

Detection of mining-induced fractures around a stope in Ezulwini gold mine, South Africa, by using AE events with similar waveforms

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INTRODUCTION

The ability to predict rock failure is desirable for the prevention of disasters in mines. The acoustic emission (AE) method is a well-known tool for monitoring fracture growth in rock masses that is used to help ensure safety during excavations. In mines, AE can indicate the location of fractures and damage zones. If AE could be used to detect the initiation and extension of fractures in rock masses and determine their precise source locations, that information would be helpful in forecasting the locations of rock failure. A study of AE in the Ezulwini gold mine in South Africa has been conducted under the Japan–South Africa collaborative project titled “Observational studies to mitigate seismic risks in mines” [1, 2], in which a large number of events have been detected around the mining front. In this paper, we report on the determination of the source location of AE by the joint hypocenter method and multiplet analysis, and we delineate structures in the AE cloud.

OBSERVATION OF AE EVENTS IN EZULWINI GOLD MINE

The Ezulwini gold mine is about 40 km southwest of Johannesburg, on the outskirts of the town of Westonaria in Gauteng province, South Africa. The mine was opened more than

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40 years ago. The mine is in an Archean sedimentary basin containing a stratigraphic sequence of several kilometers thickness, consisting mainly of quartzite and shale with minor scattered volcanic units. The gold is hosted in the upper Elsburg and middle Elsburg reefs underlying the mine. Mining is taking place at a shaft pillar from 400m to 500m across at depths about 1000m from surface where vertical stress is dominant and significantly enhanced. Panels (mining faces) are typically 30m across and 1-2m high. By daily blasting, the panels advance at a rate of about 10m per month typically, causing stress perturbation and generating cracks. AE monitoring was performed during mining operations, using 6 three-component accelerometers and 24 single-component AE sensors installed in a volume measuring 95 m N-S, 50 m E-W, and 30 m in depth. Three of the accelerometers had a flat frequency characteristic up to 25 kHz (Wilcoxson Model 736) and the other three had a flat frequency characteristic up to 10 kHz (Wilcoxson Model 728). The AE sensors, made by GMuG, were capable of detecting events with frequencies up to 50 kHz. These detectors were cemented to their borehole walls. Seismic signals were transmitted to the acquisition system through coaxial cables and stored in the hard disk. AE events were recorded on all 42 channels if the amplitude of an AE event exceeded a threshold at any one of the detectors. Events were acquired as digitized waveforms of 65.5 ms duration with a sampling frequency of 500 kHz (32 768 samples). High-pass filters with cutoff frequencies of 50 Hz and 1 kHz were applied to the signals from the accelerometers and AE sensors, respectively, before recording.

ESTIMATION OF SOURCE LOCATION BY JOINT HYPOCENTER DETERMINATION METHOD

We analyzed the AE events observed from 30 Sep. to 5 Oct. 2011. The source locations of 40555 events were automatically located [3], between the stope and the monitoring network in a volume with dimensions of 100 m N-S, 180 m E-W, and 50 m depth (Fig. 1). The joint hypocenter determination (JHD) method was used to re-estimate the source locations and analyze location error. JHD refines source locations by decreasing systematic errors, adjusting all the AE events jointly to iteratively compensate for the station correction in each channel [4]. The station correction values were ranging from -0.77 ms to 0.256 ms (P-wave) and from -0.223 ms to 0.284 ms (S-wave). The contours in Fig. 1 show the value of the condition number, an index indicating the extent to which the source locations are well determined and the location error is not prejudiced in space. The distribution of condition numbers is important information for delineating error trends before the evaluation of the source distribution, because artifactitious trends often appear in the AE cloud due to the geometrical relationship between the detector and source locations. The condition number was calculated by applying principal component analysis to the matrix consisting of the spatial derivatives of the travel times from the hypocenter to the stations [5, 6]. The condition number is the ratio of the largest and smallest singular values of the matrix, and it represents how well a source location is constrained [7]. In Fig. 1, the source location region is an area of low condition number (< 200), an indication that the source locations, especially near the detectors, were well constrained.

RELOCATION OF AE EVENTS WITH SIMILAR WAVEFORMS

Multipler analysis was applied to determine precise source locations of the AE events [8]. Similar AE events were searched by calculating the coherence between all combinations of waveforms. The coherence was calculated using a fast Fourier transform algorithm, and the data length for spectral estimation was 32.768 ms from the P-wave and S-wave portions of

the waveform. The mean value of coherence was calculated within the frequency range 1–5 kHz, and values were given as the similarity of two waveforms.

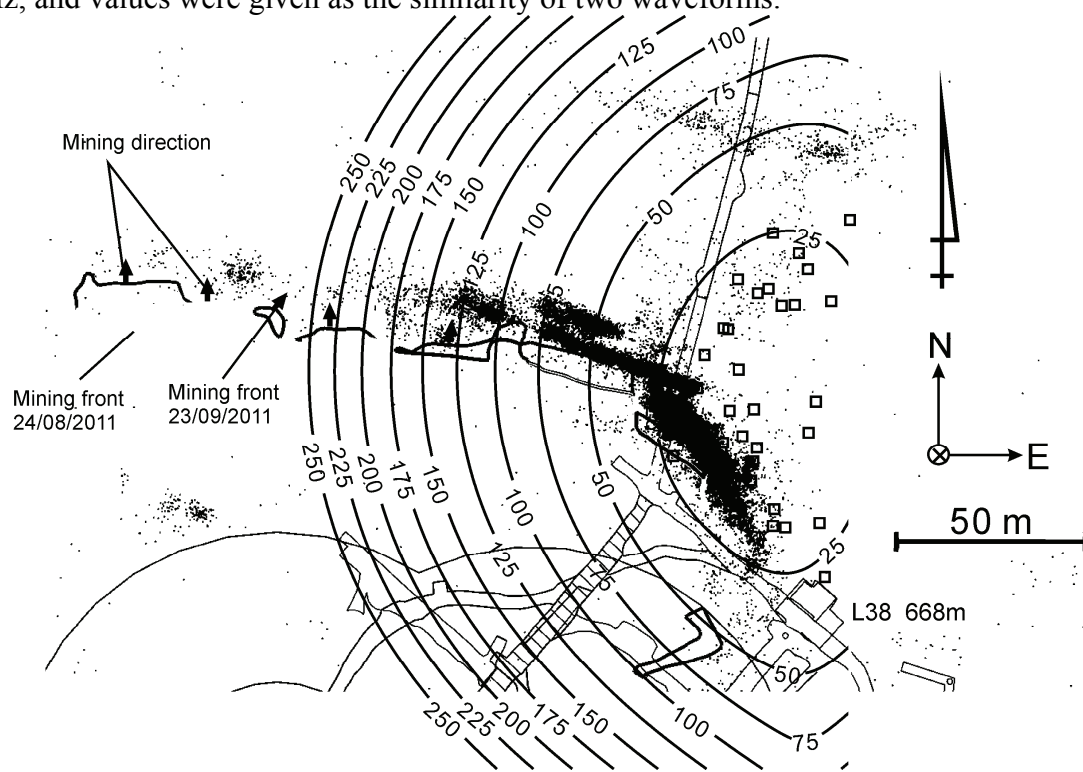


FIG. 1—Source locations determined by JHD with contours of the condition number. The open boxes denote the position of the sensors.

If the coherences between two AE events exceeded 0.95, the events were regarded as a pair of similar AE events. Pairs of similar AE events were automatically detected using the coherence function, and multiple pairs of similar events were combined as one group (a multiplet) if the coherence among all the pairs of AE events exceeded 0.95. The relative delay of the P-wave arrival time was detected among all AE events in each group from the cross-correlation function using the waveform from all the channels. Fig. 2 shows waveforms of a multiplet. Fig. 3 shows an example of two similar waveforms and their normalized cross-correlation functions. A time window of 4 ms was used and the cross-correlation function with a time lag of 0.6 ms was calculated. It was easy to identify the peak value in the cross-correlation function. The detected P-wave arrival time delays at all the channels were used as input to the double-differential equation [8–11] and the source locations of AE events were determined, using the initial source locations given by JHD. The equations for 2245 different groups were combined and the source locations were estimated. Fig. 4 shows the relocated source locations for 8273 events. The mean value of RMS

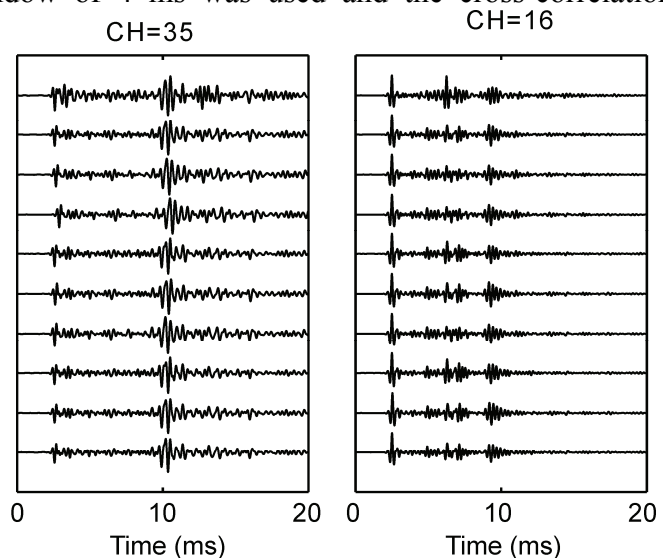


FIG. 2— Waveforms of a multiplet group.

decreased from 0.1 to 0.04 ms.

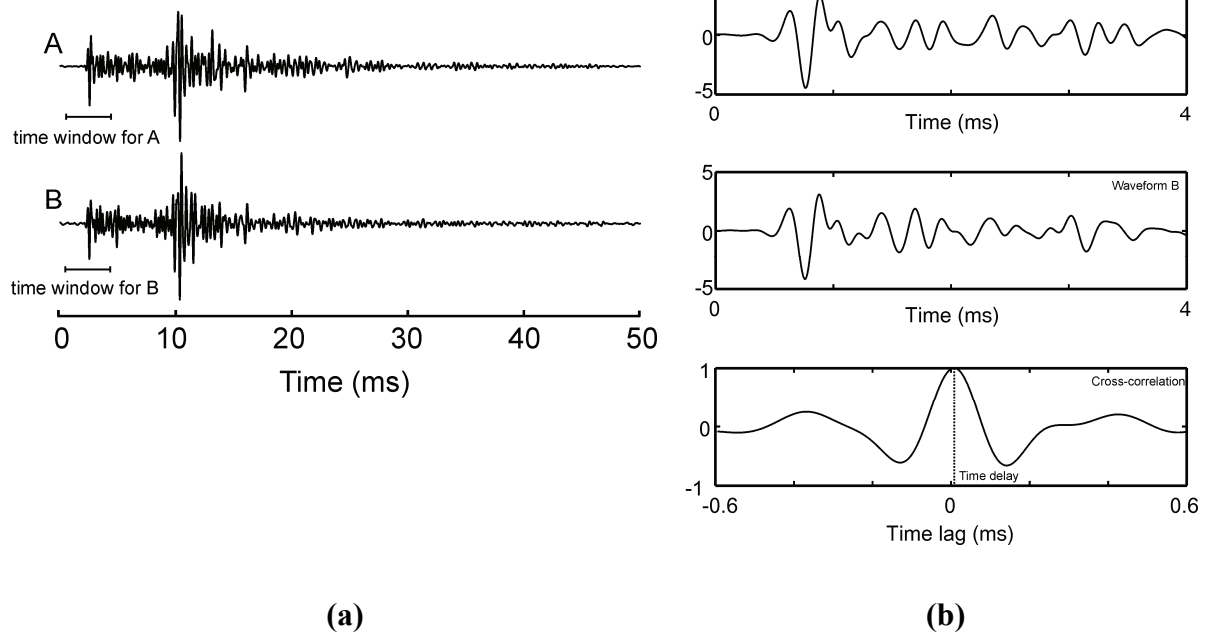


FIG. 3—(a) Two similar waveforms and (b) their cross-correlation functions from the P-wave portion, where the bars show the time window for the calculation of the cross-correlation function.

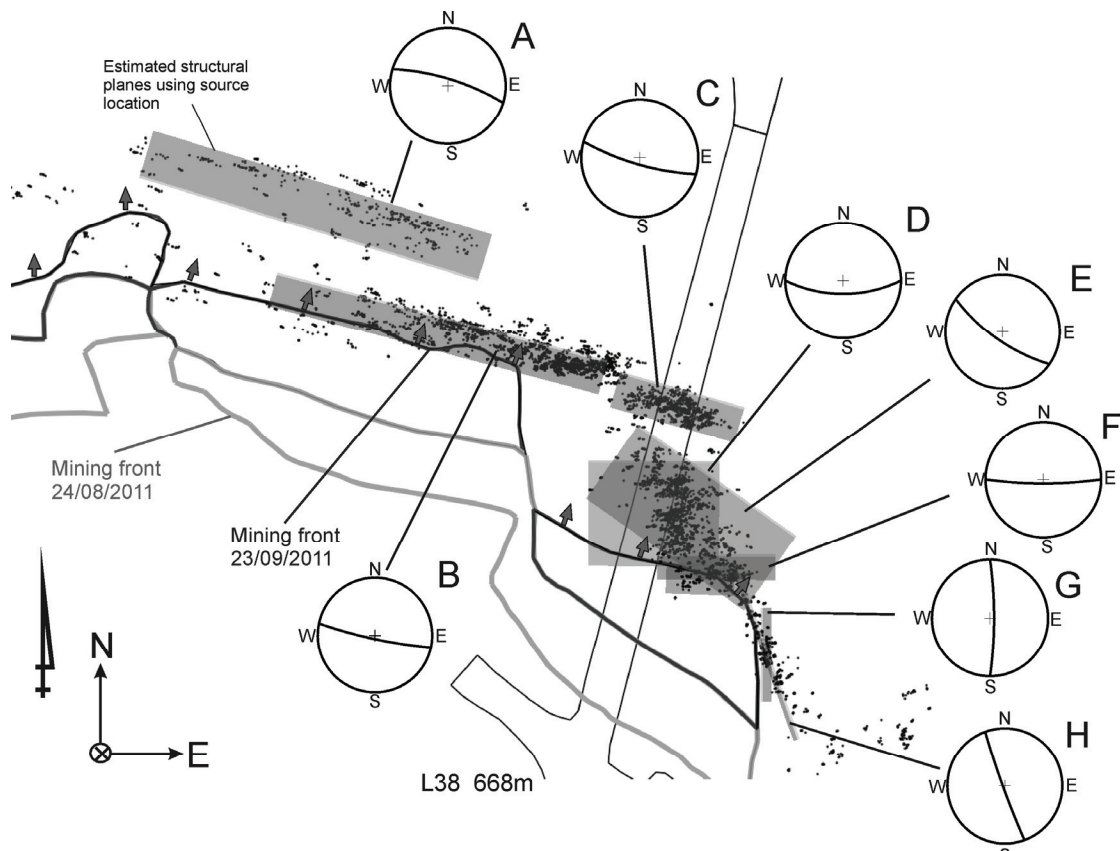


FIG. 4—Source locations of similar AE events estimated by using P-wave arrival time delays. Planes estimated from the source distribution are shown as gray rectangles with accompanying lower-hemisphere stereographic projections.

TABLE 1—Strike, dip, and dimensions of estimated planar AE source structures.

Structure	Strike (degree)	Dip (degree)	Length along strike (m)	Length along dip (m)
A	287.0	76.0	28.3	15.3
B	105.0	83.0	27.3	21.3
C	106.0	77.0	10.3	12.3
D	90.3	63.0	6.5	15.5
E	125.3	71.0	15.4	22.5
F	90.3	82.0	9.5	14.8
G	360.0	82.6	7.5	5.5
H	160.3	86.6	14.5	5.5

DISCUSSION

AE events occur near the mining front because the formation of the cavity decreases the horizontal stress and increases the differential stress in the rock mass. A large number of AE events were observed during mining, and our results imply that a well designed AE monitoring system can detect small rock failures and estimate their locations. The AE monitoring system in this study can detect AE events with M_w less than -5 , and the condition numbers show that source locations can be well constrained with this observation system. The condition numbers also showed that the AE sensor geometry was well organized and that AE source locations were well constrained. The multiplet analysis yielded RMS accuracies in source location of 0.04 ms, corresponding to around 0.2 m in position.

The AE source distribution outlined eight steeply dipping planes between the sensors and the mining face (Table 1), and the strikes of the planes well agreed with the orientation of mining front. Source locations did not migrate on the planes, thus we were unable to detect fracture growth. The planes in Fig. 4 were approximated by rectangles ranging in length from 6.5 m to 28.3 m along strike and 5.5 m to 22.5 m in the dip direction. This result implies that shear failure occurred in the study area to release the shear strain, over several tens of meters within 6 days, consistent with the typical fracture patterns observed at mining front[13].

SUMMARY

Thousands of AE events induced during mining were recorded, and their source locations were estimated using the JHD method and multiplet analysis. Source locations determined by multiplet analysis using similar waveforms delineated planes with a scale of up to 30 m. The best location accuracy was about 0.2m. We think the planes are manifestations of relieving shear strain in the area critically stressed associated with mining.

This study shows that AE events associated with small failures can be detected by a well designed AE monitoring network, and locating AE sources by multiplet analysis provides accurate indications of rock failures near the mining front.

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REFERENCES

- [1] Ogasawara, H., Durrheim, R.J., Nakatani, M., Yabe, Y., Milev, A., Cichowicz, A., Kawakata, H. and Moriya, H., “JST-JICA SA research group, a Japanese–South African collaboration to mitigate seismic risks in deep gold mines,” Proc. First Hard Rock Safe Safety Conference, J. Van der Westhuizen (ed), 28–30 September 2009, Sun City, South Africa, South African Institute of Mining and Metallurgy, pp. 115–134.
- [2] Durrheim, R.J., Ogasawara, H., Nakatani, M., Yabe, Y., Milev, A., Cichowicz, A., Kawakata, H., Moriya, H. and the JST-JICA SA research group (2010) “Observational Study to Mitigate Seismic Risks in Mines: a new Japanese–South African collaborative project,” Proc. Fifth International Seminar on Deep and High Stress Mining, M. Van Sint Jan and Y. Potvin (eds), 6–8 October 2010, Santiago, Chile, Australian Centre for Geomechanics, pp. 215–225.
- [3] Horiuchi, S., Y. Horiuchi, Y. Iio, Y. Sawada, S. Sekine, H. Nakamura, T. Okada, M. Nakatani, M. Naoi, Automatic P and S Wave Arrival Time Picking Compared to Manually Picking, IUGG, 3430, Melbourne, Australia, 2011.
- [4] Nakatani, M., Yabe, M., Philipp, J., Morema, G., Stanchits, S., Dresen, G., and JAGUARS-group, “Acoustic emission measurements in a deep goldmine in South Africa—Project overview and some typical waveforms,” *Seismol. Res. Lett.*, 79(2), 311, 2008.
- [5] Douglas, A. “Joint Epicentre Determination,” *Nature*, 215, pp. 47–48, July 1967.
- [6] Lay, T. and Wallace, T.C., “Modern global seismology,” Chapter 6.4, pp. 223–236, Academic Press Inc., 1995.
- [7] Lee, W. H. and Stewart, S. W., “Principles and applications of microearthquake networks,” Academic Press, p. 121, B. Saltzman (ed).
- [8] Moriya, H., Niitsuma, H., Baria, R., “Multiplet-clustering analyses reveals structural details within the seismic cloud at the Soultz geothermal field, France,” *Bulletin of the Seismological Society of America* 93, pp. 1606–1620, April 2003.
- [9] Waldhauser, F., and Ellsworth, W. L., “A double-difference earthquake location algorithm: Method and application to the Northern Hayward Fault, California,” *Bulletin of the Seismological Society of America*, 90, pp. 1353–1368, June 2000.
- [10] Moriya, H., Nakazato, K., Niitsuma, H., Baria, R. “Detailed fracture system of the Soultz-sous-Forets HDR field evaluated using microseismic multiplet analysis,” *Pure Applied Geophysics*, 159, pp. 517–541, April 2002.
- [11] Spottiswoode, S.M, Milev, A/M, “The use of waveform similarity to define planes of mining-induced seismic events,” *Tectonophysics* 289, pp. 51–60, April 1998.
- [12] Jones, R. H., and Stewart, R. C., “A method for determining significant structures in a cloud of earthquakes,” *J. Geophys. Res.*, 102(4), pp. 8245–8254, April 1997.
- [13] Chamber of Mines of South Africa, *An Industry Guide to Methods of Ameliorating the Hazards of Rockfalls and Rockbursts - 1988 Edition*, Chamber of Mines of South Africa, 1-114, 1988.