GROUND TRUTH COLLECTION FOR MINING EXPLOSIONS IN NORTHERN FENNOSCANDIA AND NORTHWESTERN RUSSIA

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ABSTRACT

We concluded comprehensive ground truth collection at the Khibiny, Olenegorsk, Kovdor, and Zapolyarnyi mines, and have basic information on 2,052 explosions. In the past two years we used this ground truth information to extract waveform data from the ARCES array and a number of regional stations (KEV, LVZ, APA) as well as from six stations that we deployed along two lines stretching between the Khibiny Massif mines and the region around the ARCES array. We calculated P/S ratios using the Seismic Array in Northern Norway (ARCES) array data for many of these events comprising several source types (compact underground explosions, underground ripple-fired explosions, surface ripple-fired explosions). We found that the P/S ratios of small compact underground explosions in mines of the Khibiny Massif are systematically lower than the P/S ratios of large ripple-fired surface explosions. We had anticipated that smaller underground shots would appear more like single well-coupled explosions, thus having higher P/S ratios than large ripple-fired explosions. A possible explanation for this phenomenon is that the compact underground explosions in these mines are designed to fracture and drop a large quantity of ore from the ceiling of a horizontal shaft. The potential energy released by the falling ore may express as shear wave energy, which may be considerably greater than the (P wave) energy released directly by the explosive.

We concluded the deployment of the six stations along the Khibiny-ARCES lines this past summer; this year we are examining the data from these stations to see how P/S ratios vary with range from the source. We have an update on the P/S ratio analysis contrasting different source types, with the addition of an analysis of range dependence using data from the temporary stations.

The portable stations were redeployed in the fall of 2004 to the Kiruna and Malmberget underground mines in northern Sweden. The stations deployed in Malmberget also record events from the surface mining operations at the Aitik mine, located some 15 km from Malmberget mine. The data from these stations will allow comparisons of seismic waveforms resulting from different types of shooting practices at different locations within the mines. These stations will provide ground truth on a large number of explosions at these mines allowing future analyses of the dependence of discriminants on source type, possibly assessing the portability of results obtained with the Khibiny explosion observations.

OBJECTIVE(S)

This year the project had 3 principal objectives:

1. Complete assembly of a comprehensive mining explosion database of waveforms from permanent network stations in the region and the temporary Khibiny-ARCES line stations.

2. Operate temporary stations at the iron mines of Kiruna and Malmberget in Sweden for ground truth collection and near-source event waveform characterization.

3. Continue preliminary analysis of the variation of regional discriminants with source-receiver range and source type.

RESEARCH ACCOMPLISHED

Database assembly

By late June 2005, we had assembled a comprehensive database of ground truth information and waveforms for the 2,052 ground truth explosions identified in the Kola Peninsula. The waveforms have been collected from the six temporary stations (Figure 1) described in the next section, as well as the ARCES array, broadband stations KEV and LVZ, and the Apatity array and broadband station (APA). This database is an outstanding resource for studying general propagation effects with range, and the performance of detectors, location algorithms, discriminants, and magnitude-yield relations for a wide range of explosion types.

Completion of the Khibiny-ARCES temporary lines deployment

Our deployment of temporary stations in Finnmark, Norway and Finland was concluded in September 2004. The stations were recovered then for shipment to Sweden. Figure 2 shows the periods of operation of the temporary stations. Difficult access to the stations compounded by some equipment failures led to significant down times.

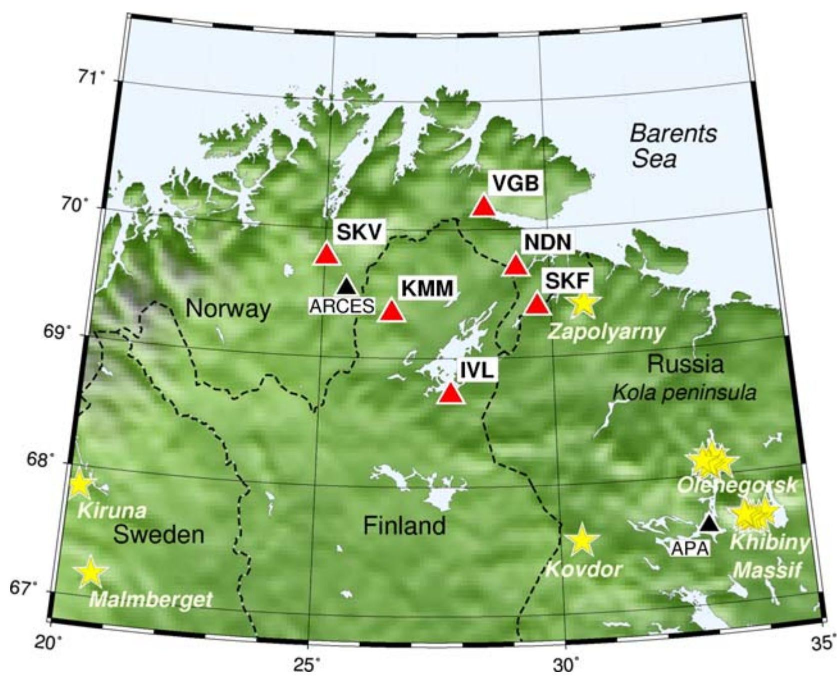

Figure 1. The deployment of six temporary three-component stations in Finnmark, Norway and Finland was concluded in early September 2004. The stations (shown as red triangles) had GS-13 sensors and 24-bit Reftek recorders.

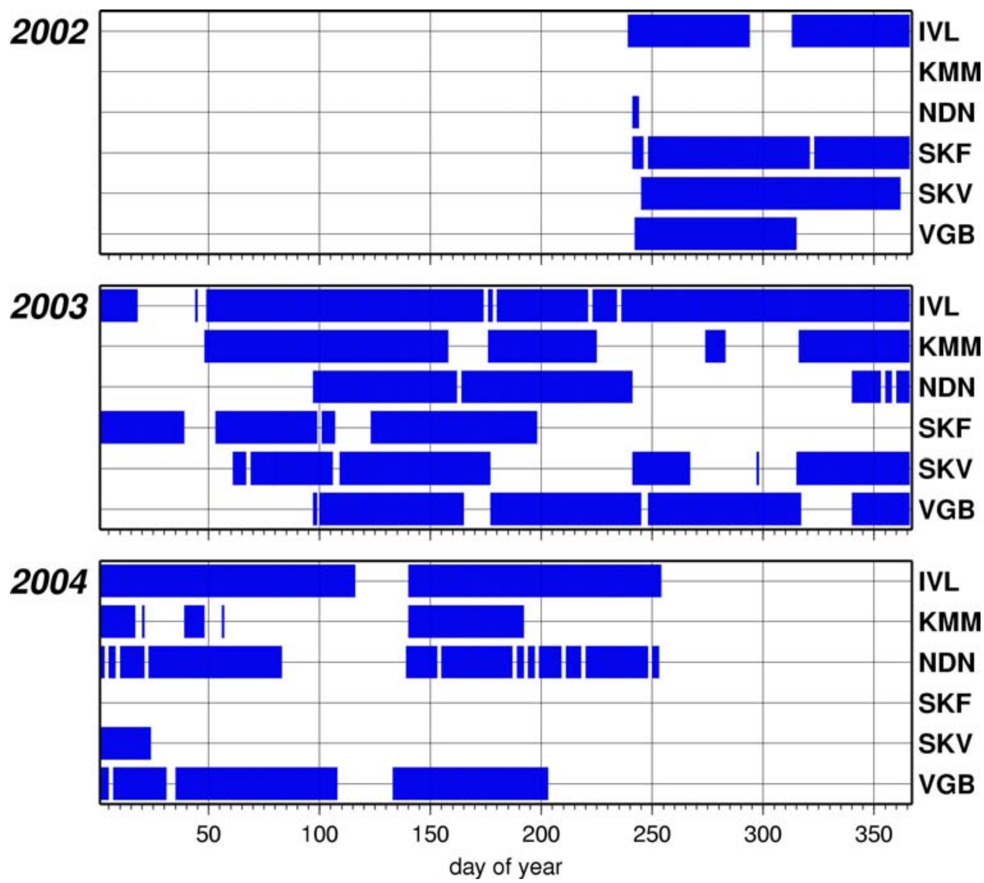

Figure 2. Periods of operation (blue bars) for the six stations in the temporary line deployments. We extended the deployment at no cost from one year to two years to assure collection of an adequate amount of data. The temporary deployment had significant amounts of down-time, due to difficulties in retrieving data and maintaining stations in high arctic conditions.

Consequently, we extended the period of operation by a year at no cost to the Department of Energy (DOE) to achieve an adequate collection of data.

Operation of temporary stations at the Swedish mines at Kiruna and Malmberget

The six LLNL Reftek field recorders that had been deployed in Finnmark in northern Norway and in Finland until September 2004 were redeployed to northern Sweden in the beginning of October 2004. The recorders are deployed around two iron mines operated by Swedish company LKAB. One of these mines, at Kiruna, is the largest underground iron mine in the world. The second, at Malmberget, exploits multiple iron ore deposits some 75 kilometers SSE of Kiruna. Figure 3 shows the locations of the mines and the temporary stations, and Figure 4 shows the time periods for which data are available following our first collection trip.

Three three-component stations (KPN, MJR, STR) were deployed around Malmberget (Figure 5) in a triangle spanning an aperture of about 1.5 kilometers. These stations use S6000 sensors; the recorders operate in trigger mode, recording 60 seconds of data per trigger at 250 samples per second with a 10-second pre-event noise window.

Two small arrays were deployed at Kiruna, one in the basement of a laboratory building of the LKAB mine, and the second in the basement of a hotel 1.2 km to the east of the first array (Figure 6, upper right). These arrays each consist of one S6000 three-component sensor and three geophones. The aperture of the first array is about 60 meters and that of the second is 30 meters. The S6000 in the second array is collocated with one of the geophones allowing direct comparison of the responses of the two types of sensors. A third station (ALN) was set up in Puoltsa about 20 kilometers WSW of Kiruna (Figure 6, lower right). This station is placed roughly midway between a fault and the mine. We hope to observe small earthquakes on the fault and mining explosions at approximately the same distance, enabling discriminant studies at local distances and small magnitudes. This fault is one of the more active faults in northern Fennoscandia and is thought to be driven by elastic rebound following the melting of the continental ice sheet. The sensors at this station consist of a three-component set of GS-13 seismometers.

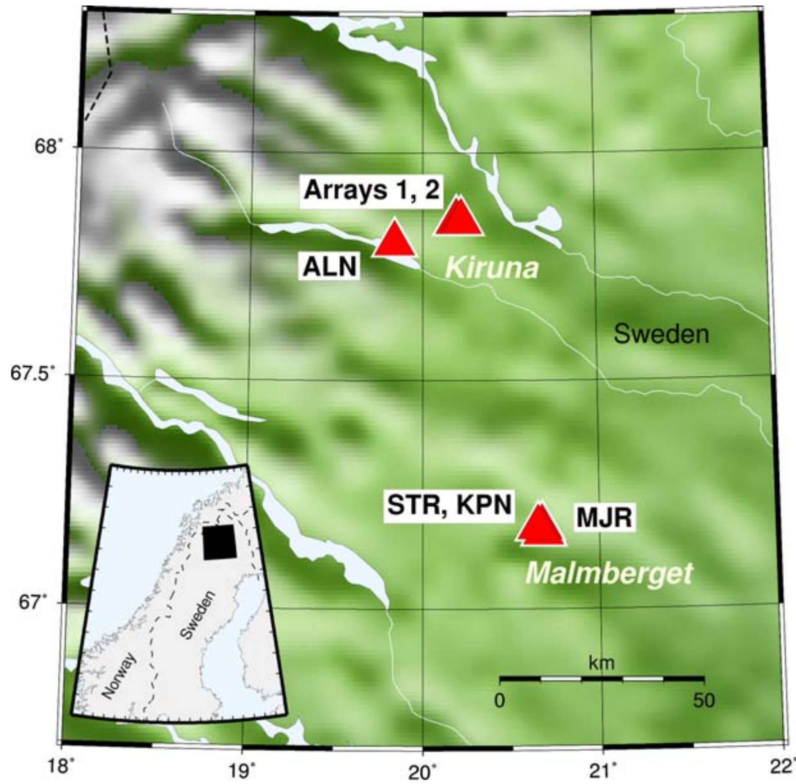

Figure 3. Following completion of our deployment in Finnmark and Finland, we redeployed the field recorders with a variety of sensors to the vicinity of the iron mines at Kiruna and Malmberget in Sweden. One three-component station with GS-13 seismometers was deployed to the west of Kiruna roughly midway between a fault and the mine.

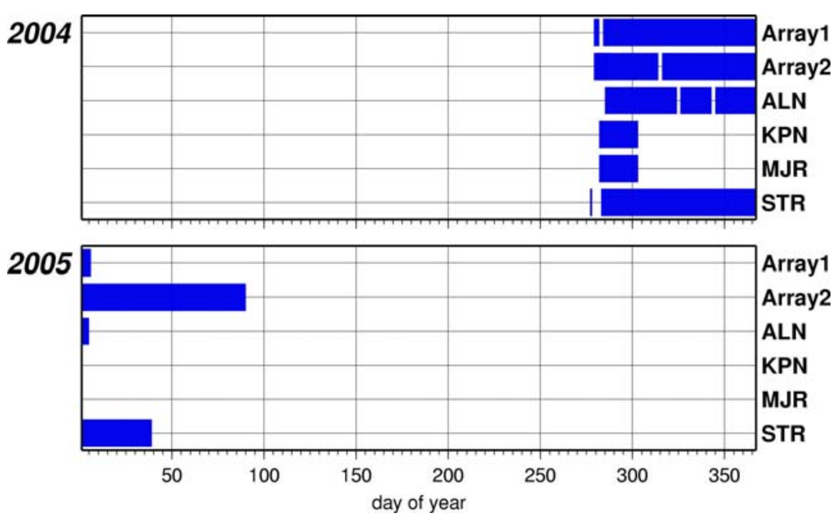

Figure 4. Periods of operation (blue bars) for the stations around the Kiruna and Malmberget mines. Additional data have been recorded but not yet collected from the field recorders.

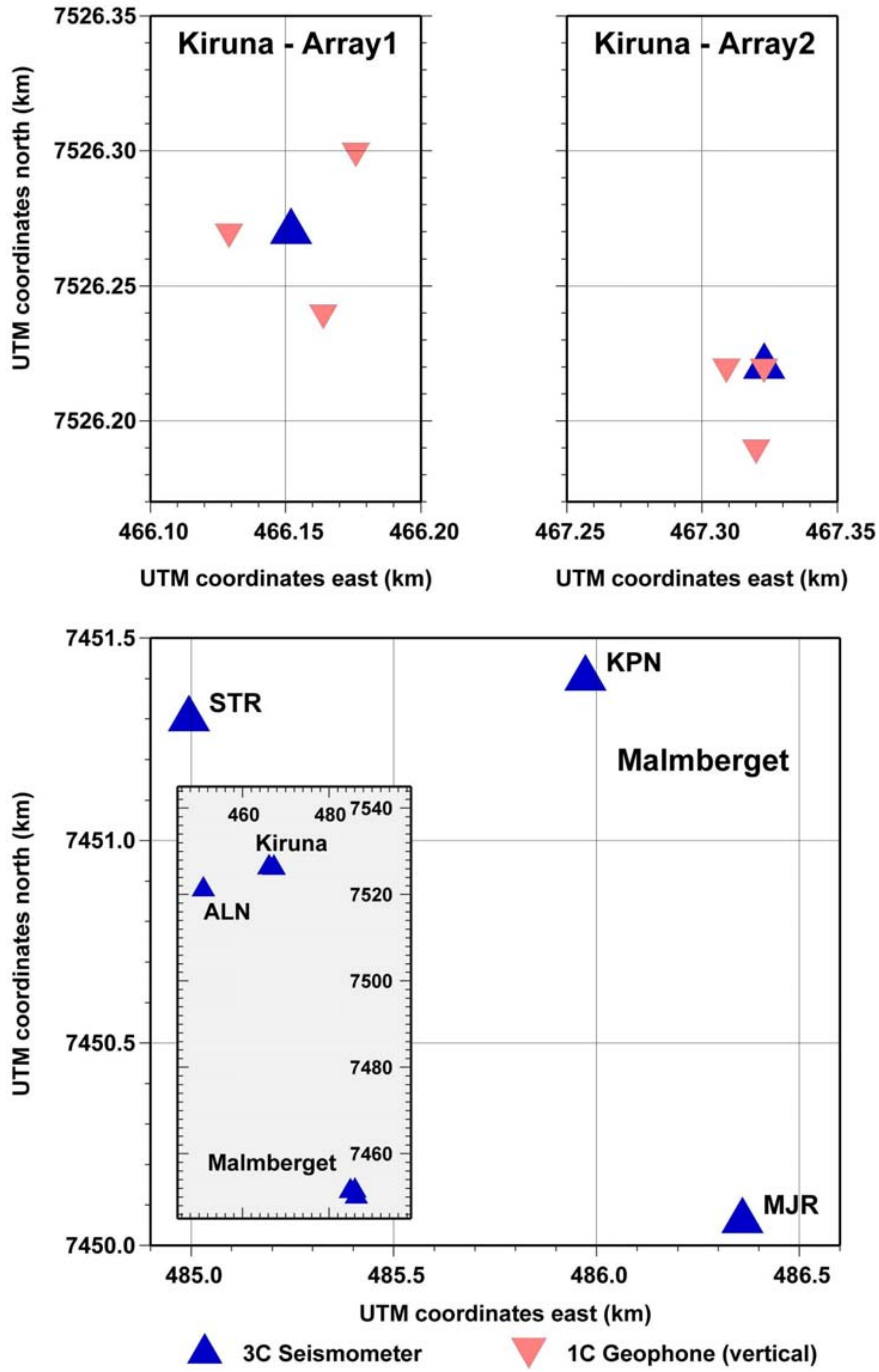

Figure 5. Detail of the deployments at the Kiruna and Malmberget iron mines. Two small arrays were deployed at Kiruna and three three-component stations were deployed at Malmberget.

Initial data collections (Figure 7) have provided observations of rockbursts and production explosions at very close ranges (~ 1 kilometer) at the Kiruna and Malmberget mines. These observations suggest that rockbursts and explosions have different spectral content (Figure 7). At this range, phase ratio discriminants may not be feasible, since even direct P and direct S are not well separated. It appears that spectral ratio discriminants, or more generally, spectral shape discriminants may have potential.

The mines of Sweden offer an opportunity to examine the portability of observations made at ARCES in previous years [Harris et al., 2004] (and examined in the next section) that compact underground explosions have smaller Pn/Lg ratios than adjacent surface ripple-fired explosions. The mine at Aitik is approximately 17 km southeast of the Malmberget mine, and conducts weekly, large ripple fired explosions that may be compared to the underground explosions at Malmberget. The stations deployed at Malmberget, and the relationship developed with LKAB will provide ground truth information essential to that comparison.

Figure 6. Photographs of Kiruna and Malmberget deployments. The historic surface mine is apparent as the gap in the hill in the photograph at top left. Today the ore is mined underground. The collocated S6000 and geophone in array 2 at Kiruna are shown in the upper right photograph. A typical Malmberget deployment in the basement of a private home is shown at lower left. Station ALN is shown at lower right.

<u>Regional discriminant analysis</u>

We have continued analysis of P/S discriminants using data from ARCES and temporary station IVL. This year we recalculated Pn/Lg and calculated Pn/Sn ratios for compact underground explosions at the Kirovsk mine and surface ripple-fired explosions at the Central mine using data from ARA0. The mines are adjacent and about 410 kilometers from the ARCES. Histograms of the Pn/Lg ratios in five frequency bands (2-4, 4-6, 6-8, 8-10 and 10-12 Hertz) are shown in Figure 8 for the two types of explosions and display a distinct low bias for the compact undergournd explosions relative to the surface explosions. This bias is most pronounced in the 4-6 and 6-8 Hertz bands, though noticeable in the 2-4 and 10-12 Hertz bands. In previous years we speculated that this bias may be due to differences in the style of the explosions. The compact underground explosions are designed to drop the roofs of adits, while the surface explosions fracture rock into rubble in-place. Energy from the underground events may be dominated by rockfall rather than by the explosion itself, and may be richer in shear waves as a consequence.

Figure 9 shows Pn/Sn ratios for the same suites of explosions. The pattern is similar here in the 4-6, 6-8 and 8-10 Hertz band, though not in the 2-4 Hertz band. These results suggest that the difference in sources is observed similarly independent of the take-off angle of the shear energy from the source.

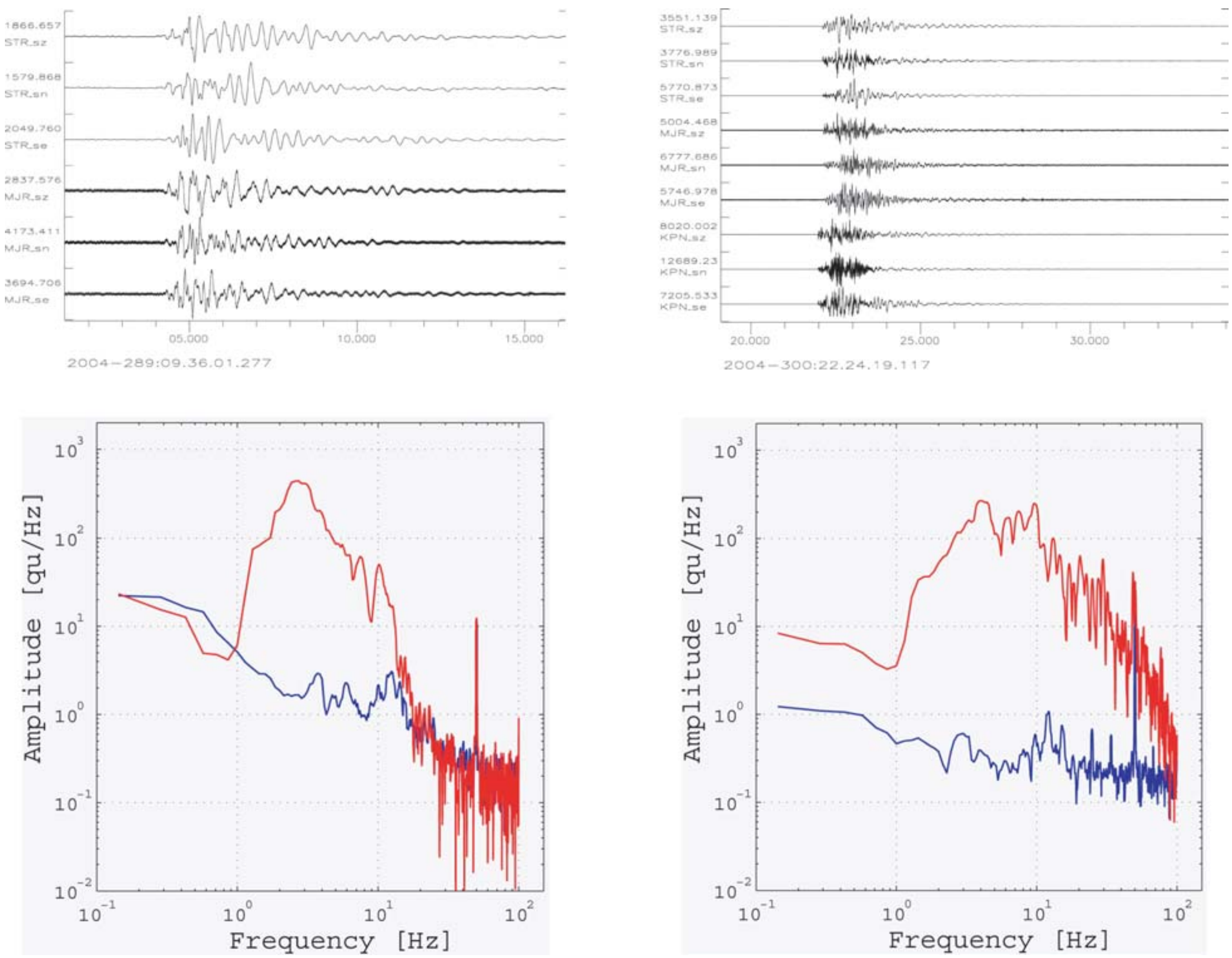

Figure 7. Waveforms and spectra for a rockburst (left) and an explosion (right) in the Malmberget mine recorded by local station STR demonstrate the much higher frequency content of explosions. The rockburst was observed at a range of about 1 kilometer. The signal spectra are shown in red and pre-event noise spectra are shown in blue. Both are uncorrected for instrument response.

With its good recording history IVL also offers many observations of the Khibiny explosions. Pn and Lg phases (but not Sn) are sufficiently distinct at this range to allow amplitude measurements to be made. However, the histograms of Pn/Lg ratios (Figure 10) do not show the same pattern for the two shot types as at ARA0. Since IVL and ARA0 are roughly on the same backazimuth from the Khibiny mines, this difference suggests strong distance and/or site dependencies in the Pn/Lg ratios, which should be better quantified and removed before final conclusions are drawn about biases between source types. Frequency- and phase-dependent path and site corrections for phase amplitudes could be derived from MDAC calibrations using the earthquakes in the region. Given the relative scarcity of earthquakes in Fennoscandia and northwest Russia, it may be desirable to develop such corrections directly from mining explosions. This is a research topic given the considerable complexity of the explosion sources. Possibly two-station techniques could be employed to minimize the effects of the source in estimating path and site corrections.

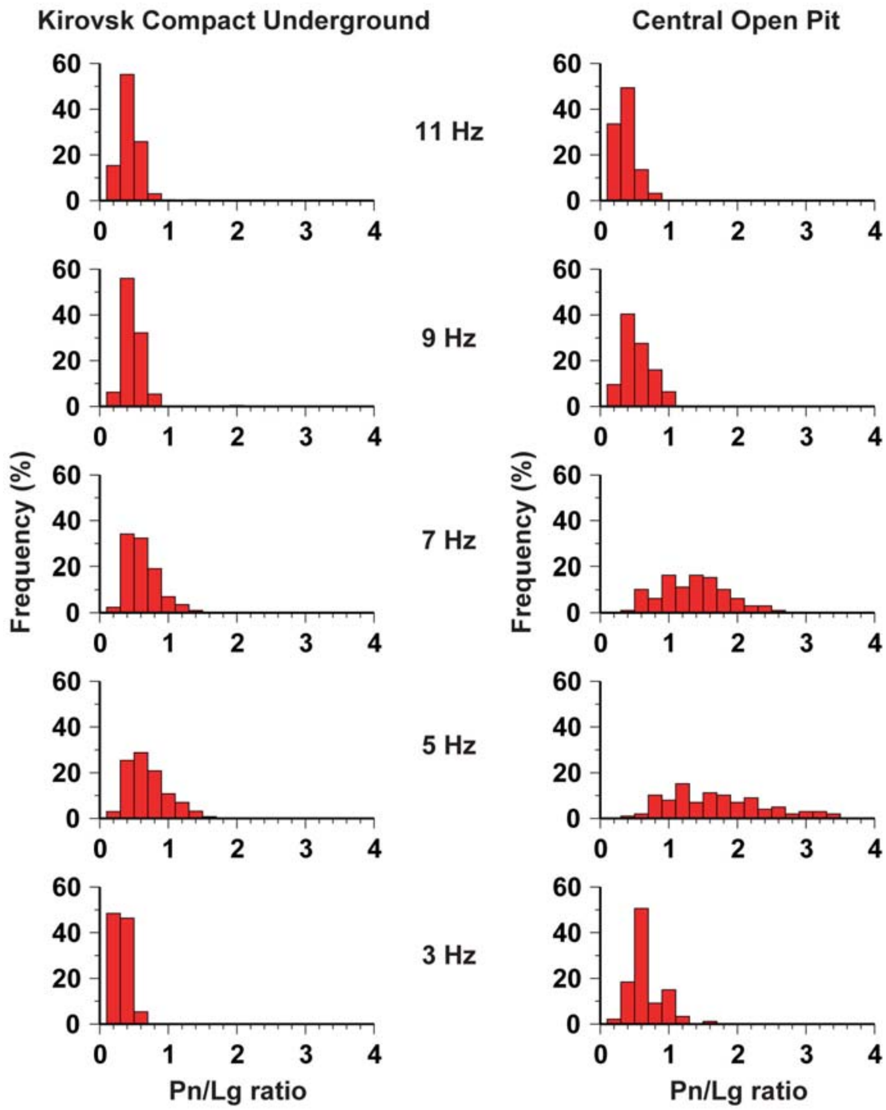

Figure 8. Histograms of Pn/Lg ratios observed at station ARA0 of the ARCES array demonstrate that, at this station, compact underground explosions typically have smaller Pn/Lg ratios than surface ripple-fired explosions. The two mines examined here are adjacent in the Khibiny Massif and at an approximate range of 410 kilometers from ARA0. The ratios are displayed in five frequency bands with bandwidths of two Hz and labeled by their center frequencies. The differences in the distributions are most pronounced in the 4-6 and 6-8 Hz bands, but significant in the 2-4 Hz band.

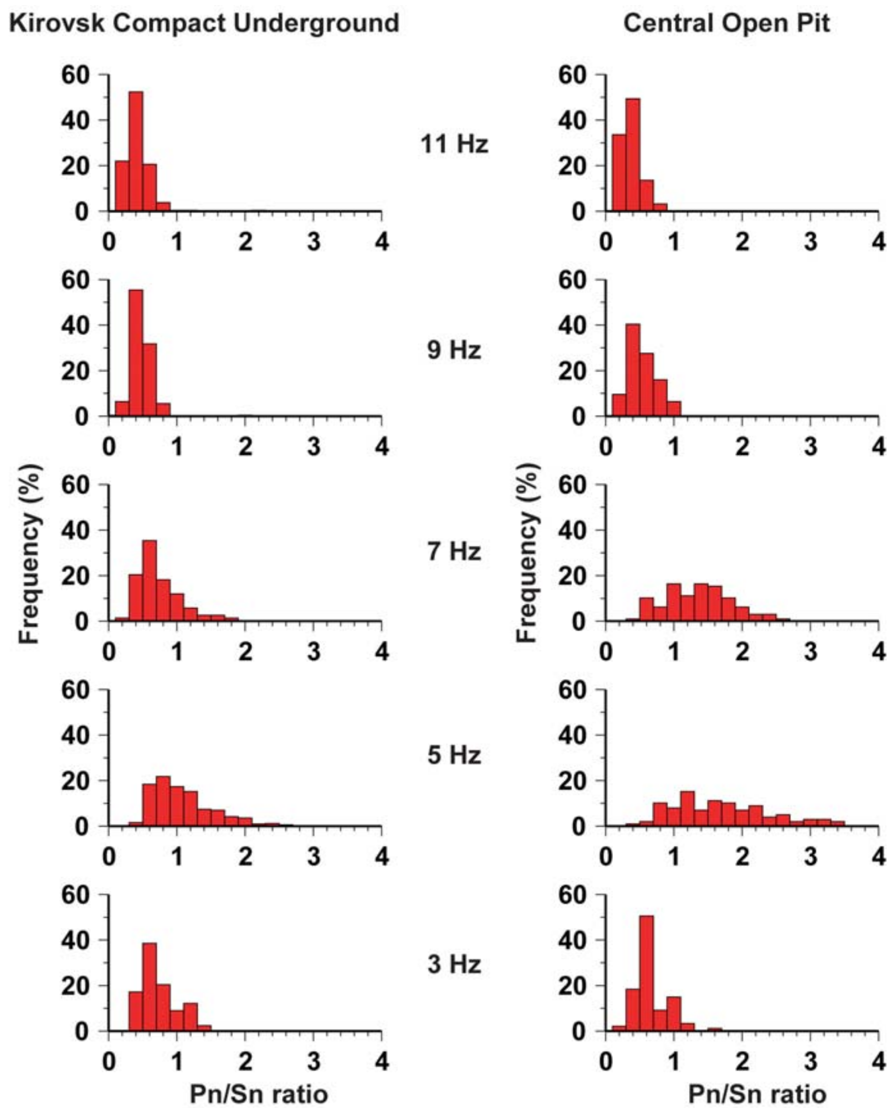

Figure 9. Pn/Sn ratios observed at station ARA0 also display significant differences in the 4-6 and 6-8 Hertz bands. The compact underground explosions have the smaller Pn/Sn ratios in these bands.

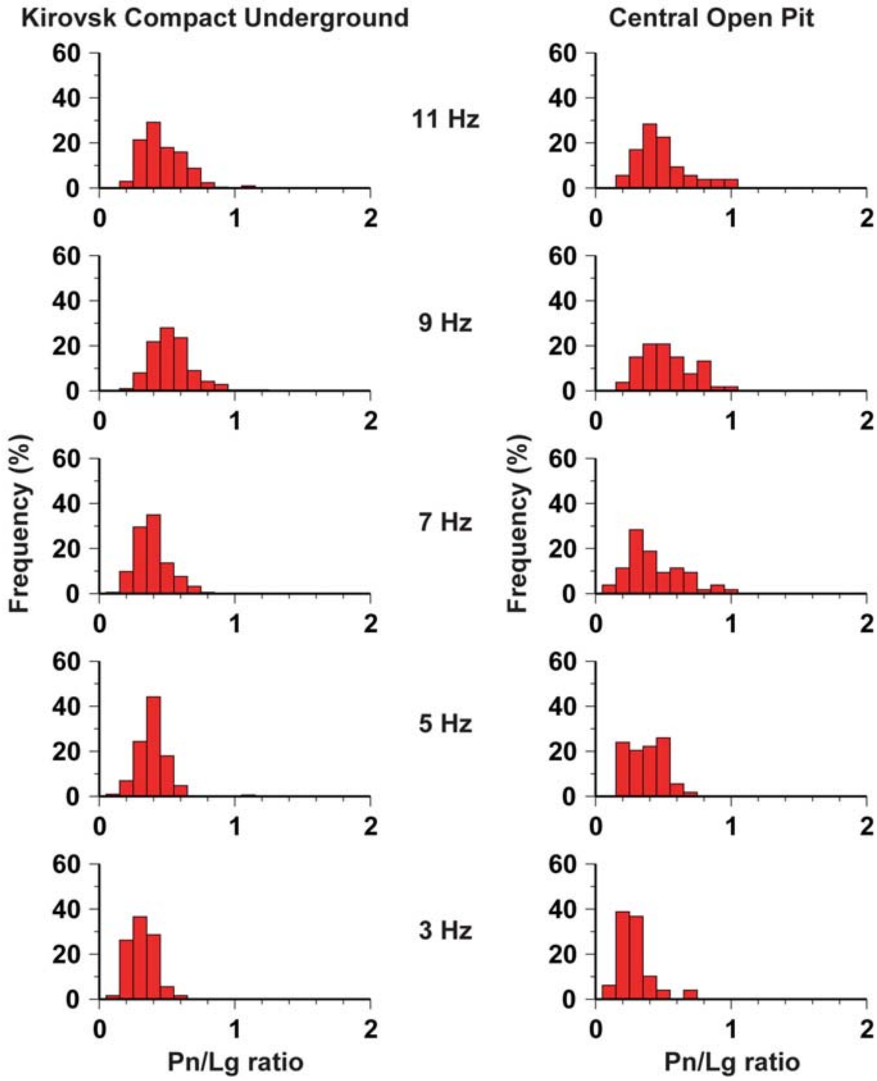

Figure 10. Pn/Lg ratios observed at temporary station IVL. This station is much closer (280 km) to the mines of the Khibiny Massif, but still outside of the Pn/Pg crossover. The Pn/Lg ratios for the compact underground explosions at this station show little or no tendency to be smaller than the surface ripple-fired ratios.

CONCLUSIONS AND RECOMMENDATIONS

We conclude that we have assembled a valuable data set for examining the relative excitation of different seismic phases and discriminants by several types of mining explosions. Initial examination of the data has revealed significant differences in P/S ratios observed by the ARCES array for distinct types of mining explosions conducted in the Khibiny mine group, which may be linked to the different ways that ore is moved by the explosions in surface and underground mines. We recommend that a number of additional analyses be conducted on the data.

1. Development of path/station corrections allowing comparison of explosions at different ranges from a station and among different observing stations. Such corrections should be used to sort out whether the variations in P/S discriminants among different explosion types are due to different source mechanisms.
2. Conduct a comparison (using ARCES and other stations) of the underground explosions at Malmberget and the surface ripple-fired explosions at Aitik to determine whether the P/S variations observed for compact underground explosions and surface ripple-fired explosions at the Khibiny mines are reproduced for a different source region.
3. Examine the behavior of the same (path corrected) discriminants for earthquakes in the region.
4. Examine the performance of spectral shape and spectral ratio discriminants for rockbursts and explosions at local distances using data from close-in sensors. Such data are being collected in the vicinity of Kiruna and Malmberget mines as this project concludes.

REFERENCE

Harris, D., F. Ringdal, E. Kremenetskaya, S. Mykkeltveit, D. Rock, J. Schweitzer, T. Hauk, and J. Lewis (2004), Ground-Truth collection for mining explosions in Northern Fennoscandia and Russia, in *Proceedings of the 26th Seismic Research Review*: *Trends in Nuclear Explosion Monitoring,* LA-UR-04-5801, Vol. 1, pp. 73-82