

REGIONAL SEISMIC THRESHOLD MONITORING

Tormod Kvaerna, Erik Hicks, Johannes Schweitzer, and Frode Ringdal

NORSAR

Sponsored by Defense Threat Reduction Agency

Contract No. DTRA01-00-C-0107

ABSTRACT

This three-year project was completed by the end of March 2003, and has resulted in a Final Scientific Report and software with documentation. The work has focused on the development and testing of a method for optimized, regional seismic monitoring, using a sparse network of regional arrays and three-component stations. Specifically, the following topics have been addressed during the project period:

- An experimental application of the threshold monitoring method to a small region of the Barents Sea, surrounding the accident site of the Russian submarine Kursk in August 2000. This study demonstrated how a number of small underwater explosions in the area following the accident have been detected using the threshold monitoring technique.
- A preliminary study of Pn amplitude attenuation relationships for the Barents Sea and adjacent regions. In particular, this work provided information on the expected spatial variability of the Pn amplitudes for regions of different extents.
- Compilation and analysis of a database of 45 seismic events, selected to provide the best possible ray path coverage of the Barents Sea and adjacent areas. This analysis was different from that in the standard analyst reviewed bulletin, in that we required that all discernible phases should be timed, regardless of whether or not they provide a good fit in the event location process. The readings were used for a mapping of phases observable for the different propagation paths, and for an assessment of the travel-time models applicable to this region.
- A detailed attenuation and inversion study, using the compiled database, aimed at obtaining attenuation relations for each of the major regional phases (Pn, Pg, Sn, Lg). We showed that these new attenuation relations represented an improvement relative to previously available relations, and that they provided consistent magnitude estimates based on different phase amplitudes. However, some significant blockage features in the Barents Sea and adjacent regions were noted.
- A regional threshold monitoring (TM) case study for the Novaya Zemlya region, which illustrated the performance of the regional threshold monitoring method using different combinations of monitoring stations. Using as an example a small seismic event about 100 km from the Novaya Zemlya test site, we made a special study addressing the trade-off between the beam radius and the beam focusing sharpness (noting the desire to have a single beam represent the largest possible area with no significant loss in performance).
- A regional threshold monitoring case study focusing on the Kola Peninsula. This study gave us the opportunity to obtain an impression of the potential TM performance in a case where a local network is available. Not unexpectedly, the monitoring thresholds turned out to be much lower than for the case of Novaya Zemlya.
- Development and delivery of software for Regional Seismic Threshold Monitoring, including a manual with descriptions of the programs and the basic operational procedures.

For the Novaya Zemlya region we have shown that for a threshold monitoring target region with radius as large as 100 km, the variations in threshold magnitudes are all within 0.2 magnitude units. For the investigated station geometry, it will therefore be meaningful to represent the monitoring threshold of the entire Novaya Zemlya region with the values of a single target point, together with *a priori* determined uncertainty bounds. For areas with larger variations in threshold magnitudes, like in the vicinity of the arrays or when local networks are available, denser deployment of the target regions is required for complete coverage.

OBJECTIVE

The main objective of this research is to develop and test a new, advanced method for applying regional seismic array technology to the field of nuclear test ban monitoring. To that end, we address the development and testing of a method for optimized seismic monitoring of an extended geographical region, using a sparse network of regional arrays and three-component stations. Our earlier work on optimized site-specific threshold monitoring serves as a basis for the development of this new method. Emphasis of the research is on algorithms that can be efficiently applied in a real-time monitoring environment, which are using primarily automated processing, and which can be readily implemented in an operational Comprehensive Nuclear-Test-Ban Treaty (CTBT) monitoring system.

RESEARCH ACCOMPLISHED

As described in the abstract, several sub-tasks have been addressed during this project. The results from most of these studies have been presented at earlier Seismic Research Reviews, but we will in this paper present some new results from a regional threshold monitoring study of the Kola Peninsula of northwestern Russia with its active mining regions. In addition, the conclusions and recommendations from the work on this contract will be provided at the end of the paper.

Regional Threshold Monitoring - A Kola Peninsula Case Study

As a case study of the performance of regional threshold monitoring, we have selected the mining areas in the Kola Peninsula, Russia. Figure 1 shows the location of the major mines in this area, together with the location of the two seismic arrays ARC and APA. Both the primary International Monitoring System (IMS) array ARC and the non-IMS station APA record high-SNR observations of all important regional phases at a range up to at least 500 km, which is the maximum distance range being considered in this case study. Furthermore, for the more distant recordings, these phases are well-separated in time.



Figure 1. Map of the Kola Peninsula with the main mining areas. Also shown are the locations of the ARCES and Apatity arrays.

Under a separate project funded by DoE, an effort is being undertaken to collect ground truth information, and explosion and rockburst observations for mines of the Kola peninsula. Such information is regularly collected from the mine operators by the Kola Regional Seismological Center (KRSC), and will serve as a reference set for our study. The mining areas comprise Khibiny, Olenegorsk, Kovdor and Zapolyarnyi.

In particular, the mines of the Khibiny Massif provide a natural laboratory for examining and contrasting the signals generated by different types of mining explosions and rockbursts. Of the five mines in the Massif, three have both underground operations and surface pits. Underground shots range in size from very small (~2 tons) with only a few delays and durations on the order of a few hundred milliseconds, to very large (400 tons) with many delays and durations approaching a half second (Ringdal et al., 1996). Shots above ground range from 0.5 tons to 400 tons with a wide range of delays and durations. Induced seismicity is frequent and triggered rockbursts accompany a significant fraction of the underground explosions (Kremenetskaya and Trjapitsin, 1995).

A grid system with a spacing of 0.2 degrees was used in this study. For computing the threshold traces, magnitudes based on the attenuation of Pg and Lg amplitudes were used for grid point to station distances within 2 degrees, while magnitudes for distances above 2 degrees are based on Pn and Sn attenuation (see Table 1). This is in accordance with the distances at which these phases are observable in the actual region. The frequency band used in the study was 3-6 Hz for all phases, except for Lg for which we used 2-4 Hz. Software to extract peak and mean threshold magnitudes for each grid point within a given time segment was used to analyze the TM results.

Table 1: Parameters used for regional threshold monitoring of the Kola mining areas

Travel time model	'barey' - Schweitzer and Kennett, 2002
Attenuation model	Hicks et al., 2002
Grid Spacing	0.2 degrees
Pg distance range	0 - 2 degrees
Pn distance range	2 - 20 degrees
Lg distance range	0 - 2 degrees
Sn distance range	2 - 20 degrees
Pg frequency band	3 - 6 Hz
Pn frequency band	3 - 6 Hz
Lg frequency band	2 - 4 Hz
Sn frequency band	3 - 6 Hz

Processing example 1

Figure 2 shows mean threshold magnitudes for each grid point for a 1-hour time segment starting at 2002-102:06.30. Even if this time interval is not without seismic events, this figure is representative of the combined TM capabilities of ARC and APA during typical noise conditions. In this and other similar plots, the individual TM grid points have been resampled onto a continuous grid using a minimum curvature surface fitting algorithm. As seen from the figure, the monitoring capability is between 0.5 and 1.0 mb units for the mining sites (marked as black squares).

Figure 3 shows the peak network magnitude thresholds with mean subtracted for the same 1-hour time interval as shown in Figure 2. This essentially shows the height of the highest peak above the background level within the time interval for each grid point. Note that an event in the Khibiny mine KH5 (see also Figure 4) creates a significant threshold peak in almost the entire region.

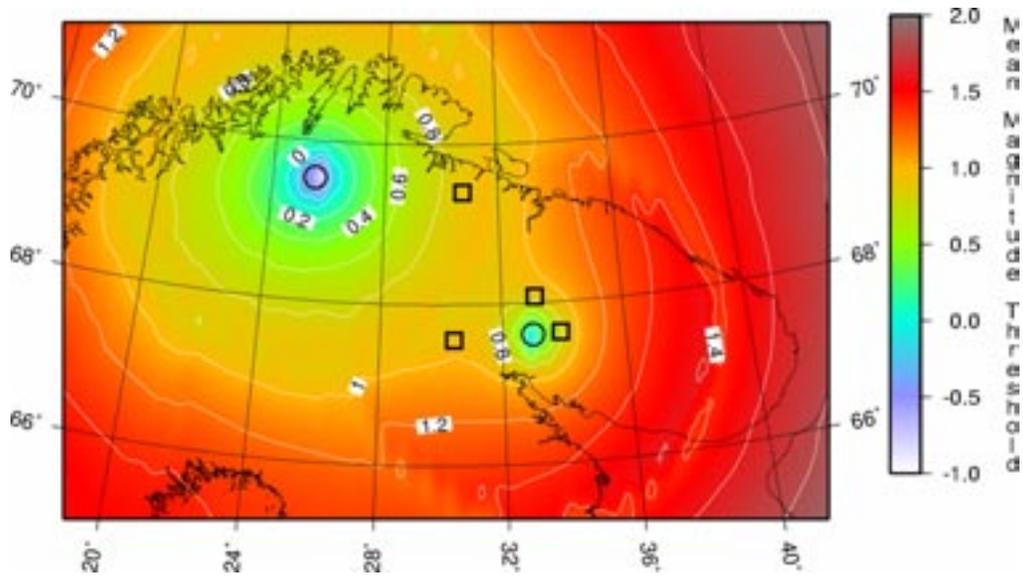


Figure 2. Mean network magnitude thresholds for a 1-hour time interval starting 2002-10-2:06.30, using the ARCES and Apatity arrays (black circles). The locations of the mining areas Khibiny, Olenegorsk, Kovdor and Zapoljarny (see Figure 1) are shown by black squares.

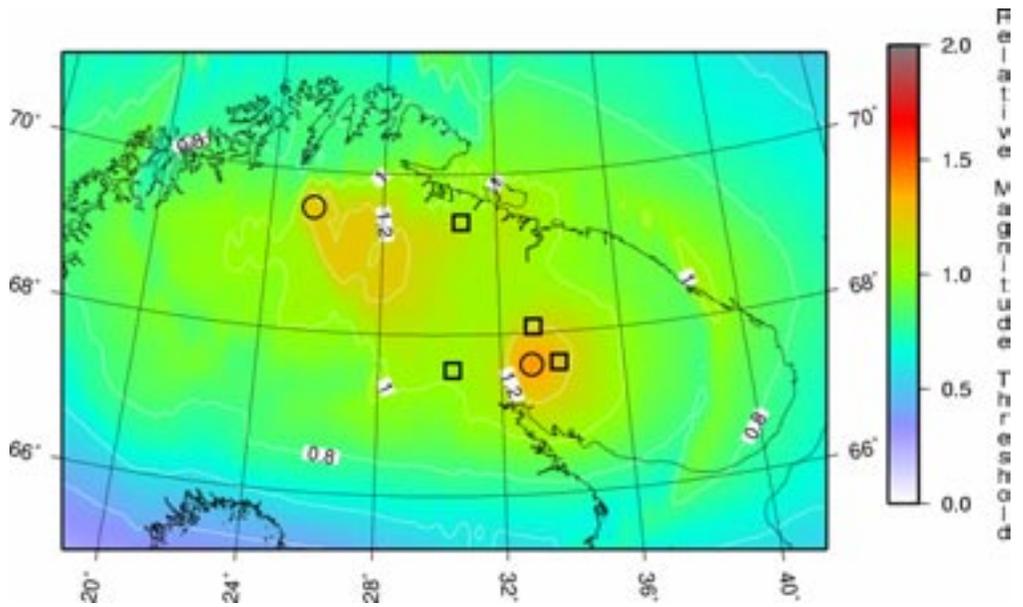
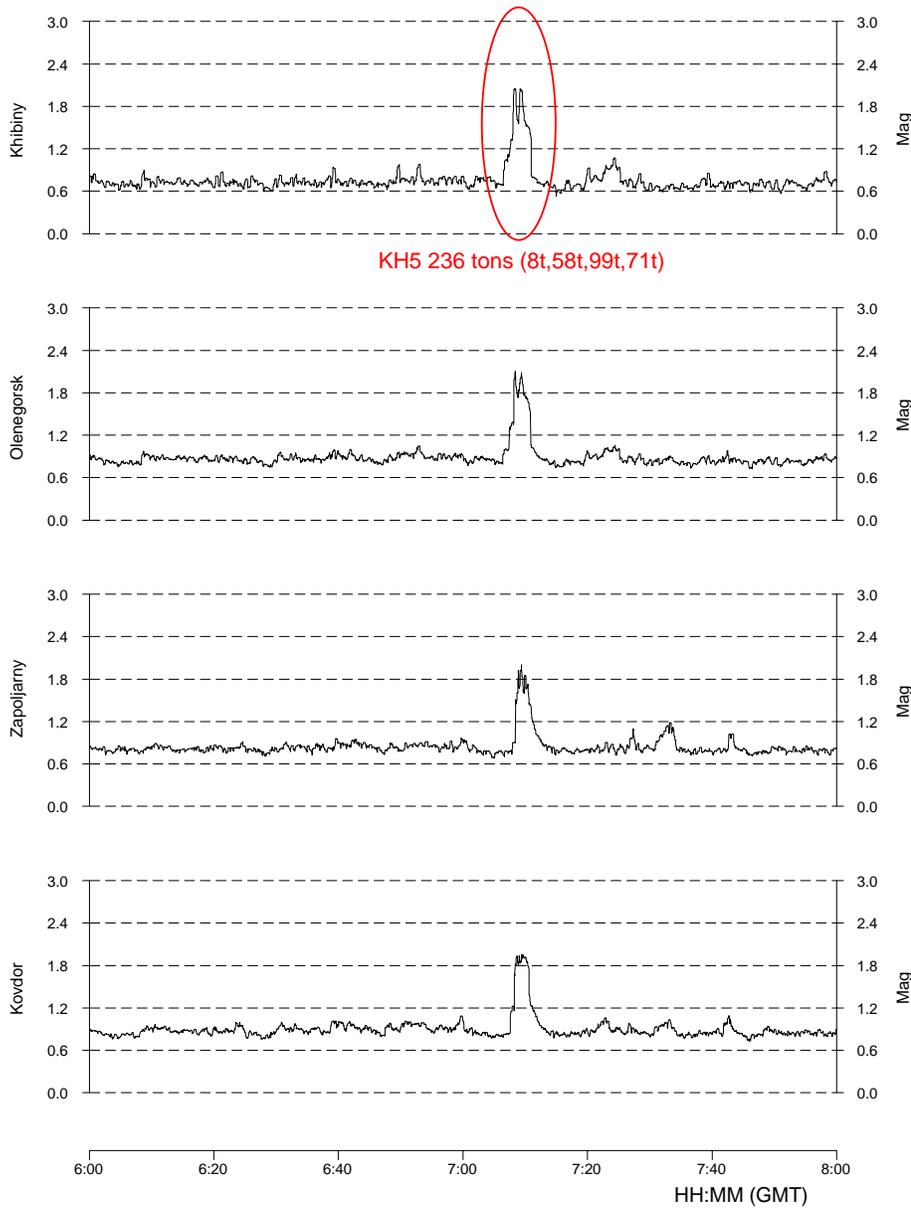


Figure 3. Peak network magnitude thresholds with mean subtracted for the same 1-hour time interval as shown in Figure 2.

Figure 4 shows the threshold time traces for a two hour interval surrounding the interval described previously. We have plotted the threshold trace of the grid point closest to the actual mine for each of the four major mining sites.

There is one large mining explosion (mine 5 of the Khibiny group) during this time interval, and this explosion causes a peak for each beam. Otherwise, the typical background threshold is between 0.5 and 1.0 mb units, consistent with Figure 2.

Regional Threshold Monitoring of the Kola mining areas



12 April 2002 Day 102

Figure 4. Network magnitude thresholds for the grid points closest to the four mining areas shown in Figure 1, for the 2-hour time interval starting 2002-102:06.00. The threshold peak corresponds to an explosion in the open mine Koashva (KH5) located in the Khibiny area. The total yield of the ripple-fired explosion was reported to be 236 tons, and consisted of 4 smaller explosions with yields of 8, 58, 99 and 71 tons.

Processing example 2

Figures 5-7 show a second example of a threshold plots, similar to the plots shown in Figures 2-4. In this second case, the time interval processed is a two-hour interval starting at 2002-102:10.00, i.e. some hours later during the same day. The mean magnitude thresholds (Figure 5) are almost identical to the mean thresholds for the first interval (Figure 2), which shows that the background noise level is stable. The peak network threshold magnitudes with the mean subtracted (Figure 6) are quite similar to those in Figure 3.

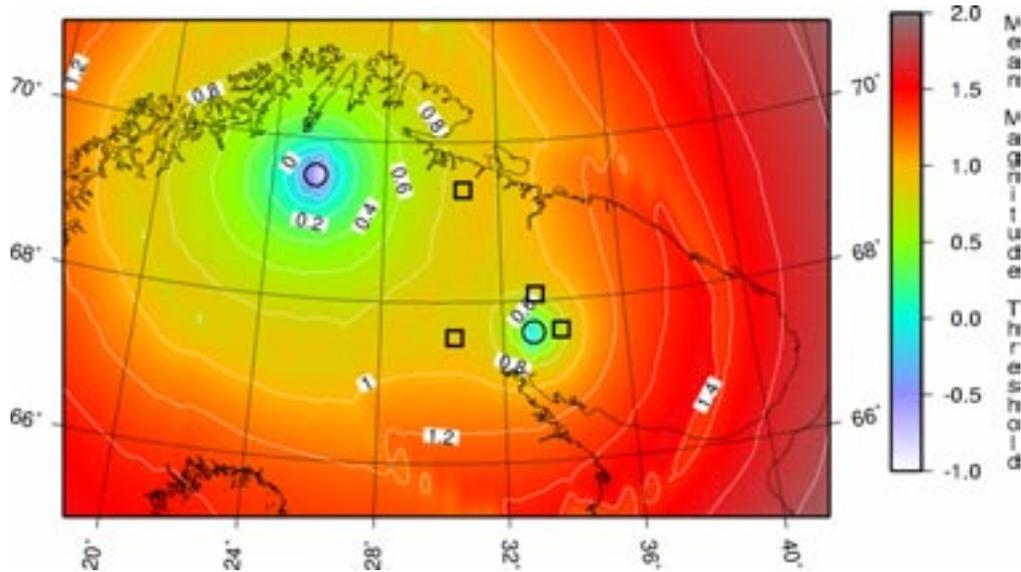


Figure 5. Mean network magnitude thresholds for a 2-hour time interval starting 2002-102:10:00.

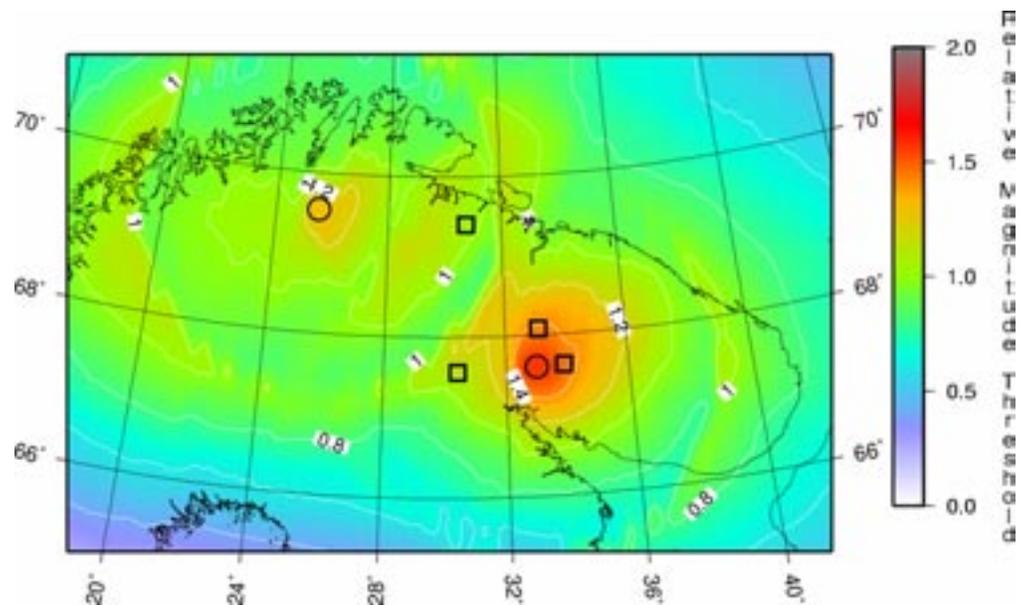
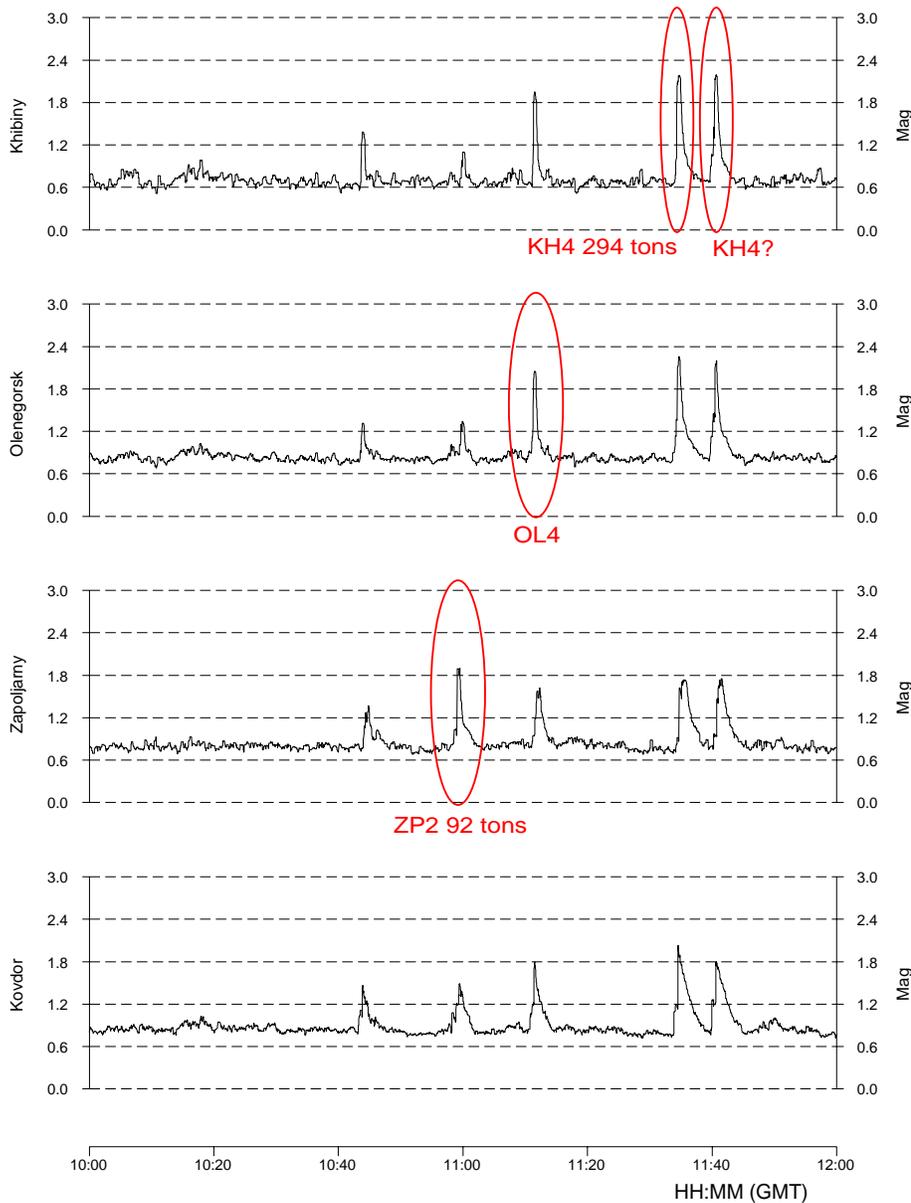


Figure 6. Peak network magnitude thresholds with mean subtracted for the same 2-hour time interval as shown in Figure 5. This essentially shows the height of the highest peak above the background level within the time interval for each grid point. The five events occurring in the region during this time interval create significant threshold peaks in the entire region.

The individual time traces for each of the four mining sites (Figure 7) show a quite significant activity during these two hours, with confirmed mining explosions both at Khibiny, Olenegorsk and Zapolyarnyi. As expected, there is a corresponding threshold increase on all the traces for each mine explosion, but in each case the increase in threshold level is greatest for the actual site of the explosion. There is also an unknown event (perhaps a small earthquake) that is located outside of the mining areas.

Regional Threshold Monitoring of the Kola mining areas



12 April 2002 Day 102

Figure 7. Network magnitude thresholds for the grid points closest to the four mining areas shown in Figure 1, for the 2-hour time interval starting 2002-102:10.00. Five significant threshold peaks are seen during this time interval, of which three are mining explosions reported by the KRSC. The last peak at 11:40 is believed to be an additional explosion at the Central Khibiny mine KH4. The first peak at 10:44 is caused by an event located approximately 70 km south-west of the Apatity array.

Processing a 24 hour interval

Figure 8 shows network magnitude thresholds for the grid points closest to the four mining areas Khibiny, Olene-gorsk, Zapoljarny and Kovdor for the entire day 12 April 2002. This is the same day from which the two previous time segments were extracted. During this day 10 events are found which are located in three of these mining areas, of which 6 are confirmed by KRSC. The corresponding mines and threshold peaks are indicated by red arrows.

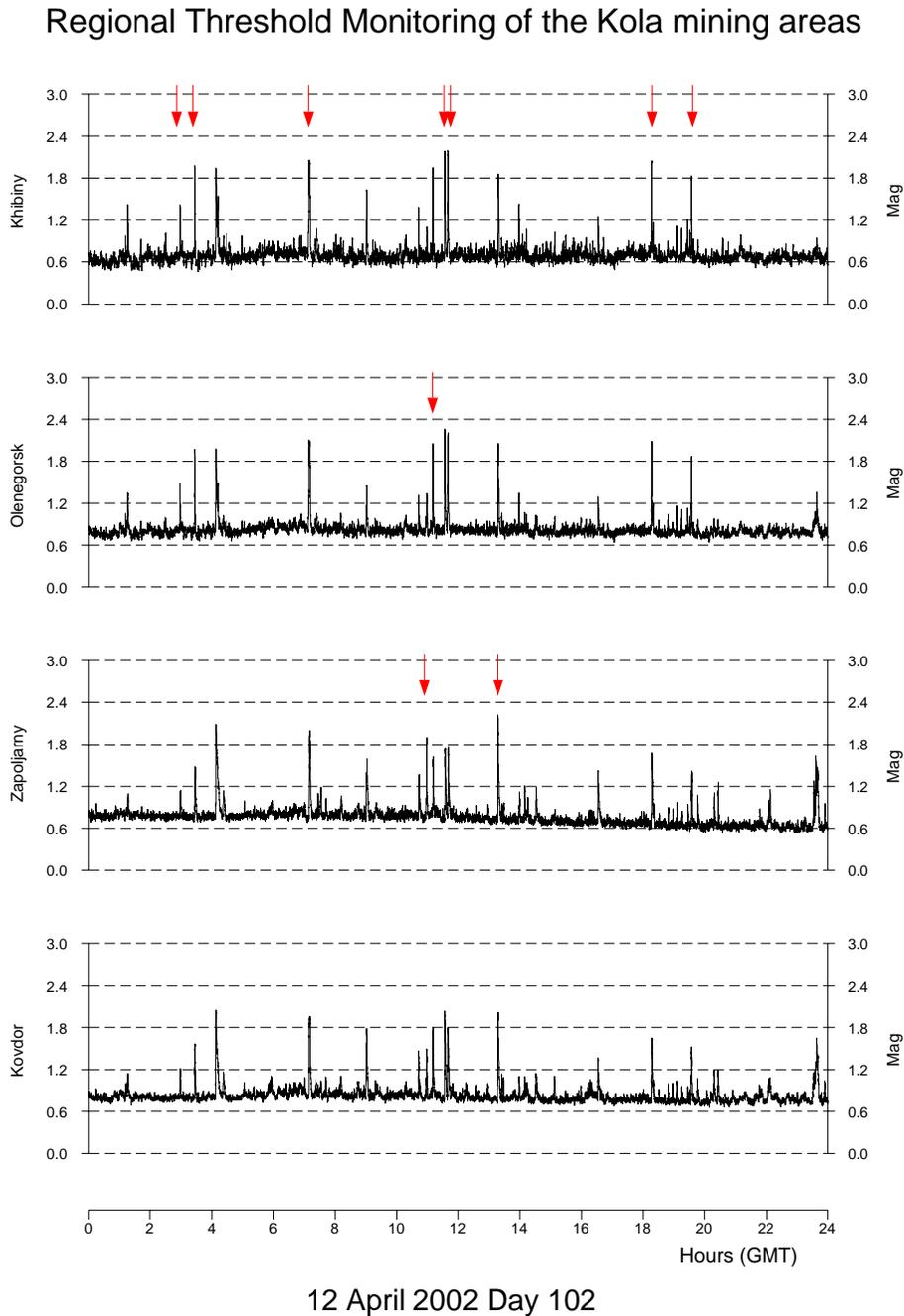


Figure 8. Network magnitude thresholds for the grid points closest to the four mining areas Khibiny, Olene-gorsk, Zapoljarny and Kovdor for 12 April 2002. During this day 10 events are found which are located in three of these mining areas, of which 6 are confirmed by KRSC. The corresponding mines and threshold peaks are indicated by (red) arrows.

CONCLUSIONS

This section contains the main conclusions from the work on all the sub-tasks associated with this contract. The results from the Regional Threshold Monitoring of the Kola Peninsula are given at the end of this section.

Regional Database and Attenuation Relations

A database comprising 45 seismic events, selected to provide the best possible ray path coverage of the Barents Sea and adjacent areas, has been compiled and reanalyzed in a consistent manner. This has resulted in new regional attenuation relations for Pn, Sn, Pg and Lg, together with a preferred average velocity model to be used for predicting the travel times of regional phases. We have applied these attenuation relations to develop and assess a regional threshold monitoring scheme for selected subregions of the European Arctic (Hicks et al., in press).

Amplitude inversion has been used in this study to resolve new attenuation coefficients and station corrections for estimating magnitudes from STA amplitude observations for Pn, Pg, Sn and Lg phases in the Barents Sea region. The distance range for observations on which the Pg and Lg relations are based is limited; a future study using a greater number of continental events could most likely provide a relation for STA based Lg magnitudes that is applicable at larger distances, albeit limited to paths within Fennoscandia.

The pattern of Lg arrivals and associated amplitudes supports the previously published indications that the deep sediment basins and Moho topography under the Barents Sea efficiently block Lg wave energy from crossing. From this, it is clear that Pn and Sn are the most useful phases for calculating stable and consistent magnitudes for events in the Barents Sea.

The BAREY model from Schweitzer and Kennett (2002), based on a model for the Barents Sea area from Kremenetskaya et al. (2001), provides the smallest overall travel-time residuals when locating events within the vicinity of the Barents- and Kara Seas.

The seismic station in Amderma can be tied in to the regional network in Fennoscandia and on the Svalbard archipelago using an appropriate crustal model, and is able to provide important information regarding the location of events in the eastern parts of the Barents Sea and the Kara Sea (Schweitzer and Kennett, 2002). Magnitudes calculated at this station are on the whole consistent with the other observations.

The attenuation in the Barents Sea region differs somewhat from that observed in other stable tectonic regions, as evidenced by the fact that the coefficients given by Jenkins et al. (1998) for such regions do not give consistent magnitudes across frequencies, phases and stations for our amplitude observations from the events in the Barents Sea region.

Regional Threshold Monitoring

We have successfully developed a methodology and associated software for regional seismic threshold monitoring, and applied it to distinct regions of different sizes in the Barents Sea, Novaya Zemlya and the Kola Peninsula.

The Kursk accident on 12 August 2000 and subsequent underwater explosions occurring during the fall and winter of 2000 provided an excellent opportunity to test and evaluate the usefulness of the threshold monitoring method. By tuning the processing parameters using the recordings of the Kursk accident, we were able to consistently monitor the numerous underwater explosions in the area around the accident site down to magnitude 1.5. The study demonstrated that the threshold traces steered to the accident site also provided excellent results for the underwater explosions that occurred in a relatively small geographical area (some tens of kilometers across) surrounding the accident site.

An initial grid system with an approximately 100-km grid spacing has been deployed to cover the entire Barents Sea region, and the observations at the arrays, ARCES, SPITS, FINES and NORES have been used for calculating threshold magnitudes for each of the grid points. During an interval without seismic signals, the threshold magnitudes showed large variations over the region, and, in particular, in the vicinity of each array. However, for the region around the island of Novaya Zemlya the variations are modest, varying around a mean of magnitude 2.1-2.2, when using this array network.

In order to investigate in more detail the variations in threshold magnitudes for the Novaya Zemlya region, we have deployed a dense grid with an areal extent of about 500 x 500 km around the former Novaya Zemlya nuclear test site. For each of the grid nodes, we calculated magnitude thresholds for the two-hour time interval 00:00 - 02:00 on 23 February 2002. At 01:21:12.1 there was an event with a magnitude of about 3, located about 100 km northeast of the former nuclear test site.

Regions of different sizes have been constructed by selecting grid points within different radii from the former nuclear test site. Average, minimum and maximum threshold magnitudes have been compared for circular regions with radii of 20, 50, 100 and 200 km, respectively. The most important result is that even for a target region with radius as large as 100 km, the variations in threshold magnitudes are all within 0.2 magnitude units. This applies both for the time interval with the event and for background noise conditions. For the investigated station geometry, it will therefore be meaningful to represent the monitoring threshold of the entire Novaya Zemlya region with the values of a single target point, together with the *a priori* determined uncertainty bounds.

For areas with larger variations in threshold magnitudes, like in the vicinity of the arrays, a 100-km radius target region will obviously show larger differences between the maximum and minimum values. Examples illustrating this point have been shown.

In cases when data from the Amderma station can be retrieved we find significant variations in threshold magnitudes over the island of Novaya Zemlya, ranging from 1.4 at the southern tip to 2.2 at the northern tip during noise conditions. This applies to the time interval immediately preceding the event on 23 February 2002. During this time interval, the monitoring capability for the former nuclear test site is lowered by about 0.3 magnitude units to about 1.9. This implies that a regional threshold monitoring scheme for the NZ region has to be divided into geographical sub-regions having similar threshold magnitudes during background noise conditions.

Using data from the ARCES and Apatity arrays, we have implemented a regional threshold monitoring scheme focusing on the Kola Peninsula. For the most active mining areas in this region (Khibiny, Olenegorsk, Zapoljarny and Kovdor), the magnitude thresholds during normal noise conditions vary between 0.7 and 1.0 magnitude units. During the studied time interval (12 April 2002), 10 out of 18 peaks exceeding threshold magnitude 1.2 at any of the mining areas were caused by events in the actual mining areas. However, the spatial resolution of the threshold traces when using the ARCES and Apatity arrays is quite low. In fact, each mining event created significant threshold peaks not only for the threshold trace associated with the actual mine, but also for the traces for the other mining areas.

This implies that for a regional threshold monitoring scheme for the Kola Peninsula it will be sufficient to deploy a set of targets for the most active mining areas. When a threshold peak is found at any of these targets, the peaks have to be associated with seismic events as outlined for the Kursk study.

RECOMMENDATIONS

We recommend that the work with amplitude attenuation relations for regional phases in Fennoscandia and adjacent areas be continued and extended to broader regions. The development of consistent regional magnitude scales is an important problem which still is far from a solution, but the results obtained in this study are encouraging.

The software which has been developed for this project should be considered for operational implementation. The necessary procedures and parameters for such implementation are provided in the final report of the project.

The automatic explanation facility for peaks on the threshold traces provided in the final report of the project assumes that a reasonably accurate on-line seismic detection bulletin is available. The joint development of combined threshold monitoring and reliable automatic detection bulletins is a future priority area.

The application of the regional threshold monitoring technique to other regions of monitoring interest should be considered. It would be particularly useful to investigate the benefits of adding local (non-IMS) stations to the IMS Primary and Auxiliary networks in such applications.

REFERENCES

- Hicks, E.C., Kv rna, T., Mykkeltveit, S., Schweitzer, J. and Ringdal, F. (in press), Travel-times and attenuation relations for regional phases in the Barents Sea region, *Pure and Applied Geophysics*, in press.
- Jenkins, R.D., T.J. Sereno, and D.A. Brumbaugh (1998), Regional attenuation at PIDC stations and the transportability of the S/P discriminant. AFRL-VS-HA-TR-98-0046, Science Applications International Corporation, San Diego, CA, USA.
- Kremenetskaya, E.O. and V.M.Trjapitsin (1995): Induced seismicity in the Khibiny Massif (Kola Peninsula), *Pure and Applied Geophysics*, 145(1), 29-37.
- Kremenetskaya, E., Asming, V., and Ringdal, F. (2001). Seismic location calibration of the European Arctic, *Pure Appl. Geophys.* 158, 117-128.
- Ringdal F., E.Kremenetskaya, V.Asming, I.Kuzmin, S.Evtuhin, V.Kovalenko (1996): Study of the calibration explosion on 29 September 1996 in the Khibiny Massif, Kola Peninsula. Semiannual Technical Summary 1 April - 30 September 1996, NOR SAR Sci. Rep. 1-96/97, Kjeller, Norway.
- Schweitzer, J., and Kennett, B.L.N. (2002), Comparison of location procedures - the Kara Sea event 16 August 1997, Semiannual Technical Summary, 1 July - 31 December 2001, NOR SAR Sci. Rep. 2-2001/2002, Kjeller, Norway, 97-114.