NORSAR Scientific Report No. 1-2013

Semiannual Technical Summary

1 January – 30 June 2013

Tormod Kværna (Ed.)

Kjeller, December 2013

6.5 Seismological Research Related to Geophysical Processes in the European Arctic

6.5.1 Introduction

The characteristics of earthquake activity in the European Arctic are poorly known, mainly due to the scarcity of high-quality seismic stations in many parts of this region. However, a number of significant earthquakes have been recorded in the last decades, the most recent one occurring on 21 February 2008 in Storfjorden, Spitsbergen (Pirli *et al.*, 2010). This earthquake had magnitude 6.1, which makes it one of the largest instrumentally recorded earthquakes on Norwegian territory. Several thousands of aftershocks were recorded after this earthquake, the aftershock sequence slowly progressing towards its end more than five years later (Pirli *et al.*, 2013). Fortunately, the earthquake occurred offshore, and no injuries or considerable damage to infrastructure was reported, however, its nucleation on a previously unmapped fault underlines the necessity for improved mapping of seismic sources in the region.

Moreover, this earthquake is a reminder that the Svalbard Archipelago and surrounding regions are far more exposed to seismic hazard than the northern Eurasian mainland. Active earthquake zones are found on Heerland and on Nordaustlandet (e.g., Mitchell *et al*., 1990). In addition, there is significant earthquake activity along the Mid-Atlantic Ridge (Knipovich Ridge) about 100-200 km west of Spitsbergen and the Gakkel Ridge, north of the Barents Sea (e.g., Engen *et al*., 2003; Korger and Schlindwein, 2012). The Western Barents Sea south of Svalbard also exhibits frequent earthquake activity (see Fig. 6.5.1), as exemplified by observed events close to the island of Hopen, with magnitudes up to 5.4 (4 July 2003, see e.g., Stange and Schweitzer, 2004).

The eastern part of the Barents Sea is somewhat less exposed to earthquake activity, although an interesting recent event, with a magnitude of 4.6, which is uncharacteristic for the particular region, occurred on 11 October 2010 on the north part of Novaya Zemlya (Kværna and Gibbons, 2011). It should be noted that the monitoring of the eastern Barents Sea has until recently been less than satisfactory due to a shortage of high-quality seismic stations east of the Norwegian border. The situation is now changing, as is further discussed in this paper.

6.5.2 Monitoring the seismicity of the European Arctic

NORSAR has for more than 20 years cooperated with the Kola Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS), situated in Apatity, in seismic and infrasonic monitoring of the western part of the Barents region. This cooperation began with the establishment of a modern seismic array in Apatity, and the most recent of the joint projects has been aiming at improving the seismological infrastructure in the Barentsburg settlement on Spitsbergen (Roth *et al*., 2011). This project was completed by the end of 2012, and the resulting improved infrastructure forms an important component of the seismic network described in this paper.

One of the benefits of the cooperation has been the establishment of several new contact points between Norwegian and Russian scientists. In particular, in 2012 a trilateral agreement for scientific cooperation was signed between NORSAR, the KB GS RAS and the Institute of Environmental Problems of the North of the Ural Branch of the Russian Academy of Sciences (IEPN UB RAS), stationed in Arkhangelsk, Russia. The IEPN UB RAS group operates several seismic stations along the southern shoreline of the Barents Sea between the Kola Peninsula and Novaya Zemlya, and on Franz-Josef Land in the high Arctic (Morozov and Konechnaya, 2013). This network is still under development, and will complement the previously available seismic network.

Fig. 6.5.1 shows locations of seismic stations and arrays in and around the target area from which data are currently available. Russian (triangles) and Norwegian (squares) stations are shown in yellow. We have also access to data from other international stations (red triangles) in the region. The grey symbols show seismic events since 1980 with magnitudes of 2.5 or larger as listed in the event catalogue of the International Seismological Centre - ISC (ISC, 2010).

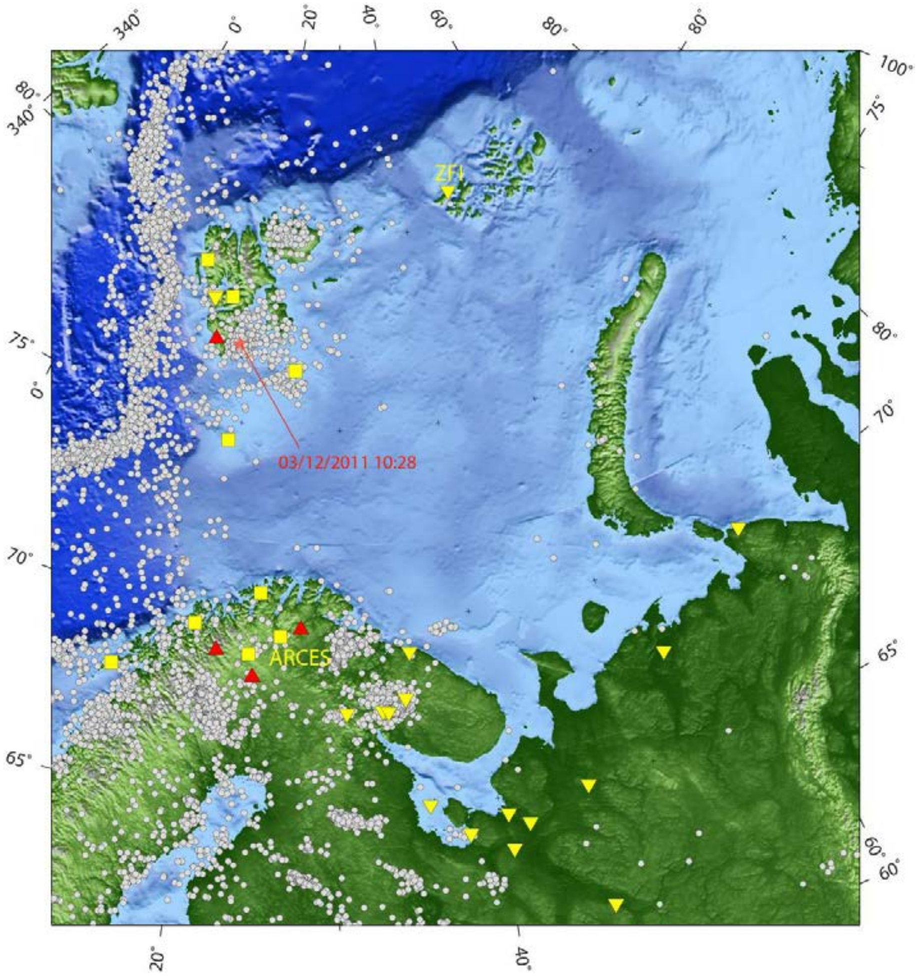

Fig. 6.5.1 Seismic stations (squares and triangles) currently available for monitoring the European Arctic and observed seismicity (circles) in the Barents Sea and the surrounding regions since 1980 (ISC, 2010). Russian stations (triangles) and Norwegian stations (squares) are shown in yellow, while some of the international stations are shown in red. The star notes the location of the earthquake shown in Fig. 6.5 2.

NORSAR is partner in the Norwegian National Seismic Network (NNSN) jointly operated with the Department of Earth Science of the University of Bergen. As NNSN partner NORSAR has free access to all NNSN station data. NORSAR has furthermore access to the data from the International Monitoring System (IMS) for the Comprehensive Nuclear-Test-Ban Treaty (CTBT), and the circum-arctic stations in this system are useful for locating the larger earthquakes in the European Arctic. However, by far the most important contributions for monitoring this region comes from the Norwegian and Russian stations mentioned earlier and shown in Fig. 6.5.1, since monitoring of earthquake activity at low magnitudes requires stations at local or near- regional distances.

6.5.3 Data processing

Currently, data from the station networks of the different institutions (Norwegian and Russian) in the Arctic and around the Barents Sea (see waveform example in Fig. 6.5.2) are separately analyzed at the different institutes. We have begun a process to jointly analyze the data from the combined networks of our three institutions, as further detailed below. In addition, we consider it important to carry out a study of a complete set of all observed data and a common relocation of all events in the region. Such a study should cover both recent historic data (e.g., the last two decades) and current observations, and would result in a more complete seismic bulletin with improved earthquake locations for the entire European Arctic. For a relocation of all events the latest 3D seismic velocity models of the Barents Sea developed at or jointly with NORSAR (Hauser *et al*., 2011; Levshin *et al*., 2007; Ritzmann *et al*., 2007) could be used to achieve a more realistic picture of event distribution and their uncertainties. Alternatively, the RSTT model (Myers *et al*., 2010) can be employed. To achieve this, NORSAR’s existing seismic event location algorithm HYPOSAT (Schweitzer, 2001) could be extended to utilize 3D velocity models. Such a complete, high-quality and up-to-date seismic bulletin of relocated events for the Barents Sea and surrounding areas would constitute the basis for future seismic risk studies in the region and for crustal structure investigations.

To indicate the potential of the joint seismic network to improve the coverage of the European Arctic, we present in Figs.6.5. 3, 6.5.4 and 6.5.5 a comparison based on the first six months of 2013 between the Reviewed Event Bulletin of the CTBT International Data Centre (Fig. 6.5 3), the NORSAR reviewed regional seismic bulletin using data from Fennoscandia, Spitsbergen and the Kola Peninsula (Fig. 6.5 4), and the bulletin produced by IEPN UB RAS using data from their own network (Morozov and Konechnaya, 2013) in combination with the data used to produce the NORSAR bulletin (Fig. 6.6 5).

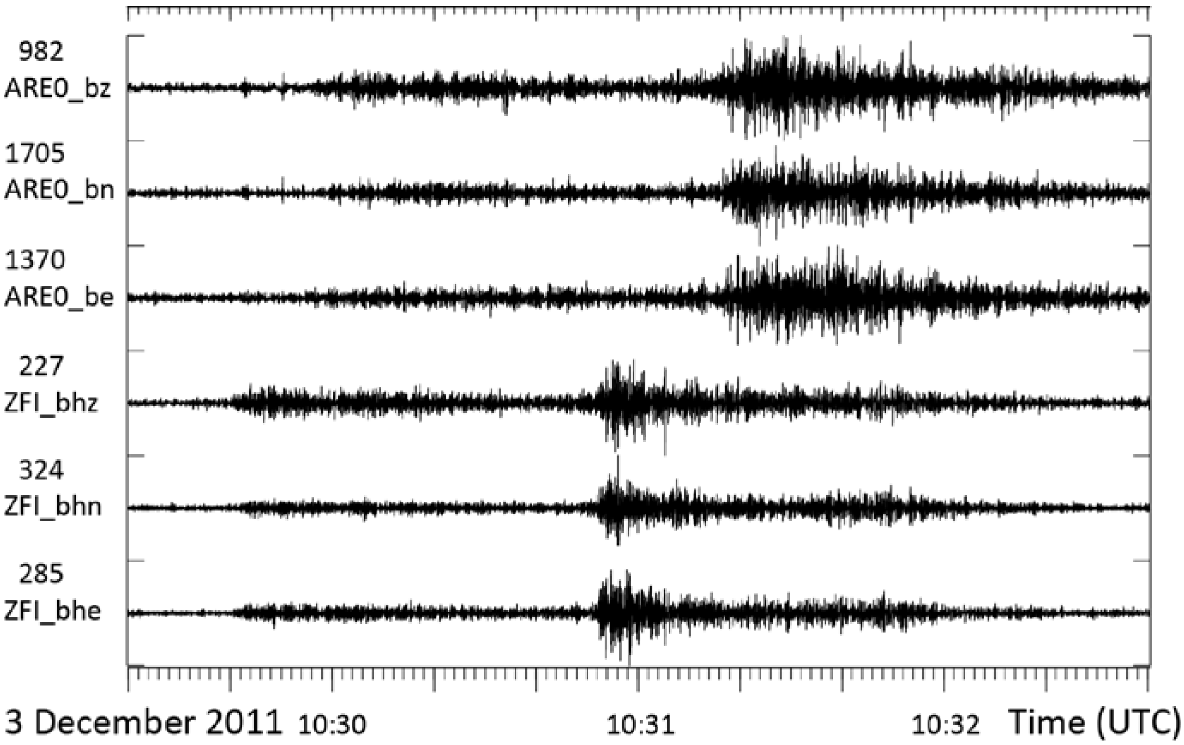

Fig. 6.5.2 Seismograms of a low magnitude (M = 2.9) aftershock from the 2008 – 2012 Storfjorden sequence as recorded at one site of the Norwegian seismic array ARCES (ARE0) in Finnmark and at the Russian seismic 3-component station on Franz-Josef Land (ZFI) in the high Arctic. Both stations are located at comparable distances from the activity in Storfjorden. Note the high data quality of the records at ZFI, which is comparable to that of ARCES – one of the highest quality stations in the CTBT International Monitoring System. The location of the event and the two stations are shown in Fig. 6.5.1.

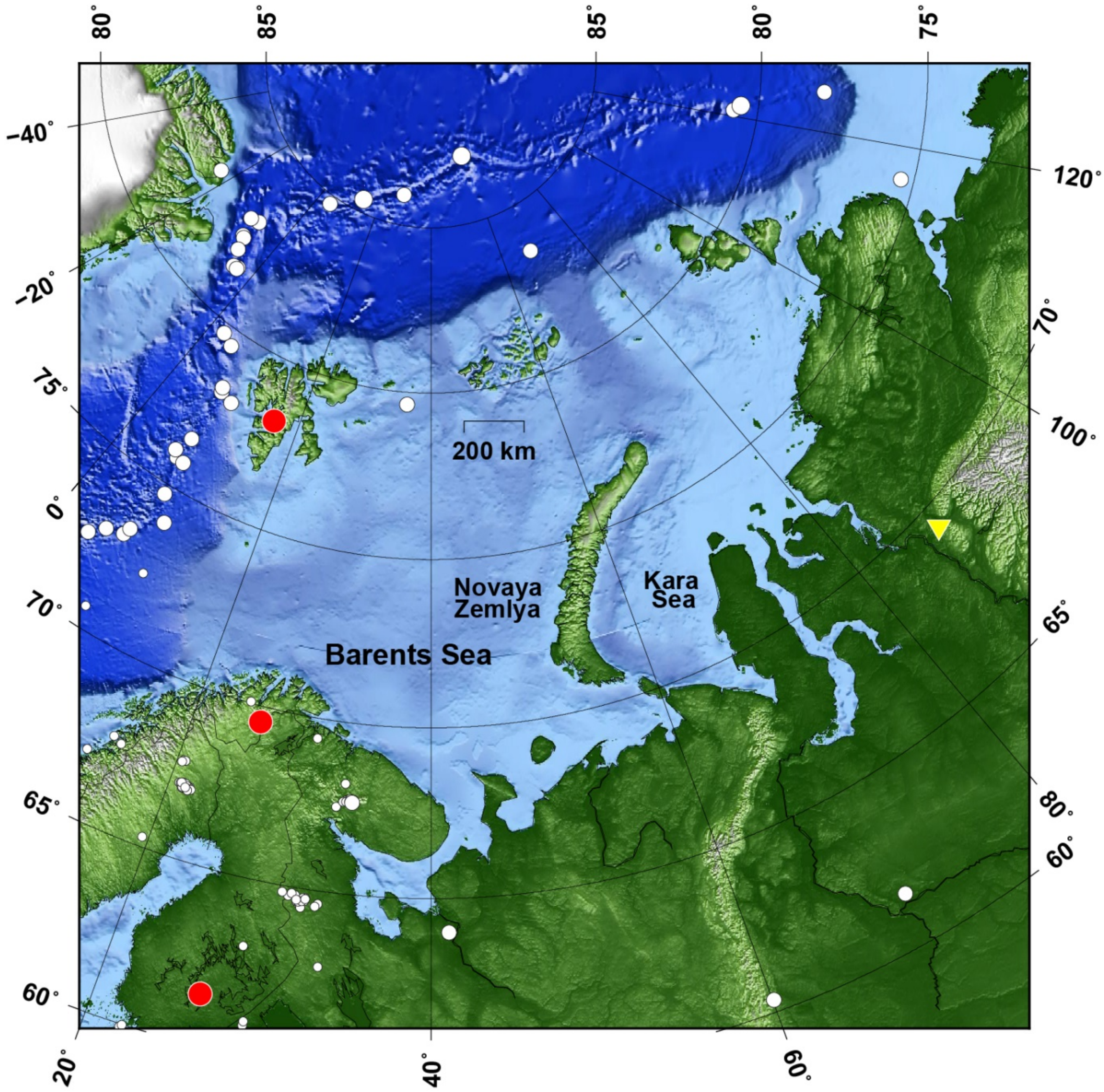

Fig. 6.5 3 Seismic events (white dots) listed in the Reviewed Event Bulletin (REB) of the CTBT International Data Centre (IDC). The size of the event symbols is scaled with magnitude and spans in this figure the magnitude range between 3 and 5. The figure covers data from the first 6 months of 2013. The red dots denote the IMS seismic arrays in the region, and the yellow triangle denotes an IMS 3-component seismic station (Norilsk). Note that the array on Spitsbergen is an IMS auxiliary station, while the other facilities are IMS primary stations. Also note that the IMS network covers the entire globe, although the stations shown here provide the main contributions to recording of seismicity in the European Arctic.

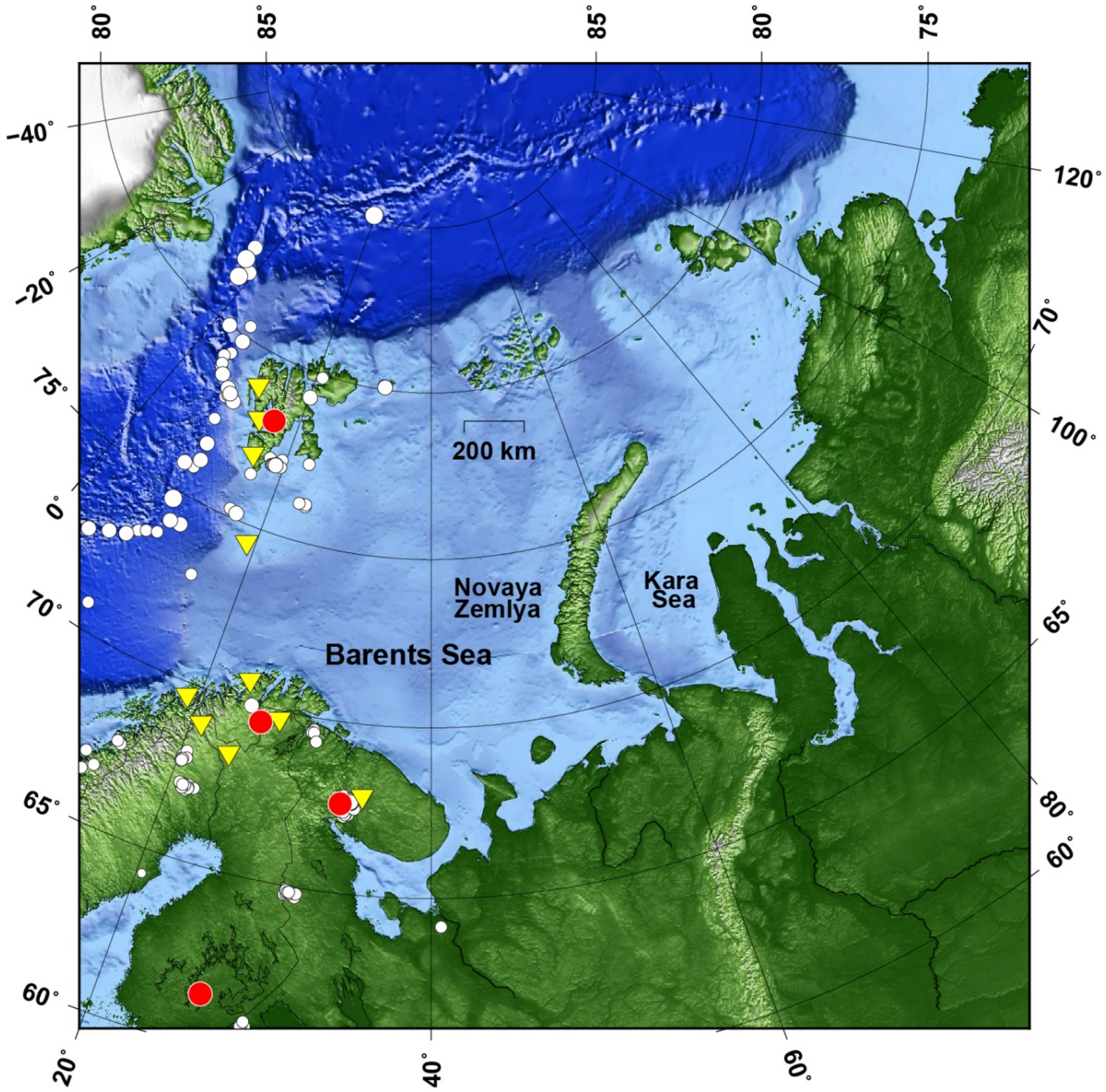

Fig. 6.5.4 *Seismic events (white dots) listed in the reviewed regional seismic bulletin issued by NORSAR. This bulletin makes use of stations in Fennoscandia, Spitsbergen and the Kola Peninsula. The figure covers data from the first 6 months of 2013. The red dots denote seismic arrays and the yellow triangles denote 3-component seismic stations. Some additional stations in Fennoscandia which provide minor contributions to this bulletin are not shown on the map.*

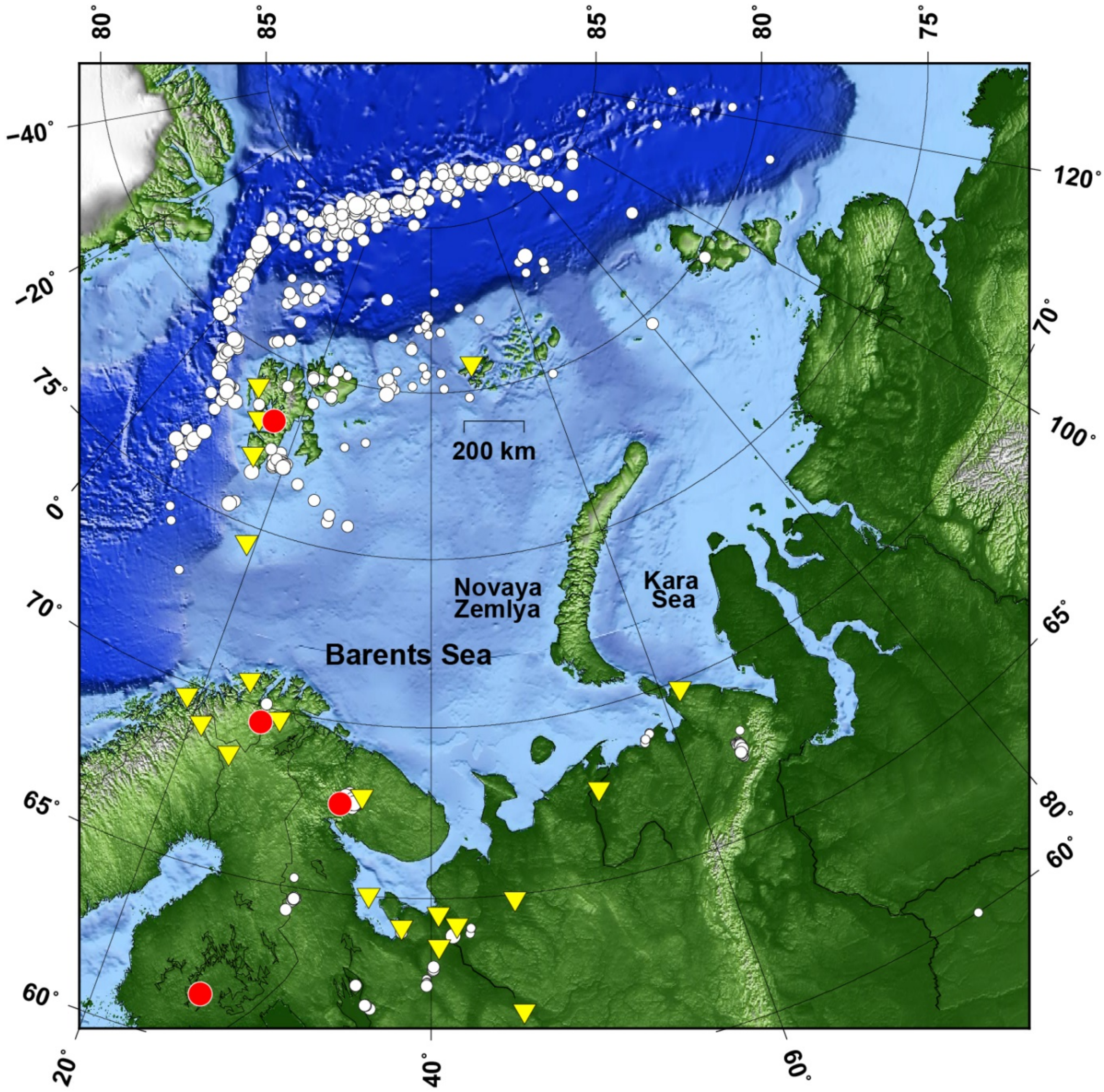

Fig. 6.5 5 Seismic events (white dots) listed in the bulletin produced by the Arkhangelsk data center. This bulletin is based on data from the stations used to produce the NORSAR regional bulletin (Fig. 6.5 4) as well as the Arkhangelsk seismic network. The figure covers data from the first 6 months of 2013. The red dots denote seismic arrays and the yellow triangles denote 3-component seismic stations. Note the remarkable increase in recorded seismicity compared to Figs. 6.5.3 and 6.5.4, especially along the Gakkel Ridge north of Spitsbergen and Franz-Josef Land.

It is important to be aware that the criteria for event definition are different in the three cases. The REB has the strongest requirement for including a seismic event in the bulletin (3 primary IMS stations), whereas the NORSAR bulletin requires at least two arrays with P-wave detections and additionally at least one detected S-wave, further restricting the dataset by the application of a magnitude threshold of 2. The Arkhangelsk event list includes also events detected by only one station (requiring in such cases both a P and an S phase).

When comparing the three maps in Figs. 6.5.3-6.5.5, we note that the REB and the NORSAR bulletin are quite similar, which is not so surprising given that the three most sensitive seismic arrays in Fennoscandia (ARCES, SPITS and FINES) are part of the International Monitoring System (IMS) network. The REB has a few more events than the NORSAR bulletin in the far north, whereas the NORSAR bulletin has more events in Svalbard and on the mainland. It can also be noted (although not illustrated here) that the more complete Late Event Bulletin (LEB) issued by the IDC, which has a more relaxed event definition threshold than the REB, still has only a few additional events compared to the REB.

We note that the addition of the Arkhangelsk network leads to a considerable increase in the number of located seismic events. This is particularly pronounced along the Gakkel Ridge to the north of the Svalbard and Franz-Josef Land archipelagos. A closer investigation shows that these additional events in the High Arctic are included due to the contribution from the station ZFI on Franz-Josef Land. These events are either located by ZFI in combination with the Spitsbergen stations SPITS or KBS, or in some cases located using P and S phases from ZFI alone. We also note that the vast majority of the events along the Gakkel Ridge have been located slightly to the south of the ridge. We interpret this as an effect of the lack of recording stations closer to and north of the Gakkel Ridge, and the use of a one-dimensional velocity model which is not fully representative for travel-times along observed propagation paths.

Fig. 6.5.6 shows an example of three-component recordings of a low-magnitude Gakkel Ridge earthquake (ML=2.6) from the Spitsbergen array center site and from the station ZFI on Franz-Josef Land. ZFI is closer to the earthquake epicenter and has a higher signal-to-noise ratio (SNR) than the SPITS central site. However, the SPITS array beam (not shown) achieves a similar SNR to the ZFI station for the P-phase. It appears that these two stations in combination would be capable of detecting and locating earthquakes in this area even down to about a full magnitude unit below that of the event shown in Fig. 6.5.6.

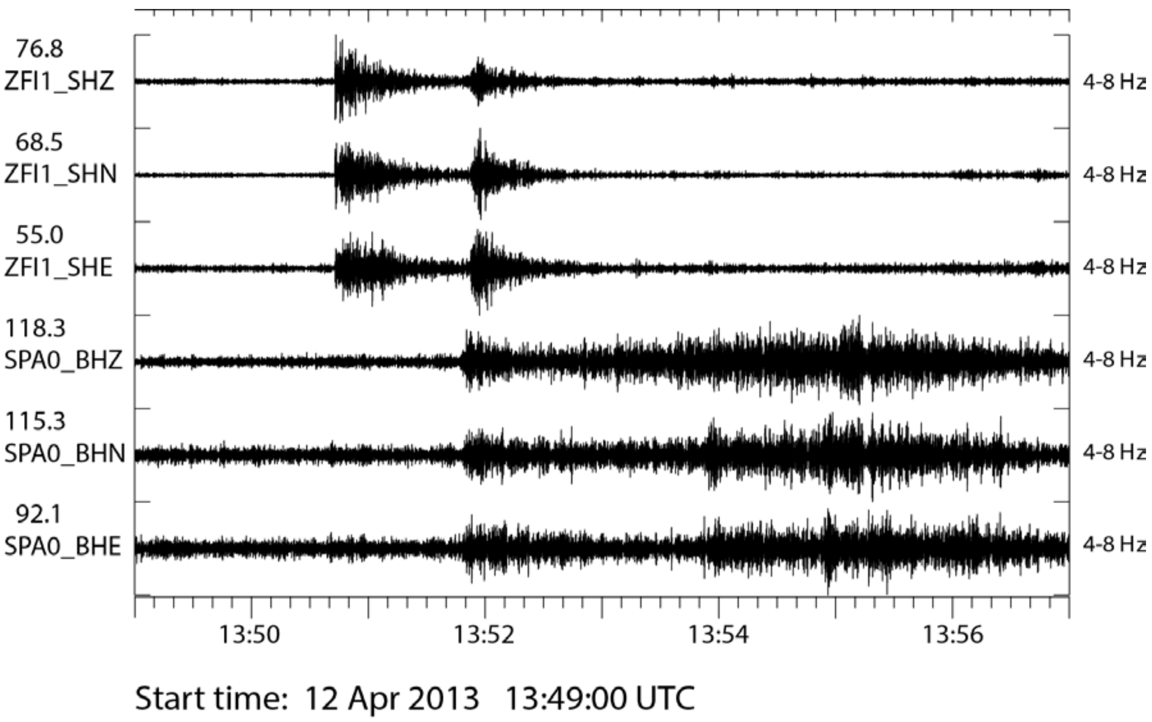

Fig. 6.5.6 Seismograms of an earthquake on the Gakkel Ridge recorded at the Russian seismic 3-component station on Franz-Josef Land (ZFI) and the central site (SPA0) of the Spitsbergen array (SPITS). The ZFI station is located somewhat closer to the event than SPITS. Note the high signal-to-noise ratios at both stations.

In contrast to ZFI, the other stations in the Arkhangelsk network mainly contribute to record events at local distances from those stations. Thus, the six-month bulletin contains several hundred mining related events near Vorkuta, all of them recorded by the Amderma station, as well as a number of mining related events south of Arkhangelsk. Only very few such events are detected by stations contributing to the NORSAR bulletin.

Another potential contribution of the Arkhangelsk network is the overall improvement in event detection capability in the Barents Sea region. The fact that only very few events in the Eastern Barents Sea are included in the Arkhangelsk bulletin (none during the six month period studied here), is important by itself, since this network can be expected to have a superior detection capability for this region compared to either the Fennoscandian network or the International Monitoring System. This would be important for e.g. assessing the 'background seismicity' of the region, since even in the absence of recorded seismic events a high detection capability would provide a strong constraint on the seismic background level in the region. We have at this stage not attempted to quantify the detection capability of the joint networks, but as more data is accumulated, this will be an interesting topic for future studies. In any case, the addition of the Arkhangelsk network to the previously existing networks has the potential of providing a considerable improvement in the monitoring of seismicity in the European Arctic region, both in terms of detecting and locating additional seismic events and with regard to establishing a baseline for the seismic background level.

6.5.4 Developing a joint seismic bulletin

With the perspective of this increased potential in mind, the primary objective of the continued cooperation among the three parties is to produce a very high quality reviewed seismic bulletin for the Barents Sea and surrounding areas. This will be an important contribution to all future seismic risk studies in the region, and will also provide a baseline for future studies of microseismicity during oil and gas extraction. It will require the full use of the networks operated by the Norwegian and Russian partners, in combination with other available data. Additional seismic stations, which are planned to be installed in the region, may in the future contribute to a further improvement of the monitoring capability.

From a technical point of view, the emphasis of the cooperation will be on maintaining high quality operation and joint processing of the data from the existing station networks. For some of the stations in the networks, data transmission is already in place, but for most of the newer stations (Morozov and Konechnaya, 2013) this is not the case. In those cases, we will maintain the on-site recording of seismic signals, with the aim to join all data in a common database with free access for all partners.

6.5.5 Conclusions and future perspectives

The cooperation among NORSAR, the Kola Branch and the Arkhangelsk Branch of the RAS involves joint seismological research related to geophysical processes in the European Arctic, using the combined seismic networks of the parties, as well as other available seismic stations in the region. Such research will contribute to a vastly improved mapping of the seismicity in the European Arctic and to achieving a more accurate baseline for background seismicity in the region. This is important for establishing the level of earthquake risk in this environmentally sensitive region, in particular when considering possible future exploration activities for oil and gas, while it is also crucial for the possibility to monitor microseismicity in connection with future hydrocarbon exploitation.

The application of microseismic recording methods for studying production and injection responses of reservoirs both for production optimization and for safety reasons is increasing in the hydrocarbon exploration industry. For the successful interpretation and utilization of microseismic recordings, the knowledge of the background seismicity (i.e., the spatiotemporal distribution of naturally occurring seismic events) is crucial. The low magnitude seismic activity in the European Arctic is poorly known, but can be significantly improved by establishing the appropriate cooperative seismic recording infrastructures as discussed in this paper.

Galina Antonovskaya **IEPN UB RAS**
Yana Konechnaya **IEPN UB RAS**
Elena O. Kremenetskaya **KB GS RAS**
Vladimir Asming **KB GS RAS**
Tormod Kværna **NORSAR**
Johannes Schweitzer **NORSAR**
Myrto Pirli **NORSAR**
Frode Ringdal **NORSAR**

References

Engen, Ø., O. Eldholm and H. Bungum (2003). The Arctic plate boundary. *J. Geophys. Res*., **108**(B2), doi:10.1029/2002JB001809.

Hauser, J., K.M. Dyer, M.E. Pasyanos, H. Bungum, J.I. Faleide, S.A. Clarck and J. Schweitzer (2011). A probabilistic seismic model for the European Arctic. *J. Geophys. Res*., **116**, B01303, doi: 10.1029/2010JB007889.

International Seismological Centre (2010). On-line Bulletin, http:// www.isc.ac.uk, *Internatl. Seis. Cent.*, Thatcham, United Kingdom.

Korger, E.I.M. and V. Schlindwein (2012). Performance of localization algorithms for teleseismic mid-ocean ridge earthquakes: the 1999 Gakkel Ridge earthquake swarm and its geological interpretation. *Geophys. J. Int.*, **188**(2), 613-625.

Kværna, T. and S.J. Gibbons (2011). The Novaya Zemlya event on 11 October 2010. *NORSAR Sci. Rep*., 2-2011, 36-43.

Levshin, A., J. Schweitzer, C. Weidle, N. Shapiro and M. Ritzwoller (2007). Surface wave tomography of the Barents Sea and surrounding regions. *Geophys. J. Int*., **170**, 441-459.

Mitchell, B.J., H. Bungum, W.W. Chan and P.B. Mitchell (1990). Seismicity and present-day tectonics of the Svalbard region.*Geophys. J. Int*., **102**, 139-149.

Morozov, A.N. and Y.V. Konechnaya (2013). Monitoring of the Arctic region: contribution of the Arkhangelsk seismic network. *J. Seismol*., **17**, 819-827.

Myers, S.C., M.L. Begnaud, S. Ballard, M.E. Pasyanos, W.S. Phillips, A.L. Ramirez, M.S. Antolik, K.D. Hutchenson, J.J. Dwyer, C.A. Rowe and G.S. Wagner (2010). A crust and upper-mantle model of Eurasia and North Africa for Pn travel- time calculation. *Bull. Seism. Soc. Am*., **100**(2), 640-656, doi: 10.1785/0120090198.

Pirli, M., J. Schweitzer, L. Ottemöller, M. Raeesi, R. Mjelde, K. Atakan, A. Guterch, S. J. Gibbons, B. Paulsen, W. Dębski, P. Wiejacz and T. Kværna (2010). Preliminary analysis of the 21 February 2008 Svalbard (Norway) seismic sequence. *Seism. Res. Lett*., **81**(1), 63-75, doi: 10.1785/gssrl.81.1.63.

Pirli, M., J. Schweitzer and B. Paulsen (2013). The Storfjorden, Svalbard, 2008-2012 aftershock sequence: Seismotectonics in a polar environment. *Tectonophysics*, **601**, 192-205.

Ritzmann, O., N. Maercklin, J.I. Faleide, H. Bungum, W.D. Mooney and S.T. Detweiler (2007). A 3D geophysical model for the crust in the greater Barents Sea region: Database compilation, model construction and basement characterization. *Geophys. J. Int*., **170**, 417-435.

Roth, M., M. Pirli, J. Schweitzer and E. Kremenetskaya (2011). Installation of the seismic broadband station in Barentsburg, Svalbard. *NORSAR Sci. Rep.* 1-2011, 53-60.

Schweitzer, J. (2001). HYPOSAT – an enhanced routine to locate seismic events. *Pure Appl. Geophys*., **158**, 277-289.

Stange, S. and J. Schweitzer (2004). Source depths at regional distances: An example from the western Barents Sea/Svalbard region. *NORSAR Sci. Rep*., 1-2004, 45-50.