RESEARCH IN REGIONAL SEISMIC MONITORING

F. Ringdal[1)], E. Kremenetskaya[2)], V. Asming[2)], T. Kværna[1)] and J. Schweitzer[1)]
[1)] NORSAR, Kjeller, Norway
[2)] KRSC, Apatity, Russia

Sponsored by the Department of Defense

Contract No. F08650-06-C-0001

ABSTRACT

During the last decades, a network of sensitive regional arrays has been installed in northern Europe in preparation for the global seismic monitoring network under the Comprehensive Nuclear-Test-Ban treaty (CTBT). This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia provides a 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. We have continued our studies to use data from the regional networks operated by the Kola Regional Seismological Centre (KRSC) and NORSAR to assess the seismicity and characteristics of regional phases of the Barents/Kara Sea region, as well as the application to seismic event screening.

We have studied the seismicity (i.e. seismic events apart from confirmed nuclear explosions) of the Western Russia/ Novaya Zemlya region for the past 25 years, and found an average of less than one seismic event per year exceeding m_b 3.5. Thus, the event occurrence in this region is so low that no event of m_b 3.5 and greater located in this region should be screened out in the IDC screening process. The same consideration could apply in some other regions of the world, and the study of detailed seismicity patterns is an important part of the further screening developments.

In discrimination studies, our results for the European Arctic show that the P/S discriminant should be applied with great caution in this region, and further research is required. The regional M_S:m_b discriminant has considerable promise, and the shorter-period energy available in surface waves recorded at regional distances can be exploited in improving the monitoring capabilities during periods with strong interfering surface waves from large distant earthquakes.

We recommend that the current efforts to improve m_b determinations and to reconcile the current m_b values with the “historic” magnitude scale be continued. A project to apply maximum-likelihood techniques to reassess the m_b of past seismic events should be undertaken.

We have analyzed data from the Eurobridge profiling experiment which comprised a 1130 km seismic refraction profile crossing the Baltic Shield in the northwest and the Ukrainian Shield in the southeast. We have investigated in detail observed deviations in P-wave travel times from those predictions by the Fennoscandian crustal and upper mantle velocity model. Our study has revealed several instances of documented timing errors at the various arrays. An important outcome of this study is the development of a method to identify possible timing anomalies at IMS stations. This method could be useful both in validating calibration data and in providing a tool for continuously checking the timing accuracy and consistency of IMS stations.

We have also analyzed data from some recent profiling experiments near the Spitsbergen array in order to improve the calibration of this station. Not unexpectedly, the study has demonstrated that the crust and uppermost mantle around the SPITS station is very heterogeneous. However, with the exact travel times available through this study for different azimuths in the range 0-3 degrees, the location and detection processing of local and near-regional events at SPITS will be considerably improved.

The location calibration effort will continue to be an important part of our work. The recommendations provided in the paper CTBT/WGB/TL-2/49 should be followed up by the international community, and the progress of this work will be reviewed in a planned workshop in Oslo in 2001.

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 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 CTBT monitoring network. This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia (see Figure 1) 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 Semiannual Technical Summaries. In the present paper we will limit the discussions to some recent results of interest in the context of applying screening criteria to seismic events in the European Arctic and within the location calibration effort currently underway for the International Monitoring System (IMS). We also report on some recent developments in monitoring mining events in the Kola Peninsula.

SCREENING

The development of event screening criteria is one of the main tasks of the expert work currently conducted by Working Group B of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The purpose of event screening is to “screen out” events that are thought to be consistent with natural causes (such as earthquakes), so that detailed analysis can be focused on those events that are truly of interest for monitoring purposes. The current seismic screening procedure employed at the International Data Centre (IDC) is applied only for seismic events exceeding a m_b threshold of 3.5, and focuses on two criteria: event focal depth and M_s:m_b. These are considered to be the most robust criteria currently available, but have the disadvantage that they are difficult to apply to small events or events recorded only by few stations. Other criteria, such as the high-frequency P/S ratio, hold the promise of being applicable at much lower event magnitudes, and this is currently an area of active research (see e.g. Ringdal et.al., 2000).

The purpose of screening is not to identify events, but rather to limit as far as possible the number of events that need to be subjected to special analysis. It might be argued that in some regions of the world, seismic events exceeding m_b 3.5 are so infrequent that any particular screening criteria based on signal characteristics may be superfluous. We have studied the region comprising Western Russia and Novaya Zemlya, including the surrounding parts of the Barents and Kara Seas in this perspective. Our recommendation, as detailed below, is that the event occurrence in this region is so low that no event of m_b 3.5 and greater located in this region should be screened out. This would exclude the possibility of accidentally missing events of potential monitoring interest, and at the same time improve confidence that the treaty is adhered to.

Seismicity of the European Arctic

The seismicity of the Barents/Kara sea region has previously been discussed by Ringdal (1997). Nuclear and chemical explosions were conducted at Novaya Zemlya until 1990, and in addition a number of PNEs were carried out in Western Russia until 1988. We have carried out a detailed study of the seismicity of Western Russia, including the Ural Mountains and the Novaya Zemlya region. Our emphasis has been on collecting information on available seismic events (in addition to the confirmed nuclear explosions) for a region bounded by 50-78 deg North, 30-65 deg East, and with m_b of 3.5 or greater. This is of interest in the screening process at the IDC, since the current event screening criteria are applied only to events above this magnitude.

Table 1: Seismic events with m_b at least 3.5 during 1975-2000 in the region 50-78N, 30-65E. Confirmed nuclear explosions are not included.

No	Date/time	Location	mb (MLE)	Comment/Reference
1	15.11.78/ 08.30.00	73.40 N, 55.00 E	3.6	obably chemical explosion, Novaya Zemlya ingdal, 1997)
2	10.04.81/ 19.43.33	68.76 N, 36.96 E	4.4	rthquake, felt in Murmansk, Kola Peninsula
3	01.08.86/ 13.56.3	72.945 N, 56.549 E	4.3	assified as earthquake by Marshall et.al. (1989)
4	26.02.87/ 00.18.21	60.10N, 60.20 E	4.1	ckburst in Sevuralboksitruda mine, 50m of tunne stroyed, 150 cubic m rock volume (VNIMI, 1989
5	16.04.89/ 06.34.4	67.67 N, 33.73 E	3.5	rthquake in Kirovsk mine, faulting observed, 3 fl tunnels (total 200m) destroyed (Kremenetskaya a sming, 1995)
6	14.05.89/ 11.46.56	50.84 N, 51.24 E	4.3	EIC/PDE
7	28.05.90/ 00.35.48	55.17 N, 58.72 E	4.3	llapse of Kurbazakskaya mine of shnouralboksitruda, 450 000 sq. m area affected omakin and Yunusov, 1993)
8	28.05.90/ 02.41.28	55.17 N, 58.72 E	4.4	e preceding event. Reference: Lomakin and Yunu 993)
9	16.06.90/ 12.43.2	68.52 N, 33.09 E	4.0	rthquake, felt in Murmansk, Kola Peninsula
10	05.01.95/ 12.46.01	59.60 N, 56.65 E	4.5	llapse at the Silvinit salt mine near Solikamsk. 3(0 sq.m. area affected.
11	10.06.96/ 17.16.47	59.74 N, 43.11 E	3.7	EB (PIDC)
12	13.06.96/ 19.22.38	75.2 N, 56.7 E	3.5	cated by Ringdal et. al. (1997)
13	16.08.97/ 02.11.00	72.510 N, 57.550 E	3.5	assified as earthquake by Richards and Kim (199
14	17.08.99/ 04.44.36	67.885 N, 34.532 E	4.3	rthquake/collapse, mine Umbozero of Sevredmet 0 000 sq.m area affected. 50 cubic m rock volum ver changed course
15	18.01.00/ 04.05.32	58.06 N, 49.42 E	3.5	EB (PIDC)

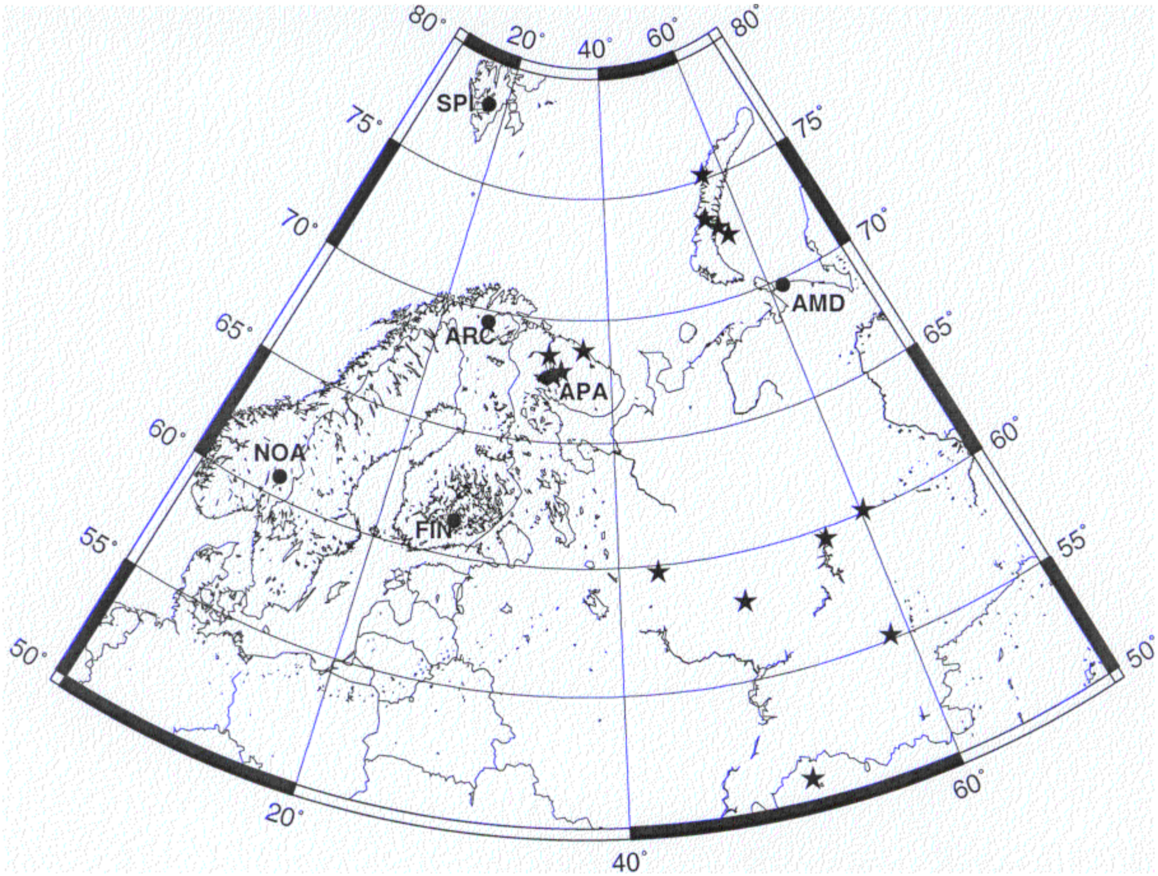

Fig.1 Map showing the regional network operated by NORSAR and KRSC. The map also shows the location of the events in Table 1, which comprises all known events 1975-2000 (apart from nuclear explosions) with m_b of 3.5 or greater in a region bounded by 50-78 deg North, 30-65 deg East.

In this compilation, we have used available international bulletins (ISC, USGS/NEIC, PIDC) together with the regional bulletins issued by NORSAR and KRSC. We have re-assessed the m_b estimates, making use of the maximum-likelihood method developed by Ringdal (1986) as well as the regional magnitudes provided by NORSAR and KRSC, adjusted to world-wide m_b. We have attempted to make our magnitude estimates consistent with "historic" world-wide m_b, as opposed to the current values which have been shown to have a slight negative bias relative to the traditional estimates.

The result of this compilation is listed in Table 1, which covers the 25-year time interval 1975-2000 (see also Figure 1). Only 15 reported seismic events (not counting confirmed nuclear explosions) have exceeded magnitude 3.5 in this period, i.e. less than one event per year on the average. We note that the detectability of the current global network is sufficiently high so that we consider this catalog to be essentially complete since 1990, but a few small events may certainly have been missed for the earlier years. Nevertheless, the average occurrence of events of m_b=3.5 or greater in this region seems to be at most 1 event per year. It thus appears that any screening of seismic events above magnitude 3.5 in this region is superfluous, so it is currently not necessary to develop screening criteria for this region. This could of course change if the screening is applied at a lower magnitude threshold in the future.

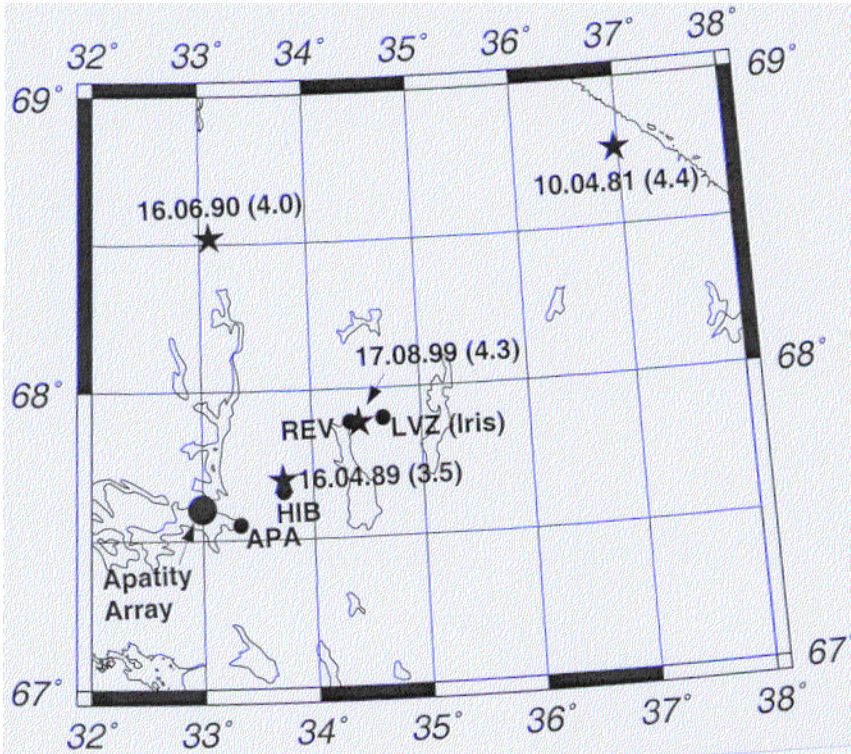

Fig. 2. Station network operated by KRSC in the Kola Peninsula. Two new stations (HIB and REV) have been deployed in 2000. The locations of those seismic events in Table 1 which occurred in the Kola Peninsula are also indicated.

It is interesting to note, as explained in Table 1, that many of the events are associated with mining activity (i.e. collapses, rockbursts or earthquakes inside known mines). This means that true tectonic earthquakes of m_b=3.5 or greater in this region are very rare indeed. Any significant seismic event located by the IDC inside this region should be subject to special analysis, as part of the confidence-building process that is essential in CTBT verification.

We might note that other parts of the European Arctic have a much higher level of natural seismicity than the Western Russia/Novaya Zemlya region discussed above. For example, there are many significant earthquakes in the intraplate areas of Fennoscandia, and the seismicity is of course even higher along the tectonic plate boundary areas, such as the North Atlantic Ridge, Spitsbergen and the Lomonosov Ridge.

Study of P/S ratios

A paper by Ringdal et. al. (2000) discusses the application of the P/S ratio for discriminating seismic events in the European Arctic. It is shown that the P/S ratios of Novaya Zemlya nuclear explosions measured in the 1-3 Hz filter band scale with magnitude, indicating a need for caution and further research when applying P/S discriminants. Using mainly data from the large NORSAR array, the authors note that observed P/S amplitude ratios in the European Arctic shows large variability for the same source type and similar propagation paths, even when considering closely spaced observation points. This effect is most pronounced at far-regional distances and relatively low frequencies (typically 1-3 Hz), but it is also significant on closer recordings (around 10 degrees) and at higher frequencies (up to about 8 Hz). The conclusion from the study is that the P/S ratio at high frequencies (e.g. 6-8 Hz) shows promise as a discriminant between low-magnitude earthquakes and explosions in the European Arctic, but its application will require further research, including extensive regional calibration and detailed station-source corrections. Such research should also focus on combining the P/S ratio with other short-period discriminant, such as complexity and spectral ratios.

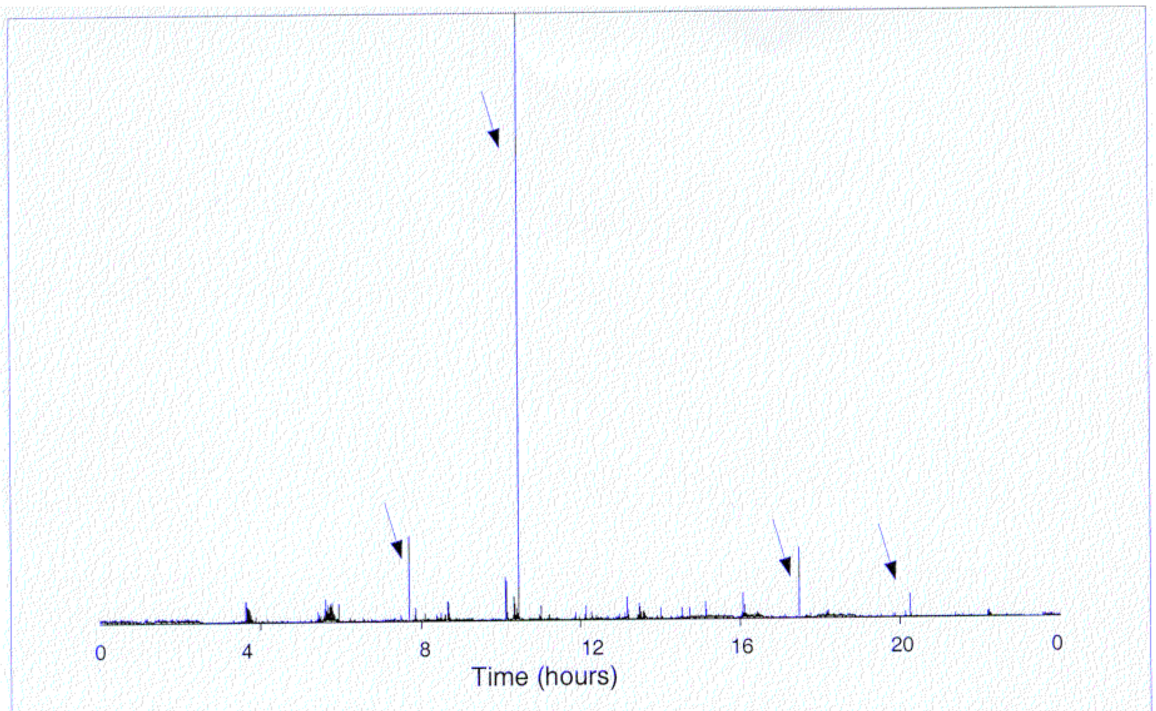

Fig 3. STA trace (filter 4-12 Hz) for station REV in the Kola Peninsula. The data cover the 24 hours of 12 April 2000. The arrows mark detected microearthquakes in the Revda mine (magnitudes 0.0-1.0)

Study of Regional M_s:m_b

A paper by Kremenetskaya et. al. (2000) describes the historical archive of regional long-period data (on analog form) available at KRSC since 1970 for the station APA in Apatity, Kola Peninsula. Since the station APA is situated at a regional distance from the Novaya Zemlya test site, these recordings provide a unique source for studying the performance of M_s:m_b at regional distances for the European Arctic. Selected seismograms from APA have been digitized, and the quality of the analog recordings at this station is demonstrated by comparing recordings from a modern broad-band seismometer at the same place to signals digitized from the analog equipment.

In the paper, it is further shown that the APA surface wave recordings, normalized for distance and magnitude, provide an encouraging degree of separation between earthquakes and explosions in the European Arctic. It is demonstrated that this separation can be achieved in a wide frequency band (at least 10-25 seconds period), and the authors note that this gives promise for applying the M_s:m_b discriminant down to lower magnitudes and at lower signal periods than is possible using teleseismic recordings. They also note that the shorter-period energy available in surface waves recorded at regional distances can be exploited in improving the monitoring capabilities during periods with strong interfering surface waves from large distant earthquakes.

NETWORK DEVELOPMENTS

Kola network and earthquake studies

On 17 August 1999, only 4 hours after the large earthquake in Turkey, an earthquake of m_b=4.3 occurred in a mining area in Revda, Kola Peninsula. This is the largest seismic event in Kola for almost 20 years, and has been the subject of considerable interest. The earthquake, which was associated with a large mine collapse in the Lovozero Massif, was preceded by numerous foreshocks several months in advance, and was followed by several aftershocks.

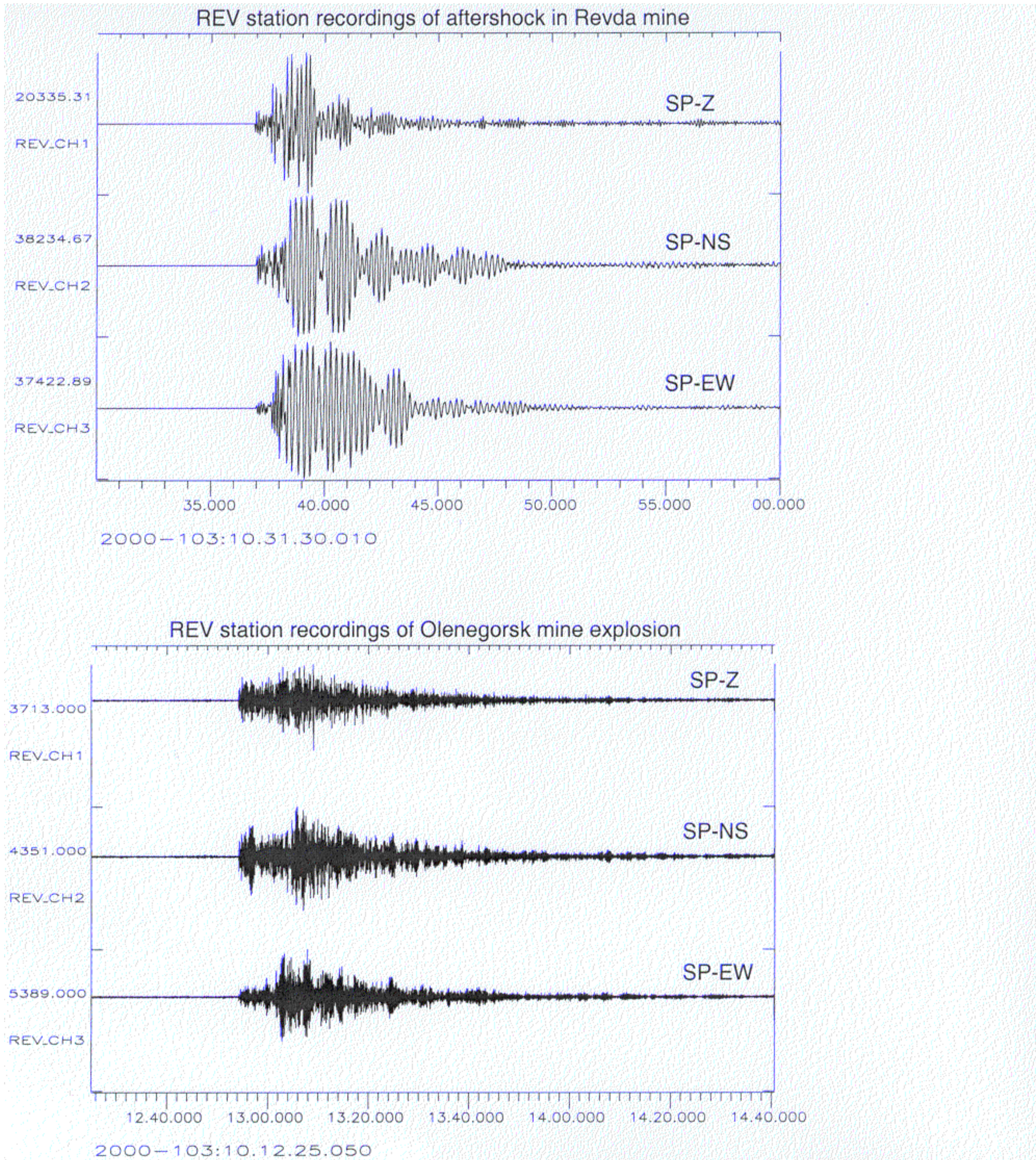

Fig.4. REV 3-component short period recordings on an aftershock in the Revda mine (top) and a mining explosion in the Olenegorsk mine 50 km away (bottom). Note the strong Rg phases on the top traces.

KRSC installed in early 2000 3-component seismic stations in the Khibiny Massif (HIB) and in Revda (REV) - see Fig. 2. The station at Revda was deployed for the purpose of studying the aftershocks of the 17 August 1999 event, and the station in Khibiny had as its main purpose to enable improved locations and origin times for seismic events in the Khibiny mines. An example of a one-day STA trace for the Revda station is shown in Figure 3. This trace could be seen as a simple version of the Threshold Monitoring technique applied to this mining site, and most of the peaks on the trace are in fact associated with the Revda mine. Examples of recordings for two of the peaks are shown in Figure 4 (for an aftershock at Revda and a mining explosion in Olenegorsk).

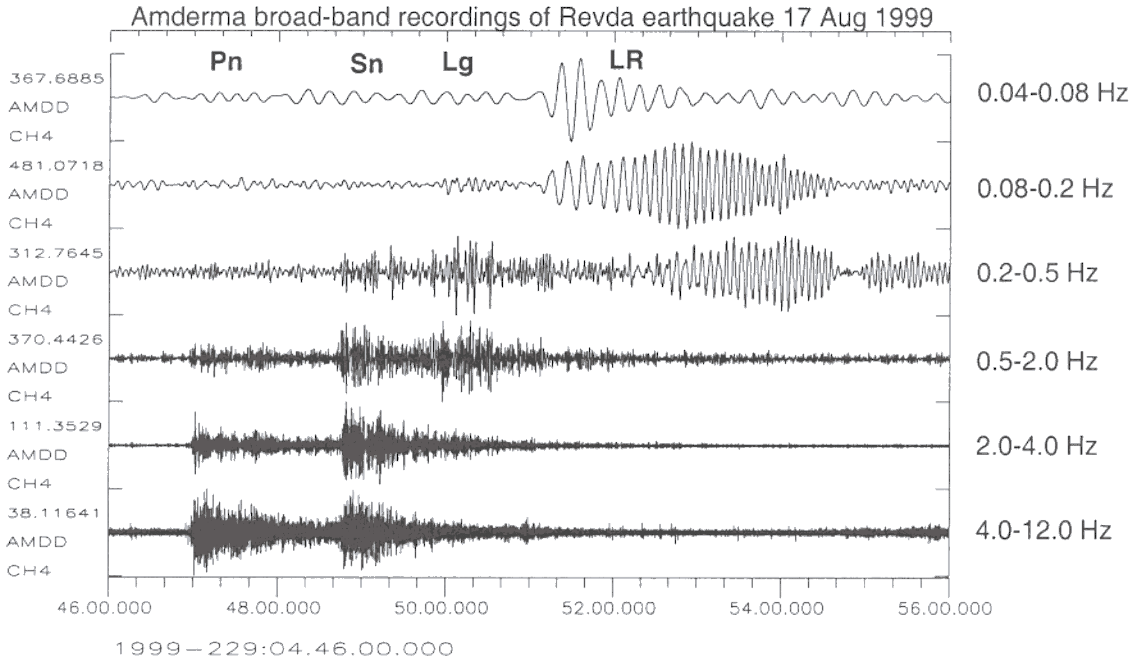

Fig.5. Amderma broad-band vertical channel recording of the Revda earthquake of 17 August 1999. The traces are filtered in several different bands. The distance from the event to the station is approximately 10 degrees.

Amderma station

The seismic station at Amderma is a key monitoring resource for the Kara Sea region. In 1999, KRSC installed a broadband 3-component seismometer (Guralp) at this site, and implemented a dial-up mechanism to enable rapid retrieval of data of special interest. An example of data retrieved in this way for the 17 August 1999 Revda event is shown in Figure 5. We note the strong surface waves recorded for this event, and in particular the high Rayleigh wave energy in the frequency band near 0.1 Hz (10 seconds period) is noteworthy. The prominence of energy at these high frequencies and their possible usefulness in regional M_s:m_b discrimination has been pointed out by Kremenetskaya et al (2000). Otherwise, the traces show a feature which is common for many paths in the European Arctic: The Pn and Sn phase are dominant at frequencies above 2 Hz, whereas the Lg phase is strongest near 1 Hz.

LOCATION CALIBRATION

Eurobridge profile

We have analyzed data from the Eurobridge profiling experiment which comprised a 1130 km seismic refraction profile crossing the Baltic Shield in the northwest and the Ukrainian Shield in the southeast. There were three series of shots, one in 1995 and two in 1996. Observations of these explosions at the Fennoscandian arrays provide an opportunity to check the accuracy of the travel-time tables in use at NORSAR for Fennoscandia. At the same time, these refraction shots provide a useful extension to the pIDC ground-truth database. P-phases from most of the Eurobridge shots were observed at the FINES, HAGFORS and NORES arrays, and even at the more distant ARCES array as many as 12 out of the 29 events were seen. We have investigated in detail observed deviations in P-wave travel times from those predictions by the Fennoscandian crustal and upper mantle velocity model. Our study has revealed several instances of documented timing errors at the various arrays. Even when accounting for these timing errors, there remains a considerable scatter in the travel times as compared to the theoretical model. The interpretation of these anomalies in terms of crustal and upper mantle structure is not obvious. An important outcome of this study is the development of a method to identify possible timing anomalies at IMS stations. This method could be useful both in validating calibration data and in providing a tool for continuously checking the timing accuracy and consistency of IMS stations.

Calibrating the Spitsbergen array

We have analyzed data from some recent profiling experiments near the Spitsbergen array in order to improve the calibration of this station. Data from airgun shots in the water as well as small underwater explosions of 25 to 50 kg conventional explosives could be observed at distances up to 350 km when using the double-beam technique for SNR enhancement. Not unexpectedly, the study has demonstrated that the crust and uppermost mantle around the SPITS station is very heterogeneous. However, with the exact travel times available through this study for different azimuths in the range 0-3 degrees, the location and detection processing of local and near-regional events at SPITS will be considerably improved. This is particularly important because there are large numbers of local events recorded at SPITS every day, and a correct location and phase identification will help eliminate these phases from interfering in the GBF process for network association and event definition analysis.

Oslo Workshop on location calibration

A workshop was held in Oslo, Norway during 20-24 March 2000 in support of the global seismic event location calibration effort currently being undertaken by PrepCom's Working Group B in Vienna. Among the contributions were recent results provided by NORSAR and KRSC of our joint regional calibration effort in the European Arctic, which has resulted in much improved travel-time models for the Barents region. We show that the Barents model, which is known to give accurate locations in the Fennoscandian and NW Russia area, can be successfully applied to the more general northern Eurasia region. The recommendations from this workshop have been provided in the paper CTBT/ WGB/TL-2/49, issued by Working Group B of the CTBTO Preparatory Commission.

CONCLUSIONS AND RECOMMENDATIONS

The seismicity of the Western Russia/Novaya Zemlya region is very low, with an average of less than one seismic event per year exceeding m_b 3.5. Thus, the event occurrence in this region is so low that no event of m_b 3.5 and greater located in this region should be screened out in the IDC event screening process. This would exclude the possibility of accidentally missing events of potential monitoring interest, and at the same time allow for special analysis of all significant events in this region. This would contribute to improved confidence building with respect to treaty adherence. We consider that the same consideration could apply in some other regions of the world, and the study of detailed seismicity patterns is an important part of the further screening developments.
Our results for the European Arctic show that the P/S discriminant should be applied with great caution in this region, and further research is required. The regional M_S:m_b discriminant has considerable promise, and the shorter-period energy available in surface waves recorded at regional distances can be exploited in improving the monitoring capabilities during periods with strong interfering surface waves from large distant earthquakes.

We recommend that the current efforts to improve m_b determinations and to reconcile the current m_b values with "historic" magnitude scale be continued. A project to apply maximum-likelihood techniques to reassess the m_b of past seismic events should be undertaken.

The location calibration effort will continue to be an important part of our work. The recommendations provided in the paper CTBT/WGB/TL-2/49 should be followed up by the international community, and the progress of this work will be reviewed in a planned workshop in Oslo in 2001.

Key Words: Detection, Location, Discrimination, Screening, Seismic Data Analysis

REFERENCES

Kremenetskaya, E. and V. Asming (1995). Induced seismicity in the Khibiny Massif (Kola Peninsula). *PAGEOPH, 145 No. 1,* 29-37.

Kremenetskaya, E.Asming, V. and F. Ringdal (1999). Seismic location calibration of the Barents region. *Semi-annual Technical Summary 1 October 1998 - 31 March 1999*, NORSAR Sci. Rep. 2-98/99, Kjeller, Norway.

Lomakin,V.S. and Ph.Ph.Yunusov (1993). Effective methods for seismological observations in mines. In: *Prediction and prevention of rock bursts in ore deposit.* Apatity, Kola Science Centre, Mining Institute, pp.73-76 (in Russian).

Kremenetskaya, E.Asming, V. and F. Ringdal (2000). Study of regional surface waves and frequency-dependent Ms:mb discrimination in the European Arctic, submitted to *PAGEOPH Special Issue on CTBT Monitoring.*

Marshall, P.D., R.C. Stewart and R.C. Lilwall (1989): The seismic disturbance on 1986 August 1 near Novaya Zemlya: a source of concern? *Geophys. J.*, 98, 565-573.

Richards, P.G. and Won-Young Kim (1997). Test-ban Treaty monitoring tested, *Nature*, 389, 781-782.

Ringdal, F. (1986). Study of magnitudes, seismicity and earthquake detectability using a global network, *Bull. Seism. Soc. Am.* 76, 1641-1659.

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.

Ringdal, F., E.Kremenetskaya, V.Asming, T.Kvœrna, J. Fyen, J. Schweitzer (1998). Seismic monitoring of the Barents/Kara Sea Region. *Proceedings from the 20th Annual Seismic Research Symposium on CTBT Monitoring, September 21-23, 1998*

Ringdal, F., T.Kvœrna, E.Kremenetskaya, V.Asming (1997). The seismic event near Novaya Zemlya on 16 August 1997. *Semiannual Technical Summary 1 April - 30 September 1997*, NORSAR Sci. Rep. 1-97/98, Kjeller, Norway.

Ringdal, F., E.Kremenetskaya and V. Asming (2000): Observed characteristics of regional seismic phases and implications for P/S discrimination in the European Arctic, submitted to *PAGEOPH Special Issue on CTBT Monitoring*.

VNIMI - State Scientific Research Institute for Mining Geomechanics (1989): Catalog of rockbursts in ore and non-ore deposits. Leningrad, VNIMI, 1989, 189pp (in Russian).