depth of 35 km. The area of the error ellipse is 2388 km^2. The size of the ellipse can be explained by the wide azimuthal gap and the narrow range of epicentral distances (Fig. 5, Table 13).

3.8 11.11.2009 seismic event

The seismic event that occurred on November 11, 2009 was registered at the seismic stations of the ISUH. According to these data, the epicenter was located in the Barents Sea 160 km from the shores of the Yuzhniy

Table 8 Phase picks for the 23 February 2002

Station Code	Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	ISC	This study
LVZ	Lovozero, Russia	67.898	34.651	9.3	237.5	01:23:31.7	-	+	+
KEV	Kevo, Finland	69.755	27.007	9.9	257.4	01:23:38.67	01:25:21.09	+	+
SPA0	Spitsbergen Array Site A0, Norway	78.177	16.370	10.0	311.0	01:23:39.1	01:25:32.65	+	+
ARA0	ARCESS Array Site A0, Norway	69.535	25.506	10.5	258.3	01:23:43.71	01:25:38.08	+	+
KBS	Kingsbay, Norway	78.926	11.942	10.9	314.9	01:23:51.01	01:25:49.36	+	+
JOF	Joensuu, Finland	62.918	31.312	14.3	230.2	01:24:34.76	01:27:02.29	+	+
KAF	Kangasniemi, Finland	62.113	26.306	16.1	236.6	01:24:59.56	-	+	+
FIA0	FINESS Array Site A0, Finland	61.444	26.077	16.8	235.8	01:25:07.92	-	+	+
TIXI	Tiksi, Russia	71.649	128.867	20.3	60.7	01:25:50.1	01:29:30.7	+	+
NOA	NORSAR Array Beam Reference Point, Norway	61.040	11.215	20.8	254.5	01:25:58.96	-	+	+
NRA0	NORESS Array Site A0, Norway	60.735	11.541	21.0	253.6	01:26:01.76	-	+	+
NAO	NORSAR Subarray 1A Beam Reference Point	60.824	10.832	21.1	254.6	01:26:03.0	-	+	+
MKAR	Makanchi Array Beam Reference Point, Kazakhstan	46.794	82.290	29.9	142.1	01:27:27.4	-	+	+
BILL	Bilibino, Russia	68.039	166.271	31.2	42.9	01:27:30.1	-	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

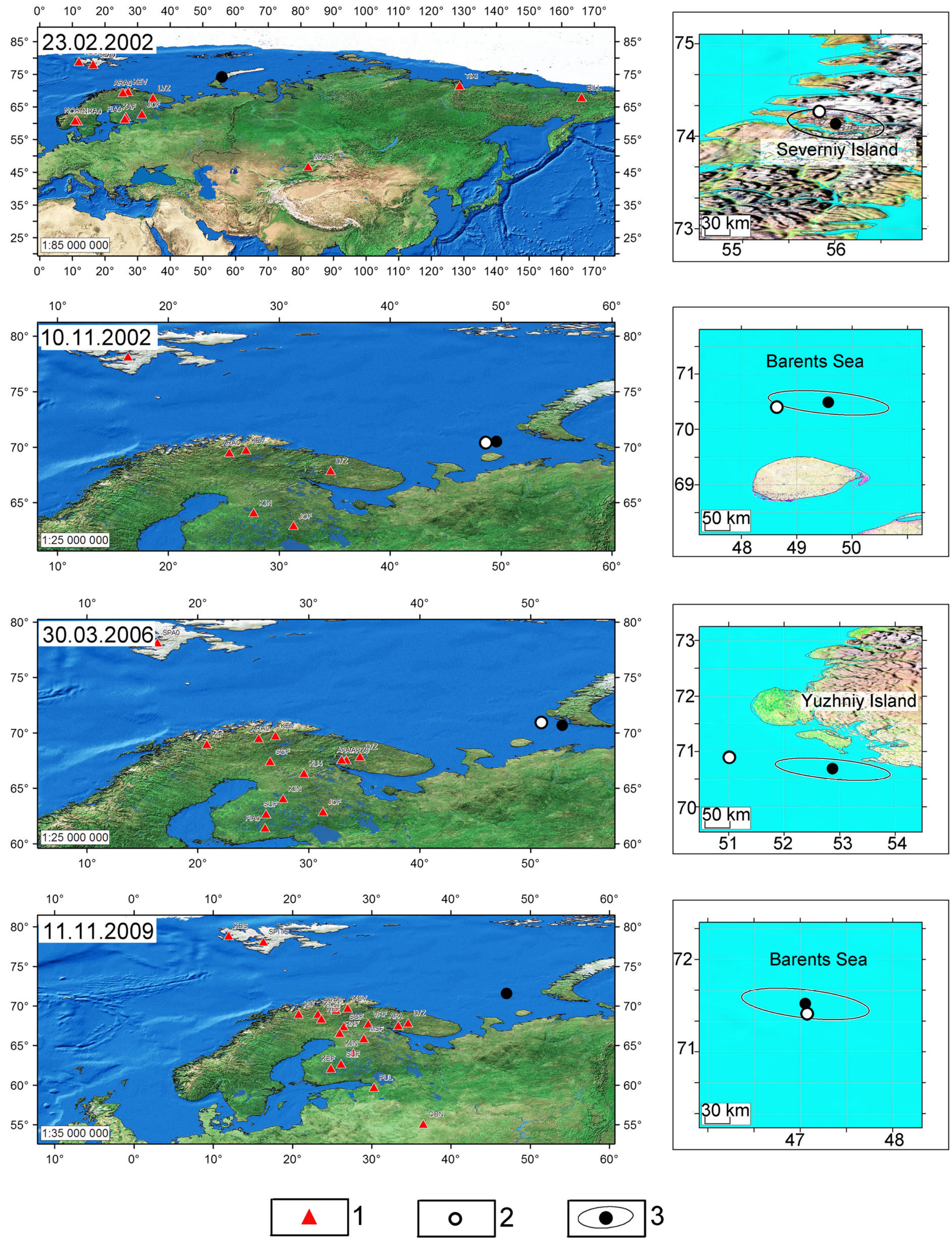

Fig. 5 Maps showing the relocated epicenters of seismic events in the area of the Novaya Zemlya Archipelago: *1* seismic stations; *2* initial coordinates; *3* new coordinates

Table 9 Phase picks for the 10 November 2002

Station Code	Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	Institute of seismology (University of Helsinki)	This study
LVZ	Lovozero, Russia	67.897	34.651	5.6	249.9	–	11:07:09.7	–	+
KEV	Kevo, Finland	69.755	27.007	7.4	275.3	11:06:28.7	11:07:50.1	+	+
ARA0	ARCESS Array Site A0, Norway	69.535	25.506	7.9	274.8	11:06:36.3	11:08:01.9	+	+
JOF	Joensuu, Finland	62.918	31.312	10.1	230.8	11:07:04.4	11:08:53.0	+	+
KJN	Kajaani, Finland	64.085	27.711	10.2	242.1	–	11:08:51.9	+	+
SPA0	Spitsbergen Array Site A0, Norway	78.177	16.370	11.5	326.5	11:07:20.6	11:09:18.9	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

Island. The ISUH calculated the hypocenter based on the following: $N_{stations}$ = 16, gap = 267°. The minimum epicentral distance is 684 km (Table 1).

The waveform data of the LVZ, OBN, and PUL Russian stations were also analyzed in respect to this seismic event. Stations LVZ and PUL detected seismic phases of the seismic event (Table 11). Thus, a relocation procedure was held based on the following: $N_{stations}$ = 18; N_{phases} = 33; gap = 235°. The epicentral distances varied from 623 to 1880 km.

According to the new location of the 2009 seismic event, the epicenter is shifted 11 km to the south with respect to the initial coordinates reported by the ISUH. Thus, the epicenter is located in the Barents Sea 160 km from the shores of Yuzhniy Island. It is impossible to compute the focal depth of the event reliably due to the

Table 10 Phase picks for the 30 March 2006

Station Code	Name, country	Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	ISC	This study
LVZ	Lovozero, Russia	67.897	34.651	6.4	250.3	–	10:46:55.7	+	+
APZ9	Apatity, Russia	67.569	33.405	7.1	250.4	–	10:49:08.7	+	+
APA0	Apatity Array Site A0, Russia	67.606	32.992	7.2	251.4	–	10:49:14.6	+	+
KEV	Kevo, Finland	69.755	27.007	8.2	273.4	10:48:04.2	10:49:35.4	+	+
ARA0	ARCESS Array Site A0, Norway	69.535	25.506	8.7	273.3	10:48:11.2	10:49:49.1	+	+
KU4	Liikasenvaara, Finland	66.365	29.579	9.0	250.2	10: 48:14.0	10:49:53.8	+	+
SGF	Sodankyla, Finland	67.442	26.526	9.3	260.2	–	10:50:02.2	+	+
KIF	Kilpisjarvi, Finland	69.004	20.802	10.5	274.1	10:48:34.5	10:50:30.9	+	+
JOF	Joensuu, Finland	62.918	31.312	11.1	233.5	–	10:50:38.4	+	+
KJN	Kajaani, Finland	64.085	27.711	11.2	243.9	–	10:50:41.8	+	+
SPA0	Spitsbergen Array Site A0, Norway	78.177	16.370	11.5	324.1	10:48:48.1	10:50:50.8	+	+
SUF	Sumiainen, Finland	62.719	26.150	11.8	233.2	–	10:51:17.63	+	+
KBS	Kingsbay, Norway	78.926	11.942	12.6	326.1	10:49:02.0	10:51:19.2	+	+
FIA0	FINESS Array Site A0, Finland	61.443	26.077	13.7	238.8	10:49:14.67	-	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

Table 11 Phase picks for the 11 November 2009

Station		Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	Institute of seismology (University of Helsinki)	This study
Code	Name, country								
LVZ	Lovozero, Russia	67.897	34.651	5.6	236.7	04:19:48.3	04:20:47.2	−	+
APA	Apatity, Russia	67.569	33.405	6.1	235.9	04:19:50.1	04:20:58.1	+	+
KEV	Kevo, Finland	69.755	27.007	6.71	264.4	04:20:01.1	04:21:17.0	+	+
VRF	Varrio, Finland	67.748	29.609	6.98	245.8	04:20:03.0	04:21:20.5	+	+
ARA0	ARCESS Array Site A0, Norway	69.535	25.506	7.28	264.6	04:20:07.6	04:21:28.3	+	+
SGF	Sodankyla, Finland	67.442	26.526	8.09	249.7	04:20:17.9	04:21:47.1	+	+
KTK1	Kautokeino, Norway	69.011	23.237	8.24	263.8	04:20:21.6	04:21:52.6	+	+
HEF	Hetta, Finland	68.408	23.660	8.41	259.6	04:20:22.1	04:21:55.8	+	+
MSF	Maaselka, Finland	65.911	29.040	8.44	237.2	04:20:22.7	04:21:55.0	+	+
RNF	Rovaniemi, Finland	66.609	26.014	8.79	246.3	04:20:27.6	04:22:03.7	+	+
KIF	Kilpisjarvi, Finland	69.004	20.802	9.02	266.5	04:20:31.6	04:22:10.5	+	+
SPITS	Spitsbergen Array Beam Reference Point, Norway	78.177	16.370	10.21	324.2	04:20:45.3	−	+	+
KJN	Kajaani, Finland	64.085	27.711	10.23	232.9	04:20:45.8	04:22:37.3	+	+
KBS	Kingsbay, Norway	78.926	11.942	11.32	326.0.	04:20:59.4	−	+	+
SUF	Sumiainen, Finland	62.719	26.150	11.8	231.9	04:21:06.2	04:23:11.9	+	+
KEF	Keuruu, Finland	62.166	24.866	12.6	232.9	−	04:23:31.4	+	+
PUL	Pulkovo, Russia	59.772	30.322	13.4	218.6	04:21:35.5	04:23:59.0	−	+
OBN	Obninsk, Russia	55.113	36.568	16.9	200.9	04:22:25.8	04:25:32.6	+	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

Table 12 Phase picks for the 04 March 2014

Station		Latitude (°)	Longitude (°)	Distance[a] (°)	Azimuth[a] (°)	*P* pick hh/mm/ss.0	*S* pick hh/mm/ss.0	Arkhangelsk seismic network	This study
Code	Name, country								
AMDE	Amderma, Arkhangel'skaya Oblast', Russia	69.761	61.678	5.2	160.7	04:43:45.2	04:44:37.0	+	+
ZFI2	Zemlya Franca-Iocifa2, Arkhangel'skaya Oblast', Russia	80.809	47.655	6.4	346.9	04:44:08.2	04:45:16.3	+	+
HOPEN	Hopen, Svalbard,Norway	76.510	25.010	8.0	297.9	04:44:28.0	04:45:52.8	+	+
SPA0	Spitsbergen Array Site A0, Norway	78.178	16.370	9.8	309.0	04:44:56.2	04:46:42.0	+	+
KEV	Kevo, Finland	69.755	27.007	10.2	256.0	04:44:59.7	04:46:51.8	+	+
ARE0	ARCESS Array Site E0, Norway	69.535	25.506	10.7	257.1	04:45:10.1	04:47:04.1	+	+
KBS	Kingsbay, Norway	78.926	11.942	10.7	313.2	04:45:07.1	04:47:03.3	+	+
ARU	Arti, Russia	56.429	58.561	18.3	176.8	04:46:45.4	−	−	+
OBN	Obninsk, Russia	55.113	36.568	21.1	213.1	04:47:21.2	−	−	+

[a] Epicentral distances and station azimuths were calculated with respect to the solution of Table 12

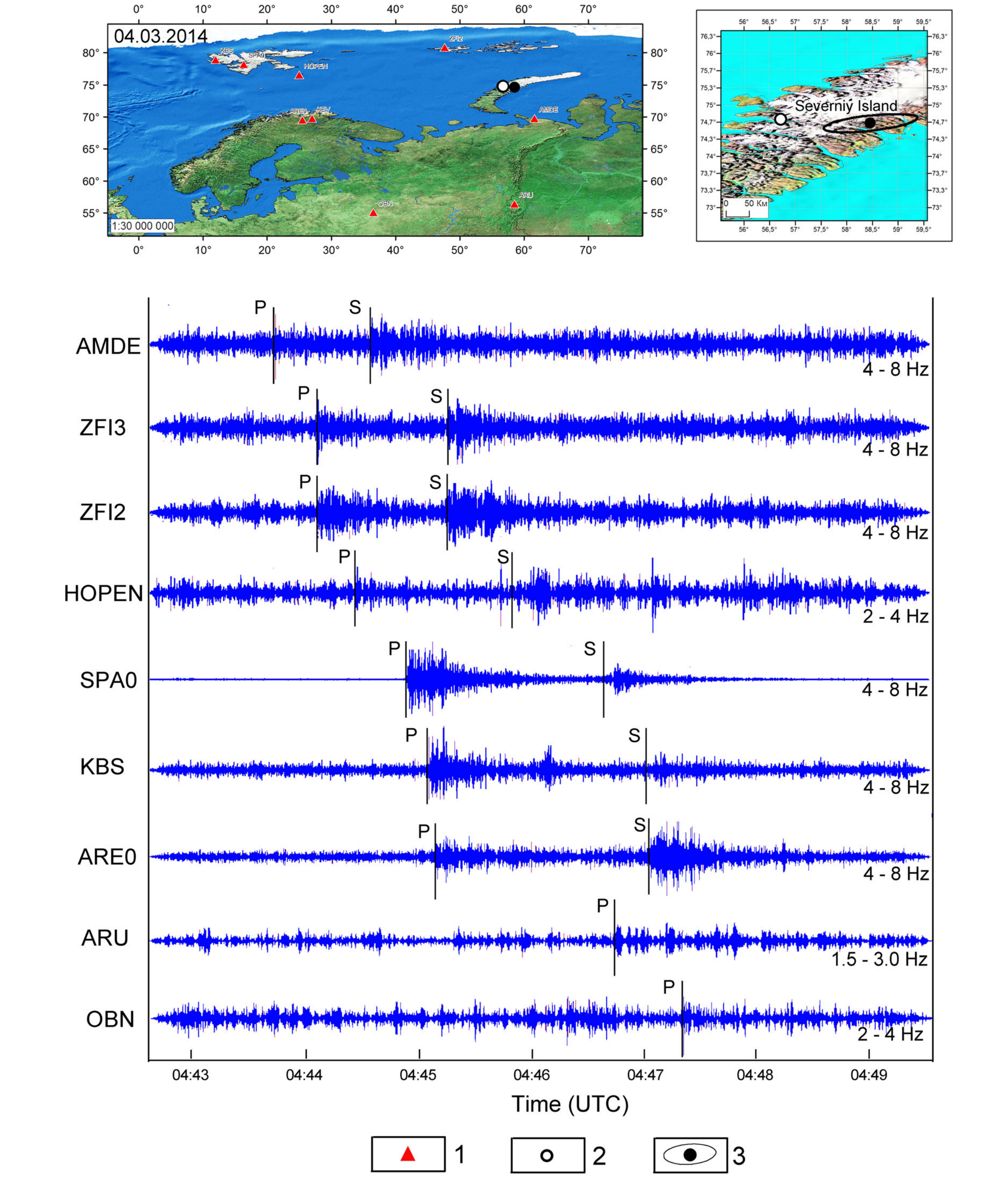

Fig. 6 Maps showing the relocated epicenters of 04.03.2014 seismic event and waveform data: *1* seismic stations; *2* initial coordinates; *3* new coordinates

small number of available stations and phases. The area of the error ellipse is 1304 km^2. The size of the ellipse can be explained by the wide azimuthal gap and the narrow range of epicentral distances (Fig. 5, Table 13). The initial epicenter is located within the error ellipse of the new epicenter. Thus, both solutions are correct.

Table 13 Catalog of relocated seismic events in an area of the Novaya Zemlya Archipelago and adjacent territories over the instrumental observation period

N	Date dd/mm/yyyy	Time hh/mm/ss.0	Hypocenter			Error ellipse			Magnitude			
			φ,°	λ,°	h, km	AzMajor	Rminor	Rmajor	mb (ISC)/MS(ISC)	mb (EIDC)/md (NEIC)	mb (NAO)/ML (NAO)	ML (HEL)/ML(AH)
1	12.12.1974	21:19:39.7	70.83	53.76	(0) 0–40	20	19.5	24.6	4.4/–			
2	15.11.1978	08:30:01.7	73.44	54.69	(0) 0–99	160	43.8	93.5			4.3/–	
3	01.08.1986	13:56:40.1	73.03	56.01	(0) 0–15	170	11.2	17.1	4.8/3.7	–/4.7	4.5/–	
4	13.06.1995	19:22:37.9	75.22	56.74	(0) 0–99	70	21.7	39.8			3.5/–	
5	23.02.2002	01:21:17.6	74.13	56.01	(0) 0–39	150	14.4	20.0	3.0/–		–/3.0	3.1/–
6	10.11.2002	11:04:41.9	70.48	49.58	(99) 0–99	110	21.2	42.3			–/2.0	2.4/–
7	30.03.2006	10:46:02.1	70.68	52.88	(35) 0–99	110	19.0	40.0			–/2.3	2.6/–
8	11.11.2009	04:18:20.2	71.52	47.06	(0) 0–99	120	15.6	26.6				3.2/–
9	04.03.2014	04:42:34.0	74.65	58.45	(40) 0–99	60	14.7	30.0				–/3.3

3.9 04.03.2014 seismic event

The seismic event on March 04, 2014 was registered at the stations of the Arkhangelsk seismic network. Initially, the relocation procedure was performed using the waveform data of the seismic stations belonging to the NORSAR and the Norwegian National Seismic Network (BER network). The epicenter was calculated based on the following: $N_{stations}$ = 4, gap = 309° (Table 1). The epicenter is located in the area of the Mashigina Bay of the Barents Sea on the shores of Severniy Island.

The waveform data of the events from the ARU, LVZ, OBN, NRIL, and ZFI2 Russian stations were analyzed. Waveform data of the KBS (78.9°N/11.9°E) and HOPEN (76.5°N/25.0°E) seismic stations were also analyzed. Seismic phases were identified at the OBN, ARU, KBS, HOPEN, and ZFI stations (Table 12). The ARU and OBN station records are noisy and the phases P are not seen clearly (Fig. 6). The NAS program, due to its generalized beamforming algorithm, ignores those phases that do not match the majority of the others. Such ignored phases do not influence on the event location. For the event 04.03.2014, the program has used the phases of these stations. It means that the phases correspond to the others within the limits of onset picking uncertainties (Δt_p = 0.5 s and Δt_s = 1 s). Thus, a relocation procedure was performed based on the following: $N_{stations}$ = 9; N_{phases} = 16; gap = 174° (Table 12). The epicentral distances varied from 578 and 2346 km.

According to the new location of the 2014 seismic event, the epicenter is shifted 52 km (Fig. 6) to the east compared to the initial one. Thus, the epicenter is located in the sea near the east coast of the Severniy Island. It is impossible to compute the focal depth of the event reliably due to the small number of available stations and phases. The maximum of the rating function is obtained at a depth of 40 km. The area of the error ellipse is 1385 km^2. The size of the ellipse can be explained by the wide azimuthal gap and the narrow range of epicentral distances (Fig. 6, Table 13).

4 Conclusions

We have not found additional seismic phases in the bulletins and waveform data for the 31.12.1992, 13.01.1996, 08.10.2003, 05.03.2006, 14.03.206, 26.06.2007, and 11.06.2010 seismic events shown in Table 1. These events also did not meet our requirements (at least 8 phases by 4 stations), so a relocation procedure was not performed.

We also did not find additional seismic phases in the bulletins and waveform data for the 16.08.1997 and 11.10.2010 seismic events in Table 1. Schweitzer and Kennett (2007) and Gibbons et al. (2016) have obtained satisfactory results based on all available bulletins and waveform data, so a relocation procedure was not performed in this case as well.

The relocation procedure was applied for 9 seismic events registered in the area of the Novaya Zemlya Archipelago (Fig. 7, Table 13). For the 01.08.1986, 13.06.1995, 23.02.2002, and 11.11.2009 events, the initial epicenters are located within the error ellipses of the new epicenters. Thus, both solutions for these events are correct. For the 12.12.1974 and 15.11.1978 events, the epicenters are located in the vicinity of a nuclear test site, which could imply a possible anthropogenic nature. It is impossible to compute the focal depths reliably for most of the seismic events due to the small number of available stations and phases. The 0-km maximum depth of the rated function is inaccurate and must not be taken into account. Other maximums of the rating function are obtained at depths within the Earth's crust.

It is known that to obtain the most realistic location of seismic events, it is necessary to use data of all available seismic stations and correct travel time model. In this study, we have additionally used data from some Russian and Soviet seismic stations that previously were not taken into account for hypocenter calculations. We have considered several travel time models and selected one with the best location accuracy for ground truth events (Novaya Zemlya nuclear explosions). We have evaluated the uncertainties of the velocities specified in the model and this made it possible to estimate correctly (or even slightly overestimate) the errors of location and depth determination. We believe that our results are true within the estimated error intervals.

We deliberately did not try to relate the recalculated epicenters to the active tectonic structures of the Novaya Zemlya Archipelago. Future research will aim to identify the relationship between geological and tectonic processes. The regional seismicity will be based on the overall set of earthquakes that occurred during historic and instrumental periods, as well as paleoearthquake data.

The present results improve our knowledge of seismic activity in the area of the Novaya Zemlya Archipelago. Using for all relocated events, the same velocity

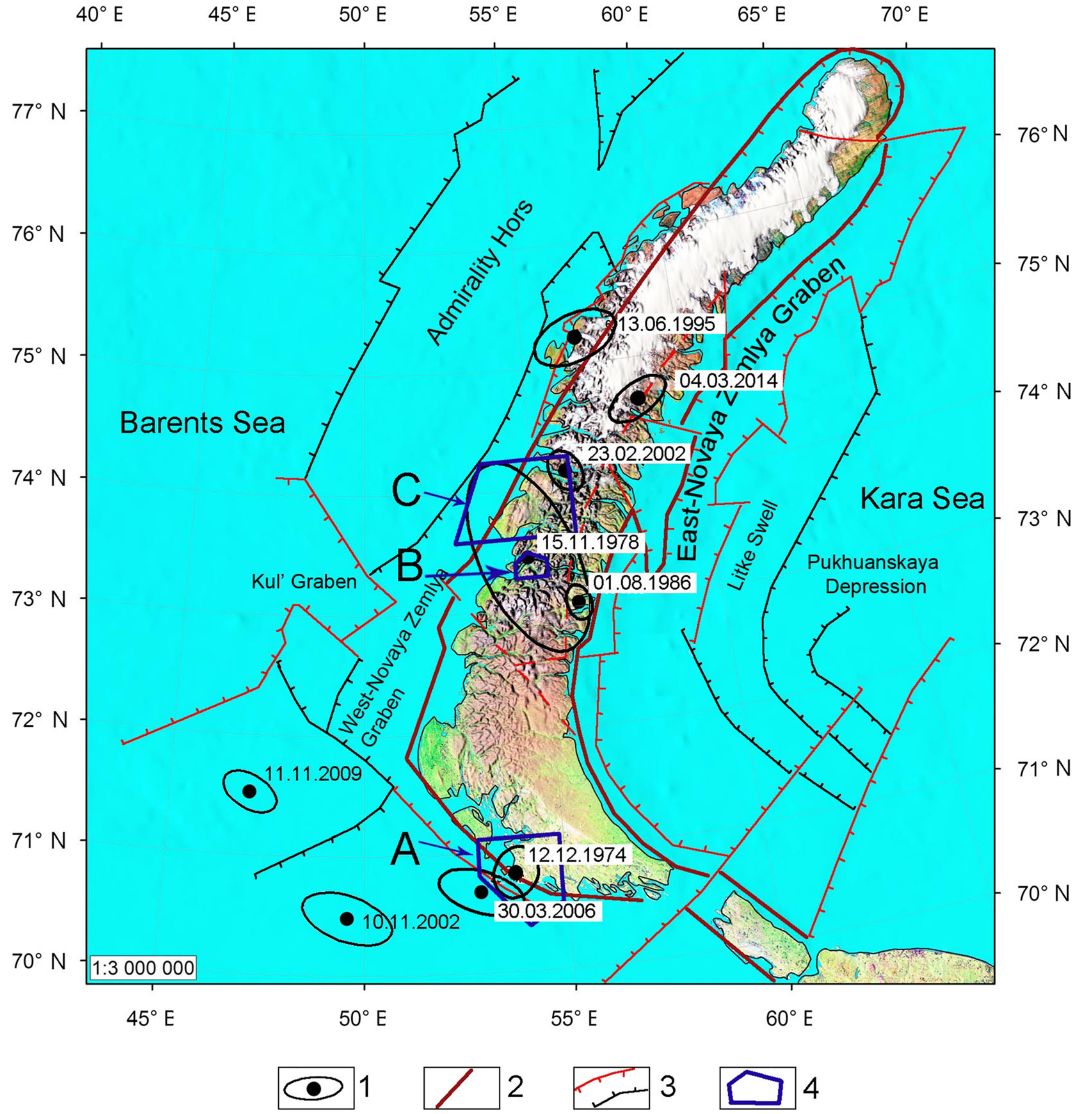

Fig. 7 Map showing the relocated epicenters of seismic events in the area of the Novaya Zemlya Archipelago: *1* new coordinates; *2* main neotectonic faults; *3* borders of neotectonic structures and dislocation with a break of continuity; *4 A*, *B*, and *C* denote three main areas (zones) of military activity (Khalturin et al. 2005): *A* = Guba (Bay) Chernaya. *B* = Guba Mityushikha, south bank of MatochkinShar. *C* = Sukhoy Nos Cape and its vicinity

model, the same methodological approach, and all the currently available waveform data and bulletins allowed us to locate the earthquakes more realistically.

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Data and Resources

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