ENERGY PARTITIONING FOR SEISMIC EVENTS IN FENNOSCANDIA AND NW RUSSIA

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ABSTRACT

In this three-year project we have been addressing the problem of energy partitioning at distances ranging from very local to regional for various kinds of seismic sources. On the local and regional scale (20-220 km) we have targeted events from the region offshore of Western Norway, where we have both natural earthquake activity and frequent underwater explosions carried out by the Norwegian Navy. 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 in a realistic mine model to investigate the physical mechanisms that partition seismic energy in the near source region in and around the underground mine.

The results from modeling and analysis of local and regional data show that mean S/P amplitude ratios for explosions and natural events differ at individual stations and are in general higher for natural events and frequency bands above 3 Hz. 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 only assist the discrimination between an explosion and a natural event. This observation is supported by synthetic seismograms calculated for simple 1-D models, which demonstrate that explosions generate shear-wave energy if they are fired close to an interface with a strong material contrast (as is the case for most explosions), e.g., free surface or the ocean bottom. The larger difference in S/P ratios between earthquakes and explosions for higher frequencies can be explained by the fact that at low frequencies (larger wavelengths), discontinuities and structural heterogeneities in the explosion source region are stronger generators of converted S energy. The S* phase, for example, is most efficiently generated whenever an explosion source is located close to (within one wavelength) a strong discontinuity.

High-frequency (50-400 Hz) S/P ratios for mine blasts (explosions) and rockbursts recorded at the Pyhäsalmi in-mine network do not show any significant dependency on the distance to the events, which ranges between 40 and 400 m. The Pyhäsalmi explosions have generally lower S/P ratios than the rockbursts for all frequencies, but the difference is far too small to be significant for classification purposes. S/P ratios for explosions and rockbursts located in the same small area of the mine show results very similar to those for the full data set. This indicates that the observed differences in S/P ratios between explosions and rockbursts are due to differences in the source characteristics, and not to propagation effects along paths in the mine.

Three-dimensional finite-difference simulations were used to model seismic events within the Pyhäsalmi mine. In particular, a January 26, 2003, rockburst was modeled at frequencies of 50 Hz (4 m grid) and 100 Hz (2 m grid). We were able to match the characteristics of the observed data at 50 Hz particularly well, and the characteristics of the 100 Hz data reasonably well. The simulations showed that significant shear-energy can be produced due to the geologic and structural heterogeneities within the mine. In fact, mode-converted shear-energy generated from mine heterogeneity can dominate the compressional energy from an explosive source. A strong correlation is observed between the distance of a source from a mine heterogeneity and the magnitude of generated shear-energy. The ratio of shear to compressional energy is about a factor of two larger when the source is located within one wavelength from a mine heterogeneity. The simulations also suggest that excavated mine volumes are significantly stronger contributors to shear-energy generation than are geologic heterogeneities.

OBJECTIVE

The main objective of this project has been 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; 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 as follows:

- How is the generation and partitioning of seismic energy affected by properties of the 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

This three-year project started on September 30, 2002 and was a collaboration between the Norwegian Seismic Array (NORSAR)—as the lead organization—and Lawrence Livermore National Laboratory (LLNL). The closing date for the award was September 30, 2005, and the results from the project have been reported at previous Seismic Research Reviews (Bungum et al., 2003, 2004, 2005). The project results were summarized in the “Final Technical Report” of January 31, 2006, and included a new section on modeling of shear-waves from explosions in water. This section is included in this paper, together with a summary of the results previously presented in SRR papers and the “Final Technical Report”.

Recent Studies on Energy Partitioning

Generally, explosions occur very close to the Earth’s surface, which is characterized by sharp discontinuities (free surface, groundwater table, transition between unconsolidated sediments to solid rock, etc.). The interaction of a seismic source with such discontinuities can generate unexpected source radiation patterns and partitioning between P- and S-wave energy. Even in the simplest case of a homogeneous medium bounded by a free surface, an explosive source can generate different types of shear-wave energy, if it is close (within one wavelength) to an interface with a strong impedance contrast, like the free surface or the ocean bottom (e.g., Roth and Holliger, 2000).

There is an ongoing discussion about the dominant P-to-S transfer mechanism. It is generally agreed that significant S-wave energy from explosions is generated in the near-source region; several such near-source energy excitation mechanisms have been investigated, including P-to-Lg scattering, pS-to-Lg conversion at the free surface, Rg-to-Lg coupling, S*-to-Lg conversion, spall excitation of S, tectonic release, and rock damage. S* is a non-geometric wave generated by P-to-S conversion whenever an explosion source is located close (within one wavelength) to the free surface (Fertig, 1984).

Recently, Myers at al. (2005) analyzed recordings from the 1993 non-proliferation experiment (NPE) at the Nevada Test Site (NTS), accompanied with wavefield simulation in a detailed geological model of the area. They found that near-source topography and geological complexity in the upper crust strongly contributed to the S waves from the NPE shot.

Xie et al. (2005) conducted numerical wavefield simulations for shallow explosions in media with 3%-7% random velocity fluctuations. Their results show that S*-Lg scattering is stronger for low frequencies and shallow depths, whereas P-Lg scattering is stronger for high frequencies. Three dimensional simulations showed considerable P-pS-SH or SV-SH generation with a 7% velocity and density perturbations. Tangential Lg energies from explosions are often observed as large as those on the vertical components (Stevens et al., 2003).

The so-called Arizona source phenomenology experiment (Bonner et al., 2005) showed that the designed test shots and mining explosions are good surrogates for nuclear explosions because the magnitude- and distance-corrected Pg/Lg amplitude ratios fall in the range of those for nuclear explosions at NTS. Differences in depth of burial and single versus multiple shots have only a small effect on the amplitude ratios.

Analysis of Semipalatinsk underground nuclear explosions (UNEs) recorded at the Borovoye station at a distance of 680 km show that Rg-to-S scattering does not appear to be a dominant mechanism for the Lg excitation from Semipalatinsk UNEs (Hong and Xie, 2005). The geology of the source region appears to influence the strength of mantle shear-waves in the expected Sn window, where slower near-surface velocities in the source region seem to enhance shear-waves. Less dependency on source region geology is found for the Lg waves, which also have lower frequencies than Sn. The results from this study imply that the source region geology tends to make strong influence on the strength of higher-frequency shear-waves.

Scaling analysis of Sn/Pn and Lg/Pn spectral ratios at Borovoye for Semipalatinsk explosions (Murphy et al., 2005) indicate an Sn/Lg source generation mechanism compatible with a linear frequency-independent conversion of direct P-wave energy from the explosions.

In order to estimate the effect of strong scatterers in the near-source region, Toksöz et al. (2005) conducted 3-D wave-field modeling in media with well-defined tunnels, chambers, shafts, or surface topography. Their simulations show that a tunnel near an explosion acts as a very strong scatterer. P-to-S scattering is much stronger than P-to-P, and some energy is scattered into SH. A hill or a mesa above the explosion source causes strong scattering of the surface waves.

In this project we have further addressed the problem of energy partitioning at distances ranging from very local to regional for various kinds of seismic sources. On the local and regional scale (20-220 km), we have targeted events from the region offshore of Western Norway, where we have both natural earthquake activity as well as frequent underwater explosions carried out by the Norwegian Navy.

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 in a realistic mine model to investigate the physical mechanisms that partition seismic energy in the near-source region in and around the underground mine.

Modeling of Shear-Waves from Explosions in Water

In order to investigate S waves generated from explosions in water, we have conducted additional calculations using a frequency-wave number code (Wang, 1999), allowing both the source and the receivers to be located at depth. We have replaced the uppermost 200 m of the Fennoscandian crustal model with water, shown in Figure 1, and put the sensors at a depth of 210 m, i.e. 10 m below the sea bottom. Figure 2 shows the vertical-component synthetic seismograms for an explosion source in water at a depth of 10 m. The dominant frequency of the signal pulse is about 2 Hz.

The large Rg phase and the resonance effect of the water layer on Rg is not very interesting in our context, as the continuous water waveguide carrying the Rg phase is generally absent for the propagation paths addressed in this study; i.e., events located offshore Western Norway recorded at land stations of the National Norwegian Seismic Network (NNSN). However, the modeled amplitudes of the P and S body wave phases provide useful insight into the degree of S-wave energy generated

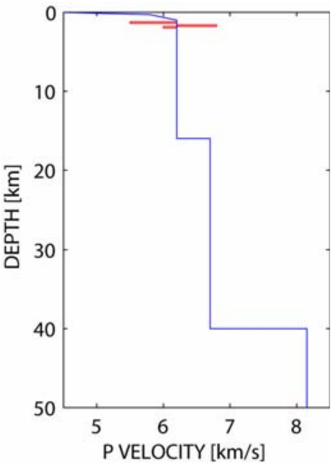

Figure 1. **Average crustal P-velocity model for Fennoscandia (blue). A perturbation for the upper crust is shown in red.**

from explosion sources, and show that similar mechanisms also are in effect for more realistic complex media. It can be seen from Figure 2 that the first-arriving S phase has a comparable amplitude to the P phase, at least for distances greater than 100 km. The effect of reverberations in the water layer is seen as coda energy related to the different arrivals.

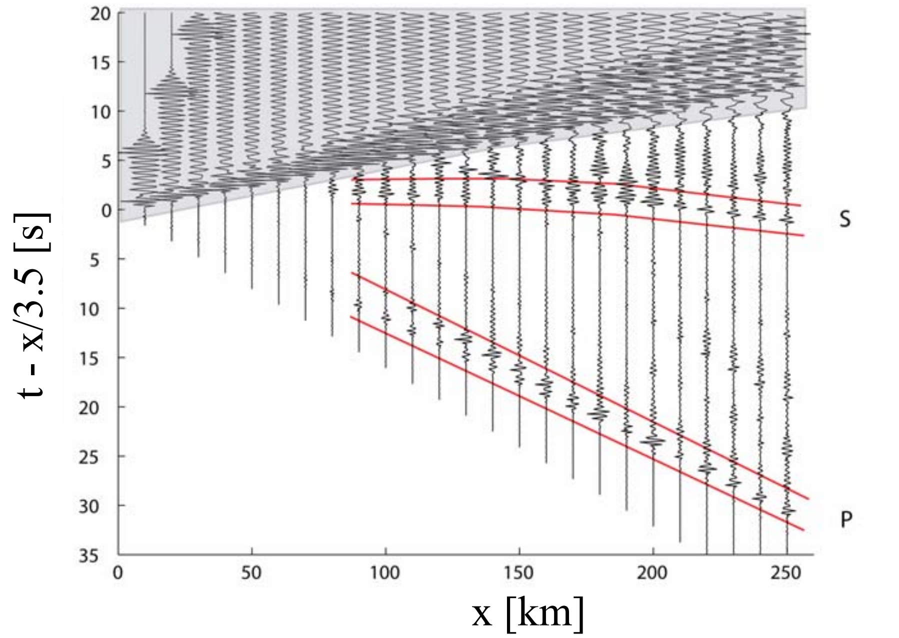

Figure 2.

Trace-normalized vertical component seismogram section for an explosion in water at a depth of 10 m, as described in the text. Rg is the dominant phase (shaded area), but is not important in this discussion of shear-waves. Significant energy travels with S-wave velocities, generated by interaction between the source and the sea bottom. The S-wave amplitudes are comparable to those of the P phase.

For comparison, we show in Figure 3 a similar wavefield simulation, but now without the 200 m water layer. Rg still has the largest amplitudes, now propagating with higher velocity than in the case shown in Figure 3. Also in this case, some shear-energy can be observed, but with an amplitude 2-3 times smaller than P.

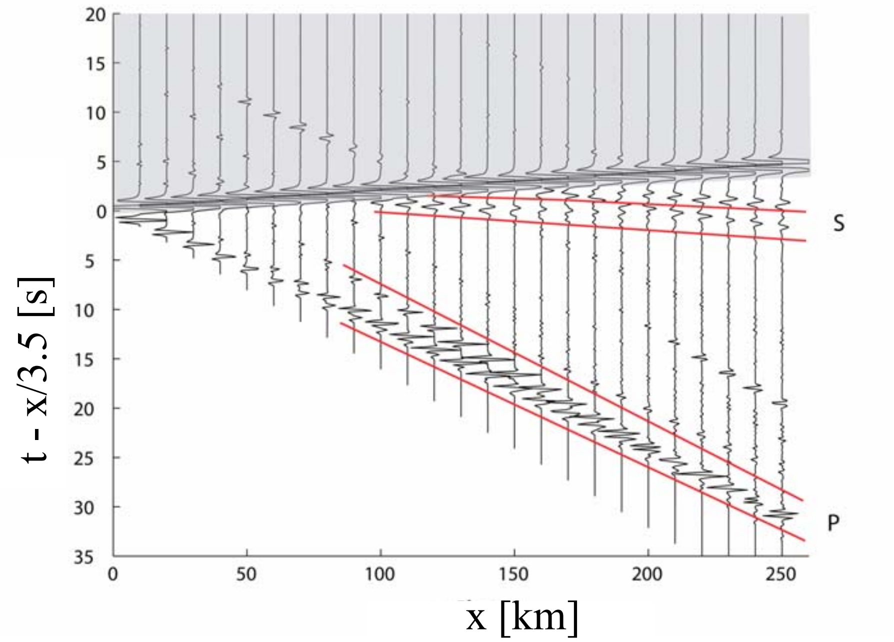

Figure 3.

Trace-normalized vertical component seismogram section for an explosion at a depth of 10 m into the crust, as described in the text. Rg is the dominant phase (shaded area) but is not important in this discussion of shear-waves. Some energy travels with S-wave velocities, generated by interaction between the source and the free surface. The S-wave amplitudes are 2-3 times smaller than those of the P phase.

Energy Partitioning for Seismic Events near the Coast of Western Norway; Summary of Analysis and Modeling Results

The database used in this study has been 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 4). The seismic stations are part of the permanent NNSN, and the data were provided by the University of Bergen (UiB). The selected source region is located around 60N, 5E, where both event types, earthquakes and explosions, occur.

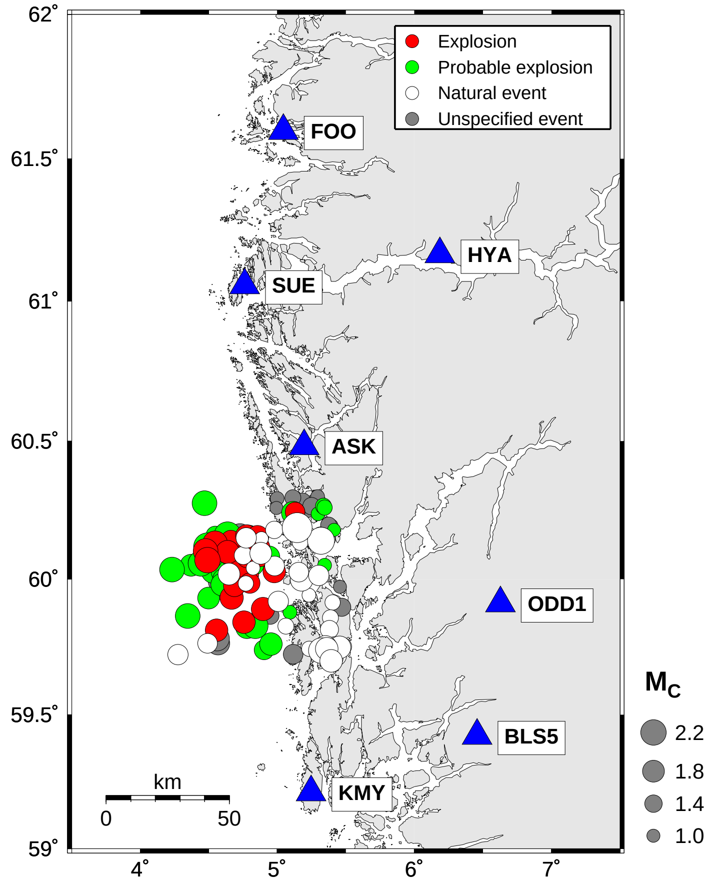

Figure 4. **Seismic three-component short-period stations (triangles) and events used for this study: ASK = Askøy, BLS5 = Blåsjø, FOO = Florø, HYA = Høyanger, KMY = Karmøy, ODD1 = Odda, and SUE = Sulen.**

The results obtained during the analysis of this data set and the associated modeling efforts can be summarized as follows:

- The S/P ratios of the analyzed data sets give only an indication of the source type. Variation of layer topography and 3-D heterogeneities can focus and defocus P- as well as S-wave amplitudes in different ways. This variation in S/P ratio is one reason for the width of the observed distributions and the overlap between the data sets.
- For the analyzed data set, there is a larger difference in S/P ratios between earthquakes and explosions for higher frequencies. This can be explained by the fact that, at low frequencies (larger wavelengths), discontinuities and structural heterogeneities in the explosion source region are stronger generators of converted S energy. The S* phase, for example, is most efficiently generated whenever an explosion source is located close to (within one wavelength) a strong discontinuity.
- The path dependence of the observed S/P amplitude ratios may also get a significant contribution from lateral heterogeneities in the source region, producing variable levels of P-to-S conversion in different directions from the source.
- Mean S/P amplitude ratios for explosions and natural events differ at individual stations and are in general higher for natural events and frequency bands above 3 Hz. 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 only assist the discrimination between an explosion or a natural event.
- Synthetic seismograms calculated for simple 1-D models demonstrate that explosions also generate shear-wave energy if they are fired close to an interface with a strong material contrast (as is the case for most explosions), such as the free surface or the ocean bottom.
- A single force source generates much stronger S waves than an explosion. The same is assumed to hold for double-couple sources averaged over the radiation pattern.
- Synthetic seismogram calculations confirm that the generation of S-type energy at impedance contrasts later along the ray paths contribute essentially only to the seismic coda of the direct P and S arrivals. This coda energy does

not dominate the amplitude behavior of the seismograms. Therefore, in simple 1-D models, S/P-ratios can be used as a discrimination criterion.

Analysis of In-Mine Data from the Pyhäsalmi Ore Mine, Central Finland

The Pyhäsalmi mine in central Finland has been a key element in our research, and we have been provided with all data from the in-mine seismic monitoring system that became operational in January 2003. This data set consisted by the end of 2005 of more than 30,000 seismic events, including the mine blasts (explosions). An interesting observation from the mine blast is the occurrence of shear-wave energy at the in-mine seismic stations (see Figure 5). The results from analysis of mine blasts and natural events (rockbursts) are summarized below:

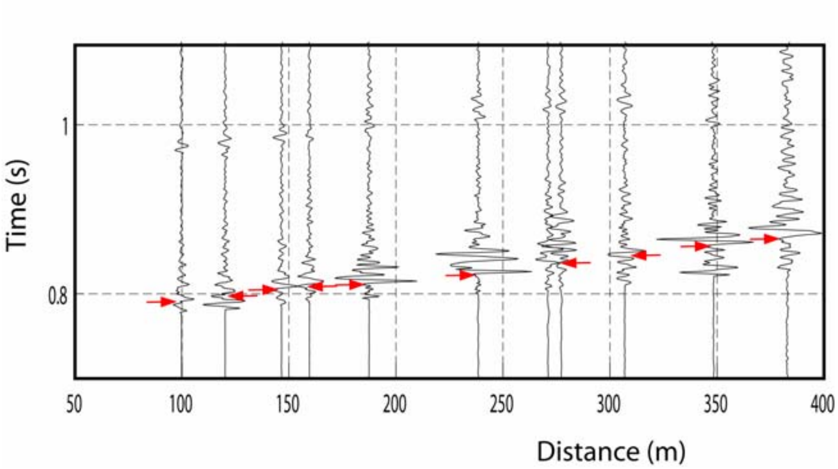

Figure 5.

Record section in the Pyhäsalmi in-mine network for a single detonation of a ripple-fired production shot. For each of the three-component sensors, we have chosen the component having the largest S phase. We have not included vertical-component observations where the rays approach the sensors at steep angles, as the S-arrivals on these sensors have very small amplitudes. The S arrivals are indicated with arrows.

- There is significant generation of S waves from production explosions in the Pyhäsalmi mine. Strong S-wave generation from explosions is observed at all distances and all frequencies considered in this study.
- The S/P ratios of explosions are, on the average, only marginally smaller than the S/P ratios of rockbursts. The overlap of the two populations is so large that the S/P ratio does not appear to be a useful discriminant for this data set.
- The observed S/P ratios do not show any significant dependency on the distance to the source, either for explosions or rockbursts.
- The observed S/P ratios also do not show any clear dependency on frequency bands among the frequencies considered in this study.
- Our results confirm that the major part of the S-wave energy for the explosions is generated in the near-source region.

Modeling of In-Mine Data

There is a lower limit to the distances at which we can practically observe signals at the Pyhäsalmi in-mine network, e.g., it would not be possible to carry out a mine blast in the immediate vicinity of a seismic sensor without risking damage to the hardware. The analysis of S/P ratios showed that there is a lower distance limit at which we can separate P and S energy for the frequencies of interest, and we have consequently no information on the S/P ratios for the first tens of meters from the source. To further investigate the physical mechanisms that partition seismic energy in the near-source region, we have conducted wavefield modeling studies of the Pyhäsalmi mine. Our efforts centered around three primary activities:

- Validation of our seismic modeling techniques in the presence of underground voids.
- Comparison of observed data from seismic events at the Pyhäsalmi mine with synthetic data generated using a 3-D finite-difference wave-propagation code and a 3-D geologic model of the mine.
- Synthetic sensitivity tests to determine the cause and characteristics of shear-energy generation in the near-source region.

The first two activities served to demonstrate our ability to model seismic wave propagation in a mine environment. The third activity was directed at the generation mechanisms for mode-converted shear-energy.

The E3D finite-difference code was used for many of the seismic simulations performed during this study (Larsen and Schultz, 1995; Larsen and Grieger, 1998). For this project, the E3D code utilized a 3-D geologic model of the Pyhäsalmi mine (see Figure 6). The model parameterized the different geologic and structural components of the mine on a regular grid. The geologic components included the background rock and ore bodies. The structural components included excavated regions such as tunnels, voids, and backfilled material produced by mine activity. The 3-D model was 500 m in all three dimensions. The material P-wave and S-wave velocities and the material densities have been discretized onto uniformly spaced grids of 2- and 4-m spacing. The E3D code utilized these discretized grids.

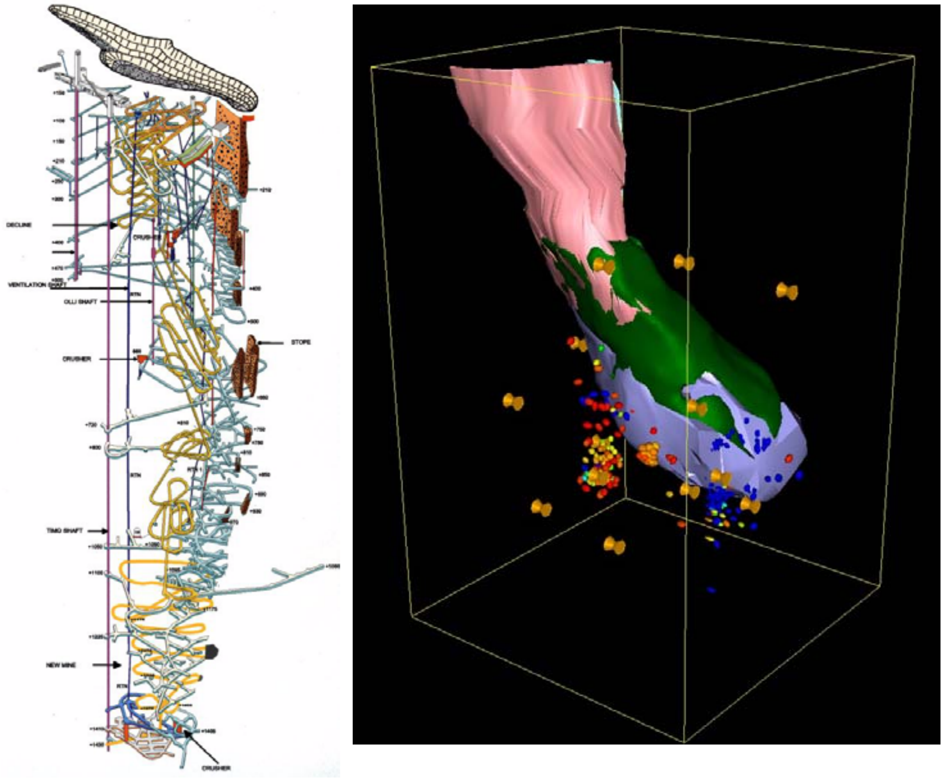

Figure 6.

The left-hand part of the figure shows the shafts and access tunnels of the Pyhäsalmi mine from the surface down to a depth of 1500 m. The right-hand part of the figure shows a 3-D model of the mine, for the depth range 800 - 1500 m. Green represents copper ore, blue represents zinc ore, and pink represent backfilled material. The locations of the initial 16 in-mine monitoring stations are indicated by yellow symbols. Events comprise mine blasts and microearthquakes during September 2003.

Below is a brief summary of our finite-difference modeling efforts. It includes the modeling of observed data from real seismic events within the Pyhäsalmi mine, as well as sensitivity studies.

- **Finite-Difference Modeling of Observed Data**
  Three-dimensional finite-difference simulations were used to model seismic events within the Pyhäsalmi mine. In particular, a January 26, 2003, rockburst was modeled at frequencies of 50 Hz (4 m grid) and 100 Hz (2 grid). We were able to match the characteristics of the observed data at 50 Hz particularly well and the characteristics of the 100 Hz data reasonably well. These results validate the reliability of our simulations.

- **Heterogeneity-Induced Shear-Energy Generation**
  Two Dimensional and 3-D finite-difference simulations were performed to investigate shear-energy generation within the Pyhäsalmi mine. We found that significant shear-energy can be produced due to the geologic and structural heterogeneities within the mine. In fact, mode-converted shear-energy generated from mine heterogeneity can dominate the compressional energy from an explosive source.
- **Correlation between Source Location and Shear-Energy Generation**
  Multiple suites of over 15,000 2-D finite-difference simulations were performed to quantify and investigate the correlation between source location and the magnitude of shear-energy generated within the Pyhäsalmi mine. A strong correlation is observed between the distance of a source from a mine heterogeneity and the magnitude of generated shear-energy. The ratio of shear to compressional energy is about a factor of two larger when the source is located within one wavelength from a mine heterogeneity.
- **Mine Excavation vs Geologic Heterogeneity**
  Finite-difference simulations at 50 Hz suggest that mine excavation is a significantly stronger contributor to shear-energy generation than is geologic heterogeneity.
- **Shear-Energy Generation from Non-Explosive Sources**
  Finite-difference simulations reveal that the magnitude of shear-energy generated as part of a shear-producing source mechanism (e.g., rockburst, mine collapse) can be as large or larger than that caused by an explosion close to a heterogeneity within the mine.
- **Finite-Difference Modeling of Voids**
  Similar synthetic waveforms are produced when the excavated regions within the Pyhäsalmi mine model are filled with air or water.

CONCLUSIONS AND RECOMMENDATIONS

In this project we have addressed the problem of energy partitioning at distances ranging from very local to regional for various kinds of seismic sources. On the local and regional scale (20-220 km), we have targeted events from offshore Western Norway, where we have both natural earthquake activity and frequent underwater explosions.

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 in a realistic mine model to investigate the physical mechanisms that partition seismic energy in the near source region in and around the underground mine.

The results from modeling and analysis of local and regional data show that mean S/P amplitude ratios for explosions and natural events differ at individual stations and are in general higher for natural events and frequency bands above 3 Hz. 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 only assist the discrimination between an explosion and a natural event.

This observation is supported by synthetic seismograms calculated for simple 1-D models, which demonstrate that explosions also generate shear-wave energy if they are fired close to an interface with a strong material contrast (as is the case for most explosions), e.g., free surface, the ocean bottom. The larger difference in S/P ratios between earthquakes and explosions for higher frequencies can be explained by the fact that at low frequencies (larger wavelengths), discontinuities and structural heterogeneities in the explosion source region are stronger generators of converted S energy. The S* phase, for example, is most efficiently generated whenever an explosion source is located close to (within one wavelength) a strong discontinuity.

The Pyhäsalmi explosions have generally lower S/P ratios than the rockbursts for all frequencies, but the difference is far too small to be significant for classification purposes. The maxima for the explosion distributions are all below 2, whereas they are all above 2 for the rockbursts. The rockbursts also have a wider distribution of S/P ratios, which can be explained by the variability of the radiation patterns from the rockburst sources. S/P ratios for explosions and rockbursts located in the same small area of the mine show results very similar to those for the full data set. This indicates that the observed differences in S/P ratios between explosions and rockbursts are due to differences in the source characteristics and not to propagation effects along paths in the mine.

Three-dimensional finite-difference simulations were used to model seismic events within the Pyhäsalmi mine. In particular, a January 26, 2003 rockburst was modeled at frequencies of 50 Hz (4 meter grid) and 100 Hz (2 meter grid). We were able to match the characteristics of the observed data at 50 Hz particularly well, and the characteristics of the 100 Hz data reasonably well. These results help validate the reliability of our simulations.

The simulations showed that significant shear-energy can be produced due to the geologic and structural heterogeneities within the mine. In fact, mode-converted shear-energy generated from mine heterogeneity can dominate the compressional energy from an explosive source. A strong correlation is observed between the distance of a source from a mine heterogeneity and the magnitude of generated shear-energy. The ratio of shear-energy to compressional-energy is about a factor of two larger when the source is located within one wavelength from a mine heterogeneity. The simulations also suggest that mine excavation is a significantly stronger contributor to shear-energy generation than geologic heterogeneity. However, the simulations reveal that the magnitude of shear-energy generated as part of a shear-producing source mechanism (e.g., rockburst, mine collapse) can be as large or larger than that caused by heterogeneity within the mine.

It is also interesting to note that analysis and modeling at the local/regional scale provide results that are in accordance with the results obtained from analysis and modeling of in-mine data. Both studies show that strong discontinuities in the source region are efficient generators of P-to-S converted energy, although at very different frequencies for the different scales investigated. The large overlap in the populations of S/P ratios for explosions and natural seismic events at both scales supports this interpretation.

In order to get further insight into the problem of energy partitioning between P- and S-waves from different types of seismic sources, we recommend further studies that include controlled explosion field experiments with near-source recording. Specifically, fully-coupled, contained explosions could be conducted in proximity to production-style shots, such as in the Pyhäsalmi mine. In this way the physical processes comprising small-scale explosions could be separated in order to enable prediction of the observables from larger and more complex explosions. Such observations should be supplemented with numerical simulations of shear-wave energy generated directly by nonlinear source effects, as well as by linear propagation effects such as scattering from the free interfaces of the mine.

The populations of S/P ratios for explosions and natural seismic events of the data sets analyzed in this study show a large overlap and therefore cannot be used as a unique discriminant. The possibility of integrating S/P ratios with existing or new measurements should therefore be investigated further, aimed at improving the discrimination potential.

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