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Source mechanisms of mining-related seismic events in the Far West Rand, South Africa

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ABSTRACT

The Far West Rand mining district is known for its deep gold mines and the associated high levels of seismic activity. Thousands of tremors are recorded every day by geophones installed in the mine workings. These events range in local magnitude M_L from -1 to 4. Some of the biggest events (M_L>3) are external to the network deployed on a single mine. We combined data from three mines (Savuka, Tautona and Mponeng) to improve the location of these events. Source mechanisms were calculated by minimizing the L2 norm of the difference between the observed and predicted P, SV and SH spectral amplitudes, with visually assigned polarities. The preliminary results from the Savuka mine show that the major principal stress is compressional, oriented near to the vertical, and with a significant isotropic component in the moment tensor solution.

Key words: Witwatersrand basin, Far West Rand, seismicity, source mechanisms.

INTRODUCTION

Most of the seismic activity in South Africa is related to deep-level mining activities. One of the most active regions is the Far West Rand mining district, about 80 km west of Johannesburg near the town of Carletonville, where many of the mines are more than three kilometres deep. Thousands of tremors are recorded every day by geophones installed in the mine workings. These events range in local magnitude M_L from -1 to 4. Some of the tremors (say with M_L>3) are large enough to be recorded by broadband seismic stations located throughout southern Africa operated by the Council for Geosciences (CGS) and AfricaArray (Figure 1). However, we find that there are often significant differences in the source parameters (location, magnitude, etc) reported by adjacent mine networks and the regional networks. We seek to understand the reason for these differences and improve the calculation of source parameters.

This project, funded by the US Department of Energy, has three main aims:

1. To improve the location and source parameters calculated independently by each mine network and the CGS Seismology Unit by combining in-mine and surface data. This will help us gain insights into the source mechanism of large magnitude tremors in the region.
2. Provide ground-truth focal mechanisms for large-magnitude mine tremors (M_L>3) and compare the focal mechanisms determined by conventional P-wave polarity inversion of regional data with spectral amplitude inversion of high frequency in-mine data.
3. To develop better methods to determine source parameters of earthquakes recorded at regional distances.

We will use the seismograms recorded by the in-mine networks and a local broadband surface array to provide "ground truth" hypocentral locations, and compare how well we can identify and locate events in the M_L 3–4 range.

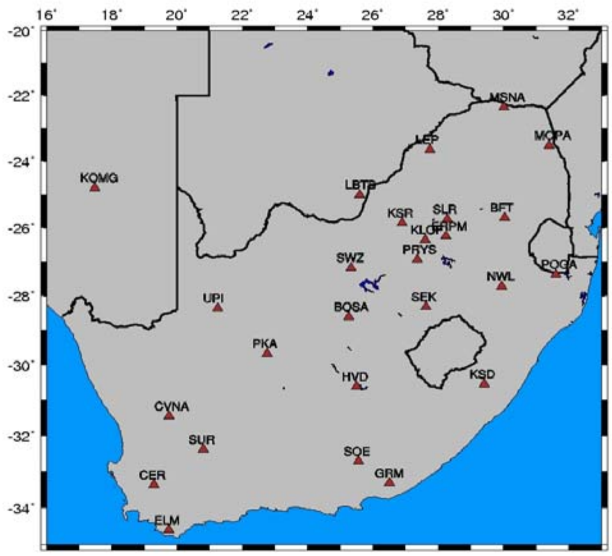

Figure 1. Regional stations operated by CGS and Africa Array used for relocation of the big events

RELOCATION OF SEISMIC EVENTS

The accurate location of seismic sources is critical in pin-pointing the source region and understanding the relation between the geological, the seismicity and the mining activity. One of the difficulties in determining accurate locations is that the hypocentres of many of the large events are external to the network of a single mine. This is because of the small volume covered by a single in-mine network. Most seismic events occur in areas subjected to high mining-induced stresses, which are mostly near the active mining faces on the perimeter of the mine and ahead of the geophone array. Consequently, locations calculated from a single mine network are sometimes poorly constrained.

We have compared the hypocentres of large events located independently by three adjacent mine networks (Savuka, Tautona and Mponeng) and found significant differences between them, as well as with the epicentre determined by the SANSN (Figure 2).

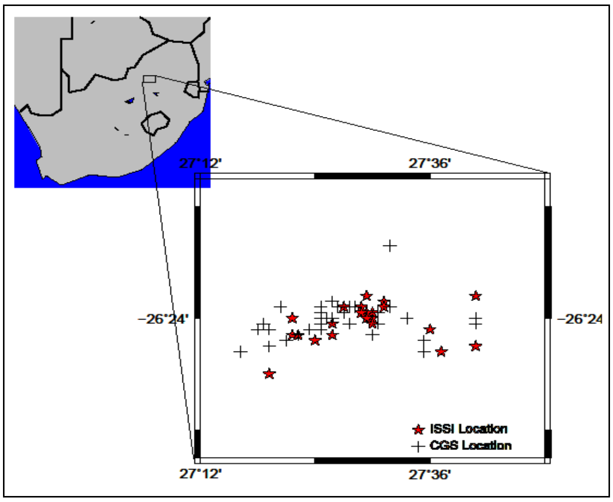

Figure 2. Comparison of locations of the same events by a single mine network (operated by Integrated Systems International, ISSI) and the regional network operated by the Council for Geoscience (CGS).

We attempted to combine the data from the three mine networks to improve the accuracy of the source location. We plotted the arrival times picked on seismograms from all the three mines on a Wadati diagram. This revealed that the arrival times picked some events in the Mponeng data base had time shifts that we could not account for. These arrivals were excluded from relocation calculation.

The final location determined by the combined networks generally deviated from any of the independent locations. This suggests that the locations can be improved for events outside the network by incorporating data from other mines.

FOCAL MECHANISMS

P-wave polarities were picked on seismograms recorded by SANSN and AfricaArray stations located 200-1000 km from the Far West Rand source zone. FOCMEC (Snoke, 2003) was used to calculate focal spheres. Out of the 34 events analysed, we were only able to assign P-wave polarities to 5 large earthquakes. Furthermore, the stations with clear polarities were all situated southwest of the source region, while a well-constrained focal mechanism ideally requires a data point in each quadrant. Figure 3 shows the results obtained using the available polarity readings.

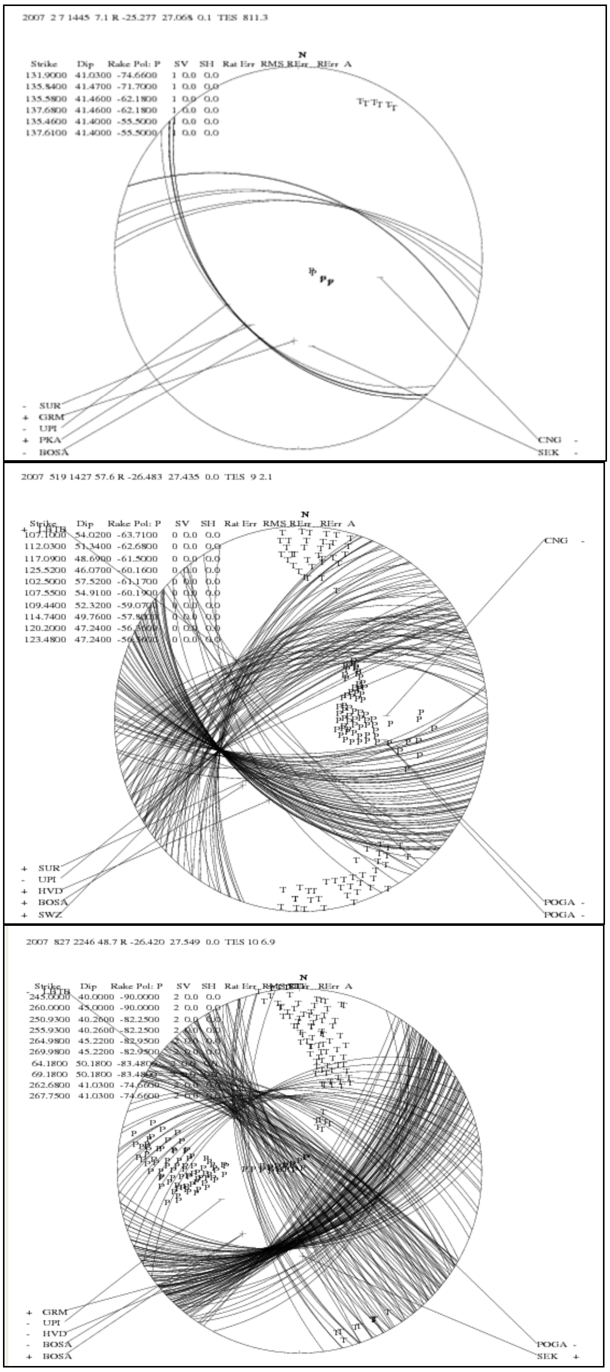

Figure 3: Focal spheres showing poorly constrained solutions owing to unfavourable station distribution

MOMENT TENSOR INVERSION

The three-component seismograms recorded by the in-mine seismic networks for the 34 big events were extracted from the database, and rotated into the P, SV and SH axis. Any seismograms that showed a high energy in the wrong component due to sensor misorientation were omitted from the analysis. Spectral amplitudes for P, SV and SH pulses were obtained in the time domain from the rotated waveforms through integrals of squared velocities and squared displacements [Trifu et al., 2000].

$$u = \frac{2S_{D2}^{3/4}}{S_{v2}^{1/4}}$$

where u is the spectral amplitude and

$$S_{D2} = \int D^2(t)dt \text{ and } S_{V2} = \int V^2(t)dt$$

with D = displacement and V = velocity.

Polarities were assigned visually by comparing low-pass filtered instrument response with low-pass filtered observed P and S wave pulse, where ~10 Hz was found to give a relatively clear reading (Figure 4).

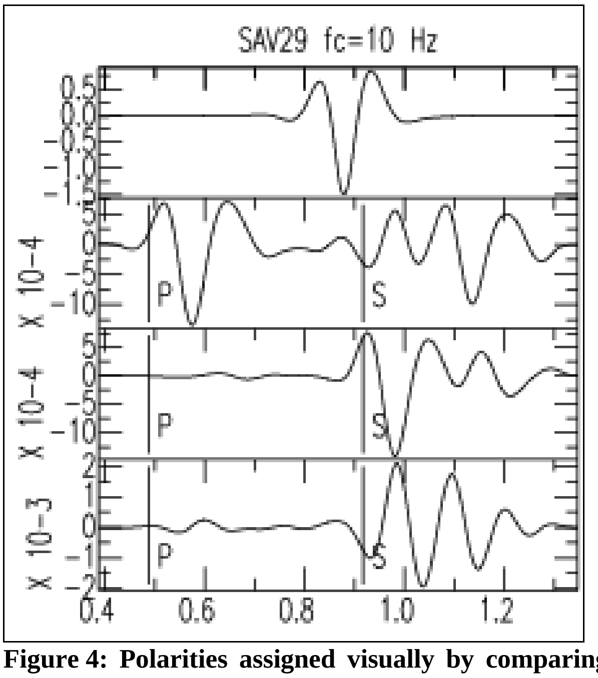

Figure 4: Polarities assigned visually by comparing lowpass filtered instrument response with lowpass filtered observed P and S wave pulse around 10 Hz

Six independent components of the moment tensor were obtained by inverting P, SV and SH spectral amplitudes with polarities attached. Assuming the ray paths traverse the ~500m thick quartzite layer between the gold-bearing reefs, the forward problem can be formulated as [Trifu et al., 2000; Julia et al., 2009]

$$u = c\mathbf{F}:\mathbf{M}$$

where u = vector of spectral displacements, $c = 1/(4\rho V^3 R)$, ρ = density, V = P- or S-wave velocity, R = hypocentral distance, **M** = the matrix defining the seismic moment tensor in a geographic coordinate system, and **F** the excitation matrix. Due to symmetry of the moment tensor, **M** can be written as

$$u_j = \sum c_j^i f_k^i m_k \quad j = 1 \ldots n$$

where n is the number of data points. This equation defines a linear problem which can be solved for the moment tensor elements M_k with no constraints [i.e. full moment tensor solutions] after the singular value decomposition of the matrix $c_j^i f_k^i$ [e.g. Menke, 1994].

A representative result from the Savuka mine is shown in Figure 5. The solutions show a significant isotropic moment, supporting the assertion by McGarr (1992) that many mining-related events are strongly coupled to the mining and involve shear failure plus a co-seismic volume reduction.

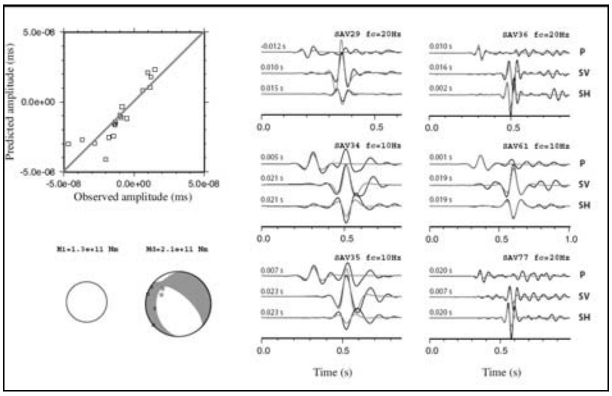

Figure 5: Moment tensor inversion results and coverage of the focal sphere for event 2007.02.21.18.21.56.591. The upper left diagram compares predicted and observed spectral amplitudes for P, SV, and SH components. The lower left diagram shows the P-wave radiation pattern for the isotropic and deviatoric moment tensors, along with the coverage of the focal sphere (overlying the deviatoric "beach-ball"). The waveforms on the right are shown to compare the corresponding observed (black) and predicted (grey) P, SV and SH amplitudes in the time domain. The event origin time is at t = 0 s and the synthetic waveforms have been shifted by the amount noted above each trace, to facilitate the comparison with the observations. The time shifts between observed and synthetic waveforms are due to inaccuracies in the event location, assumed wave-speed, and/or anisotropic effects. Note that only spectral amplitudes were inverted, so the observed time shifts did not influence our moment tensor solutions. The waveforms are shown in velocity.

CONCLUSIONS

The work reported here is part of a larger project intended to develop techniques that will assist in the verification of the nuclear test ban treaty.

In this first phase, we have determined the source parameters of a variety of mining-related events using seismograms recorded by the in-mine network. We will extend the work by attempting to determine the source parameters using seismograms recorded by surface broadband stations at local and regional distances, where seismograms are complicated by reverberations in the crustal layers.

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