

DEVELOPING AND EXPLOITING A UNIQUE SEISMIC DATASET FROM SOUTH AFRICAN GOLD MINES FOR SOURCE CHARACTERIZATION AND WAVE PROPAGATION

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ABSTRACT

In this project, we are developing and exploiting a unique seismic dataset to address the characteristics of small seismic events and the associated seismic signals observed at local (< 200 km) and regional (< 2000 km) distances. The dataset is being developed using mining-induced events from three deep gold mines in South Africa recorded on in-mine networks (< 1 km) comprised of hundreds of high-frequency sensors, a network of five broadband seismic stations installed as part of this project at the surface around the mines (1–50 km), and a network of 16 existing broadband seismic stations at local/regional distances (50–1000 km) from the mines. The final dataset will contain: (1) events spanning 5 orders of magnitude (M from ~-1 to 3) well recorded at a wide range of local and regional distances, (2) events from a range of source depths (0–4 km), and (3) events from a variety of source types correlated with in-mine information, such as pillar collapse and shear failure.

We are exploiting the dataset to improve U.S. operational capabilities to monitor for low-yield nuclear tests by analyzing the mining-induced events in 10 areas of interest. We are gathering and analyzing hundreds of events with $M > 2.5$ and many more selected smaller events, including point explosions (mine blasts), mine-related stress release, mining activities, and shallow earthquakes. We are creating cataloged information on origin times and locations (GT 0), source parameters, focal mechanisms, coda-derived source spectra, coda magnitudes, local-to-regional phase propagation characteristics, relative P and S excitation, source apparent stress variation, and local-to-regional body-wave amplitude ratios that can discriminate between the different source categories. We are systematically analyzing the direct body-wave and coda wave properties of these events in terms of variability with source type, depth, magnitude, distance and other characterization factors. These direct and coda wave amplitudes are of fundamental importance to yield estimation and source type discrimination.

INTRODUCTION

In this project we are developing and exploiting a unique seismic dataset for addressing the characteristics of small seismic events and the associated seismic signals observed at local (< 200 km) and regional (< 2000 km) distances. The dataset is being developed using mining-induced events from three deep gold mines in South Africa recorded on in-mine networks comprised of hundreds of high-frequency sensors, a network of five broadband seismic stations installed at the surface around the mines, and a network of 16 broadband seismic stations at local/regional distances from the mines (Figure 1). The in-mine data are providing high-fidelity recordings of the seismic wave field at distances of a few meters to a few kilometers from the source. The surface mine network is providing broadband recordings of the wave field at distances of 1–2 km from the source out to distances of about 50 km, and the local/regional stations are providing broadband recordings from about 50 km out to distances of ~1000 km.

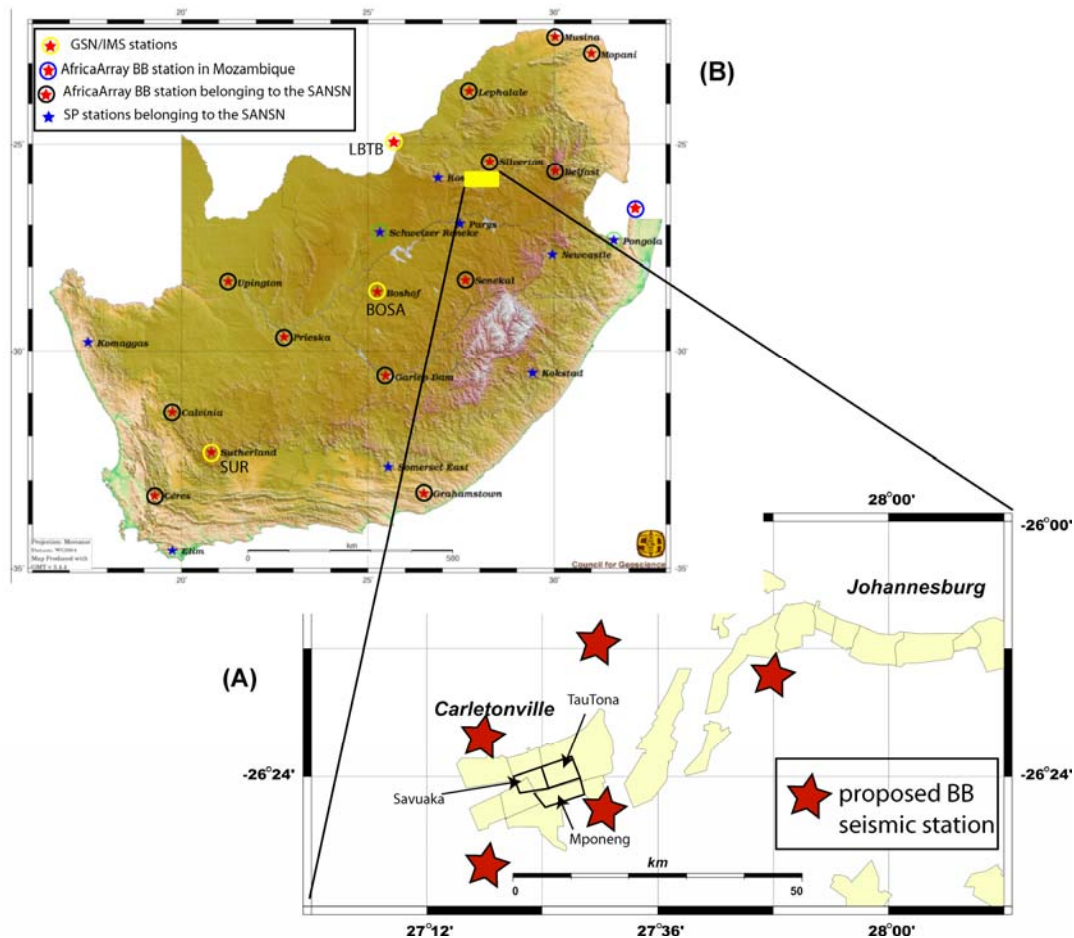


Figure 1. (A) Map showing the locations of the gold mines (yellow areas) on the northwestern side of the Witwatersrand basin (Far West Rand region). Data for this project come from the three mines labeled. The red stars show preliminary station locations of the surface mine network that is being constructed. (B) Map showing location of broadband (BB) stations at local and regional distances.

This dataset will be unique in that it will contain (1) events spanning 5 orders of magnitude (M from ~-1 to 3) well recorded at a wide range of local and regional distances, (2) events from a range of source depths (0-4 km), and (3) events from a variety of source types (e.g., normal faulting, strike-slip faulting, mine blasts, pure double-couple events, isotropic events). In addition, the dataset will include details of mine plans that will enable us to correlate certain mining events with mining activities, such as blasting and pillar collapse, and investigate the influence of mine cavities and lithology on wave propagation. We plan to exploit the dataset by using the mining events in 10 related areas of research aimed at improving U.S. operational capabilities to monitor for low-yield nuclear tests: (1) create an event catalog with accurate origin times and locations; (2) determine seismic moment, radiated energy,

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corner frequency, and stress drop; (3) obtain focal mechanisms from moment tensor inversion; (4) define several categories of event types (shear slip, tensile failure with volumetric component, explosions) using focal mechanisms and in-mine observations (e.g., pillar collapse); (5) define and calibrate a coda M_w scale for southern Africa; (6) determine M_w for all cataloged events using calibrated coda techniques; (7) investigate the effects of depth and source mechanism on the coda-derived source spectra and evaluate the potential of using coda spectral peaking as a depth discriminant; (8) define and calibrate local-to-regional phase (direct P and S, Pn, Pg, Sn, and Lg) propagation characteristics, including the use of the magnitude and distance amplitude corrections (MDAC) technique to determine appropriate geometrical spreading and frequency dependent Q values for the region; (9) characterize relative P and S excitation and source apparent stress resulting from variations in source parameters, including magnitude, mechanism, depth, rock characteristics and source type; (10) define regional phase ratios that can discriminate between the different source categories, and compare these discriminants and their performance with ongoing work done for other types of mining events, such as in Scandinavia and the western U.S.

Data

As mentioned above, three complimentary datasets are being assembled in this project: (1) High-frequency in-mine seismic data from three mines along the northwestern edge of the Witwatersrand basin; (2) Seismograms from mine events recorded at distances of 1 to 50 km will be provided by five new broadband stations installed and operated by the Council for Geoscience; and (3) Broadband recordings of the mine events at local and regional distances will be provided by twelve *AfricaArray* stations in South Africa that are part of the South African National Seismic Network (SANSN), International Monitoring System (IMS) stations BOSA (South Africa) and LBTB (Botswana), a ground station network (GSN) station (SUR, South Africa), and an *AfricaArray* station in southern Mozambique.

Gold Mines and Mining Seismicity. The Witwatersrand basin is part of a granite-greenstone complex constituting the basement of the Kaapvaal craton. The basement evolved between 3.8 and 2.8 billion years ago and has remained relatively stable except for the development of stratified basins. Subsidence of the Witwatersrand basin probably began before basement evolution was complete and resulted in the deposition of three major stratigraphic units: the Dominion Group, the Witwatersrand Supergroup, and the Ventersdorp Supergroup. Most of the gold is mined from the quartzites (commonly referred to as reefs) within the Witwatersrand Supergroup.

The mining activities of the Witwatersrand basin induce thousands of seismic events per day, many of which are larger than $M=2$. The data are recorded at depth (1–5 km) by arrays of three-component geophones operated by AngloGold Ashanti, Ltd. and Integrated Seismic Systems International (ISSI). We will obtain from three mines (Mponeng, Savuka, and TauTona) in the Far West Rand region (80 km southwest of Johannesburg; Figure 1a), waveforms from over 500,000 mining-induced events recorded on hundreds of high-frequency geophones within the mines. Based on seismicity rates in these mines, the dataset will contain between 20 to 35 $M>3$ events per year, about 200 events per year between magnitude 2 and 3, and hundreds of mining blasts (mostly $M<0$).

These mines are some of the deepest in the world and extract ore from two gold-bearing quartzites, the Ventersdorp Contact Reef and the Carbon Leader Reef (Figure 2). These two units are separated by 900 m vertically, extend 2–4 km below the surface, and dip to the south at 21 degrees (Figure 2). The mines contain faults and dykes with two major trends: N 5° E and N 96° E. Some of the faults have been reactivated by the mining, providing sources for many of the larger events.

Details of the geology within the mines have been determined by underground mapping, surface surveys, and well logs from deep boreholes. Densities of major lithologies present in the mines have been measured from rock samples, and the shear and bulk modulus of the lithologies have been determined using V_s and V_p measurements from test-blasting.

The geophones sample at frequencies of 400–10,000 Hz and are located at depth on the quartzite reefs. The station spacing underground is on the order of 100 m in the active mining zones. Because there are two horizons being mined simultaneously, event depth is well-constrained by the geophones at different depths, especially compared to other mining-induced datasets in which the seismometers are usually situated on a single plane.

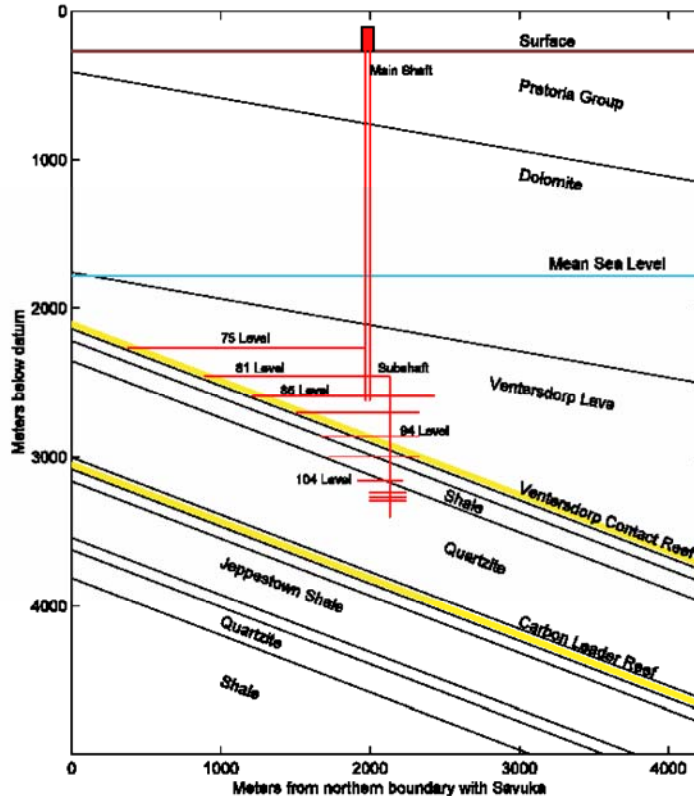


Figure 2. Cross-section through main shaft of the Mponeng mine looking east. The two gold-bearing horizons are marked in yellow. The datum is measured from an elevation in Johannesburg, so it is above the ground surface.

In order to determine the locations of the mine events, ISSI technicians routinely pick P-wave and S-wave arrival times and run a ray-tracing algorithm. This method of locating events is successful (uncertainties are on the order of 10–20 m) because the geologic setting of the Far West Rand consists of layers without appreciable lateral heterogeneities. The layered velocity model used is based on geologic units that have been determined by underground surveying and mapping as well as surface-based refraction profiles and borehole data. The accuracy of the velocity model has been verified by test blasting used to determine wavespeeds through various strata.

The ray-tracing algorithm is outlined in Mendecki (1993, 1997). In general, a system of equations consisting of arrival time and azimuth information is constructed, and the minimum of the residuals of these measurements is found with respect to the system's L1 norm. Using the L1 norm prevents large outliers from having too great an effect on the results (Prugger and Gendzwill, 1988; Jeffreys, 1932). In order to improve locations of events of special interest, the "arrival time difference" method or "master event" method is used to refine the location determined by ray-tracing (Spence, 1980). In this case, the master event will be a test blast whose precise location is well known, and other events in a nearby cluster are relocated relative to the master event based on arrival time differences. To relocate events, they must be close enough to the master event so that the seismic waves travel through the same geologic structures. This ensures that only location differences contribute to arrival-time differences among the events in a cluster.

Surface Mine Network. Mining-induced events from the three mines described above will be recorded at distances of 1 to 50 km using a new permanent, surface mine network comprised of broadband seismic stations. The surface mine network will also provide data from many thousands of other events that occur in other deep mines around the Witwatersrand basin for which we will not obtain in-mine data, including many hundreds of events with $M > 2.5$. The location of the proposed stations with respect to the three mines is shown in Figure 1A.

Local/Regional Broadband Seismic Network. Sixteen permanent broadband seismic stations across southern Africa will provide high-quality seismograms of the mining-induced events, data that will compliment the data from

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the in-mine and mine surface networks. The locations of the local/regional stations are shown in Figure 1B. Twelve of the stations are part of the SANSN, and data from these stations are being archived as *AfricaArray* data at the IRIS data management center. These stations are equipped with a 24 bit data loggers and broadband sensors (STS-2, Guralp 40T, KS 2000). Two of the sixteen stations are IMS stations (BOSA in South Africa and LBTB in Botswana) and one is an IRIS GSN station (SUR in South Africa). The final station is a new *AfricaArray* station in southern Mozambique at Changalane and equipped with a 24-bit digitizer and a Guralp CMG-3T sensor.

OBJECTIVES

In this section we provide details of how the seismic data will be modeled and analyzed to meet the research objectives for each of the research areas identified in the Introduction.

Create an Event Catalogue with Accurate Times and Locations. The in-mine network operators routinely locate and catalog events, and we will obtain these catalogs and use them as a starting point to create an event catalog with accurate origin times and locations in universal coordinates. Each mine network is operated independently using a local coordinate system and a different timing system. We will transform station and events locations into a universal coordinate system and use the 5-station surface mine network to calibrate the timing of each in-mine network by using larger, well-recorded events. An ML magnitude will also be included in the catalog based on the ML scale used routinely by the Council for Geoscience in their event bulletins. As the mining-induced event locations are typically constrained to within 10 to 20 meters by the mine network operators, we will not need to relocate any of the events.

Determine Source Parameters. In work recently completed (Richardson et al., 2004, 2005), we have determined for 27 $M > 2.5$ mine events in the Far West gold fields recorded between 1998 and 1999 seismic moment, radiated energy, corner frequency, and stress drop using the method of Richardson and Jordan (2002), which was adapted from the spectral method first developed by Andrews (1986). In order to determine source parameters, we median-stacked each event's spectra and integrated the results up to the Nyquist frequency to determine the integral of the displacement power spectra, the integral of the velocity power spectra, and the acceleration power spectral level. These parameters were then used to determine the source parameters radiated energy, seismic moment, and static stress drop using the equations provided in Richardson et al. (2004, 2005). During the three year duration of this project we anticipate recording over 100 $M > 2.5$ events from the three mines described above, and we will use the in-mine data to determine seismic moment, radiated energy, corner frequency and stress drop using the same method.

Obtain Focal Mechanisms from Moment Tensor Inversion. We will determine focal mechanisms for events with $M > 2.5$ and a select number of smaller events using moment tensor inversion of the in-mine data. One important difference between mine tremors and natural earthquakes is the effect of mining voids on the recorded waveforms. The voids can influence the frequency content of the seismograms, cause focusing and defocusing of the wave field, as well as cause unexpected amplifications. In addition, the moment tensor calculated for an event near the free surface of a stope, for example, can have a significant isotropic component related to the closure or convergence of the excavation. The mining geometry also can influence source parameters calculated for an event. For example, the seismic moment calculated for a crushed pillar would have contributions from the failure of the pillar as well as from the convergence of the surrounding stope. (Gay et al., 1995, McGarr, 1992; Milev et al., 2005; Napier et al., 2005).

Many of the past open studies of small ($M < 5$) event mechanisms in the mining environment have been limited by the quality of the available seismic data, and therefore a number of inconsistent interpretations have been published. Studies that analyzed P- and S-wave first motions interpreted fractures around stope faces as having isotropic components consistent with implosional mechanisms. These fractures have been assumed to be related to closure of excavations and crushing of rock ahead of the stope face (Joughin, 1966; Joughin and Jager, 1983; McGarr, 1992). First-motion studies have also concluded that explosional isotropic events occur occasionally.

However, all of these results have been debated because the coverage of the focal sphere often proved inadequate to reject a pure double-couple solution (Wong and McGarr, 1990). In addition, other first-motion studies and waveform analyses found predominantly double-couple sources (McGarr, 1971; Spottiswoode and McGarr, 1975). Recent developments using moment-tensor inversions corroborate evidence that both pure double-couple and mechanisms with significant isotropic explosional components exist in mine settings (Sellers et al., 2003; Wright et al., 2003; Talebi and Young, 1990; Feignier and Young, 1992; McGarr, 1992; Baker and Young, 1997; Gibowicz, 1997).

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We will invert the in-mine data to determine moment tensor solutions for all events with $M > 2.5$, and a select number of smaller events. We anticipate that a number of the events will have non-double couple mechanisms, based on previous results from other researchers. To help characterize the non-double couple mechanisms, these mechanisms will be examined further using regional full waveform modeling following an approach that was developed for modeling other non-double couple sources, such as large mine collapses in Wyoming (Pechmann et al., 1995) and Germany (Bowers and Walter, 2002).

Define Several Categories of Event Types. Using the focal mechanisms and in-mine observations, we will define several categories of event types, such as shear slip, tensile failure with volumetric component, and explosions. The mine plans will be very important for correlating with focal mechanisms to categorize event types, as will the records of blasting in the mines.

Defining and Calibrating a Coda Mw Scale for Southern Africa. Determining meaningful and accurate measures of the size of seismic events is a critical part of characterizing and cataloging the seismicity in a region. For the southern Africa region, we want to define a useful scale that can cover the expected range of mining induced and natural events from about magnitude -1 to 4. Teleseismic magnitudes such as m_b and M_s are limited mainly to events greater than magnitude 4. Local magnitudes scales such as M_L are valid for comparing relative sizes of events within the region but make it difficult to compare events across regions such as with other parts of the world. Local magnitude scales are also difficult to relate to fundamental physical properties of the source. For these reasons seismic moment magnitude has become the measure of choice for modern digital networks (e.g., Pasyanos et al., 1996; Kubo et al. 2002). However, if waveform modeling were required to determine the moments, it would be difficult to systematically determine moments for events less than about 3.0. Techniques based on regional coda envelopes (Mayeda and Walter, 1996; Mayeda et al., 2003) offer the potential to determine seismic moments for events over the entire range of interest down to magnitude -1 with local and in-mine data.

The scattered seismic energy following the direct phase arrivals (e.g., L_g or S_n) is called the seismic coda. Techniques measuring the amplitude of seismic coda on local and regional envelopes have provided some of the most stable measures of source spectra available (e.g., Mayeda and Walter, 1996; Mayeda et al. 2003). Comparisons with amplitudes from the direct phases have shown that coda-based amplitude measures have 3–5 times smaller standard deviations when the amplitudes determined at two stations are compared. This means that a single station can provide as accurate a measure of source amplitude as a 9-to-25 station averaged measure of a direct arrival. Thus coda-based measures are ideal for smaller events and sparse station networks.

To determine coda based source spectra and moments we will first calibrate for path and site effects in each narrow frequency band using a set of well-recorded events distributed in distance. Then we will tie the lower frequencies to moments determined from waveform modeled events in the region. For southern Africa there are a few larger events that have previously been modeled (e.g., Bowers, 1997) as well as some of the smaller mine events (Richardson et al., 2004, 2005). As part of this project we will perform additional moment tensor inversions of mining events as well as a few of the largest events using regional waveform modeling techniques to improve our calibrations. Finally a number of very small events will be used as empirical Green functions to determine the high-frequency corrections. These events are chosen such that their corner frequencies are higher than the calibration frequencies, and we can assume their spectra is flat.

Determining Coda Source Spectra and Mw for Selected Catalogued Events. Once the regional stations are calibrated, we will use existing LLNL scripts to calculate coda derived source spectra and Mw. Processing will be done for the subset of cataloged events selected for detailed analysis as part of this project.

Analyzing Depth Effects on Coda-Derived Source Spectra. The displacement source spectra of normal tectonic depth earthquakes (e.g., 5–20 km) determined from local and regional coda envelopes have typical Brune (1970) style shapes: flat at long periods and then falling off at frequencies above a corner frequency. In contrast very shallow events (<1 km) produce unusual “peaked” source spectra when the coda method is calibrated using normal depth earthquakes (e.g., Mayeda and Walter, 1996; Myers et al., 1999).

The coda derived source spectral shape differences appear to depend on the differences in the excitation of coda as a function of depth. It has been hypothesized that this peaking is related to the stronger excitation with shallower depth of the fundamental Rayleigh wave R_g that is then scattered into the coda (e.g. Myers et al., 1999). If quantified these shape differences could be exploited to flag very shallow events for nuclear monitoring purposes. The mine-induced seismicity completely covers the depth range of interest of 0 to 4 km depth. The in-mine network will provide very good control on the source depth so this effect can be investigated. In addition we will use the

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moment tensor results to explore the effect of focal mechanism on the coda spectra as well. In particular we want to see if the coda spectral shapes differ for events with isotropic components when compared with double-couple events.

Local-to-Regional Phase Propagation Characteristics. In southern Africa, the local P and S phases as well as all four major regional phases Pn, Pg, Sn, and Lg propagate and can be identified in seismograms. In order to be able to compare events of different distances or sizes with each other, we need to be able to correct for source and path effects. Walter and Taylor (2002) developed a procedure to do this called Magnitude Distance Amplitude Correction (MDAC). The MDAC method includes path corrections due to geometrical spreading, frequency dependent attenuation, and site effects. The MDAC process also simultaneously corrects for source effects by removing a generalized Brune (1970) style spectra. It corrects both local P and S phases as well as the four regional phases in all frequencies allowing the researcher the freedom to explore any possible ratio of body-wave amplitudes. In this project we will use a much larger dataset to determine optimal MDAC parameters for the broadband stations in the region. We will explore the variability of the body wave amplitudes as a function of local to regional distance. These MDAC corrections will allow us to investigate both source parameter and discriminant behavior for the southern Africa events.

Source Parameters and Scaling. The regional amplitudes and their ratios show very large variation in southern Africa. We want to try and understand this scatter in terms of variations in source parameters such as relative P and S excitation and apparent stress with mechanism, depth, rock type and other source region properties. We will take advantage of the in-mine data to look for correlations of seismic properties observed regionally with what is known to have happened near the source.

Regional Phase Amplitude Ratio Discriminants. It is well established that amplitude ratios of regional body-wave phases at frequencies of 1 Hz and higher can discriminate explosions from earthquakes (e.g. Bennett and Murphy, 1986; Taylor et al., 1988; Baumgardt and Young, 1990; Dysart and Pulli, 1990; Kim et al., 1993; Walter et al., 1995; Taylor, 1996; Fisk et al., 1996; Hartse et al., 1997; Rodgers and Walter, 2002, and Taylor et al., 2002). Such ratios include ratios of P phases to S phases (phase ratios), low frequencies to high frequencies within a phase (spectral ratios) and ratios of high frequency in one phase to low frequencies in another (cross-spectral ratios). We will explore how well some of these ratios can discriminate between the different source categories of mine region events. These may include shear slip, tensile failure with volumetric component, and explosions. We will compare these discriminants and their performance with ongoing work done for other types of mining events and other major mining regions, such as in Scandinavia (e.g. Bungum et al., 2004) and the western U.S. (e.g. Leidig et al. 2004).

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