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7.4 Monitoring seismic events in the Barents/Kara Sea region

Introduction

NORSAR has for many years been cooperating with the Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences in the continuous monitoring of seismic events in North-West Russia and adjacent sea areas.

KRSC began its seismic network processing in 1982. Initially, this was done primarily by processing data from the KRSC network of seismological stations (see Table 7.4.1), but in recent years the analysis has been supplemented with data from IRIS stations (KBS, LVZ, KEV, ARU, ALE, NRI etc.) and the Scandinavian seismic arrays (ARCESS, SPITS, FINESS, HFS, NORESS) for analyzing of the most interesting events.

As the result of KRSC's operations and research activities a large amount of information has been collected. It comprises seismic bulletins and catalogues, waveforms from digital stations, digitized seismograms for selected interesting seismic events recorded by the analog stations in the network, results of spectral processing etc.

Because of industrial and other man-made activity in the Kola region a number of artificial seismic signals of different types has been registered, including open-pit, underground and underwater explosions, explosions followed by acoustic signals etc. This provides a good basis to make attempts to work out some criteria for discrimination between various source types and for evaluating previously proposed discriminants.

This paper describes briefly the KRSC seismic network and the approaches to data processing and event location implemented at the KRSC data center. We will also describe some of the most interesting seismic events occurring in the region in recent years. We will demonstrate by examples that the S/P ratio is a highly questionable discriminant for regional events, even at high frequencies.

Kola regional seismic network

Before 1992 KRSC applied data from analog seismic stations only in the regular analysis. All of the analog stations have been equipped with SKM-3 short-period seismometers with identical amplitude-phase response (amplification 50000 in frequency range 1.25-2 Hz). In addition the Apatity station has included three-component long-period seismographs of type SKD (Ts=25 sec).

Seismograms from all the stations (excluding KHE) are stored in Apatity. Data from KHE has been transferred to KRSC by telex in the form of daily bulletins.

In 1991 an extensive cooperative research program between KRSC and NORSAR (Norway) was initiated. Part of this cooperation involved the installation in NW Russia of three modern digital seismic stations, two of which are arrays.

One array (aperture 1 km) comprising 11 short-period sensors (Geotech S-500) is situated about 17 km to the west of Apatity. In the town of Apatity there is a 3-component broad band digital station (Guralp GMG-3T). A micro-array with aperture about 150 m was installed in Amderma in 1993. The array is situated in an underground fluorite mine and comprises 3 vertical sensors and 3-component station in the centre. The sampling rate is 40 measurements per second.

Table 7.4.1. Kola seismic network

Name	Latitude (N)	Longitude (E)	Type	Worked since	Until
APA	67.558	33.442	Analog	1956	now
PLQ	66.410	32.750	Analog	1985	now
BRB	78.073	14.197	Analog	1982	1990
PYR	78.659	16.216	Analog	1983	1987
AMD	69.744	61.648	Analog	1983	1995
KHE	80.600	58.200	Analog	?	1990
APA	67.558	33.442	Digital 3-C	1991	now
APO	67.603	32.994	Array	1992	now
AMD	69.744	61.648	Micro-array	1993	now

Seismicity

The seismicity of the Barents/Kara sea region is quite low as discussed by Ringdal (1997). This is illustrated in Fig. 7.4.1 which shows the epicenters in northern Europe and adjacent areas determined in the Revised Event Bulletin of the GSETT-3 IDC during 1995-1996. Because of the high-quality coverage of regional arrays in Fennoscandia, a large number of seismic events (mostly mining explosions) are detected in this region. The seismic event occurrence is also very high in the Spitsbergen area and offshore Norway (to the north and west). These events are presumably mostly earthquakes.

On the other hand, the figure shows that there are almost no recorded events in the region comprising the eastern part of the Barents sea, the Kara Sea, Novaya Zemlya and the northern part of Russia (excluding Kola). While the GSETT-3 network has a lower detection capability in this region compared to Fennoscandia, its capability is nevertheless around magnitude 3.0-3.5 and it is thus clear that seismic events of such magnitudes or larger occur rather infrequently in the region specified above.

Event location

Since the IASPEI-91 model is not suitable for Barents region (Ringdal et al, 1997), it has been necessary to study local travel-time curves using data from a set of strong explosions with known locations. In addition, an underground calibration explosion has been carried out in the Khibiny Massif (29.09.1996, 350 ton), see Ringdal et al (1996).

We have attempted to fit a one-dimensional velocity model to agree with these results. This has resulted in the compilation of a model which is a combination of the NORSAR model for smaller depths (up to 200 km) and IASPEI-91 at greater depths. To validate the model we have re-located several previous seismic events (see Table 7.4.2). As can be seen from this table, and further illustrated in Figure 7.4.2, the locations by the regional network are within 5-10 km of the locations obtained by joint hypocentral determination (JHD) using world-wide data.

Table 7.4.2. Location comparison - regional versus global network

Date	KRSC location	JHD location	Comment
18.08.83	73.289 N, 54.893 E	73.358 N, 54.943 E	
01.08.86	72.945 N, 56.549 E	73.031 N, 56.726 E	Marshall et.al. (1989)
02.08.87	73.298 N, 54.398 E	73.324 N, 54.597 E	
07.05.88	73.275 N, 54.436 E	73.314 N, 54.557 E	
24.10.90	73.304 N, 54.634 E	73.317 N, 54.803 E	

The model therefore seems to be satisfactory for event location in the Barents region. In addition, the documented consistency with precise global network locations is especially important since we are able to use the network to locate regional events far smaller than those which can be detected teleseismically. For example, the KRSC network was the only network with sufficient data to locate reliably the smallest recorded nuclear explosion on the Novaya Zemlya test site (m_b=3.8) on August 26, 1984 (Michailov et. al., 1996). The result is shown in Fig.7.4.3. Our estimated epicentral coordinates of this explosion are 73.326N, 54.763E, thus placing the event within the group of explosions shown in Fig. 7.4.2. While we have no other network solution with which to compare our result, we believe this explosion to be rather accurately located.

Data analysis

The KRSC detection and location software is based on a specially developed algorithm which is very close to the generalized beamforming approach (Ringdal and Kvœrna, 1989). It operates well when data from several seismic stations are available.

The Amderma station is far from all the other seismic stations in the network so we have to locate weak events near this station using only one-station data. The small aperture makes it difficult to use beamforming or some other array-based procedure to determine backazimuths. Moreover, strong industrial noise (probably due to construction work) occurs quite regularly in this place.

Under such circumstances a completely automatic processing often results in wrong phase association (true phases may be associated with noise bursts, etc.). To avoid this we use a semi-automatic routine. We first run a detector to identify segments of the recording which contain seismic energy above a given threshold. The analyst then marks approximately those parts of the recording which may contain phases of real seismic events and a new automatic procedure is executed for these parts. (For the Amderma station this automatic process includes filtering, STA/LTA detection and joint polarization analysis for P and S phases). Although the accuracy of this method is limited, it is often sufficient to obtain preliminary location with reasonable accuracy (see examples below).

To carry out this automatic analysis we have developed a variant of site-specific monitoring (SSM), as described in the Appendix. It scans pairs of detected phases and for each pair assumes a hypothesis that the first phase is P-wave and the second one is S-wave from an event occurring somewhere inside a given region. The validity of this hypothesis is estimated by joint polarization analysis for P and S phases and application of several additional criteria such as frequency and amplitude compatibility. Those pairs for which a resulting rating function is greater than some predefined threshold are assumed to correspond to possible real seismic events.

Naturally, such an automatic process will occasionally result in false alarms, but their number is within reasonable limits. We will illustrate this by an example. During the day 16 August 1997, five real seismic events occurred near the Amderma station. Two of them were very similar events of unknown nature occurring at the same point in the Kara sea (distance from Amderma about 320 km). The waveforms are shown in Fig. 7.4.4. Two others were explosions near Vorkuta (about the same distance but to the south-west from Amderma) and one event was too weak to locate.

The result of site-specific monitoring for this day is shown in Fig.7.4.5. The SSM procedure has detected and located the Kara events and the two Vorkuta explosions. False alarms are also shown (the total number of false alarms for this day was five). The results of the semi-automatic location process for two of the events, the smallest Kara sea event (16.07.1997, 6.20 GMT) and one Vorkuta explosion (16.07.1997, 7.02 GMT) are shown in the insertions.

The problem of event discrimination

As mentioned above the network often registers seismic events of a nature which cannot be determined by traditional criteria like spectral characteristics or P/S ratios. For example, the numerous explosions at Vorkuta recorded by Amderma have much lower dominant frequencies for P and S waves than the 16 August 1997 Kara sea events, which some investigators have characterized as earthquakes, even though the epicentral distances are the same (about 300 km).

As another example, the 1 August 1986 Novaya Zemlya event, generally assumed to be an earthquake, had essentially the same S/P characteristics at the Barentsburg station (distance 10 degrees) as the 26 August 1984 nuclear explosion. Admittedly, because we had only analog recordings available at this time, we are unable to compare the characteristics at very high frequencies, but the picture is very clear in the 1-3 Hz band.

An event occurring on February 9, 1998 near Murmansk (69.18 N, 32.63 E, origin time 16.51:07) was recorded by the seismic arrays ARCESS and SPITS with very different signal characteristics. The S-wave amplitude for SPITS was much less than the P-wave amplitude regardless of which bandpass filter was used. On the other hand, ARCESS recordings showed a strong S-wave and even Lg and Rg phases.

The most striking example of the variations in P/S ratios was observed for an event which occurred on April 18, 1998 in Norwegian Sea near Bear Island. The waveforms (recordings by APA, ARCESS and SPITS) together with our estimated location are shown in Fig.7.4.6.

The nearest station is SPITS (about 470 km) and its recording contains no noticeable S phase in any frequency band. In contrast, ARCESS (670 km) has recorded strong S-waves, whereas APA (1020 km) registered P-waves only in the band 8-12 Hz. This illustrates that attempts to use the P/S ratio of a single station to discriminate between various source types can give rather contradictory results, depending on the radiation pattern and path attenuation.

Conclusions

The combined regional networks of the Kola Regional Seismological Centre and NORSAR is capable of locating even very low magnitude events with high accuracy in the Barents/Kara sea region. Studies of historic recordings in the past 15 years have revealed that there are almost no seismic events in this area exceeding magnitude 2.5, except for in the western part between Norway and Spitsbergen.

Case studies, some of which are discussed briefly in this paper, have demonstrated that traditional regional discriminants are not effective for separating between seismic source types at low event magnitudes in this region. In particular, we conclude that the S/P ratio, even at high frequencies, is rather unstable and should not be relied upon for regional event discrimination.

With regard to the two Kara sea events on 16 August 1997, we respectfully disagree with those scientists who have claimed that these events can be positively identified as earthquakes on the basis of seismological evidence. On the other hand, neither is there any seismological evidence to confidently classify these events as explosions. In our opinion, the source type of these two events remains unresolved.

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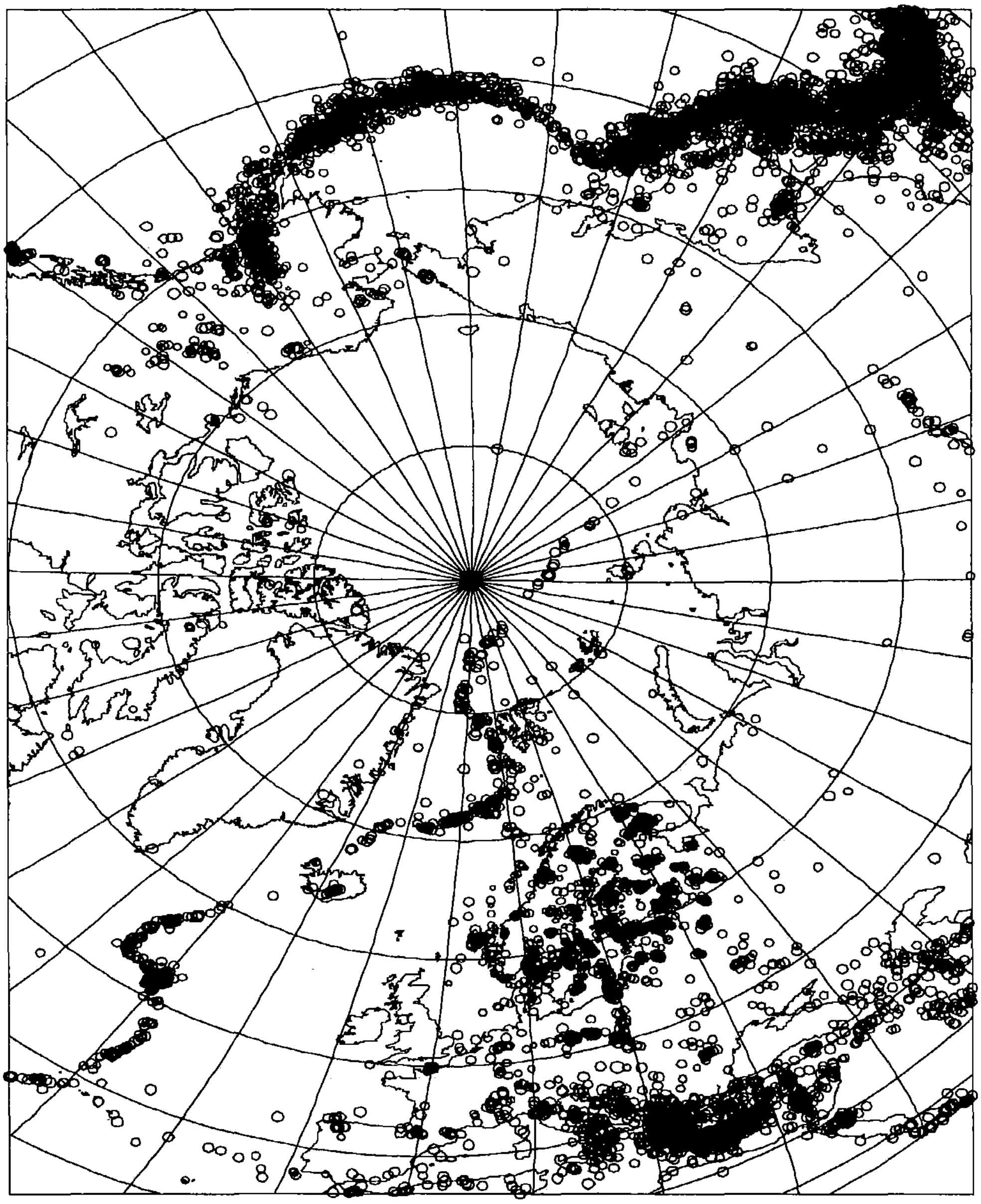

Fig. 7.4.1. Epicenters in northern Europe and adjacent areas determined in the Revised Event Bulletin of the GSETT-3 IDC during 1995-1996. Note the large number of seismic events (mostly mining explosions) in Fennoscandia and the high seismicity in the Spitsbergen area and offshore Norway (mostly earthquakes). Also note the low observed seismicity in the Barents/Kara sea region.

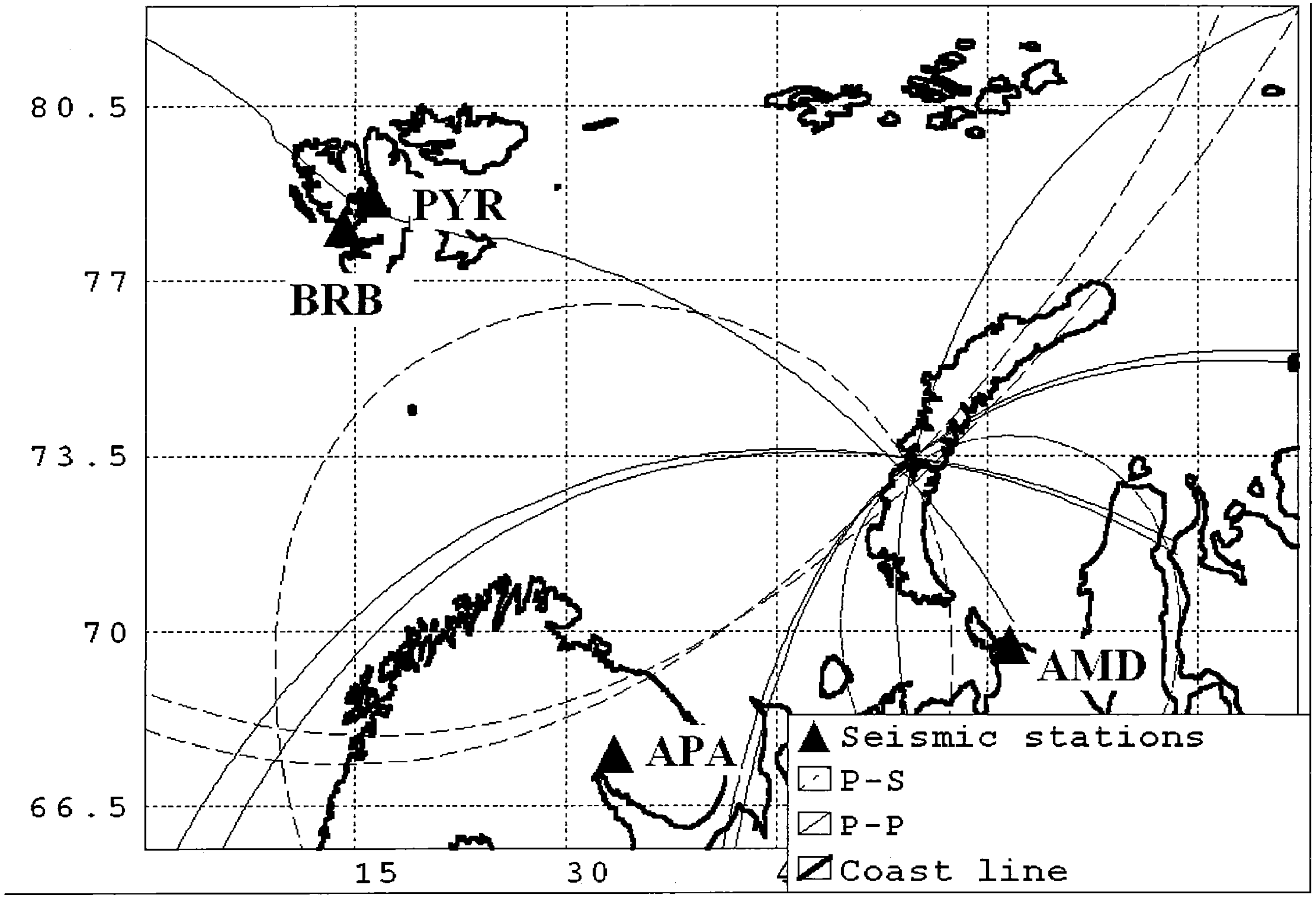

Fig. 7.4.2. Location of the smallest recorded Soviet nuclear explosion (26 August 1984, m_b=3.8) at Novaya Zemlya using data by the stations PYR, BRB, APA and AMD.

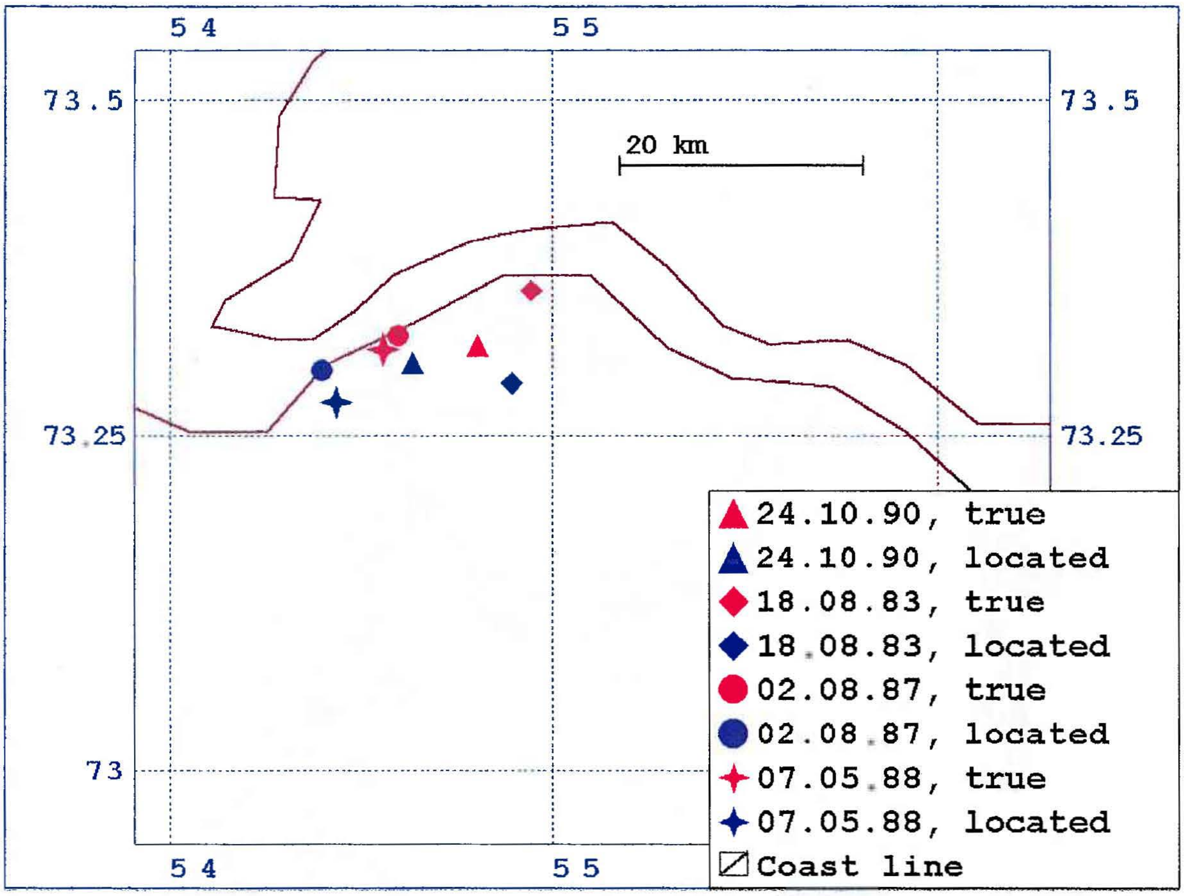

Fig. 7.4.3. Comparison of the locations of well-recorded seismic events at Novaya Zemlya using joint hypocentral determination from a global network with the same events located using only the data by the stations PYR, BRB, APA and AMD in the KRSC regional network. Note the excellent consistency.

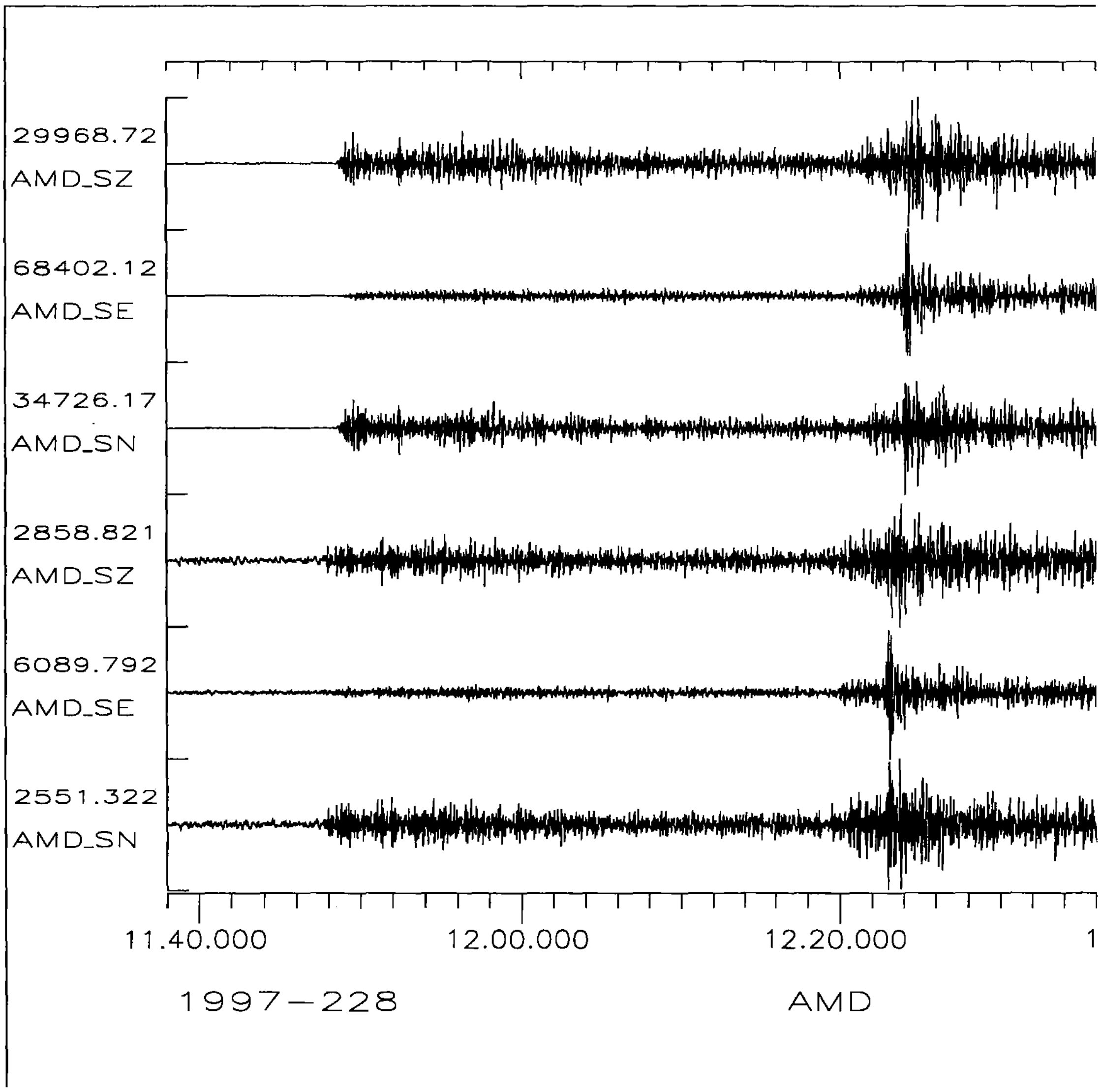

Fig. 7.4.4. Recordings by the Amderma 3-component center station of the two seismic events on 16 August 1997. The upper three traces are three-component data for the first event (m_b=3.5), and the lower three traces correspond to the second event (m_b=2.5) The traces are filtered in the 2-16 Hz band. The scaling factors in front of each trace is indicative of the event size. Note the similarity between the two event recordings.

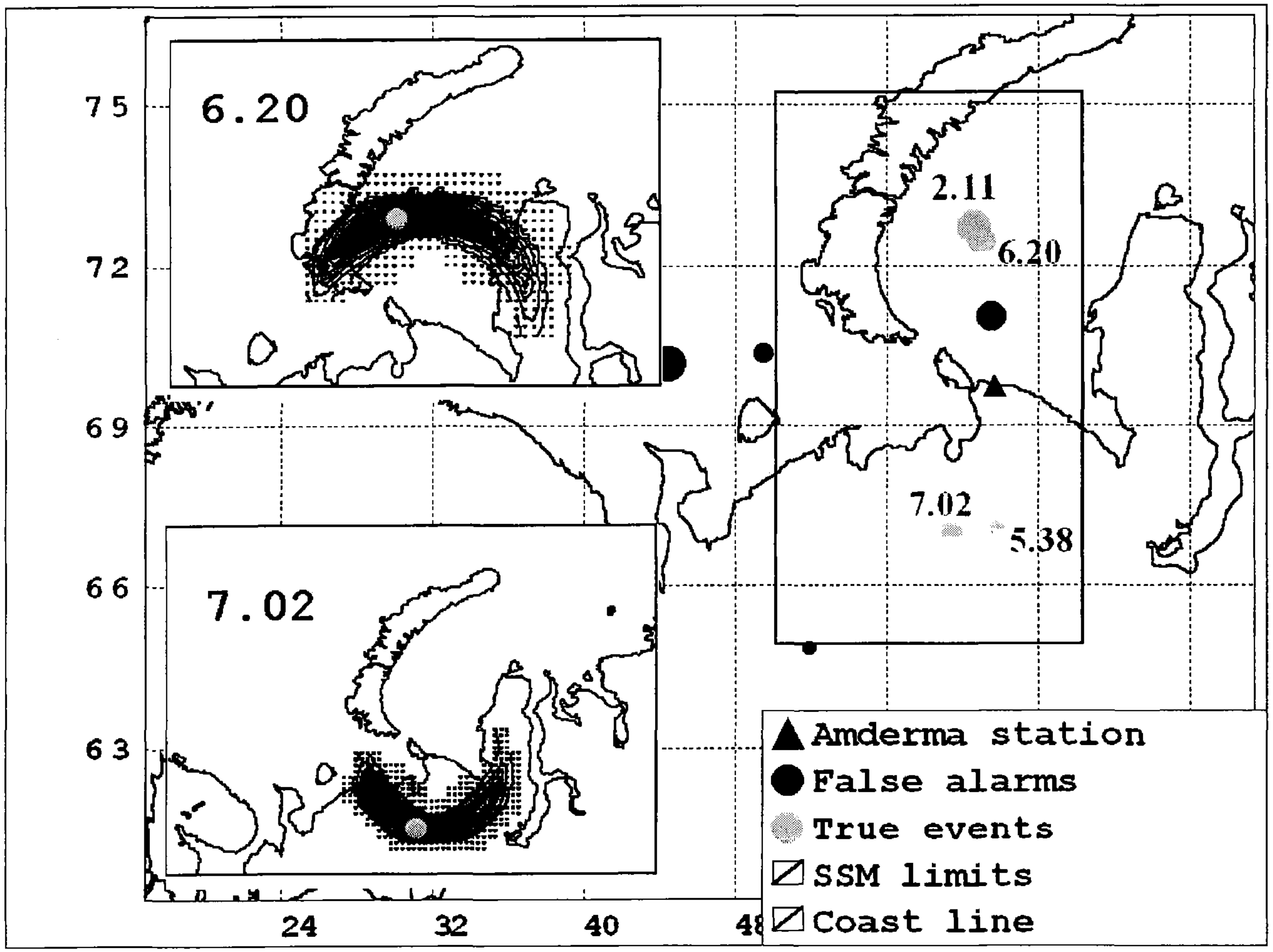

Fig. 7.4.5. Results of site-specific monitoring using the Amderma station for the day 16.08.1997. Examples of semi-automatic location (iso-lines of rating functions and their maxima corresponding to epicentres) are shown in the insertions.

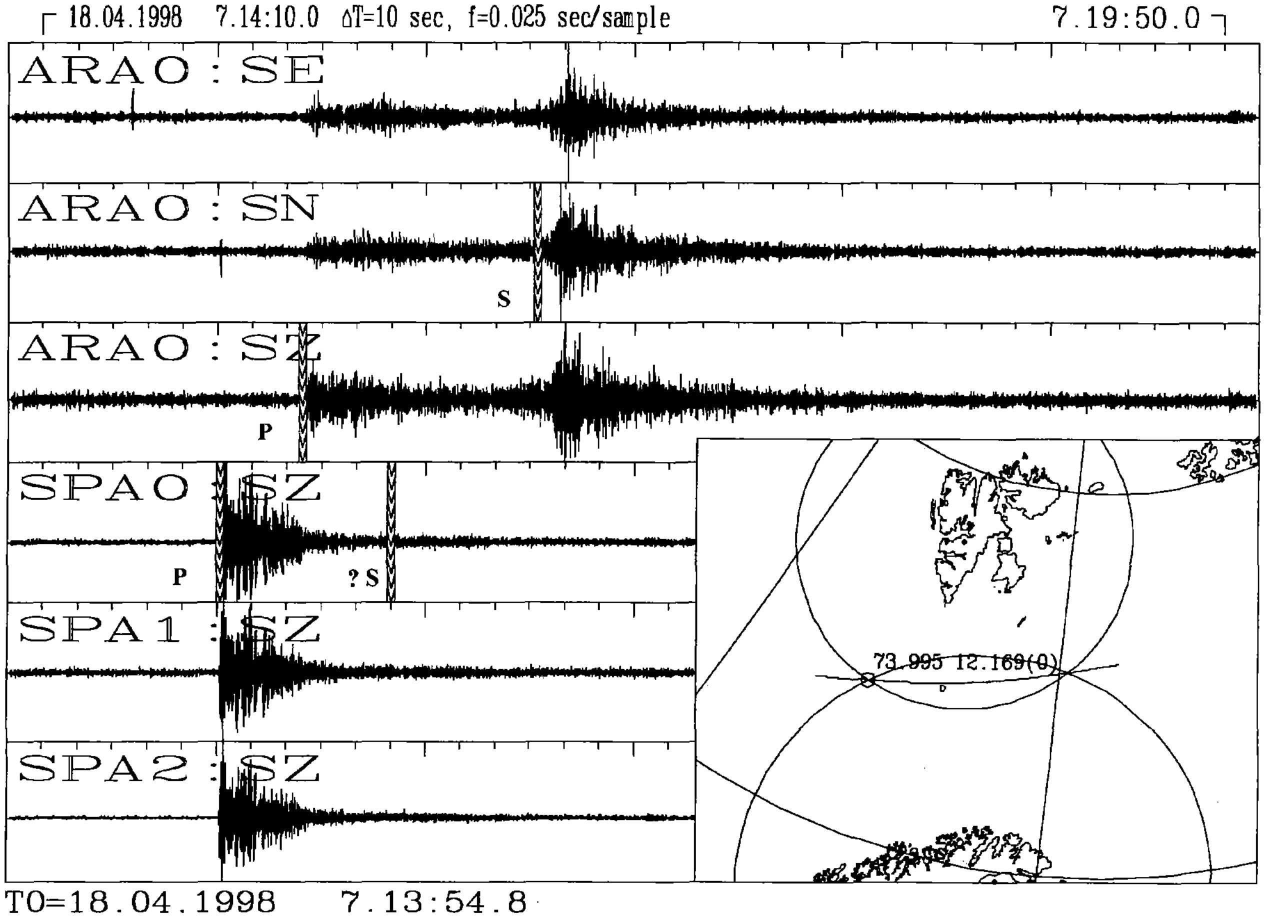

Fig. 7.4.6. Waveforms together with KRSC's location of the event near Bear Island on 18.04.1998. The symbols "? S" mark places of expected S-onsets. Note the large variation in P/S ratios for the stations shown.

Appendix

Site-specific monitoring (SSM) applied to the Amderma station

The Amderma station is situated far from other seismic stations in the KRSC network, so we need to locate weak events near this site using single-station data only. We have developed a variant of site-specific monitoring (SSM). It scans pairs of detected phases and for each pair assumes a hypothesis that the first phase is a P-wave and the second phase is an S-wave from an event occurring somewhere inside a given region. This hypothesis is validated by computinga rating function based on joint polarization analysis for P and S phases and several additional criteria such as frequency and amplitude compatibility. Those pairs for which the rating value is greater than a predefined threshold are considered as candidates for real seismic events.

1.Polarization analysis.

In this study we use the traditional mathematical coordinate system: X to the right (east), Y upward (north) and calculate angles from the X counterclockwise (to recalculate such angles into seismological backazimuths one have to substitute A by 450-A).

For each direction we calculate a function representing a projection of horizontal motion in this direction :

$$S(\alpha) = \sum_i |E_i \cos(\alpha) N_i \sin(\alpha)| \qquad (13)$$

where E_i and N_i represent samples of East-West and North-South channels respectively.

To normalize this function we introduce:

$$R(\alpha) = [S(\alpha) - S(\alpha + 90°)]/[S(\alpha) + S(\alpha + 90°)] \qquad (14)$$

This function assumes values within [-1,+1] and is maximized for P-waves when α equals the event's backazimuth (or the backazimuth +180), and for S-waves when α is perpendicular to the true backazimuth.

However, the function does not enable us to calculate the sign and real type of polarization (linear or circular). We introduce one more function which calculates the correlation between horizontal and vertical motion for a given angle:

$$CZ(\alpha) = Corr(E\cos(\alpha) + N\sin(\alpha), Z) \qquad (15)$$

where E, N and Z represent samples of East, North and vertical channels respectively. If α is a true backazimuth, this function should be maximized for P-waves. On the other hand, $CZ(\alpha + 90°)$ should be about zero for S-waves because S is polarized circularly.

Finally, we introduce backazimuth-dependent polarization criteria for P and S :

$$P_p(\alpha) = (1 + R(\alpha))(1 + CZ(\alpha))/4 \tag{16}$$

$$P_s(\alpha) = (1 + R(\alpha + 90°))(1 - |CZ(\alpha + 90°)|)/2 \tag{17}$$

Both of these functions range within [0,1]. *(1+R)* instead of *R* is used to soften the criteria : the polarization is often not seen clearly and negative weights are more difficult to analyze.

2. Calculating detection lists for Amderma station.

An ordinary analysis using a set of bandpass filters and STA/LTA criterion is carried out for each Amderma recording. When STA/LTA exceeds a fairly low threshold (now 2) the phase is considered to be detected and the polarization weights Pp and Ps are calculated using the band where STA/LTA has its maximum value. Thus, for each detected phase the detection list contains the corresponding best frequency band, the maximum STA/LTA and associated *Pp* and *Ps* estimates.

3. Site-specific monitoring.

A region for SSM is specified by ranges of angles for Amderma backazimuths (α_1, α_2) and distances (R_1, R_2) between Amderma and possible epicenters of an event. From the distance range the SSM program calculates a range of corresponding time differences between P and S onsets :

$$\Delta t_1 = [T_S(R_1) - T_P(R_1)] \le t_S - t_P \le \Delta t_2 = [T_S(R_2) - T_P(R_2)] \tag{18}$$

Subsequently the program scans the pairs of phases for which the time difference is within the limits $(\Delta t_1, \Delta t_2)$ and for each such couple (denote the first phase "A" and the second one "B") assumes the hypothesis that A is a P-wave and B is an S-wave. Then the program has to assess the likelihood of this hypothesis.

It is intuitively clearly that the following features should be taken into account :

- values of STA/LTA for both the phases;
- joint polarization.

We assume that the pair of phases correspond to the same event so that an angle maximizing the product of Pp for A and Ps for B should be found. To take into account the

STA/LTA value we use some monotoneously increasing, but bounded function F(STA/LTA). The choice for F is rather arbitrary and now the system uses:

$$F(x) = 1 - \exp(-x/(x_0)) \tag{19}$$

where x_0 is a constant (some typical STA/LTA for strong events).

We use a bounded function to obtain compatible ratings for events which are strong enough, although their STA/LTA values may differ considerably.

Finally, the rating function RV_{AB} is defined as:

$$RV_{AB} = F((STA/LTA)_A)F((STA/LTA)_B)\max_{\alpha\varepsilon(\alpha_1, \alpha_2)}\{P_{PA}(\alpha)P_{SB}(\alpha)(1 - |P_{PB}(\alpha)|)\} \tag{20}$$

The terms $(P_{PA}(\alpha))$ and $(P_{SB}(\alpha))$ are weights indicating the likelihood that A is a P-wave and that B is an S-wave. Note that the Amderma station often records significant long-duration industrial noise. Such noise often contains segments looking like event phases but with identical polarization for the two hypothesized phases.

On the other hand, the criteria $(P_{PA}(\alpha))$ and $(P_{SB}(\alpha))$ are not too strict, so that possible errors in the polarization calculations may be accepted. Thus the program could associate even identically polarized phases if their STA/LTA are large enough. That is the reason why the term $(1-P_{PB}(\alpha))$ was added. It is designed to suppress cases where the B phase is a continuation of A, i.e., has the same polarization.

When the rating function appears greater than some threshold the SSM program declares a possible event and determines its preliminary coordinates. The distance between the station and the event is determined by the time difference between the phases and the angle which maximizes the rating :

$$\alpha = \mathop{Argmax}_{\alpha\varepsilon(\alpha_1, \alpha_2)}\{P_{PA}(\alpha)P_{SB}(\alpha)(1 - |P_{PB}(\alpha)|)\} \tag{21}$$

Examples of the SSN in practical application are shown in the main body of this paper.