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GROUND TRUTH COLLECTION FOR MINING EXPLOSIONS IN NORTHERN FENNOSCANDIA AND RUSSIA

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ABSTRACT

Analysis of data from our deployments and ground truth collection in northern Fennoscandia and northwestern Russia shows systematic variations in the P/S ratios of different types of explosions. The fact that this fundamental discriminant varies with firing practice is not in itself surprising – such variations probably contribute to the spread in P/S ratios normally observed for ripple-fired explosions. However, the nature of the variations is sometimes counterintuitive. Last year [Harris, 2003] 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 be more like single well-coupled explosions, thus having higher P/S ratios than large ripple-fired explosions.

We now are performing a more extensive analysis of the data including compact and large ripple-fired explosions at additional mines and different types of explosions: small surface shots and large ripple-fired underground explosions. Our data are more complete as a result of an additional year of collection and allow a more complete sampling of the signals in range from the source. As of this writing we have measured Pn/Lg ratios on a larger number of explosions of three types: compact underground explosions, surface ripple-fired explosions and now underground ripple-fired explosions. We find that both types of underground explosions have systematically lower P/S ratios than surface ripple-fired shots; this effect is most pronounced in the 4-8 Hz frequency band. This result appears to be due to relatively diminished shear wave excitation by the surface explosions. We speculate that the relatively large shear phases in underground explosions may be caused by large amounts of rockfall in these events, which are designed to collapse the ceilings of tunnels.

We have continued comprehensive ground truth collection at the Khibiny, Olenegorsk, Kovdor and Zapolyarnyi mines, and now have basic information on 2,052 explosions. In addition, we have more detailed information for select surface and underground ripple-fired explosions and underground compact explosions. This information ultimately may help the community understand the observed P/S ratio offsets. We also are continuing the compilation of ground truth and associated regional waveform data into a database as a prelude to further analysis.

We have operated two lines of stations extending from the Khibiny Massif to the ARCES array and to the north of the ARCES array for a second year. This deployment provides the principal data for measuring the range-dependence of near-regional phase amplitudes. Data collection has been more robust in this second season of the deployment. Preparations are now underway for concluding the line deployment in late August or early September 2004 and for re-deploying the stations to the Kiruna, Malmberget and Aitik mines in northern Sweden. Like the Khibiny mines, these mines provide an interesting natural laboratory for examining questions about the phase characteristics of mining explosions since they include both underground and surface operations.

OBJECTIVE(S)

This year the project had 5 principal objectives:

1. Collect ground-truth information for a large number of explosions in a diverse set of mines in the Kola Peninsula, including more detailed ground-truth for a select set of representative explosions.
2. Assemble a database of waveform observations of these events from principal monitoring stations of the region.
3. Continue operation of temporary stations deployed to fill gaps in the set of observations.
4. Plan the redeployment of these same temporary stations to frequently-observed mines in northern Sweden.
5. Continue preliminary analysis of the variation of regional discriminants with source-receiver range and source type.

RESEARCH ACCOMPLISHED

Ground truth collection

We have begun collection of detailed ground truth information for selected events. We seek more detailed ground truth information to assist the interpretation of differences in regional observations of different types of explosions. An example of the kind of ground truth information we have been able to obtain is shown in Figure 1 below. This explosion in the Nyurkпах quarry of the Vostochny mine (Khibiny Massif) occurred at 7.08:03 GMT on August 28, 2003. The total weight of explosive was 138,346 kg detonated in 34 phases with typical delays between phases of 20 milliseconds, although 3 delays were 40 milliseconds. The total explosion time was 740 milliseconds. The figure depicts the sequence in which phases (connected dots) were detonated. The weights of explosives in each phase are shown in table 1. The 40 ms delays were between phases 0 and 1, 4 and 5, 20 and 21.

Database assembly

Waveforms from permanent and temporary stations in the region and ground truth information are being assembled into a CSS database for subsequent convenient analysis. To date, ground truth information on 2,052 events have been loaded into the database, including the following events from the Khibiny Massif mines:

Table 1. Sample numbers and types of explosions available in the data base for Khibiny Massif mines

| Mine | Explosion Type | Yield Range (tons) | Number Available |
|-------------|--------------------------|---------------------------|-------------------------|
| Kirovsk | Underground Compact | 1 – 7 | 619 |
| Kirovsk | Open-pit ripple-fired | 1 - 16 | 43 |
| Kirovsk | Underground ripple-fired | 10 - 278 | 41 |
| Rasvumchorr | Underground compact | 1 - 7 | 335 |
| Rasvumchorr | Underground ripple-fired | 14 - 257 | 5 |
| Central | Open-pit ripple-fired | 10 - 396 | 174 |
| Koashva | Open-pit ripple-fired | 21 - 249 | 111 |

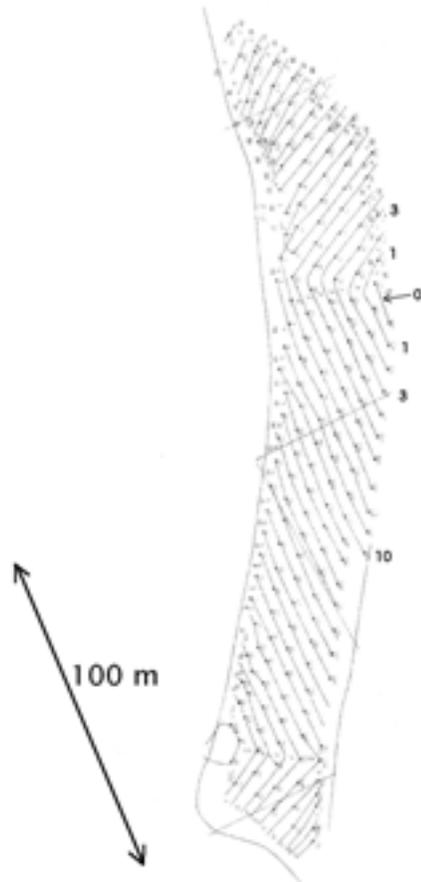


Figure 1. Plan of the August 28, 2003 Nyurkpakh explosion. Explosion phases are denoted by the lines connecting the dots; the dots denote holes with explosives. The numbers to the right of the plan indicate the sequencing of the phases. The explosion began with the phase denoted 0, which consisted of two holes.

Table 2. Weight of explosives per delay for the Nyurkpakh explosion of August 28, 2003

| Phase | Weight (kg) | Phase | Weight (kg) | Phase | Weight (kg) |
|-------|-------------|-------|-------------|-------|-------------|
| 0 | 2016 | 12 | 2929 | 24 | 5520 |
| 1 | 2540 | 13 | 4176 | 25 | 5410 |
| 2 | 3336 | 14 | 3661 | 26 | 2484 |
| 3 | 2484 | 15 | 3788 | 27 | 2622 |
| 4 | 4817 | 16 | 4689 | 28 | 1380 |
| 5 | 5740 | 17 | 5228 | 29 | 828 |
| 6 | 5238 | 18 | 6117 | 30 | 621 |
| 7 | 5045 | 19 | 7249 | 31 | 1242 |
| 8 | 4907 | 20 | 5694 | 32 | 621 |
| 9 | 5422 | 21 | 9347 | 33 | 621 |
| 10 | 4249 | 22 | 8040 | | |
| 11 | 3901 | 23 | 6384 | | |
| | | | | Total | 138,346 |

Operation of temporary stations to improve observational coverage of mining explosions

LLNL and NORSAR installed six Reftek recorders provided by LLNL along two profile lines in Finland and Norway (Figure 2) during late August/early September 2002. These units record data in continuous mode. A local NORSAR representative in Karasjok, northern Norway, travels to the six sites at appropriate intervals to retrieve data. These data are then forwarded to NORSAR for reformatting, archiving and distribution to the other project participants. KRSC has deployed two stations to provide close-in observations of the same explosions.

As of 10 July 2004, the following data from these six profile stations are available in NORSAR's data archives:

IVL: 2002: days 239-293, days 314-365. 2003: days 001-017, day 044, days 049-365. 2004: days 001-115.

KMM: 2003: days 048-157, days 176-224, days 274-282, days 316-365. 2004: days 001-016, 020, 039-047, 056.

SKV: 2002: days 245-365. 2003: days 001-041, days 061-066, days 069-172, days 241-297, days 315-365. 2004: days 001-023.

SKF: 2002: days 241-245, days 248-320, days 323-365. 2003: days 001-038, days 053-197.

NDN: 2002: days 241-243. 2003: days 097-240, days 340-352, days 355-357, days 360-365. 2004: days 001-002, days 005-007, days 010-020, days 028-081.

VGB: 2002: days 242-314. 2003: days 097-164, day 168, days 177-244, days 248-316, days 340-365. 2004: days 001-030, days 035-107.

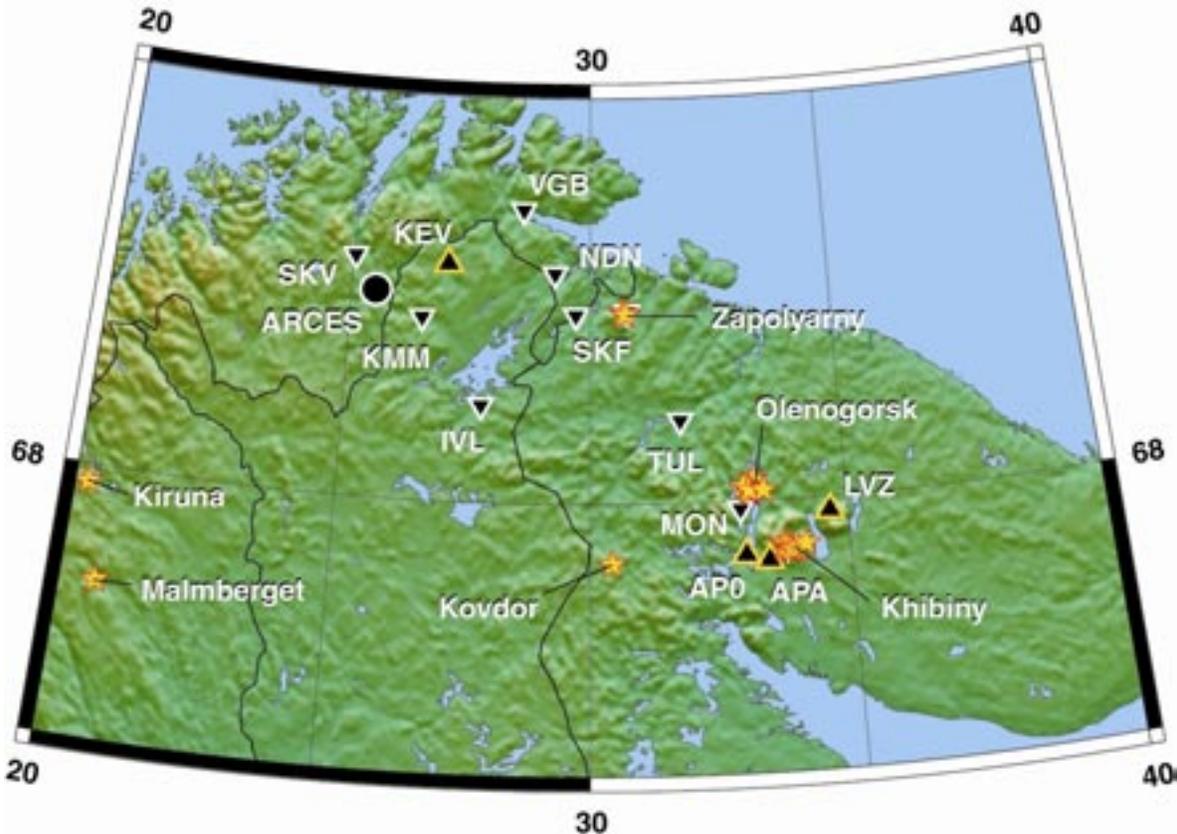


Figure 2. Locations of the temporary stations (inverted triangles) deployed by LLNL, NORSAR and KRSC (TUL, MON).

Preparation for field instrument re-deployment to mines in northern Sweden

The six Reftek field recorders that have been collecting data along two profile lines in northern Norway and Finland since the fall of 2002 will be redeployed to northern Sweden in early September 2004. The target for the redeployment is an area of active iron and copper ore mining. The company LKAB is operating the largest underground iron mine in the world at Kiruna and is also exploiting underground iron ore deposits at Malmberget, some 75 km SSE of Kiruna. The company Boliden is operating the largest open-pit mine in northern Europe at Aitik, approximately 17 km SE of Malmberget. Each of these three mines arrange blasts on a very active and also fairly regular schedule, and this area thus offers an excellent opportunity to collect data for detailed studies of different kinds of mining explosions.

A visit to these three mines was carried out in late April 2004, to establish relations with personnel involved in the blasting operations, to obtain information on their respective blasting practices, to discuss prospects for obtaining ground truth information, and to survey for suitable locations for the six field recorders. With regard to mining operations and blasting practices in particular, the following information has been derived from openly available sources, and from contacts during the visit.

The large ore body exploited at Kiruna (Figure 3) descends below the surface at an angle of 60 degrees from horizontal, is 4 km long, extends to a depth of 2 km, and is averaging 80 m wide. The mining method used is called large-scale sublevel caving. The current production level is at a depth of about 800 meters below the surface. Horizontal drifts (Figure 4) are driven through the 80 m wide ore body, and fans of 7-12 holes, typically 40-45 m long, are drilled upwards into the ore at 3-meter intervals in the drifts. Fans are charged with up to 500 kg of explosive in each hole. The explosives in a fan are detonated with delays between the various holes, so that the detonation time for a fan typically is of the order of 1.5 seconds. A single blast at the Kiruna mine is usually composed of a number of fans, located in drifts that are separated laterally along the ore body by as much as 3 kilometers. A number of such blasts are conducted every day, at around midnight, local time (23:00 GMT). LKAB has been operating a 4-element, three-component, in-mine seismic network of the ISS type in the Kiruna mine since December 2003.

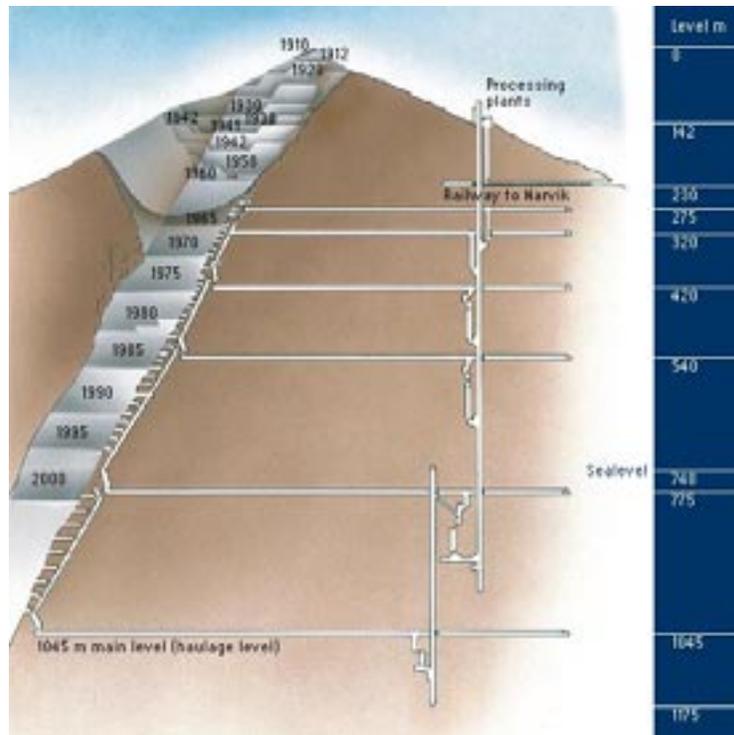


Figure 3. Exploitation of the ore body at Kiruna, Sweden.

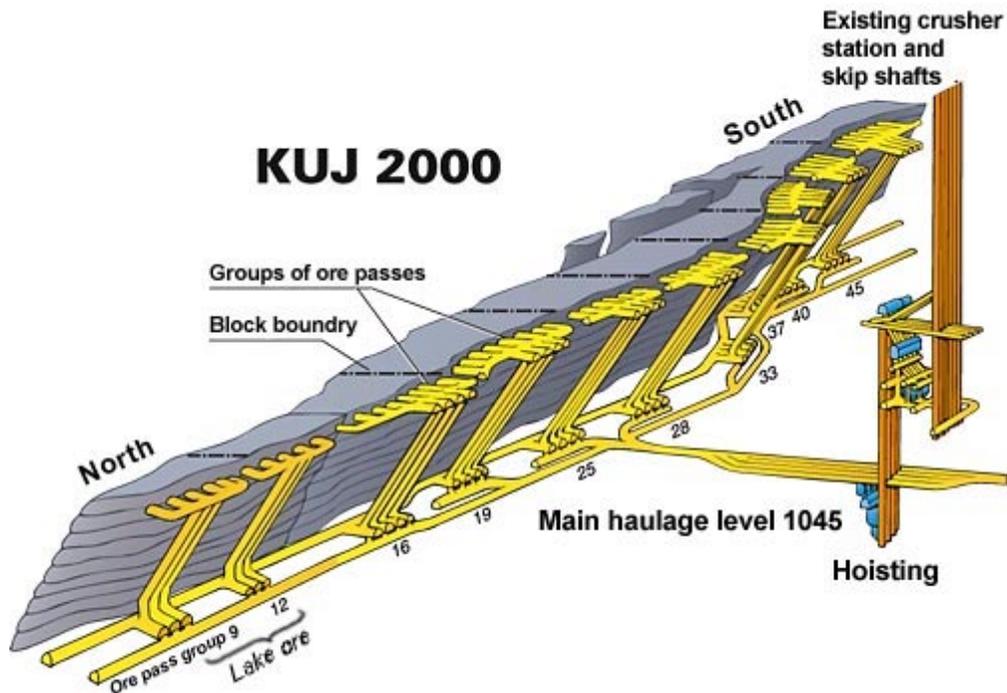


Figure 4. Groups of drifts (ore passes) in the Kiruna mine.

The iron deposits at Malmberget consist of about 20 separate ore bodies (Figure 5), 8 of which are currently mined. The mining method is the same as in Kiruna, and the main activity is currently at a depth of about 1,000 meters. There are, on average, four blasts per day, each consisting of detonation of up to 3 adjacent fans in the same drift, and blasting is confined to the time window 00:00 – 01:00 (23:00 – 24:00 GMT). LKAB plans to install an in-mine ISS network in Malmberget during the summer of 2004. The plans call for installation of an 18-element network of three-component sensors, possibly grouped in 3 subnetworks of 6 stations each.

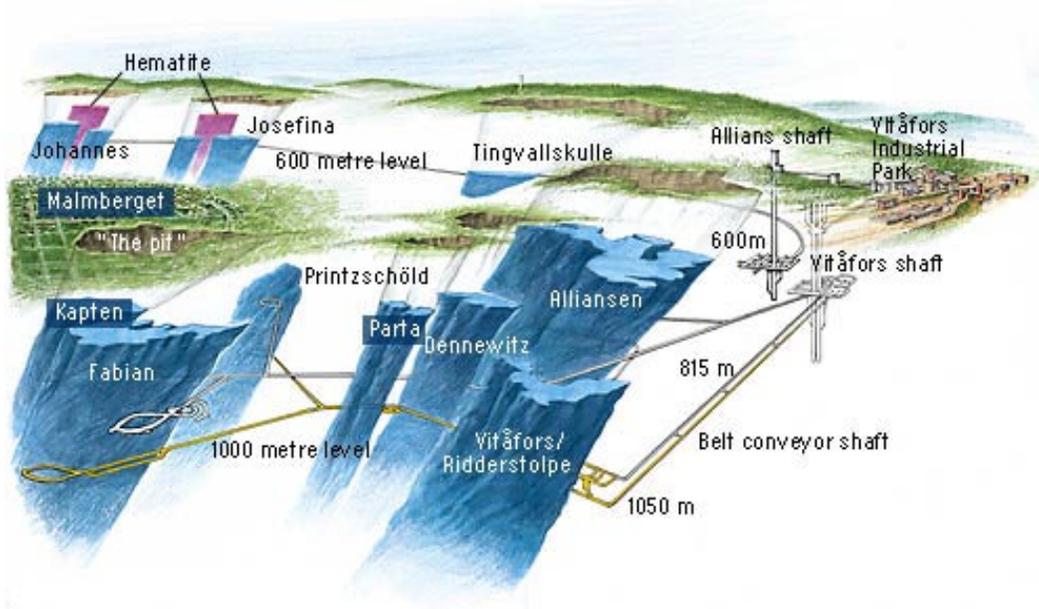


Figure 5. Multiple ore bodies at Malmberget.

The single open-pit mine at Aitik (Figure 5) exploits a low-grade copper deposit. The depth of the mine currently is 300 meters, and the mining is proceeding towards an ultimate depth of 400 meters by year 2012. Extraction of the

ore is based on so-called Nonel blasting, with explosives loaded in 17 m deep boreholes of diameter 311 mm. One blast is composed of detonations in up to 300 boreholes for a typical total shot duration of 8-10 seconds. Total yield in one blast ranges up to 500 tons. Figure 6 shows the drilling of holes for a blast that totaled 266,800 kg of explosives a few days after the photograph was taken. The event was recorded by ARCES at a distance of 333 km with a very high signal-to-noise-ratio (423). There is, on average, one explosion per week in the Aitik mine. All explosions are conducted at around 5:30 pm, local time (16:30 GMT).



Figure 6. Drilling holes for explosives at the Aitik open pit.

The exact plans for the deployment of the six Reftek recorders in and around these three mines have not been worked out as of the submission date of this paper. We expect to concentrate the resources directly on the mines, with surface deployments of two recorders at each mine. For the Aitik open-pit mine, there are possibilities of deployment on the rim of the pit, whereas deployment at Kiruna and Malmberget will be considered in light of the positions occupied by the sensors of the in-mine networks.

Regional Discriminant Analysis

With the collection of a large number of observations of mining explosions of different types and corresponding ground truth information, it is possible to begin examining the dependence of regional discriminants on source type as well as frequency and range. The large number of explosions collected (Table 1) allow distributions of discriminants to be developed. Figure 7 shows histograms of the Pn/Lg ratio in four different frequency bands for three types of mining explosions: compact underground shots (in Rasvumchorr), ripple-fired underground explosions (in Kirovsk) and surface (open-pit) ripple-fired shots (in Central). These mines are all within 10-15 kilometers of each other and are observed in these data by the ARCES central vertical element (ARA0 SHZ) at a range of about 410 kilometers (Figure 2). The data were screened to exclude superimposed seismograms from multiple shots (a frequent occurrence at the Central mine) and to assure an (amplitude) SNR of at least 2 on both Pn and Lg measurements.

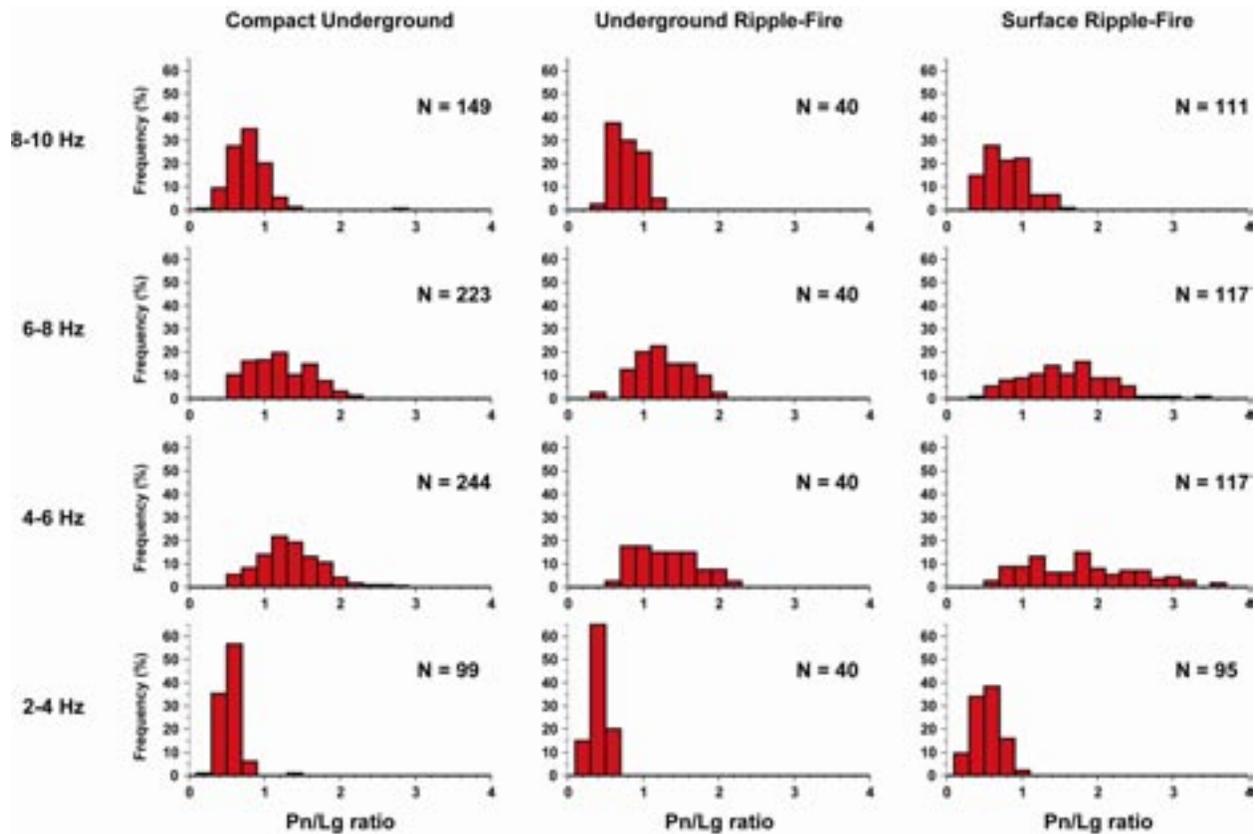


Figure 7. Histograms of P/S (Pn/Lg) ratios for three types of explosions at mines of the Khibiny Massif recorded at ARCES. The numbers in the upper-right corners of the plots indicate the number of measurements contributing to the distributions.

Several significant features and differences among the explosion types stand out. The Pn/Lg ratios for all three types of explosions are very low (below 1) in the lowest frequency band (2-4 Hz), increase markedly in the mid-bands (4-6 and 6-8 Hz), then decrease again in the highest band (8-10 Hz). Among the three event types, the surface ripple-fired explosions typically have the highest Pn/Lg ratios and the greatest scatter.

Figure 8 shows waveforms for three representative events (one for each explosion type) filtered by a bank of filters to bring out frequency content. The most noticeable features are the small amplitude of P waves in the (particularly) low band (2-4 Hz) and high band (8-10 Hz), consistent with the low Pn/Lg ratios across the board in those bands, and the relative lack of shear energy in the surface ripple-fired explosions, consistent with the high Pn/Lg ratios of the surface explosions in the 2-6 Hz band. This latter feature is particularly pronounced and might be explained by the nature of the underground explosions. These, particularly the compact underground explosions, are designed to drop large quantities of ore from the ceiling of a drift or drifts (Figure 9). As in the Kiruna mine, fans of holes are drilled into the ceiling and walls of a drift, filled with explosive and detonated to drop and rubbelize the ore. It may be that the falling rock contributes the bulk of the shear energy to the source. Surface explosions also move quantities of overburden and ore, but not with the same efficiency (tons of rock dropped per kilogram of explosive) as the underground explosions where released gravitational potential energy can be expected to be a significant if not dominant fraction of the total energy released in the explosive event.

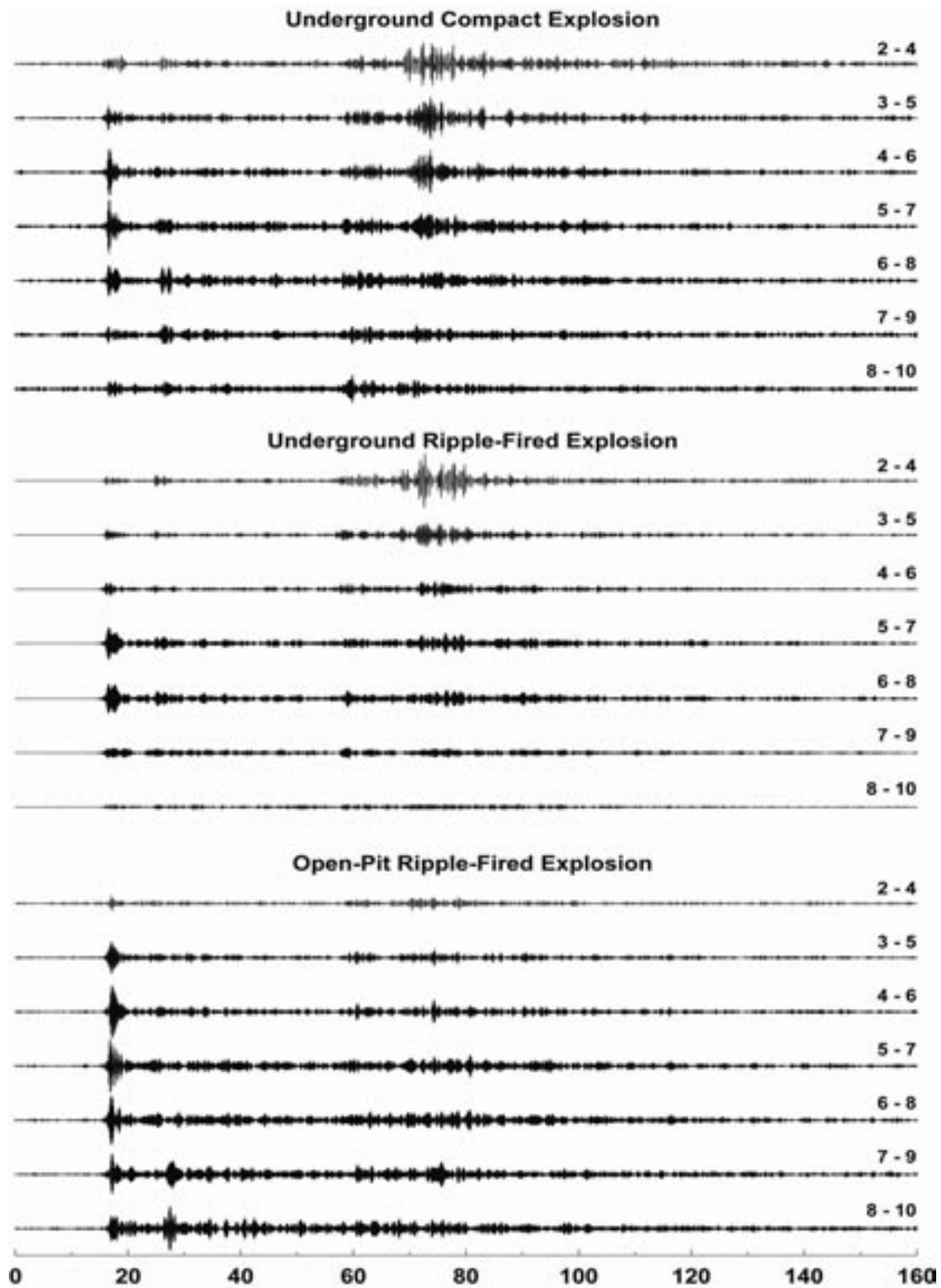


Figure 8. Sample waveforms of three different types of Khibiny mining explosions. The three signals are broken into 7 frequency bands (2 Hz wide, annotated at right) to show spectral content. The underground shots have more shear energy than the surface shot.

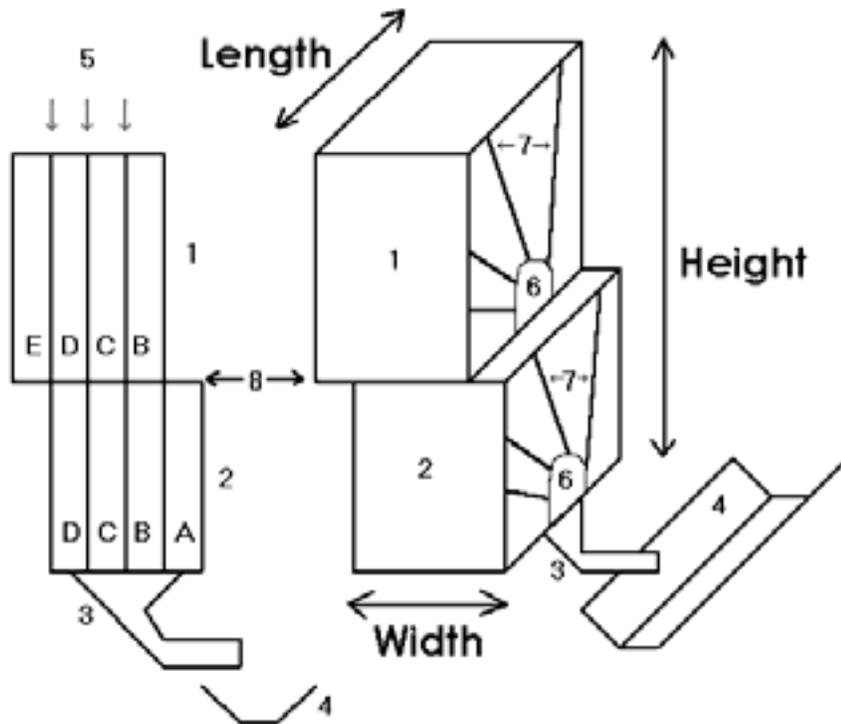


Figure 9. Simplified scheme of a typical underground explosion. 1,2 ore sub-blocks; 3 finger-like funnel; 4 haulage ort with trolleys; 5 parallel planes with charges; 6 horizontal drifts used to drill "fans" of holes and insert explosive; 7 "fans" of holes with charges arranged on parallel planes (5); A-E delayed phases, 8 intermediate horizon separating ore blocks. Dimensions can be on the order of length 100m, height 70 meters, width 20 meters.

CONCLUSION(S) AND RECOMMENDATION(S)

We conclude that we have assembled and continue to assemble a valuable data set for examining the relative excitation of different seismic phases by several types of mining explosions. Initial examination of the data has revealed significant offsets in P/S ratios for three 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:

- Compare explosion P/S discriminants with similar discriminants for the few earthquakes that we have in the area.
- Perform a thorough study of discriminant range dependence and seek corrections, perhaps similar to the MDAC correction for earthquakes, to remove range dependence. It may be possible to use the dataset assembled by this project to optimize an MDAC-like correction empirically.
- Compare Aitik surface explosions to Malmberget underground explosions to ascertain if the diminished P/S ratios for underground explosions observed in the Khibiny events is transportable to these Swedish mines.
- Examine additional discriminants, such as Pn/Sn.

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