

**RESEARCH IN REGIONAL SEISMIC MONITORING**

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**ABSTRACT**

This project represents a continuing effort to use data from the regional networks operated by NORSAR and the Kola Regional Seismological Centre (KRSC) to assess the seismicity and characteristics of regional phases of the European Arctic. Recently, seismic instrumentation has been installed inside the mines in the Khibiny Massif of the Kola peninsula in order to provide origin times of the seismic events as well as to contribute to additional validation of the location accuracy. We are now planning to expand this effort by collecting similar ground truth information for other mines in the Kola Peninsula, Spitsbergen and NW Russia. We present some initial ground truth information from rockbursts/earthquakes in a coal mine in Spitsbergen (Barentsburg). A 3-component digital seismometer system was installed in this mine in November 2000, and we present results of locating these rockbursts. The largest of these events are well recorded by the International Monitoring System (IMS) arrays SPITS and ARCES, and can therefore be useful for IMS calibration purposes.

Another area of interest for calibration is the northern Ural Mountains, where there is significant mining activity. The Amderma station, which is operated by KRSC, routinely detects a large number of mining explosions in mines near Vorkuta, and examples of such event recordings are presented. The largest of these events are also observed at the Fennoscandian arrays, especially ARCES, although they are seldom large enough to be included in the Reviewed Event Bulletin (REB), which currently requires P-detection by at least three primary IMS stations. Nevertheless, the detection, location and screening of such small events, even when observed by only a single station, are of interest in a global monitoring situation. The provision of ground truth of selected explosions and/or rockbursts in this area will help in calibrating the ARCES array (and possibly other stations) for such monitoring purpose.

The seismic events associated with the tragic accident of the "Kursk" submarine in the Barents Sea in August 2000 were recorded on several IMS stations. Observations from these stations have proved to be important in determining the sequence, characteristics and timing of these events. During the months following the accident, the Russian Navy carried out a number of underwater explosions in the Barents Sea near the site, and preliminary results from locating these events will be presented.

A workshop was held in Oslo, Norway, during 23-27 April 2001 in support of the global seismic event location calibration effort currently being undertaken by PrepCom's Working Group B in Vienna. The workshop, which was chaired by Dr. Frode Ringdal, was attended by 65 scientists from 14 countries and the Provisional Technical Secretariat of the CTBTO. Among the contributions were recent results provided by NORSAR and KRSC of our joint regional calibration effort in the European Arctic, which includes ground-truth data and regional models applicable to a number of IMS stations in this region.

**KEY WORDS:** detection, location, calibration, rockbursts, explosions, earthquakes

## **OBJECTIVE**

This work represents a continued effort in seismic monitoring, with emphasis on studying earthquakes and explosions in the Barents/Kara Sea region, which includes the Russian nuclear test site at Novaya Zemlya. The overall objective is to characterize the seismicity of this region, to investigate the detection and location capability of regional seismic networks and to study various methods for screening and identifying seismic events in order to improve monitoring of the Comprehensive Nuclear-Test-Ban Treaty. An important part of the work is contributions toward the international effort to provide regional location calibration of the International Monitoring System.

## **RESEARCH ACCOMPLISHED**

### **Introduction**

NORSAR and Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences have for many years cooperated in the continuous monitoring of seismic events in North-West Russia and adjacent sea areas. The research has been based on data from a network of sensitive regional arrays which has been installed in northern Europe during the last decade in preparation for the International Monitoring System (IMS). This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia, provides a detection capability for the Barents/Kara Sea region that is close to  $m_b = 2.5$  (Ringdal, 1997).

The research carried out during this effort is documented in detail in several contributions contained in the NORSAR Semi-Annual Technical Summaries. In the present paper we will limit the discussions to some recent results of interest in the general context of regional monitoring of seismic events in the European Arctic and also some results relevant to the location calibration effort currently underway for the IMS.

### **Amderma station**

The seismic station at Amderma is a key monitoring resource for the Kara Sea region. We have carried out a study of regional events detected by this station during the years 1994-1998. This study confirms that the occurrence of seismic events in the Kara Sea and adjacent regions is very low, with the notable exception of the Vorkuta area south of Amderma. Most of the events in the Vorkuta area are assumed to be mining explosions. We have found a few previously unknown seismic events in the Kara Sea region, all at magnitude 2.5 or below. We have made no attempt to discriminate the source type of these events.

Our results indicate a detection threshold of about ML 1.8-2.0 for the Amderma station at an epicentral distance of 300-400 km. This is the distance to the two Kara Sea events on 16 August 1997 (toward the north), and also the distance to the Vorkuta mining area south of the station. The study confirms that the Amderma station provides a very useful supplement to the Fennoscandian array network in monitoring the Kara Sea/Novaya Zemlya region.

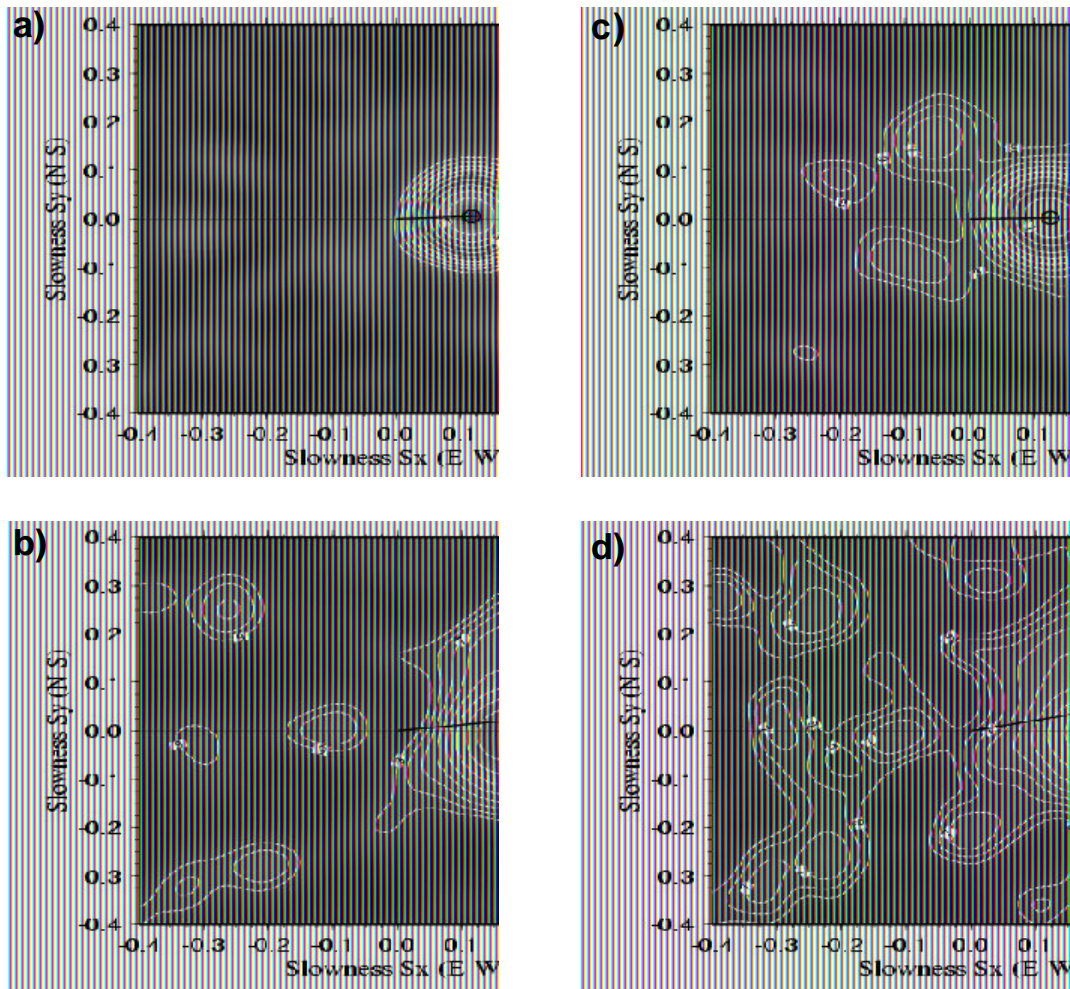
### **The Kursk disaster in August 2000**

On 12 August 2000 signals from two presumed underwater explosions in the Barents Sea were recorded by Norwegian seismic stations. The first of these, at 07.28.27 GMT, was relatively small, measuring 1.5 on the Richter scale. The second explosion, 2 minutes and 15 seconds later, was much more powerful, with a Richter magnitude of 3.5. It soon became clear that these seismic events were associated with the sinking of the Russian submarine "Kursk". NORSAR informed Norwegian authorities after analyzing the recordings, and published selected analysis results on the Internet through NORSAR's Web page ([www.norsar.no](http://www.norsar.no)).

The large underwater explosion on 12 August 2000 in the Barents Sea was located fully automatically by NORSAR's Generalized Beamforming process (GBF) with an estimated location only 14 km from the known position of the submarine. The GBF process is running on-line at NORSAR for the purpose of providing trial epicenters of seismic events in Europe and the European Arctic. Later interactive analysis gave a

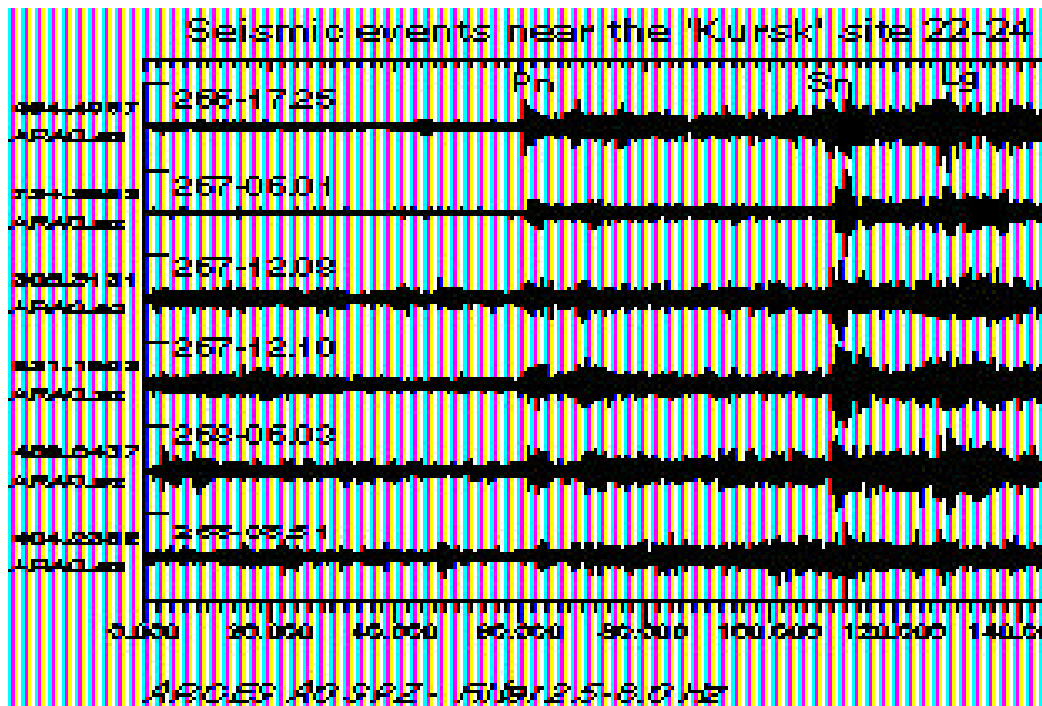
position that was as close as 5 km from the site of the accident. This high accuracy is due to the travel-time calibration available for the Barents region, as provided by the Fennoscandian/Barents velocity model.

The fact that the large explosion was preceded by a much smaller co-located event was noted by reviewing the GBF automatic output in more detail. It turned out that this smaller event was detected by the ARCES array in northern Norway. For obvious reasons, the automatic location estimate was less accurate than that of the larger event, but still close enough to the Kursk site to be associated with the accident. The similarity of the kinematic parameters of the two events can be seen in Figure 1, which shows f-k analysis results of the Pn and Sn phases of each event. It is noteworthy that the azimuth bias between the Pn and Sn phases are almost exactly the same for the two events. This confirms previous studies indicating that azimuth calibration of each phase should be done individually to obtain optimum location estimates for a given site. It also demonstrates that even very weak events can be located with high accuracy in areas where sufficient calibration information is available.



**Figure 1.** Frequency-wavenumber (f-k) plots of the Pn and Sn phases at ARCES for the two events on 12 August 2000. The labels a) and b) correspond to the Pn and Sn phases for the large event, whereas c) and d) correspond to the small event. Note the similarity of the two cases. In particular, both events show the same difference between apparent P-azimuth and apparent S-azimuth.

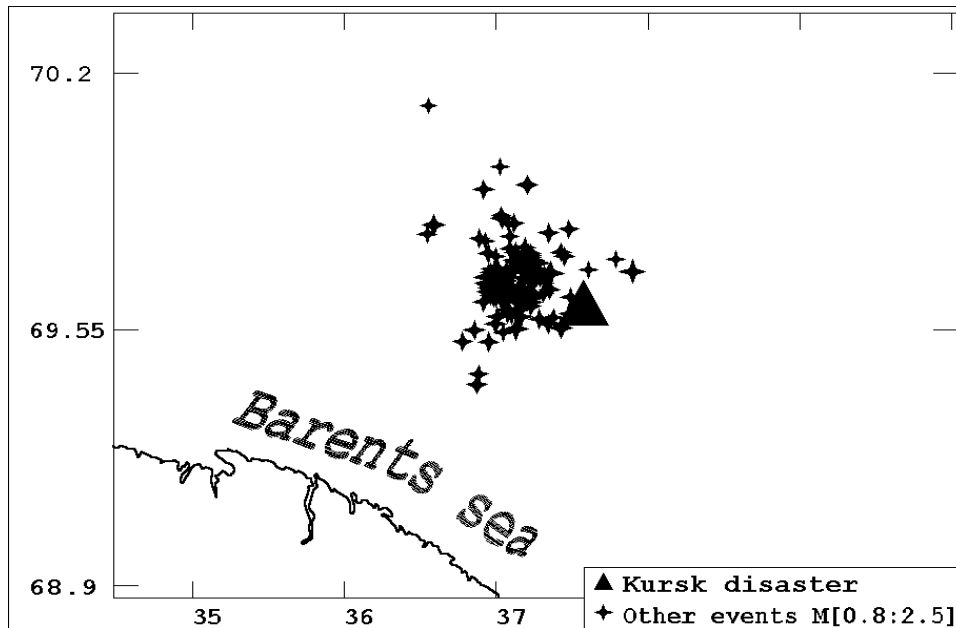
The area in the Barents Sea where the Kursk accident occurred has no known history of significant earthquake activity. Beginning in September 2000, numerous seismic events were detected in the area. The circumstances surrounding these events were initially unknown, but on 14 November 2000, the Russian authorities announced that the events were small explosions set off using grenades or depth charges, with the stated purpose to protect the Kursk submarine. Waveforms for six such explosions during 22-24 September 2000 are shown in Figure 2. These explosions were all quite small (around magnitude 1.5 on the NORSAR GBF scale), but were nevertheless seen clearly even on single ARCES seismometer recordings. They were also detected by the FINES and Apatity arrays, with a somewhat lower signal-to-noise ratio.



**Figure 2.** Waveforms for 6 small explosions near the Kursk site, as recorded on the center seismometer of the ARCES array in Finnmark, northern Norway. The data have been filtered in the band 2.5-8 Hz.

Figure 3 shows NORSAR's locations of 117 explosions detected during the period September 2000 - February 2001. The locations are based on interactive analysis of the data, and are therefore more accurate than the automatic GBF-based results. Naturally, the locations of the larger events are more accurate than those of the smaller events, and the majority of well-located events are concentrated in a cluster 10-20 km NW of the Kursk site. The magnitudes according to the NORSAR GBF scale range from 0.8 to 2.5.

The recording of the numerous small explosions near the Kursk site confirms the value of the IMS stations in monitoring seismic activity in the Barents Sea at very low magnitude levels. These explosions were particularly well recorded by the ARCES array (distance 500 km), but also the FINES, SPITS and NORES arrays detected several of the events. In addition, the Apatity array station in the Kola Peninsula (not an IMS station) provided useful recordings.



**Figure 3.** Locations of 117 underwater explosions near the Kursk site from September 2000 through February 2001. The site (true location) of the accident is marked with a triangle.

### **Spitsbergen mining events**

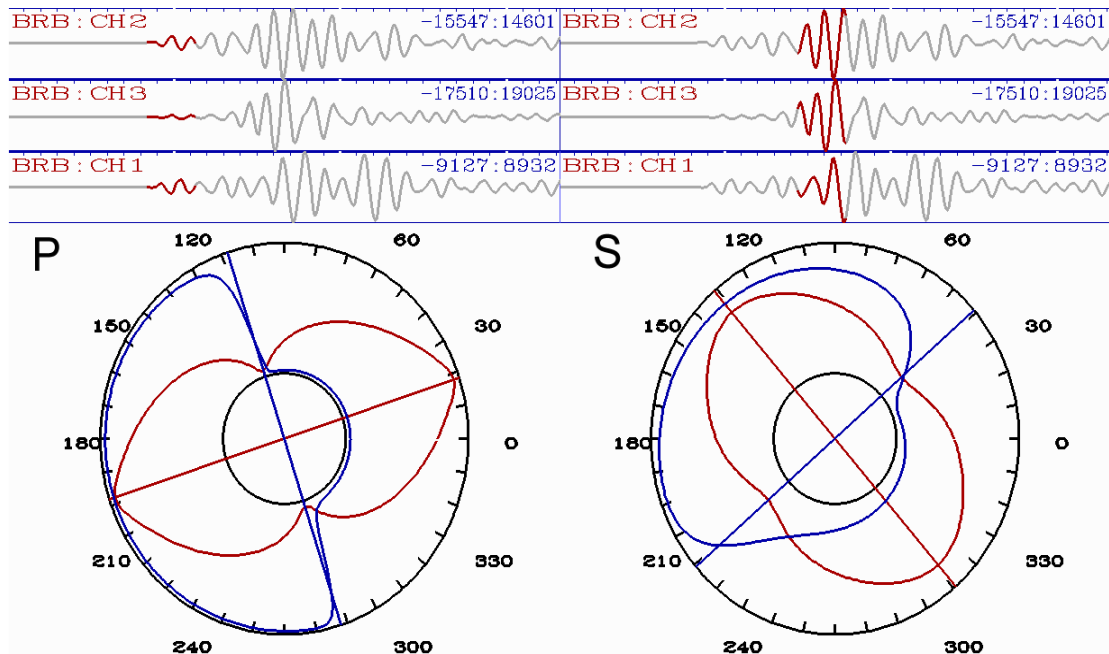
Spitsbergen and the adjacent areas are parts of a geologically complex region with moderate to high seismicity. The main seismicity in the area is associated with the North-Atlantic Ridge, and especially the Knipovich Ridge situated at a distance less than 400 km from the archipelago (Sundvor and Eldholm, 1979). In addition, some coal mines are located in the area of Spitsbergen, causing occasional induced seismicity.

During the last few years an increased occurrence of rockbursts in the mines near Barentsburg, Spitsbergen has been observed. To obtain more information about these events, KRSC and NORSAR installed a digital 3-component seismic station, BRB, in the town of Barentsburg in December 2000. The station is located at a distance of only about 5 km from the mines.

In order to locate the recorded events with only the BRB station, we applied the polarization analysis technique (Asming et al. 1998) for determination of an event azimuth and P and S phase identification. An example of applying the polarization analysis technique is shown in Figure 4. For estimating the distance to the events the time difference between the P and S phases was used. It was necessary to fine tune the velocity model in order to obtain accurate locations, and to this end, a small calibration explosion was conducted on 18 March 2001 at 11:03:00. The explosion coordinates were 78.067N, 14.36E; yield was 30 kg; the distance to BRB station was 3.12 km. To calibrate the local travel times we estimated local velocities taking into account that  $V_p/V_s$  is about 1.73 and we obtained  $V_p = 4.54$  km/s and  $V_s = 2.62$  km/s. A model for more distant stations was obtained by adding a low velocity near-surface layer to the Barents velocity model (Kremenetskaya et. al., 2001).

A total of 541 seismic events were detected near Barentsburg from 01/12/2000 to 19/04/2001. Figure 5 shows that the events can be separated into two groups, corresponding to the northern and southern mine. A closer analysis showed that the parameters of events outside the mines are very different from those occurring in either the South or North mines, whereas the South and North event parameters seem to be quite similar. This leads us to the conclusion that the events outside the mines have natural reasons whereas the events

in the mining areas are mostly technogenic. Thus, the Barentsburg area is unusual in the sense that strong technogenic seismicity is mixed with a significant natural seismic 'background'.



**Figure 4.** An example of applying the polarization analysis technique to BRB recordings.

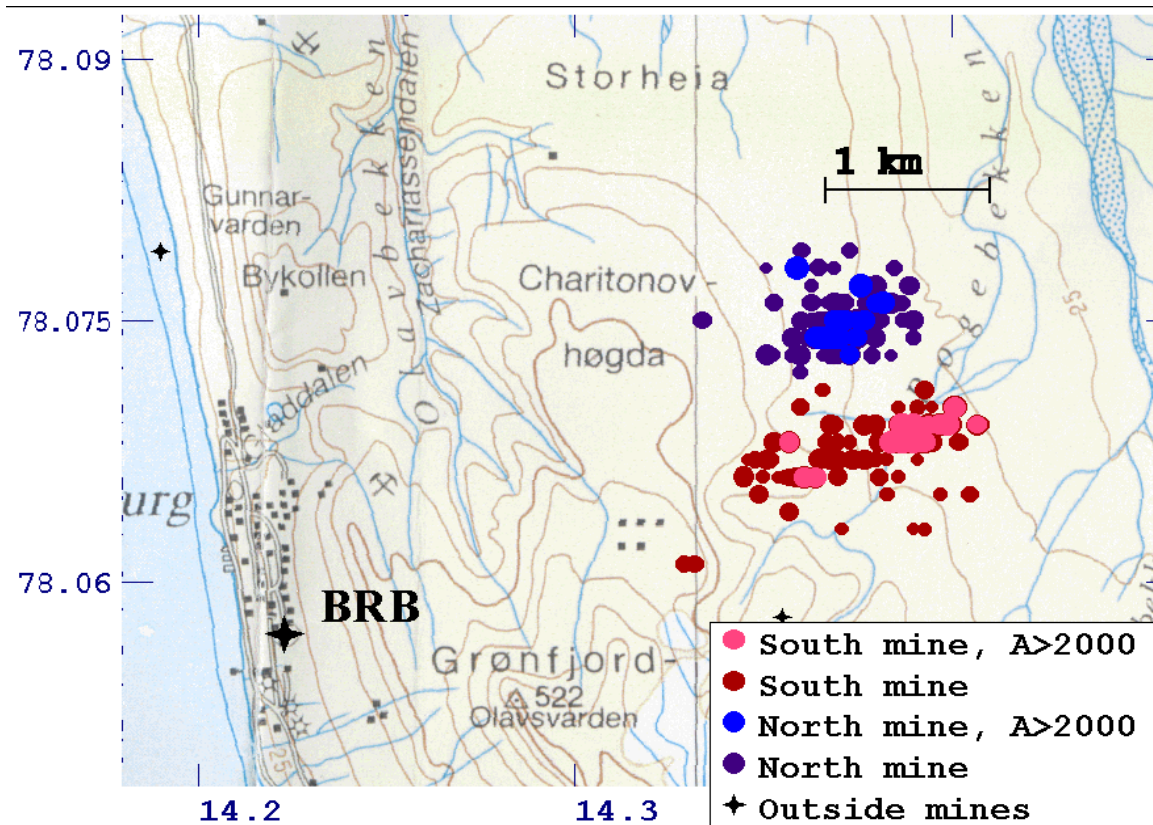
Based on reports from the mines about a number of felt rockbursts, we were able to verify that our seismic locations were quite accurate, probably with an error of less than 1 km for the larger events. The majority of events were detected by the IMS station SPITS, and some of the largest events, which had local magnitude (ML) of about 3.0, were detected also at the IMS station ARCES (distance 1000 km). The data could therefore be useful for developing and verifying travel time correction for location calibration purposes.

**Location Calibration**

*Crustal transects across the Barents Sea*

In order to develop more precise travel times for regional phases, we have studied synthetic travel times for regional crustal transects across the Barents Sea and the adjacent western continental margin. We have calculated synthetic travel times for the first arrivals along four regional crustal transects across the Barents Sea and the adjacent western continental margin (see Figure 6) and compared these with the corresponding travel times predicted by the Barents regional velocity model which today is used to locate earthquakes in this area. Along one of the transects, between the spreading axis in the Greenland Sea and SPITS on Svalbard, we have also carried out a sensitivity study concerning the effects of uncertainties in the Moho topography on the calculated travel times.

Depending on the offset, travel-time differences of up to 2 - 3 seconds are found when comparing travel-time curves from the four transects to the standard 1-D model (Barents Sea crustal model). This reveals that the Barents Sea crustal model needs to be refined in order to fit the velocity structure established along the regional transects. Because most of the observed events in this region are only observable at regional distances, it will be particularly important within this context to address upper mantle velocities, as a basis for Pn and Sn travel times.



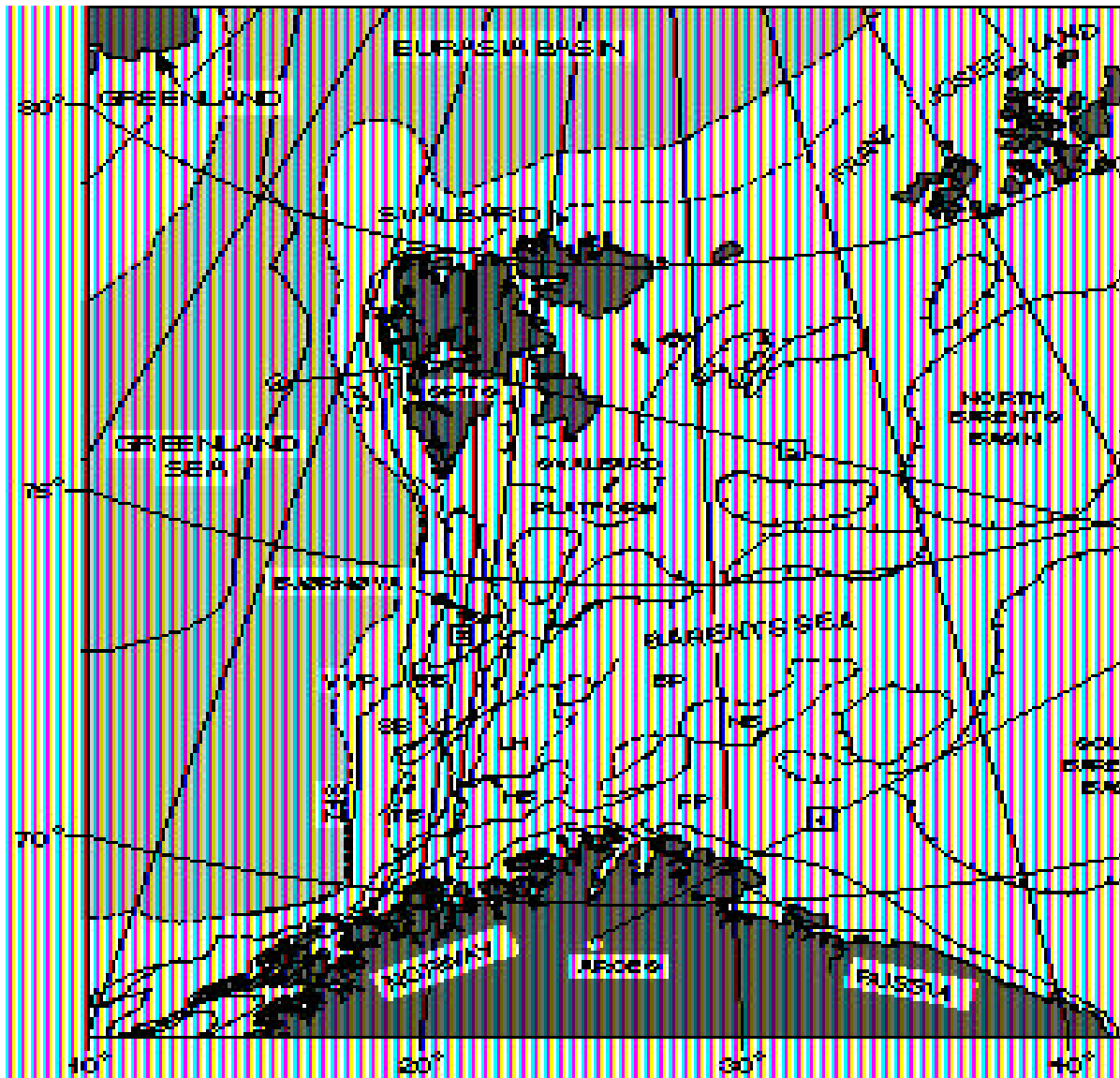
**Figure 5.** Seismic events near Barentsburg, Spitsbergen occurring from 01.12.2000 to 26.03.2001. The location of the 3-component seismic station BRB is indicated.

*Oslo Workshop on location calibration*

A workshop was held in Oslo, Norway during 23-27 April 2001 in support of the global seismic event location calibration effort currently being undertaken by Working Group B of the CTBTO Preparatory Commission in Vienna, Austria. Dr. Frode Ringdal chaired the meeting, which was attended by 65 experts from 14 countries and the Provisional Technical Secretariat of the CTBTO. The recommendations from this workshop have been provided in the paper CTBT/WGB/TL-2/61, issued by Working Group B of the CTBTO Preparatory Commission.

**CONCLUSIONS AND RECOMMENDATIONS**

Our studies demonstrate that the regional array network in northern Europe, which comprises stations in Fennoscandia, Spitsbergen and NW Russia, provides an overall detection capability for the European Arctic that is close to  $m_b = 2.5$ , using the Generalized Beamforming (GBF) method for automatic phase association and initial location estimates. In selected areas it is significantly better - for example, the capability in the Kursk accident area in the Barents Sea is close to  $m_b = 1.5$  (in terms of the GBF scale).



**Figure 6.** Regional setting - main geological provinces and structural elements in the Barents Sea and surrounding areas. Location of crustal transects and the seismic arrays SPITS and ARCES are shown. BB = Bjørnøya Basin, BP = Bjarmeland Platform, FP = Finnmark Platform, HB = Hammerfest Basin, HFZ = Hornsund Fault Zone, LH = Loppa High, NB = Nordkapp Basin, SFZ = Senja Fracture Zone, SB = Sørvestnaget Basin, SH = Stappen High, TB = Tromsø Basin, VVP = Vestbakken Volcanic province (Faleide, 2000).

We have also demonstrated, both in the case of Kursk events and in other connections, that location estimates by a single array or 3-component station can be provided with high accuracy, assuming that site-specific calibration information is available for the station-site path in question. We recommend that single-station location algorithms continue to be developed and evaluated.

In terms of location calibration, the single most important topic is to obtain accurate “ground truth” locations both for the development of site-specific station corrections and for evaluation of the performance of various



calibration schemes. We recommend that a program to install seismometers inside selected mines be implemented, with associated GPS receivers for accurate timing and location of the mining events. NORSAR is planning to pursue this issue in Fennoscandia and NW Russia in our future research in the European Arctic region.

The global location calibration effort will continue to be an important part of our work. The recommendations provided in the paper CTBT/WGB/TL-2/61 should be followed up by the international community, and the progress of this work will be reviewed in a planned workshop in Oslo in 2002.

#### **REFERENCES**

- Asming, V.E., E.O. Kremenetskaya and F. Ringdal (1998): Monitoring seismic events in the Barents/Kara Sea region, *Semiannual Technical Summary, 1 October 1997 - 31 March 1998*, NORSAR Sci. Rep. 2-97/98, Norway.
- Faleide, J. I. (2000): Crustal structure of the Barents Sea - important constraints for regional seismic velocity and travel-time models. *Semiannual Technical Report 1 October 1999 - 31 March 2000. NORSAR Sci. Report 2-1999/2000*, Kjeller, Norway, 119-129.
- Kremenetskaya, E., V. E. Asming and F. Ringdal (2001): Seismic location calibration of the European Arctic. *Pure and Applied Geophysics*, 158 No. 1-2, 117-128
- Ringdal, F. (1997): Study of low-magnitude seismic events near the Novaya Zemlya nuclear test site, *Bull. Seism. Soc. Am.* 87 No. 6, 1563-1575.
- Sundvor E. and O. Eldholm (1979): The western and northern margin off Svalbard. - *Tectonophysics*, 59, 239-250.