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ABSTRACT

In this project, we are developing and exploiting a unique seismic data set 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 3 deep gold mines in South Africa recorded on in-mine networks (< 1 km) comprised of hundreds of high-frequency sensors, a network of broadband seismic stations installed as part of this project at the surface around the mines (1-50 km), and a network of 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. Six months of data has been collected so far from the broadband seismic networks, and 3 months from the in-mine networks.

We are exploiting the data set to improve U.S. operational capabilities to monitor for low-yield nuclear tests by analyzing the mining-induced events in a number of ways. We are gathering and analyzing events with M>2.5, as well as some 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.

1.0 Introduction

In this project we are developing and exploiting a unique seismic data set for addressing the characteristics of small seismic events and the associated seismic signals observed at local (< 200 km) and regional (< 2000 km) distances. The data set is being developed using mining-induced events from 3 deep gold mines in South Africa recorded on in-mine networks comprised of numerous high-frequency sensors, a network of broadband seismic stations installed at the surface around the mines, and a network of broadband seismic stations at local/regional distances from the mines (Figure 1a, b). 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 (Figure 1d). 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 20 km, and the local/regional stations are providing broadband recordings from about 50 km out to distances of ~1000 km (Figure 1a, b, c).

The bulk of the effort in the first year of this project has gone into establishing the surface mine network and collecting data from the in-mine networks. The first stations in the surface mine network began recording in January, 2007, at which time we also began assembling data from the in-mine networks. The surface mine network stations (Figure 1a) are comprised of RefTek 24-bit data loggers and Guralp CMG-3T broadband sensors. Four stations in the surface mine network are now operating and a fifth station is under construction. Examples of the data quality are illustrated in Figures 1c and 1d.

The data set that we are assembling is unique in that it contains (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 the coming year, we will add to the data set 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 will exploit the data set 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, 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 Mw scale for southern Africa; (6) using calibrated coda techniques, determine Mw for all cataloged events; (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 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.

This project is being conducted by a team of researchers at Penn State, LLNL, and in South Africa at the Council for Geoscience, the Council for Scientific and Industrial Research, and the University of the Witwatersrand.

2.0 Data

As mentioned above, three complimentary data sets are being assembled in this project; (1) high-frequency in-mine seismic data from three mines along the northwestern edge of the Witwatersrand basin,

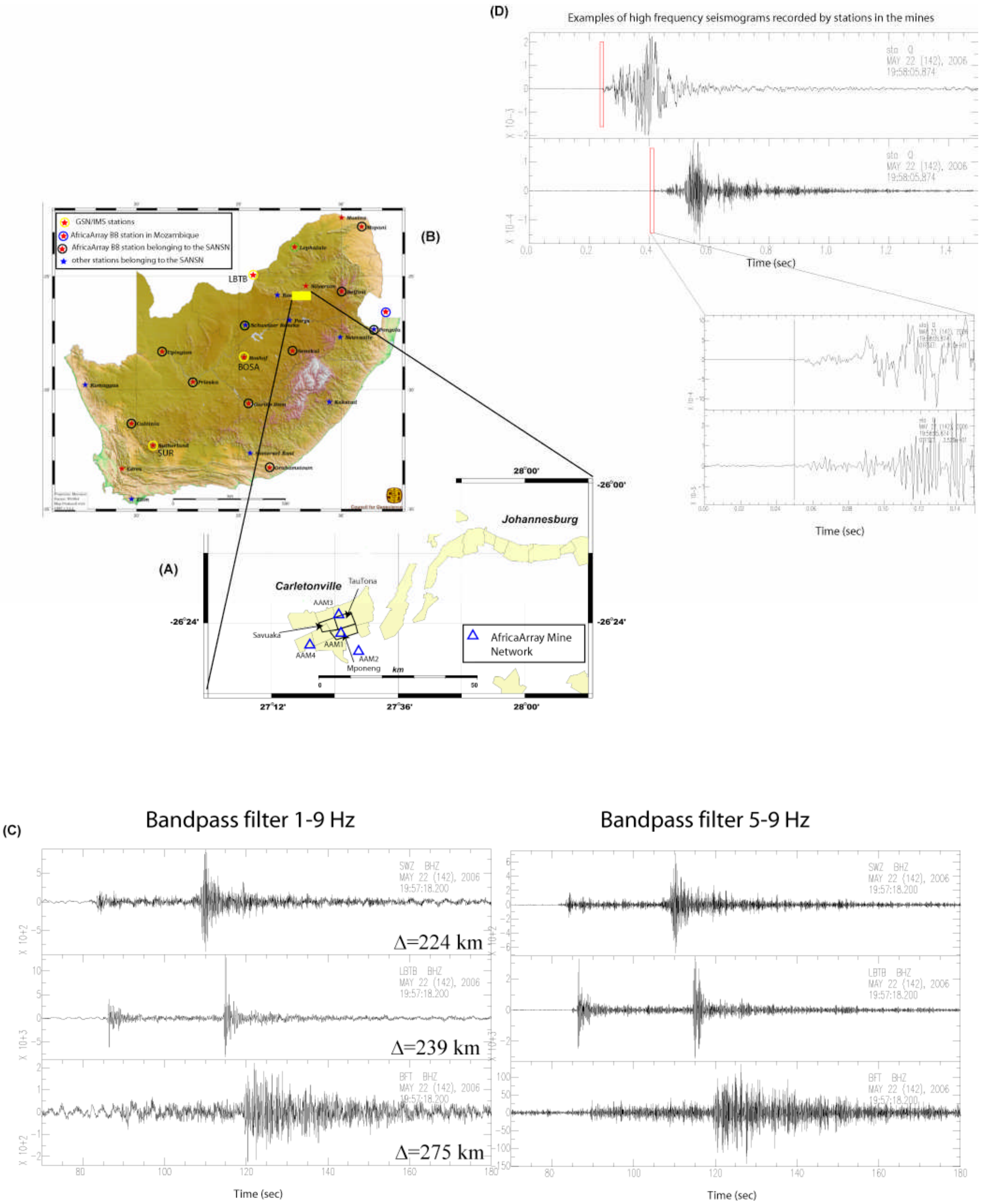

Figure 1. (a) Map showing the locations of the gold mines (yellow areas) on the northwestern side of the Witwatersrand basin (Far West Rand region). Data for this project come from the three mines labeled. The blue triangles show station locations of the surface mine network that has been constructed. (b) Map showing location of AfricaArray broadband stations at local and regional distances. (c) Vertical displacement seismograms from a M=2.2 mining event recorded a near-regional distances. (d) The same event recorded on high-frequency in-mine seismic stations.

(2) seismograms from mine events recorded at distances of 1 to 20 km from the new broadband stations installed, and (3) broadband recordings of the mine events at local and regional recorded on 12 *AfricaArray* stations in South Africa that are part of the South African National Seismic Network (SANSN), IMS stations BOSA (South Africa) and LBTB (Botswana), a GSN station (SUR, South Africa), and an *AfricaArray* station in southern Mozambique.

2.1 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 b.y. 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 Supergoup.

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 are obtaining from three mines (Mponeng, Savuka, and TauTona) in the Far West Rand region (80 km southwest of Johannesburg; Figure 1a), waveforms from mining-induced events recorded on numerous high frequency geophones within the mines. Based on seismicity rates in these mines, the projected data set should 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^{o} E and N 96^{0} 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 has 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 Vs and Vp 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.

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.

2.2 Surface mine network: Mining-induced events from the three mines described above are being recorded at distances of 1 to 20 km using a new permanent, surface mine network comprised of broadband seismic stations. The surface mine network is also providing data from many 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 locations of the stations so far installed with respect to the three mines are shown in Figure 1a.

2.3 Local/Regional broadband seismic network: Sixteen permanent broadband seismic stations across southern Africa are providing high quality seismograms of the mining-induced events, data that is complimenting the data from 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 South African National Seismic Network, and data from these stations are being archived as *AfricaArray* data at the IRIS DMC.

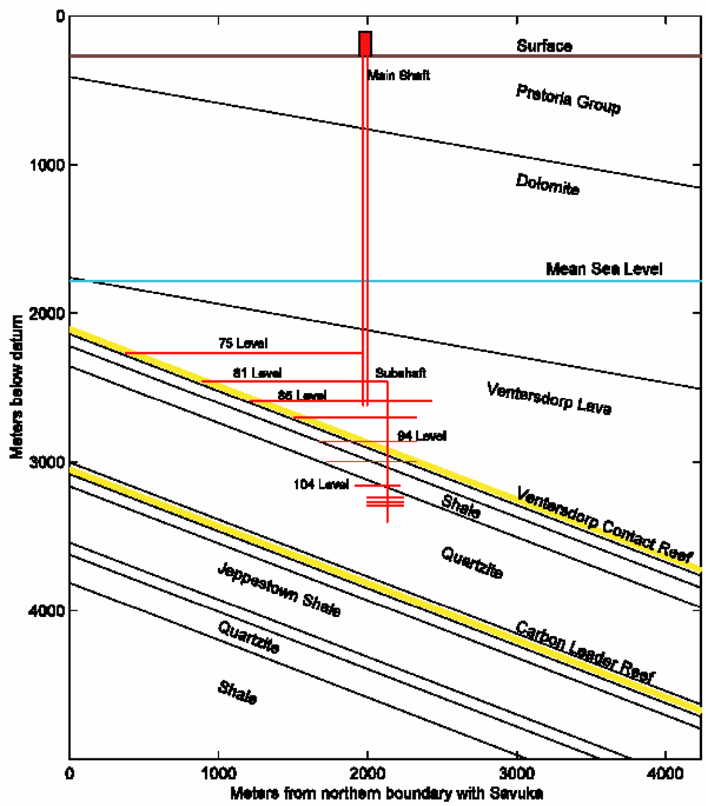

Figure 2. Cross-section through main shaft of the Mponeng mine looking east. The two gold-bearing horizons are marked in yellow. The datum is measured from an elevation in Johannesburg, and so it is above the ground surface.

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.

3.0 Research Objectives and Methodology

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

3.1 Create an event catalogue with accurate times and locations. The in-mine network operators routinely locate and catalog events, and we are obtaining these catalogs and using 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 are transforming station and events locations into a universal coordinate system and using the 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 are not relocating any of the events.

3.2 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). We are using the in-mine data to determine seismic moment, radiated energy, corner frequency and stress drop using the same method.

3.3 Obtain focal mechanisms from moment tensor inversion. We are determining focal mechanisms for events with M>2.5 and a select number of smaller events using moment tensor inversion of the in-mine data. An example of a result for a magnitude 3.9 mine event is shown in Figure 3. 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 instance, 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).

We have started to 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).

3.4 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.

3.5 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 mb and Ms are limited mainly to events greater than magnitude 4. Local magnitudes scales such as ML 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.

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.

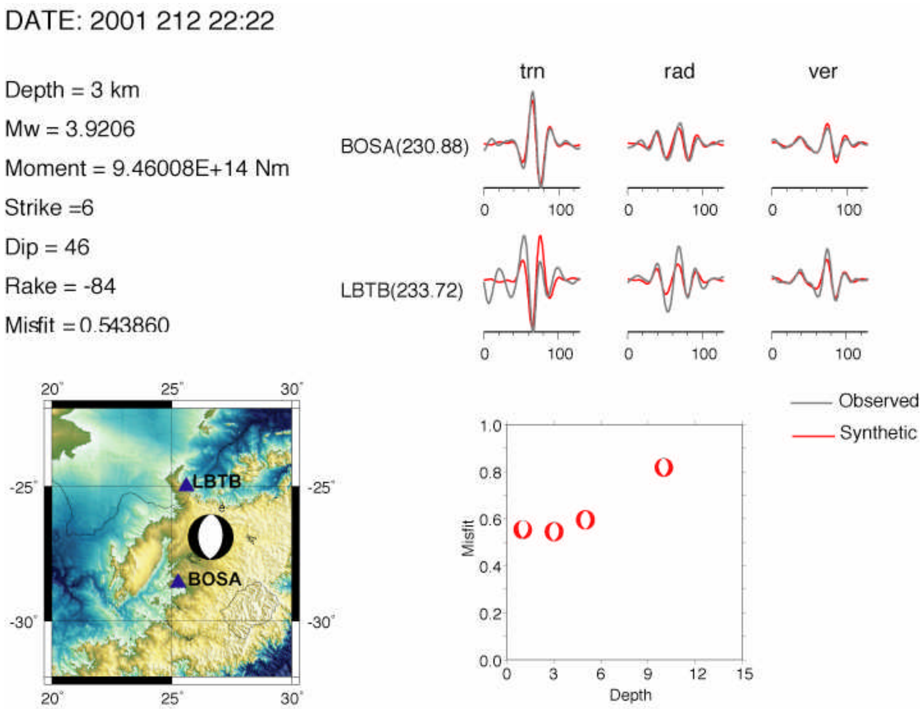

Figure 3. Body and surface waves from regional or near regional events were used to estimate the best fitting double-couple moment tensor. The technique minimizes the misfit between reflectivity generated complete synthetic seismograms and the three-component displacement data via a search over the strike, dip and rake of the source. An initial coarse grid-search to find the approximate minima is followed by a finer grid-search. For this event, we fitted the data over the period range of 20-50 sec. The displacements due to the six fundamental couples were calculated using Bowers (1997) velocity model. The best fit is obtained at 3km depth.

3.6 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.

3.7 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 Rg 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 provides very good control on the source depth so this effect can be investigated. In addition we will use the 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.

3.8 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 MDAC (Magnitude Distance Amplitude Correction). 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 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 data set 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.

3.9 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.

3.10 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, Taylor et al., 2002 and many others). 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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