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

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## ABSTRACT

This three-year project, which began on 1 September 2001, focuses on the collection of ground truth information on explosions at the principal mines within 500 km of the ARCES seismic array in northern Norway. Ground truth is being collected directly by deploying seismic stations at the mines and also by polling mine operators for shot information. In addition, two lines of seismic instruments are planned to be deployed in August 2002, extending from the Khibiny Massif of the Kola Peninsula to two points in Norway (one line includes ARCES). Observations of mining explosions collected by these instruments will enable researchers to examine the range (distance) dependence of seismic discriminants. The line will be operated for a year. In the third year of the project, the seismic stations will be redeployed to selected mines in northern Norway, Sweden, and parts of northwestern Russia to collect origin times and locations of additional commercial mining explosions.

To date, we have collected ground truth information on several hundred explosions in mines of the Khibiny Massif for a period of seven months. The data provided for each event include a seismically determined origin time, the mine conducting the explosion, the total yield of the explosion, and an indication of whether the shot was conducted on the surface or underground. The origin times are determined with data from a local network, including stations in the immediate vicinity of the mines. Frequently additional information is provided, such as the distribution of yields for individual shots in a multiple explosion event. The ground-truth catalog drives event waveform extraction for a collection of regional stations including ARCES, Lovozero (LVZ), Kevo (KEV), and Apatity stations (the Apatity array APAES and the broadband station APAZ9). Our goal is to assemble a ground truth set of waveforms useful for studying the effect of different shooting practices (e.g. underground compact explosions and ripple-fired surface explosions) on seismic observables. The mines of the Khibiny Massif are a highly desirable natural laboratory for examining this issue, since surface and underground mines conducting a variety of shot types are co-located and at regional distance from a major International Monitoring System (IMS) array -- ARCES.

Another objective of this project is to develop a strategy for allocating calibration resources in a region with many mines. Fennoscandia and western Russia illustrate the problem of resource allocation since hundreds of mines exist within regional distance of major monitoring stations. How many should be instrumented for ground truth collection and in what order are reasonable concerns for any monitoring organization. Our approach to this problem is to rank mines by their frequency of observation by the monitoring stations in question. This frequency can be determined by plotting event density geographically using automated and analyst-reviewed bulletins developed for the stations and then associating geographic clusters of events with known mine locations. This form of cluster analysis and association may be refined with waveform correlation techniques. We present an analysis of the geographic distributions of events detected and located by the ARCES array and by the Fennoscandian array network for the purpose of ranking the observability of mines in Fennoscandia and western Russia.

## OBJECTIVE

The collection of ground truth on mining explosions in northern Fennoscandia and northwest Russia underpins three efforts of interest to monitoring agencies:

1. the calibration of discriminants and location algorithms,
2. the construction of templates for event screening, and
3. the development of empirical and theoretical linkage between explosion source phenomena and observed seismic waveform characteristics.

## RESEARCH ACCOMPLISHED

### Ground truth and associated waveform data collection for events in the Khibiny Massif

One partner in this project, the Kola Regional Seismic Centre (KRSC), has begun collecting ground truth information on explosions from the major mines of the Kola Peninsula. The mines of this region provide a natural laboratory for exploring the effects of different shooting practices at mines on observed seismic signals. In particular, the Khibiny Massif (an alkaline intrusion occupying 1300 square kilometers in the Kola) contains five large mines producing apatite-nepheline ores for the superphosphate and aluminum industries. Both surface and underground mines are in close proximity in this group, and these conduct a variety of large and small explosions. The underground explosions range from small, compact shots of 2-3 tons of explosive having only a few delays to large ripple-fired shots of 120-240 tons with many delays of 20-35 milliseconds. The surface explosions range from small shots at the Kirovsk and Rasvumchorr mines in the 3- to 15-ton class up to large ripple-fired explosions averaging 150-180 tons at the Central and Koashva mines.

The information that we routinely are able to collect includes, for each explosion, the origin (which mine), a seismically determined origin time, the amount of explosive used, whether the shot was on the surface or underground, and frequently some information on the character of the explosion. The character may include whether the explosion was conducted as several distinct smaller shots (and the amount of explosive used for each) or whether it was conducted as a relatively compact explosion consisting of at most a few delays. Figure 1 shows the mines included in the study.

To improve the quality of origin time determinations and to provide some information on source time histories, KRSC has deployed several stations in the Khibiny Massif adjacent to or in operating mines. Data from their permanent stations APA and AP0 also contribute to the solutions.

As of this writing, we have information on 409 explosions covering the time period from September 2001 through March 2002, inclusive, split roughly equally between surface, open-pit explosions (212) and underground explosions (197). One hundred eighty-one compact underground explosions have been reported. The breakout of ground truth information by mine is given in Table 1. Note that one mine (Kirovsk) has explosions both at the surface and underground, and that the fairly compact group of Khibiny mines has large numbers of both types of events in close proximity. These events should permit studies of source effects of observed seismic signals.

**Table 1. Reported Explosions by Mine**

| | Surface | Underground | Total |
|---|---|---|---|
| **Khibiny Group** | (95) | (197) | (292) |
| Kirovsk | 10 | 118 | 128 |
| Rasvumchorr | 0 | 79 | 79 |
| Koashva | 29 | 0 | 29 |
| Norpakh | 14 | 0 | 14 |
| Central | 42 | 0 | 42 |
| **Olenogorsk Group** | | | |
| Olenogorsk | 14 | 0 | 14 |
| Kirovogorsk | 14 | 0 | 14 |
| Bauman | 11 | 0 | 11 |
| Komsomolsk | 6 | 0 | 6 |
| **Kovdor** | 30 | 0 | 30 |
| **Zapolyarny Group** | | | |
| Zapadny | 19 | 0 | 19 |
| Zapolyarny Central | 15 | 0 | 15 |

The ground truth information is being used to extract observation time histories for regional stations including KEV, LVZ, ARCES, and the Apatity stations. Figure 2 shows ARCES observations of eight representative small (3-10 tons) surface explosions and eight compact (1-5 tons) underground explosions conducted at the Kirovsk mine. Differences in signal frequency content between the surface and underground shots are apparent in Figure 2a (3-6 Hz) and 2b (6-9 Hz). Not surprisingly, the underground shots, though generally smaller, have similar signal amplitudes to those of the surface shots in the lower frequency band but are substantially richer in high-frequency components than the signals from the surface explosions.

One application of a database of collected waveforms is to develop waveform signatures for each of the mines observed by ARCES. Such signatures may be used as the basis for a bank of correlation detectors that screens out the background of mining explosions at that station. We plan a test of this screening operation later this year, validated by the ground truth being collected for the Kola mines.

**Developing a strategy for allocating ground truth collection resources**

One possible principle for ranking mines for ground truth resource allocation is to identify the mines that have the greatest seismic visibility to a monitoring network (in the sense of being most frequently observed and/or generating the largest signals). We are testing a data-driven approach to identifying such mines, consisting of four steps: (1) detection of geographic event clusters in NORSAR network bulletins, (2) refined waveform-correlation clustering of identified event groups, (3) relocation of the refined clusters with single-station location methods calibrated to reduce bias in order to associate the clusters with a mine, and (4) ranking the mines according to the numbers and size of the events in the associated clusters.

Our search for geographic clusters in NORSAR's bulletins is yielding significant results. Figures 3a and 3b show the result of mapping event density using two NORSAR bulletins, an automatic single-array bulletin generated from the ARCES data stream and an analyst-reviewed bulletin developed from the network of Fennoscandian arrays. Both show clearly defined clusters that, for the most part, map directly to known mining districts. The event density map from the automatic ARCES bulletin shows considerable background scatter and only delineates clusters in northernmost Fennoscandia and Russia. The second map displays considerably less scatter and more clearly defines clusters throughout Fennoscandia. The reduced scatter obviously is a function of the overlapping coverage of multiple stations and the screening effect of analyst review.

**Preparations for deployment of a line of stations between ARCES and the Khibiny Massif**

To enable studies of the evolution of phase amplitudes and discriminants with range, nine sets of 3-component instruments available to this project will be deployed temporarily on profile lines originating in the Khibiny Massif. Three systems will be deployed on the Kola Peninsula, and six systems will be deployed in Finland and Norway. A site survey is underway at this writing (July 2002); potential deployment sites are being ranked according to the availability of bedrock, local noise conditions, and the availability of power and access during winter months. Much of the area between the Khibiny Massif and ARCES is covered by lakes and also not accessible by roads. The current plan for deployment, as shown in Figure 4, consists of two lines from the Khibiny Massif, one running through the ARCES array and one passing to the north of ARCES. The deployment of two lines will allow studies of the azimuthal dependence of discriminants, in addition to range dependence. Current plans call for the lines to be deployed in late August 2002; data will be recorded continuously over a period of one full year.

## CONCLUSIONS AND RECOMMENDATIONS

The ground truth collection effort is progressing very well, yielding explosion data at a faster rate than originally anticipated. We expect to build a regional waveform database containing on the order of a thousand explosions with ground truth sufficient to perform statistical studies on the effects of firing practices at mines on regional discriminants. Initial geographic clustering results indicate that the principal observable mining groups around ARCES are identifiable from seismic bulletins, both automated and analyst reviewed. Further refinement of the clusters by waveform correlation analysis is anticipated to resolve individual mines. The methodology appears viable for identifying the most active mines for ground truth collection.


## ACKNOWLEDGEMENTS

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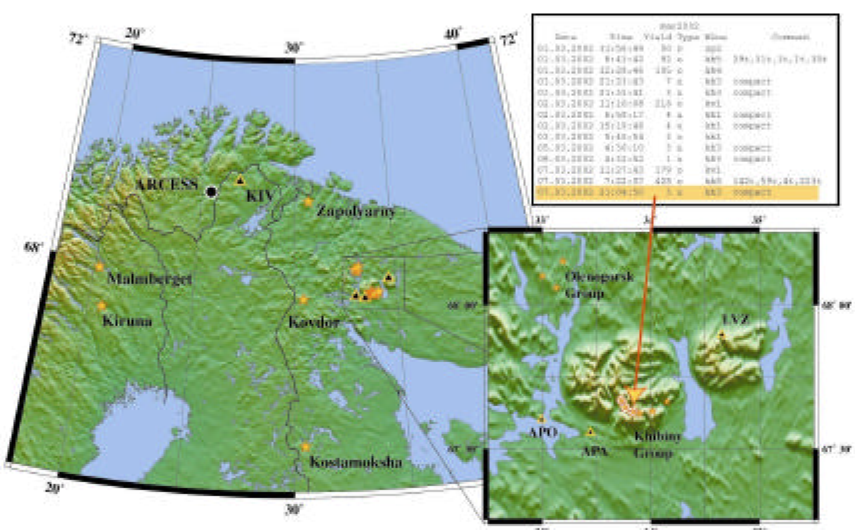


**Figure 1.** Map showing the mines for which ground truth information on explosions is being collected as part of this study and the stations from which waveform observations of the explosions are being compiled. The stations are indicated as triangles and the mines are shown as stars (those surrounded by circles are possibly underground as well as on the surface). A sample of available ground truth information is shown at upper right.

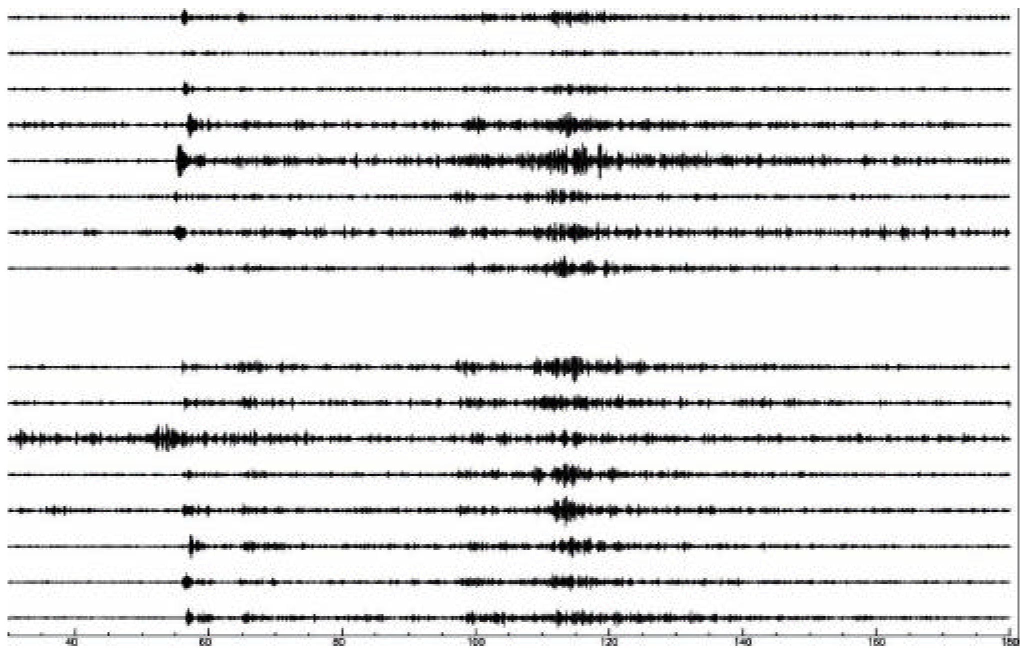


**Figure 2a.** ARCES waveform observations (single channel, A0 vertical) for 16 shots at the Kirovsk mine, filtered into the 3- to 6-Hz band. The top eight traces correspond to small surface explosions, and the bottom eight to subterranean explosions. Pn, Pg, Sn and Lg phase are evident in most of the seismograms. The observation range is approximately 410 km.

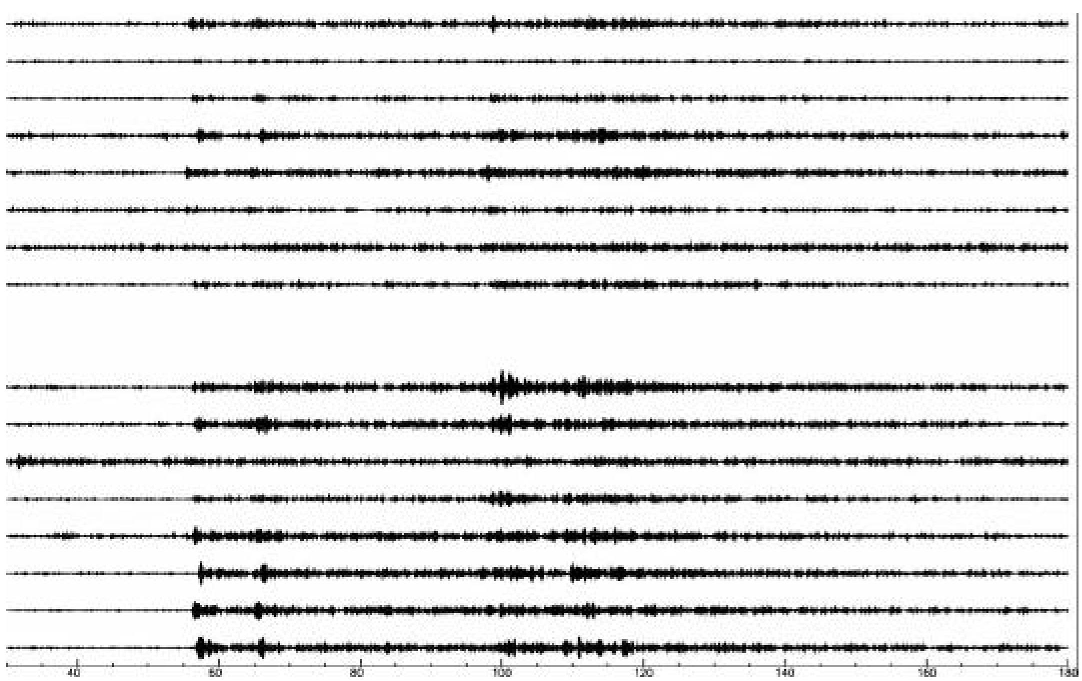


**Figure 2b.** The same events filtered into the 6- to 9-Hz band. Note the increase in energy in the underground explosions (bottom) relative to the surface explosions (top) at this higher frequency.

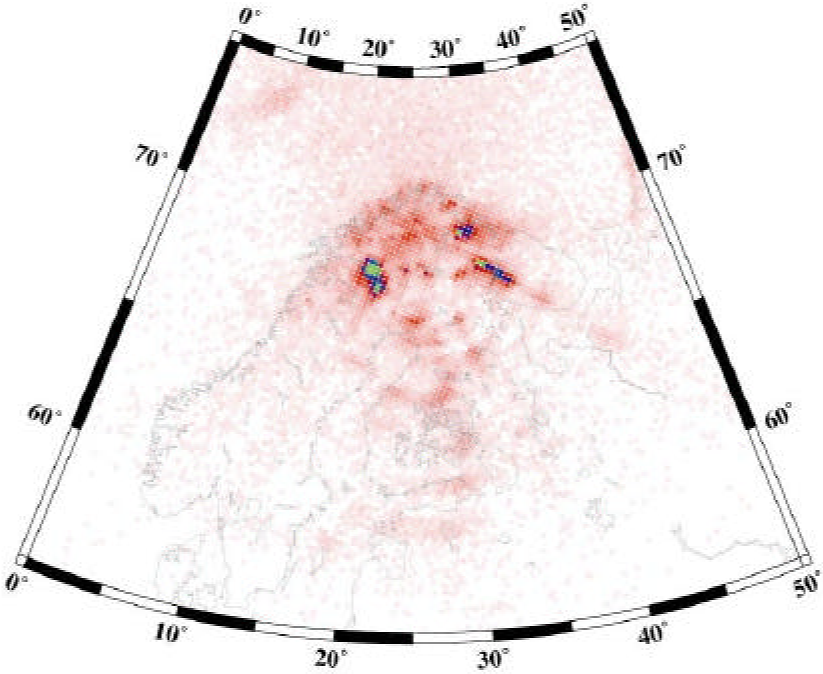


**Figure 3a.** Event density map generated from the ARCES automatic bulletin. This map clearly shows the major mines of northern Fennoscandia (especially two mines in Sweden), and the mines of the Kola Peninsula.

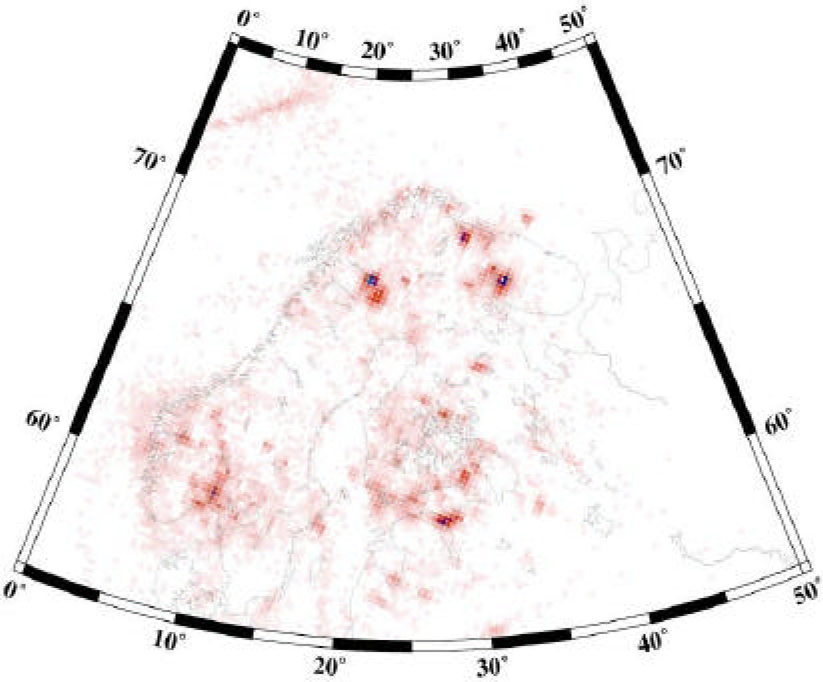


**Figure 3b.** Event density map developed from the NORSAR analyst-reviewed bulletin for the Fennoscandian array network. Major mining districts throughout Fennoscandia and Russia are much clearer in this map, because analyst review and redundant network observations eliminate artifacts that appear in the previous figure. Natural seismicity is apparent along the Arctic ridge and along the west coast of Norway. A cluster of events around the Kursk disaster site appears north of the Kola Peninsula.

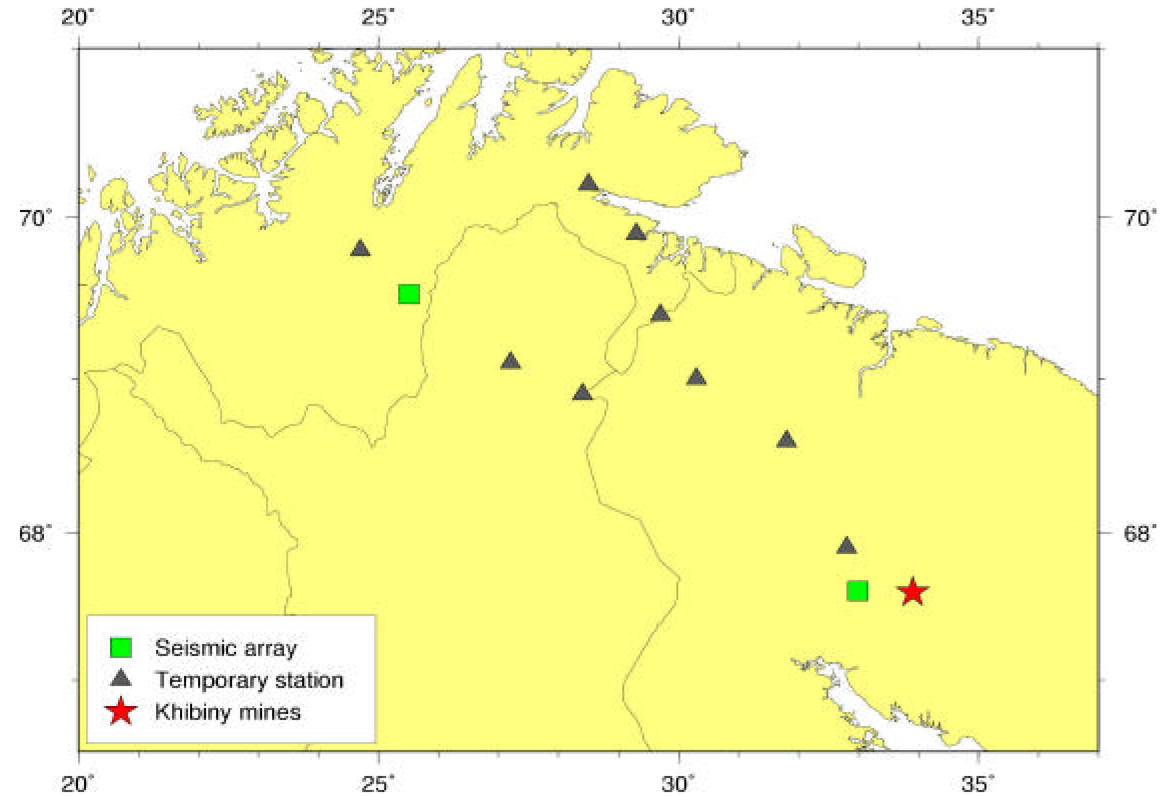


**Figure 4.** Approximate map of station sites for the year-long line deployment between the Khibiny mines and ARCES. A perfect line is not possible because of logistical, maintenance and access considerations.