SEISMIC SOURCE CHARACTERIZATION AND ENERGY PARTITIONING FROM IN-MINE AND REGIONAL BROADBAND DATA IN SOUTH AFRICA

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ABSTRACT

Mining-induced seismicity provides an important link between man-made and natural tectonic processes because it includes both fresh-fracturing events that are directly triggered by excavation and blasting, as well as events dominated by frictional slip which are analogous to tectonic earthquakes. These two types of events have distinguishable characteristics, such as different spatio-temporal clustering patterns, as well as different spectral signatures. Some previous studies using local in-mine data indicated that the fresh-fracturing events often have isotropic (explosional) moment tensors. Being able to differentiate the two types of events at regional and teleseismic distances is important for seismic verification studies.

We are studying a dataset of M > 2.5 mining-induced events that occurred between 1997 and 1999 in the Far West Rand gold-mining region of South Africa, approximately 80 km southwest of Johannesburg. The depth range of these events is 1.5 - 4 km, and they were recorded locally by four networks of 102 three-component geophones installed at depth throughout the active mining environment. These events were also recorded at regional distances by a two-year Passcal deployment of 80 broadband stations.

Using a spectral method, we have calculated source parameters for these events from the in-mine recordings, including seismic moment, stress drop, corner frequency, radiated energy, and apparent stress. Fresh-fracturing events have higher energy and larger stress drops than frictional events, although the latter generally have larger seismic moments. S/P wave amplitude ratios are lower for fracturing events as well, which can be an indication of isotropic components of the source.

INTRODUCTION

Mining-induced seismicity not only occurs at scales between those in the laboratory and those on tectonic faults but also can be recorded at the depth of seismic nucleation using in-mine seismometers, thus creating an excellent "natural laboratory" in which to study the physics of earthquake rupture. At present most gold mines in the Witwatersrand basin of South Africa use sophisticated underground arrays of geophones and accelerometers to record over 1,000 events per day. The extensive seismicity recorded at moment magnitude $M_w > 2$ provides a unique dataset to develop and test methods of discrimination between natural seismicity, mining tremors, and other industrially-related events such as chemical explosions. These $M_w > 2$ mining-induced events are large enough to be recorded on the in-mine arrays, as well as regionally by broadband seismometers. Therefore, locations, magnitudes, and focal mechanisms may be accurately determined from the high-frequency local data while regional phase propagation and energy partitioning may be studied via regional recordings. Another feature of this dataset is the variety of focal mechanisms as some mine events are purely double-couple shearing events whereas others have significant isotropic components (McGarr, 1992).

Background Information

The four adjacent mines of the Carletonville mining district in the Witwatersrand basin of South Africa, in which the events in this study were recorded, are the deepest in the world. They extract ore from two gold-bearing quartzite's, the Ventersdorp Contact Reef and the Carbon Leader Reef. These two units are separated by 900 m vertically, extend 2-4 km below the surface, and dip to the south at 21°. The mines contain old faults and dykes with two major trends: N 5° E and N 95° E. The interfaces between the faults, dykes, and host rock are planar discontinuities, many of which have been reactivated by the mining activities. It is these surfaces that provide the source region for the larger seismic events. The Witwatersrand basin itself is located in the Archean Kaapvaal cratonic province. This is not a tectonically active area. The seismicity recorded in this region is virtually all due to the strain energy accumulated over time by the mining processes of blasting and ore removal.

Figure 1 shows, in map view, the locations of the more than 100 3-component geophones installed at depth in the mines, together with epicenters of events for which we have determined source parameters (shown in Table 1). The geophones can sample at frequencies of 400-10,000 Hz. The station spacing underground is on the order of 100m 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 or borehole datasets in which the seismometers are usually situated on a single plane or in one line.

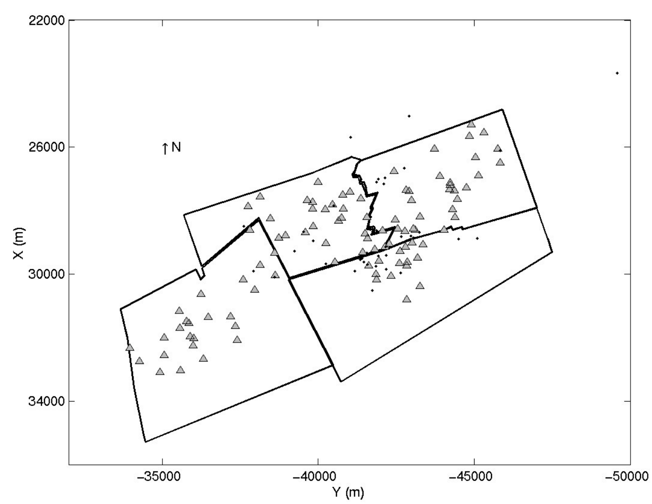

Figure 1. Map view of the lease areas of four mines in the Carletonville district (in mine coordinates). There are 102 three-component stations installed at depth (triangles). Dots represent the epicenters of large mining-induced events in this study.

Table 1. Preliminary Source Parameters of mining-induced events determined by in-mine array data*

Event	Lat	Lon	Depth	M_0	M_w	E	f_0	$\Delta\sigma$
19980111144841	-26.401	27.411	2338	1.4e13	2.7	5.5e8	15.8	5.87
19980220050356	-26.429	27.430	3694	7.8e13	3.2	1.0e10	12.9	20.00
19980328134551	-26.437	27.417	2729	1.2e13	2.7	2.8e8	16.6	3.65
19980329051801	-26.435	27.422	2587	2.2e13	2.8	4.9e8	16.3	3.46
19980331135629	-26.439	27.380	2053	2.2e13	2.8	2.1e8	9.3	1.47
19980404190603	-26.430	27.399	2047	1.1e13	2.7	1.8e8	14.6	2.51
19980420170707	-26.395	27.430	2273	2.8e13	2.9	1.6e9	13.8	8.76
19980420194749	-26.412	27.422	1925	2.5e13	2.9	9.1e8	14.8	5.72
19980502123739	-26.414	27.419	1955	2.2e13	2.8	4.9e8	11.9	3.43
19980508103233	-26.440	27.427	2661	1.1e13	2.6	1.8e8	12.1	2.46
19980622162025	-26.439	27.423	2588	1.3e13	2.7	3.4e8	15.2	4.01
19980708212049	-26.434	27.416	2553	1.2e13	2.7	3.9e8	14.8	4.83
19980727135740	-26.427	27.419	2409	2.5e13	2.9	4.3e8	9.5	2.73
19981002194336	-26.432	27.423	2569	1.0e13	2.6	1.3e8	10.2	1.90
19981007192539	-26.420	27.406	3123	2.0e13	2.8	1.3e9	16.9	10.30
19981019200410	-26.436	27.416	2505	1.3e13	2.7	2.0e8	10.5	2.40
19981021044841	-26.434	27.420	2613	1.0e13	2.6	1.3e8	11.5	2.00
19981023160058	-26.437	27.420	2745	3.1e13	2.9	7.1e8	8.7	3.50
19981027090946	-26.426	27.377	2989	1.2e13	2.7	3.6e8	15.2	4.72
19981102163835	-26.427	27.434	2552	2.5e13	2.9	6.2e8	10.4	3.90
19981110172424	-26.404	27.459	2770	1.2e13	2.7	3.1e8	15.0	4.10
19981119170822	-26.414	27.422	2268	1.1e13	2.6	3.0e8	13.3	4.20
19981223093859	-26.433	27.393	3375	2.8e13	2.9	1.1e9	12.8	5.94
19990103155836	-26.412	27.420	1748	1.1e13	2.6	1.2e7	12.1	0.87
19990118213352	-26.409	27.429	2879	9.1e12	2.6	1.6e7	15.0	1.00
19990202123021	-26.435	27.415	2582	1.2e13	2.7	3.2e7	13.6	3.00
19990209195821	-26.401	27.418	1618	4.2e13	3.0	9.2e8	9.3	3.20
19990216053511	-26.429	27.432	3761	1.2e13	2.7	9.2e6	10.4	0.56
19990226143150	-26.397	27.387	1981	4.5e12	2.4	2.2e6	12.3	0.53
19990309161938	-26.435	27.415	2464	1.1e13	2.6	6.8e7	8.1	0.99
19990310023001	-26.429	27.428	2651	1.0e13	2.6	1.7e8	14.9	2.50
19990318193538	-26.428	27.396	395	4.6e13	3.1	1.5e9	11.5	5.20
19990703111216	-26.169	27.497	3099	2.2e13	2.9	1.8e8	18.5	10.60
19990709200228	-26.395	27.413	7235	5.5e13	3.1	9.7e8	8.7	4.00
19990718173016	-26.393	27.403	3823	7.0e13	3.2	1.2e9	8.6	4.80
19990907150924	-26.386	27.446	3634	4.0e13	3.0	2.7e9	13.0	10.90
19990923132820	-26.386	27.452	4028	4.1e13	3.0	1.5e9	13.3	10.30

*Event dates and times are listed as yyyymmddhhmmss, event locations are given by their latitude (°N), longitude (°E), and depth (meters below datum). It should be noted that event depths are referenced to the origin or "datum" of the Z-axis of the local mine coordinates. This datum is a reference point in Johannesburg, and is 250 m above ground level and about 1800 m above sea level in the Carletonville Mining District where these events occurred. Seismic moment M_0 is in Nm, magnitude M_w is moment magnitude (Hanks & Kanamori, 1979), energy E is given in Joules, corner frequency f_0 is in Hz, and static stress drop $\Delta\sigma$ is in MPa.

Preliminary Source Parameters

We have assembled a dataset of large ($M_w > 2.5$) mining-induced events from 4 gold mines in the Far West Rand region. The locations of these events were determined by operators at the mines via a ray-tracing algorithm based on body wave arrival times (Mendecki, 1993, 1997). This method incorporates a layered velocity model based on geologic units that have been determined by underground surveying and mapping as well as surface-based refraction profiles and borehole log data. Since the wavespeeds and location procedures have been verified by test blasting, the location uncertainties are typically on the order of 10-20 m for events of $M_w > 2$.

Using the spectral method developed by Andrews (1986) and adapted by Richardson & Jordan (2002) for use with in-mine seismic recordings, we have calculated source parameters for 14 events that occurred in 1999 and 23 events from 1998 (see Table 1). Each of the events in this study was recorded by at least ten stations. In order to determine source parameters, we median-stacked each event's spectra and integrated the results up to the Nyquist frequency to determine S_D, the integral of the displacement power spectra (see Equation 6 of Andrews, 1986), S_V, the integral of the velocity power spectra (see Equation 7 of Andrews, 1986), and A^2, the acceleration power spectral level (see Equation 19 of Andrews, 1986). These are used to determine the source parameters radiated energy (E), seismic moment (M_0) , and static stress drop (□□) as follows:

$$E = 4\square\square v S_V$$

$$M_0 = \frac{8\square\square v^3 S_D^{(3/4)}}{S_V^{(1/4)}}$$

$$\square\square = \frac{2\square f_0 \square A^2}{C}$$

in which the corner frequency is found by

$$f_0 = \left(\sqrt{S_V / S_D}\right) / 2\square.$$

In the previous equations, □ is the rock density, which has been determined experimentally at the mines, v is wavespeed, is a constant based radiation pattern, and C is also a small constant. An advantage of this method is that the exponent of the spectral rolloff is not a fixed parameter as in the case of fitting spectra with a Brune-type curve. Because our data is band-limited, there is an upper limit to the radiated energy we can determine (Ide & Beroza, 2001). However, in practice the underestimation of energy for this dataset is very small (approximately 5%) since typical corner frequencies for the events in this study are generally 1/5 to 1/10 of the Nyquist frequency (Richardson & Jordan, 2002).

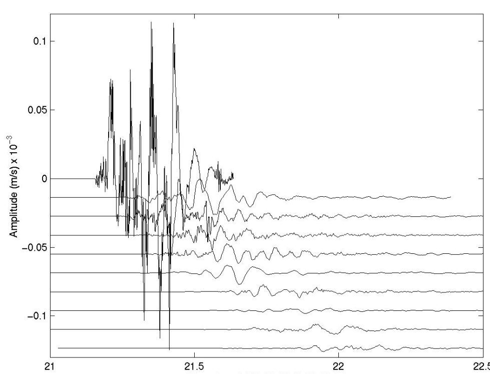

Figure 2. Vertical component velocity seismograms from nine stations of event 19990202123021 (see Table 1 for source parameters). The waveforms shown here were recorded at a range of 200 – 2500 m from the source.

CONCLUSIONS AND FUTURE WORK

To date, we have focused on producing a catalog of source parameters for several large mining-induced events. The next step is to determine focal mechanisms from waveform inversions of the near field in-mine data (see Figure 2) and then investigate the effect of energy partitioning on regional discriminants using regional broadband data.

Recent studies of mining-induced seismicity have suggested that radiated energy is a function of event size (Richardson & Jordan, 2002). However, it is not yet clear whether this property applies to natural as well as induced seismicity, nor has an adequate physical model been set forth that can account for all observations of source scaling parameters. Therefore, we intend to use this dataset to produce a catalog of regional discriminants specific to this mining region. Understanding how energy is partitioned in these events is important for basic research of the nucleation and rupture of small events as well as for increasing explosion monitoring effectiveness.

REFERENCES

Andrews, D. J., Objective determination of seismic source parameters and similarity of earthquakes of different size, in *Earthquake Source Mechanics*, S. Das, J. Boatwright, C.H. Scholz, eds, vol. 6 of Geophysical Monograph 37, pp. 259-267, Am. Geophys. Union, 1986.

Hanks, T.C. and H. Kanamori, A moment magnitude scale, *J. Geophys. Res*., **84**, pp. 2348-2350, 1979.

Ide, S. and G. C. Beroza, Does apparent stress vary with earthquake size?, *Geophys. Res. Lett.,* **28,** pp. 3349-3352, 2001.

Mendecki, A. J., ed., *Seismic Monitoring in Mines*, Chapman and Hall, 1997.

Mendecki, A. J., Real time quantitative seismology in mines, Keynote lecture in *Proc. 3rd Intl. Symp. on Rockbursts and Seismicity in Mines*, ed. By R. P. Young, Balkema, Rotterdam, pp. 1141-1144, 1993.

McGarr, A., Moment tensors of ten Witwatersrand mine tremors, *Pure Appl. Geophys.,* **139,** pp. 781-800, 1992.

Richardson, E. and T.H. Jordan, Seismicity in deep gold mines of South Africa: Implications for tectonic earthquakes, *Bull. Seism. Soc. Am*., **92**, pp. 1766-1782, 2002.