ENERGY PARTITIONING FOR SEISMIC EVENTS IN FENNOSCANDIA AND NW RUSSIA

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ABSTRACT

We address the problem of energy partitioning at distances ranging from very local to regional for various kinds of seismic sources, and are now in the last year of this three-year effort. On the small scale we have focused on analysis of observations from an in-mine network of 16-18 sensors in the Pyhäsalmi mine in central Finland. This analysis has been supplemented with 3-D finite difference wave propagation simulations to investigate the physical mechanisms that partition seismic energy in the near source region in and around the underground mine. On the local and regional scale (20-220 km) we have targeted events from the region offshore Western Norway where we have both natural earthquake activity as well as frequent occurrence of underwater explosions carried out by the Norwegian Navy.

Since the previous reporting of this project at the 2004 Seismic Research Review (Bungum et al., 2004), we have extended the finite difference simulations in the 3-D geological model of the Pyhäsalmi mine. This model, which encompasses a geologic volume 500 meters in each direction, includes 3-D representations of the ore bodies, excavated regions, tunnels, and voids. The model is discretized on both 2 and 4 meter grids making it possible to simulate seismic energy up to 100-200 Hz. We perform a variety of sensitivity tests to determine the mechanisms that produce shear energy in an underground mine environment. For example, we conduct a suite of 15,000 (2-D) explosive source simulations to quantify the influence of source location on the amplitude of generated shear energy. In fact, most of the shear energy appears to be generated within 10-20 meters from the source (at frequencies of 50 Hz). Examination of waveforms reveals that both geologic heterogeneity and the structural influences of the mine are contributors to the near-source generation of shear energy. There is some suggestion that the effects of geologic inhomogeneity are significant early in the wavetrain, whereas the mine structure is likely to produce scatter and be more significant later in the waveforms. As a validation measure, the synthetic waveforms are compared with observed data from single and multi-component instruments located in the mine. The simulated data match the amplitude and character of the observed waveforms particularly well, especially at frequencies at and below 50 Hz. This suggests that we can reliably infer energy partitioning phenomena based on these simulations.

A database of underwater explosions and earthquakes from the region offshore Western Norway, recorded at seven selected stations of the National Norwegian Seismic Network (NNSN), were analyzed for differences in the S/P amplitude ratios. In order to separate the path and source effects for the two event populations, we have investigated the station, distance, and frequency dependencies of the recorded data in detail. The results indicate that the mean S/P amplitude ratios for both underwater explosions and natural events vary from station to station but are, in general, higher for natural events. For frequencies above 3 Hz, the difference in S/P ratios between explosions and natural events is higher than for lower frequencies. However, the distributions of S/P ratios for explosions and natural events overlap in all analyzed frequency bands. Thus, for individual events in our study area, S/P amplitude ratios can assist the discrimination between an explosion or a natural event, but other measures such as spectral analysis should be included in the interpretation.

OBJECTIVE

The main objective of this project is to increase the (nuclear) explosion monitoring effectiveness through improved understanding of basic earthquake and explosion phenomenology. What this entails is detailed characterization and understanding of how the seismic energy is generated from these phenomena (including simple and complex explosions and rockbursts, i.e., stress release in mines, and ordinary tectonic earthquakes, all at different depths and in different geological environments) and how this energy is partitioned between P and S waves. Specific questions are:

- How is the generation and partitioning of seismic energy affected by properties such as source region medium and overburden, the local structure, and the surrounding tectonic structure?
- What are the significant measurable effects of the partitioning of the seismic energy into various regional P and S phases, especially at higher frequencies?
- What is the physical basis for a measurable property, such as magnitude, that can be directly related to the yield of a fully coupled explosion, and how can emplacement conditions affect the observations?

RESEARCH ACCOMPLISHED

We are now in the last year of a three-year project that started on 30 September 2002 (Bungum et al., 2003, 2004), which is a collaboration between NORSAR (as the lead organization) and Lawrence Livermore National Laboratory (LLNL). During the last year we have addressed the problem of energy partitioning at distances ranging from very local to regional for various kinds of seismic sources. On the small scale we have focused on analysis of observations from an in-mine network of 16-18 sensors in the Pyhäsalmi mine in central Finland. This analysis has been supplemented with 3-D finite difference wave propagation simulations to investigate the physical mechanisms that partition seismic energy in the near source region in and around the underground mine. On the local and regional scale (20-220 km) we have targeted events from the region offshore Western Norway where we have both natural earthquake activity as well as frequent occurrence of underwater explosions carried out by the Norwegian Navy.

3-D finite difference modeling

We have investigated physical mechanisms that partition seismic energy in the near source region by performing modeling studies of the Pyhäsalmi mine in Finland in comparison with observations. Our recent efforts have focused on the quantification of shear energy generation as a function of source location within the mine. In particular, we performed over 15,000 2-D finite-difference wave propagation simulations of the mine using an explosive (purely compressional source) positioned at different locations within the mine. We have examined the generation of shear energy as a function of source position relative to mine heterogeneities such as ore bodies and excavated regions (voids).

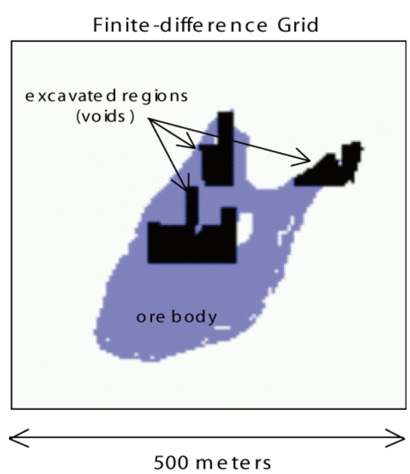

Figure 1.
2-D vertical cross section through the Pyhäsalmi mine. Blue represents high velocity ore. Black represents excavated portions of the mine. White represents the background geology.

Figure 1 shows a 2-D model cross section through the central portion of the Pyhäsalmi mine. This 2-D representation was extracted from a 3-D model of the mine. The horizontal and vertical dimensions are 500 meters. The model is discretized on a 4 meter finite-difference grid.

The E3D finite-difference wave propagation code (Larsen & Schultz, 1995; Larsen & Grieger, 1998) and the 2-D mine model are used to perform several thousand seismic simulations. A purely compressional (explosive) 50 Hz point source is used to drive the simulations. An example of one such simulation is shown in Figure 2.

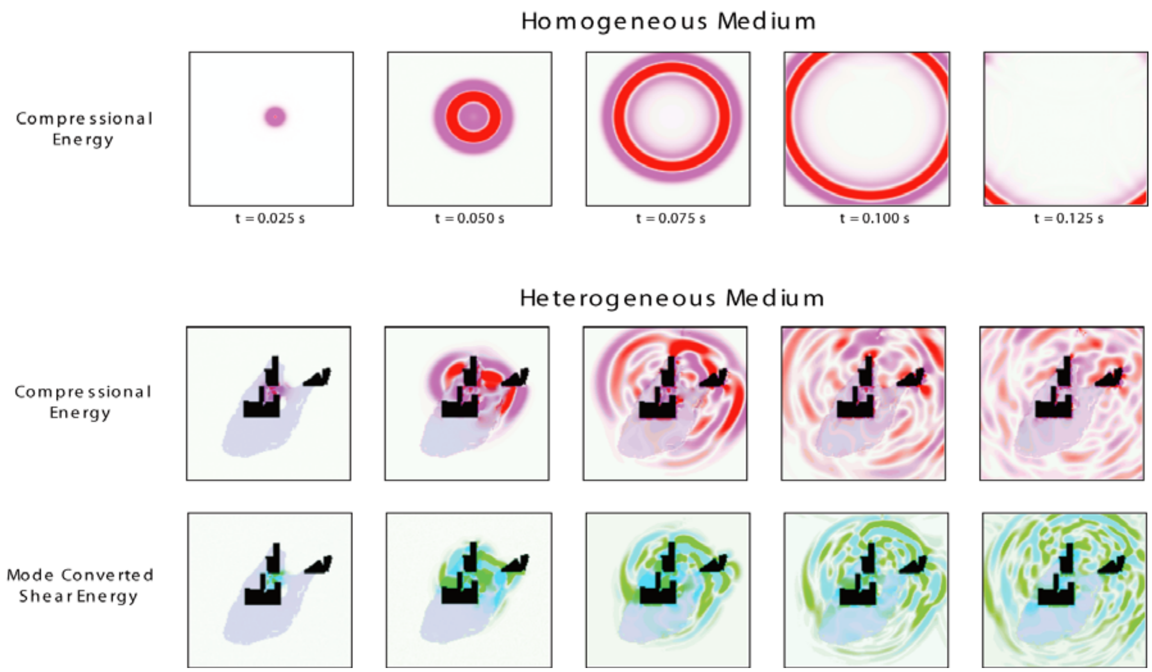

Figure 2. Simulations illustrating generation of shear energy due to an explosive source near the center of the heterogeneous Pyhäsalmi mine.

In this case, the source is located slightly off from the center of the finite-difference grid. The figure shows the seismic wavefield at multiple time snapshots for a simulation using the heterogeneous 2-D model. For reference, an equivalent simulation is performed in a homogeneous model. Red and red-blue represent compressional energy (P potential) and green and green-blue represent shear energy (S potential) at various time snapshots. Because the source is purely compressional and there are no heterogeneities in the model, no shear energy is generated in the homogeneous model. However, significant shear energy is generated in the real model. This energy is generated as the compressional waves interact with both the excavated regions of the mine (voids) and with the heterogeneity in the mine (ore body). The shear energy amplitude is comparable to that of the compressional energy.

Figure 3 illustrates the method used here to quantify the generation of shear energy. For any given source position, we compute the amount of shear and compressional energy that leaves the near-source region in an “energy flux box” near the edge of the finite-difference grid. Paraxial absorbing boundary conditions are applied to the grid boundaries so little energy is reflected back into the model. More precisely, we compute the maximum shear amplitude and the maximum compressional amplitude at each point along the flux box. We then determine the S/P ratio at each point and average these ratio’s to estimate of total shear energy generated within the model. While this method is ad hoc and does not include issues such as the duration of the compressional and shear wavefields, it does provide a first order estimate for how much shear energy is being generated for an explosive source at any given location within the model.

We have performed 15,376 2-D simulations similar to the one shown in Figure 2 and Figure 3. The source is located at a different grid point for each simulation. The results from these simulations is illustrated as the S/P ratio map shown in Figure 4. Each point within this map represents the amount of shear energy that is generated from a source located at that point using the S/P ratio method described above and in Figure 3. Red indicates source locations that promote the generation of shear energy. White indicates source locations where minimal shear energy is generated.

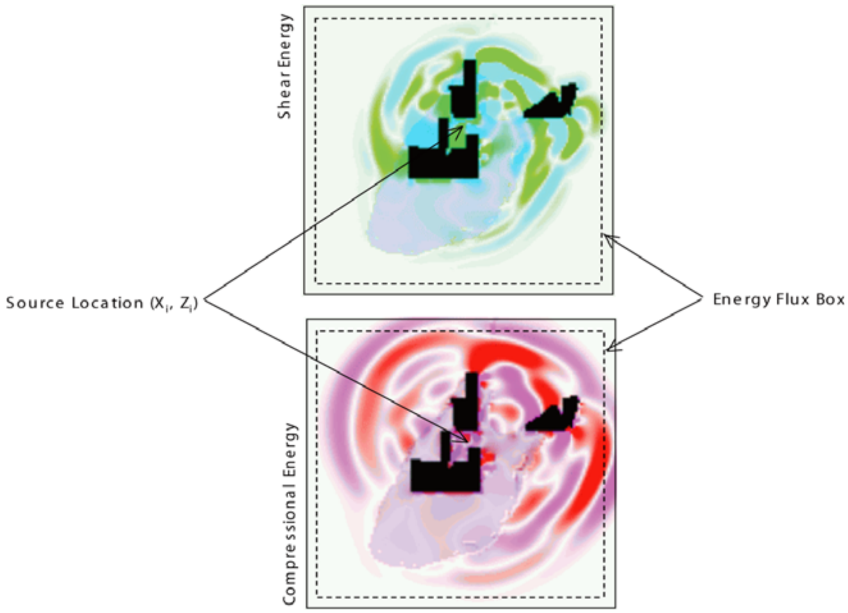

Figure 3.
Figure illustrating the method used here to quantify the generation of shear energy. P and S energy leaving the source region (flux box) can be quantified to determine how much shear energy is generated for a source at any given location.

Figure 4 suggests that shear energy is more likely to be produced when a source is located near geologic heterogeneity or a structural boundary. In fact, for these simulations, significant shear energy is most often generated when the source is located 10 - 20 meters from a natural or engineered interface. This corresponds to approximately 1 - 2 seismic wavelengths at the simulated frequency of 50 Hz.

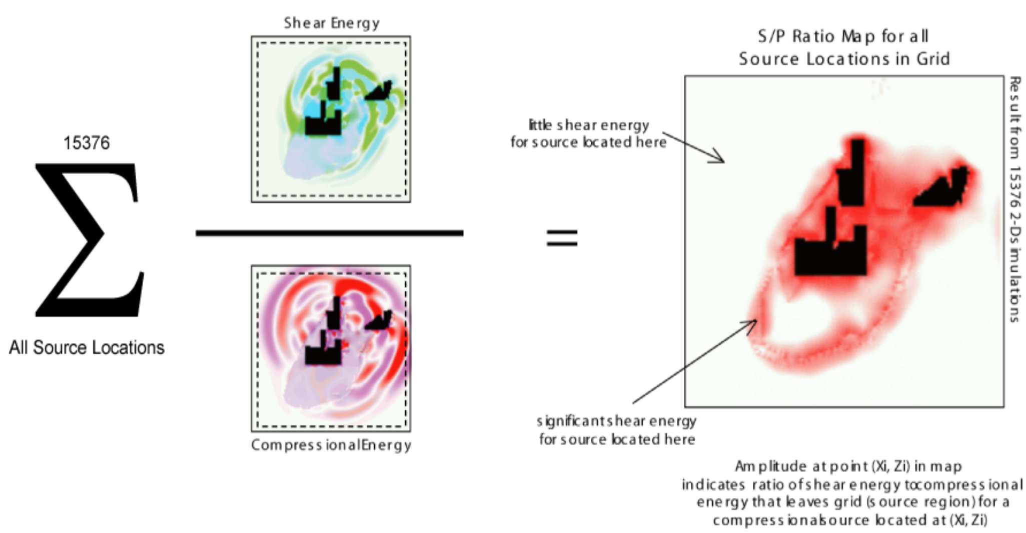

Figure 4. **Figure illustrating the method used here to quantify the generation of shear energy in the Pyhäsalmi mine. Each point within the map represents the amount of shear energy (S/P ratio) that is generated from an explosive source located at that point.**

We have performed two other sets of 15,376 simulations. In one case, only the excavated or mined-out portions of the mine are included in the 2-D model. In the other case, only geologic heterogeneities (e.g., ore body) are included in the model. The S/P ratio maps for each simulation set, along with the result for the full mine model, are shown in Figure 5. For better clarity, we also have scaled the two new S/P ratio maps and these are shown at the bottom of Figure 5.

The results from Figure 5 are somewhat puzzling. When the ore body is excluded from the model, the S/P ratio map suggests that more shear energy is generated for those sources located near excavated portions of the mine. When the excavated portions of the model are excluded, the S/P ratio map suggests that shear energy generation for sources located near the ore boundary is smaller. We have no ready explanation for this behavior. It may be that shear energy generation is non-linearly coupled to the presence of both geologic and engineered heterogeneities. It also may be true that the excavated regions are responsible for the bulk of the mode converted shear energy. This would not be too surprising since there is a stronger impedance contrast with the excavated voids than there is with geologic ore. However, further study is needed.

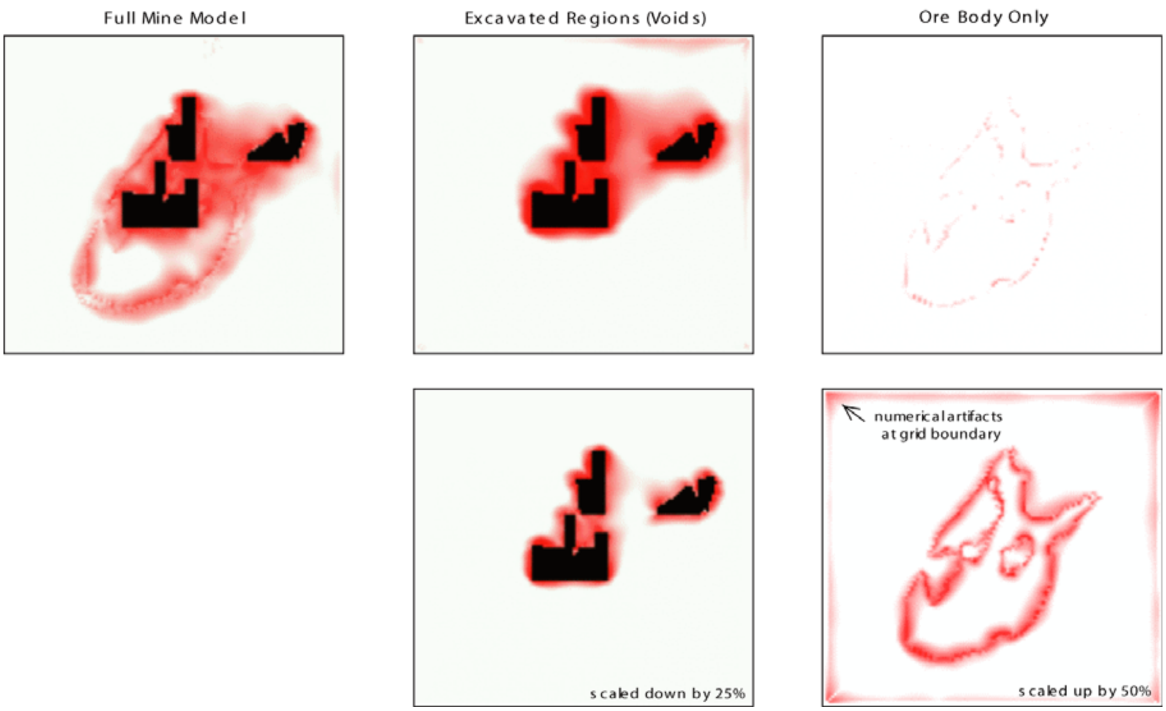

Figure 5. S/P ratio maps for different geological components of the Pyhäsalmi mine. Again, each point within the map represents the amount of shear energy (S/P ratio) that is generated from an explosive source located at that point.

The results of these modeling exercises suggest that significant shear energy generation is more likely to occur when a source is located within 1 - 2 seismic wavelengths of a natural or engineered heterogeneity. This corresponds to 10 - 20 meters for a 50 Hz source in a typical mine environment. In addition, large excavated regions of a mine may be more influential for the production of mode converted shear energy.

Energy partitioning for seismic events near the coast of Western Norway

We have addressed the question of how seismic energy is partitioned between P and S waves at regional distances between 20 and 220 km. We have chosen to target events from the region offshore Western Norway where we have both natural earthquake activity as well as frequent occurrence of underwater explosions carried out by the Norwegian Navy.

The data base for this study are seismic phase arrival times, source locations, and waveform data of natural events and underwater explosions recorded at seven selected three-component stations in Western Norway between 1997 and 2004 (Figure 6). The seismic stations are part of the permanent National Norwegian Seismic Network (NNSN), and the data were provided by the University of Bergen (UiB). The selected source region is located around 60 °N, 5° E, where both event types, earthquakes and explosions, occur.

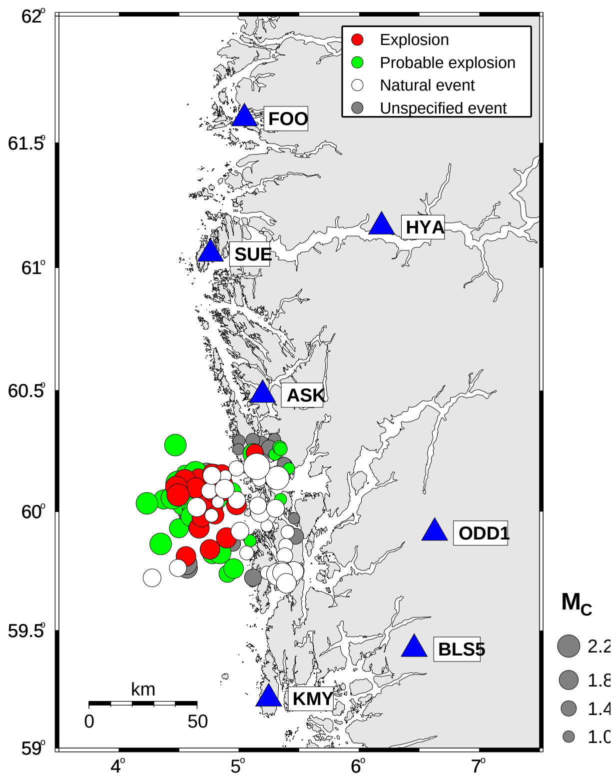

Figure 6. Seismic three-component short-period stations (triangles) and events used for this study: ASK = Askøy, BLS5 = Blåsjø, FOO = Florø, HYA = Høyanger, KMY = Karmøy, ODD1 = Odda, and SUE = Sulen.

At UiB, all events are classified as one of four main classes: explosions (E), probable explosions (P), natural events (N), and unspecified events. Typically, the explosions are detonations in the water column and confirmed by or related to the Norwegian Navy (Haakonsvern). Coda magnitudes of all events are mainly in the range $1.0 < Mc < 2.3$. Explosions usually occur at daytime. A peak at daytime in the temporal distribution of unspecified events suggests that many of these events are also explosions.

Whereas the initial database contains many confirmed explosions, only a few events in our source region are classified as natural earthquakes. Therefore, we analyzed signals and amplitude spectra of previously unspecified events in order to find more natural events for our study. The judgement was based on the fact that explosions in the water column are typically characterized by reverberations, which appear in amplitude spectra as distinct notches. Figure 7 shows vertical-component seismograms and spectra of two events, an explosion (left) and a natural event (right). The more continuous shape of the spectrum of the natural event is clearly visible. For our study we added those originally unspecified events to the set of natural ones that show a similar spectral behavior and no evidence of reverberations as seen in the example on the left. Additional constraints on the reclassification of unspecified events into natural events were that they occurred during nighttime, and that the resulting population of natural events should have a flat time-of-day distribution. After this reclassification procedure we ended up with 49 earthquakes and 24 explosions (see Figure 6).

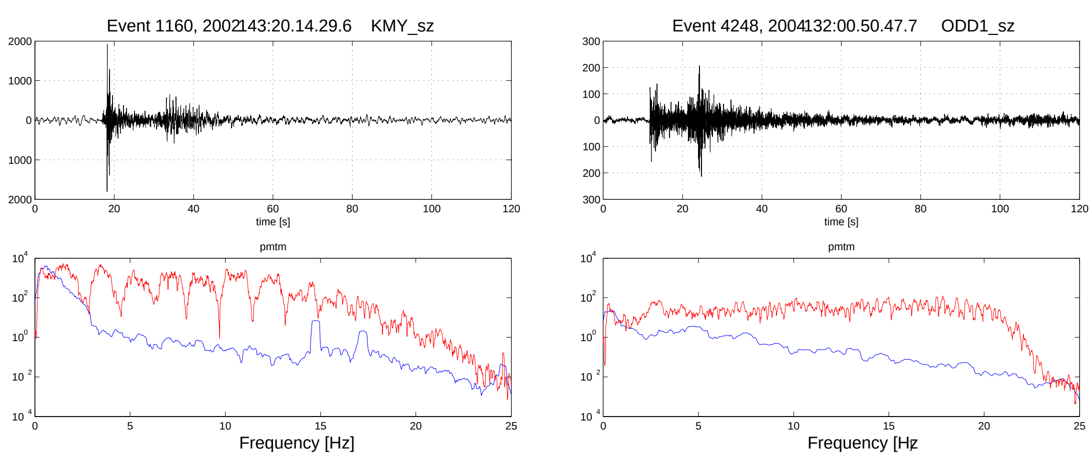

Figure 7. Vertical component seismograms and amplitude spectra of an explosion (left) and a natural event (right). Signal spectra (red) are calculated in a 60 s time window starting at the P onset and using the Thomson multitaper method (Thomson, 1982), and for noise spectra (blue) the time windows covered the time period from the origin time to 2 s before P, which were the noise data segments available in the UIB database.

The first step of the data analysis was to determine azimuth and incident angle of the P-phase using polarization analysis on bandpass-filtered data between 2 and 8 Hz. The analysis time window was 3 s long starting at the P arrival time determined by UiB. In general, calculated azimuths deviate from theoretical (geometric) values by just a few degrees. With the calculated azimuths and incident angles the data are rotated into the ray coordinate system (L, Q, T) for subsequent processing and analysis. The incidence angles and azimuths calculated from the P phases may not be optimal for the S-waves, but we do not consider this to have any significant effect on the estimates of the S/P ratios.

Figure 8 shows bandpass filtered (2-8 Hz) seismograms for two events recorded at two different stations, KMY (top) and SUE (bottom). The panels on the left show a confirmed explosion and those on the right a natural event. At the bottom of each panel are the original traces in the ZNE system, and on top the rotated ones (LQT). Here, differences in S/P amplitude ratios are clearly visible.

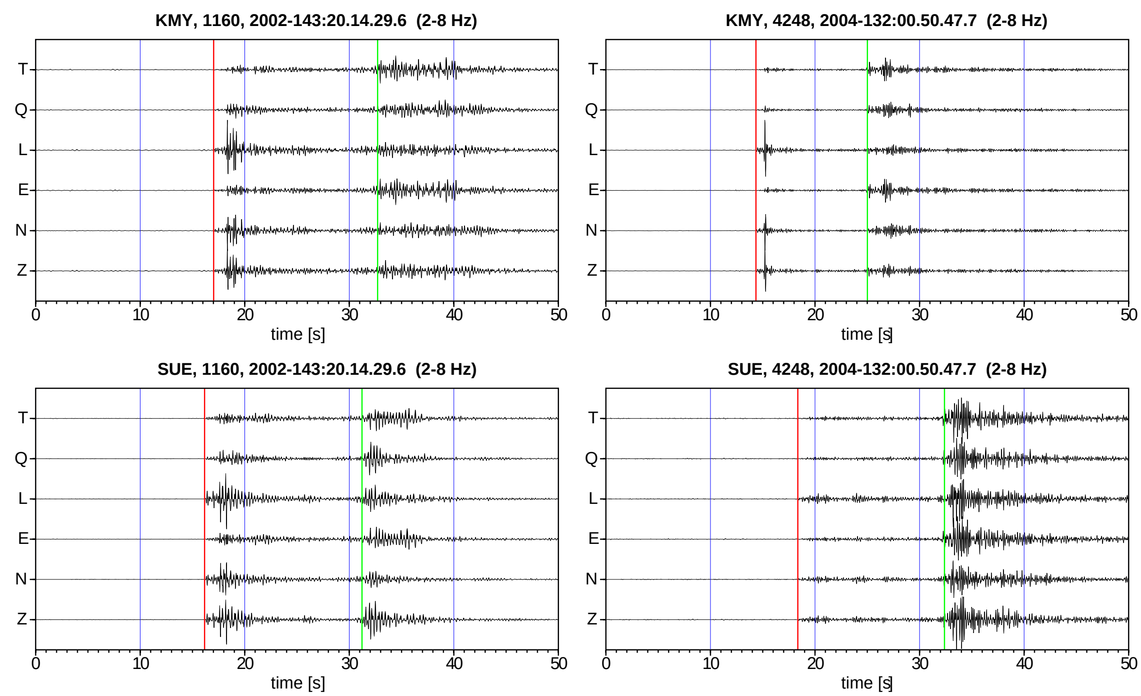

Figure 8. Three-component seismograms (2-8 Hz) recorded at the two stations KMY and SUE (see Figure 6). The time axis is relative to the origin time given on top of each panel, and red and green lines indicate the P and S onsets, respectively. Left: confirmed navy explosion (Haakonsvern), and right: natural event.

We measured S/P amplitude ratios for the two event sets in eight 1-octave passbands ranging from 1.0-2.0 to 12-24 Hz. The P amplitude was taken to be the maximum amplitude on the L component in the time window from the P onset to 0.5 s before the S onset. The S amplitude was taken to be the maximum in the orthogonal QT plane (vector sum of the Q and T components) in a 10 s time window starting at the S onset.

Figure 9 shows the distribution (histograms) of S/P amplitude ratios for all the explosions (red) and natural events (black outline) recorded at all seven stations. The abscissa (S/P ratios) is logarithmic, i.e., positive values indicate higher S than P amplitudes. The histograms for explosions exhibit a clear trend to lower S/P amplitude ratios (higher P energy) with increasing frequency, whereas the values for natural events cover a wider range and do not show such a trend.

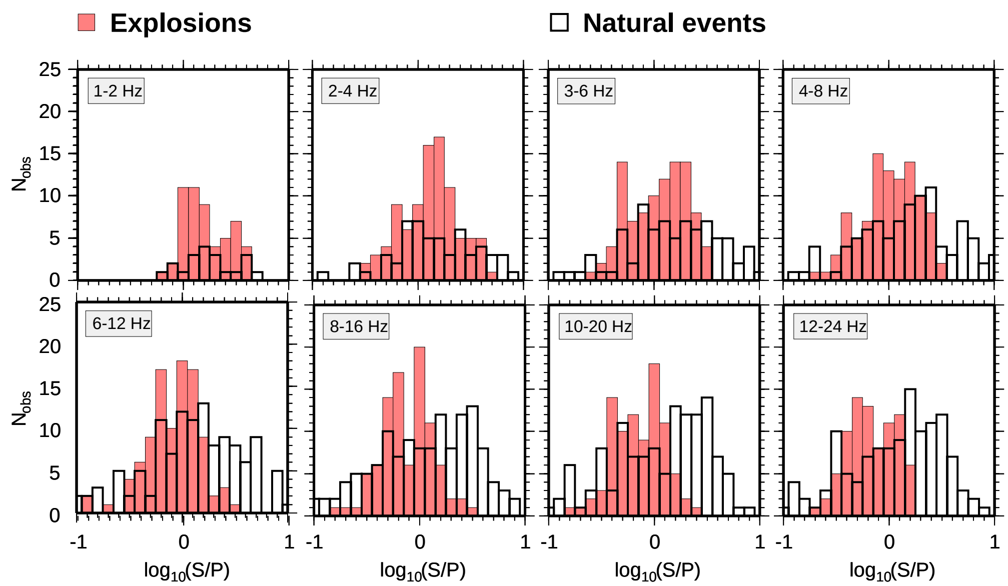

Figure 9. Histograms of S/P amplitude ratios (logarithm) for all explosions (red) and natural events (black outline).

The overall dependencies of the S/P amplitude ratios on frequency band, the source-receiver distance (20-220 km) to the different stations, as well as the S/P ratio variations with distance for individual events were investigated. Except for the trend that the average S/P ratios for explosions are generally lower than for natural events, we could not find any pronounced distance dependency.

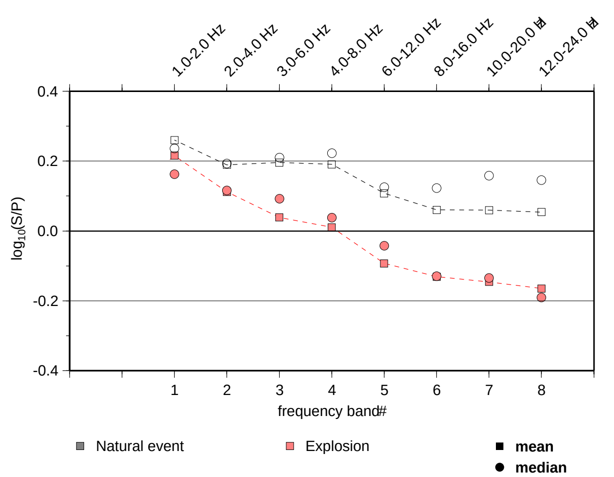

Figure 10. Mean and median S/P amplitude ratios (logarithm) for different event sets as a function of frequency band.

As seen from Figure 10, the explosions show generally decreasing S/P amplitude ratios with increasing frequency. Furthermore, explosions are characterized by higher P energy relative to S at high frequencies. S/P ratios are higher for natural events than for explosions above about 3 Hz. However, the distributions of S/P ratios for explosions and natural events overlap significantly in all analyzed frequency bands.

This may be partly related to path or site effects at different stations. This is illustrated in Figure 11 which shows measured S/P ratios and corresponding mean values for explosions and natural events recorded at four selected stations. Both absolute S/P ratios and the shape of S/P as a function of frequency differ from station to station. But at an individual station, e.g., BLS5 (bottom panels), S/P ratios for natural events seem to be better separated from those for explosions than in a combined analysis for all stations.

In order to get a better understanding of the mechanisms behind the observed S/P ratios there are additional factors that need to be investigated. Such factors are the directivity of the earthquakes sources, mixing of Pn, Pg and Sn, Sg in the measurement of S/P ratios, depth effects of the earthquake sources, and S-wave generation from underwater explosions in regions with strong topography.

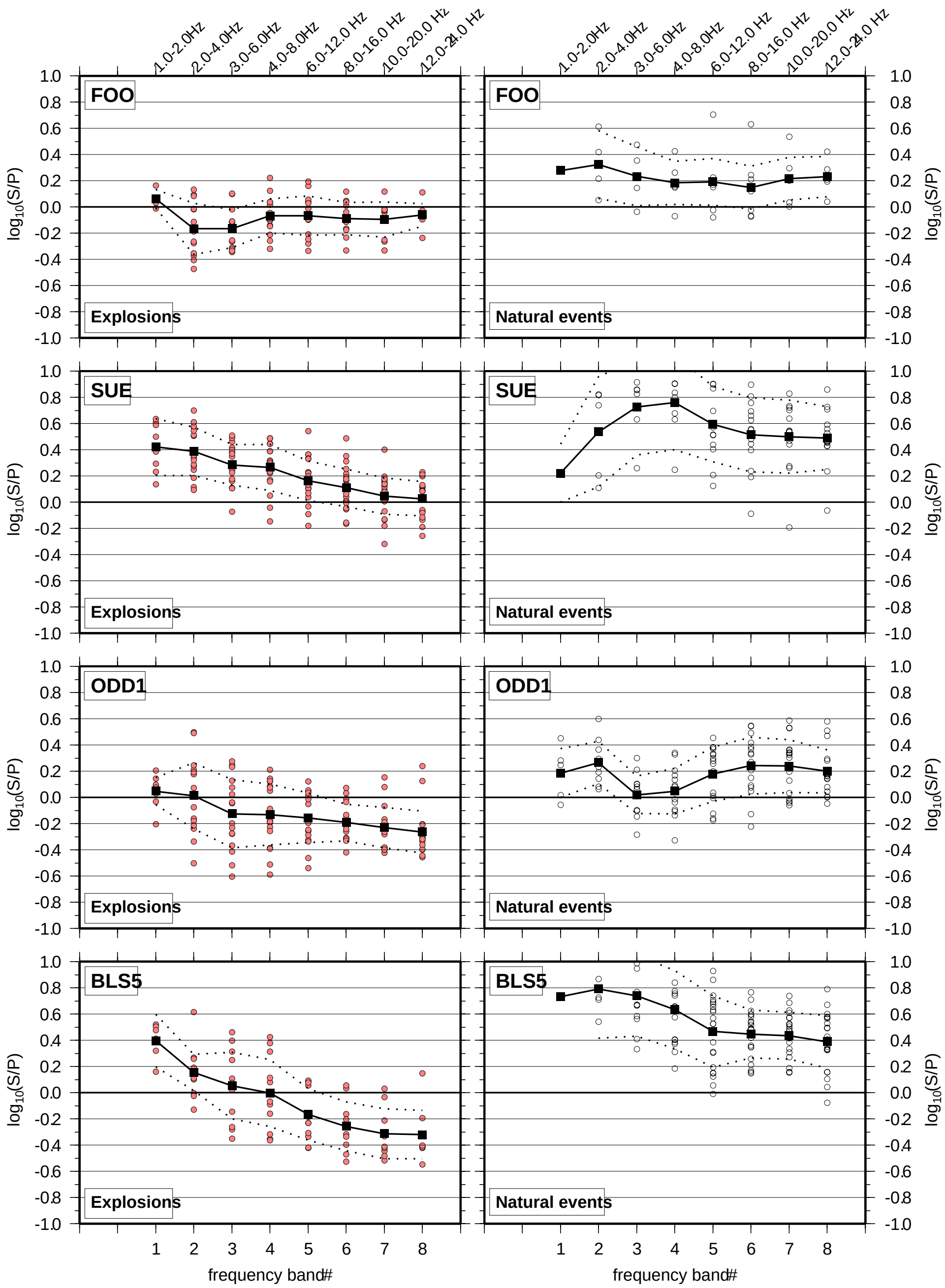

Figure 11. S/P amplitude ratios (logarithm) for explosions (left) and natural events (right) recorded at individual stations. Mean values are plotted as black squares and solid lines, and dashed lines indicate the standard deviation.

CONCLUSIONS AND RECOMMENDATIONS

One of the most significant results from this project has been the demonstration of the strong influence of the in-mine structures on the generation of S-waves from explosions. Through numerical modeling we have found that shear energy generation is particularly prevalent when the source is located near a geologic or structural boundary of the mine. Comparisons with in-mine observations from the Pyhäsalmi mine have further confirmed the reliablity of the waveform simulations. These findings are also in accordance with the results from the more conceptual study of Toksöz et al., 2004.

The strong influence of the near source structure in the generation of shear energy may explain the difficulty in using S/P ratios as reliable discriminants between explosive sources and rockbursts in mines.

We have also investigated the partitioning of S and P energy from earthquakes and underwater explosions occurring in the same region offshore western Norway. Although the earthquakes show generally larger S/P ratios than the explosions, there is a large scatter in the observations. Due to the absence of near-source recordings, these results are quite inconclusive with respect to the path effects involved in the generation of shear energy.

If the structures in the vicinity of explosion sources in general actually give rise to a significant amount of shear energy, we may have an explanation for the difficulty in using S/P ratios for reliable event discrimination. Our recommendation for further studies on energy partitioning between P- and S-energy would be to conduct controlled experiments with good near source recordings, combined with 3-D waveform modelling in both conceptual and realistic structures.

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