Observation of numerous aftershocks of an M_w 1.9 earthquake with an AE network installed in a deep gold mine in South Africa

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This is the first report from the JAGUARS (JApanese-German Underground Acoustic Emission Research in South Africa) project, the overall aim of which is to observe ultra-small fracturing in a more or less natural environment. We installed a local (∼40-m span) network of eight acoustic emission (AE) sensors, which have the capability to observe up to 200 kHz at a depth of 3.3 km in a South African gold mine. Our specific objective was to monitor a 30-m thick dyke that remains as a dip pillar against active mining ∼90 m above our network. An M_w 1.9 earthquake whose hypocenter was ∼30 m above the network occurred in the dyke. Although the mine-owned geophone (4.5 Hz) network detected only five earthquakes in the surrounding $200\times200\times150\text{-m}^3$ volume within the first 150 h following the main shock, our AE network detected more than 20,000 earthquakes in the same period. More than 13,000 of these formed a distinct planar cluster ($\sim100\times80$ m^2) on which the main shock hypocenter lay, suggesting that this cluster delineates the main shock rupture plane. Most of the aftershocks were presumably very small, probably as low as $M \sim -4$. The aftershock cluster dipped ∼60°. This is consistent with normal faulting under a nearly vertical compression field, as indicated by nearly horizontal breakouts found in a borehole crossing the rupture plane.
Key words: Semi-controlled earthquake generation experiment, acoustic emission, mining-induced earthquake, deep South African gold mines, aftershocks, main shock rupture plane.

1. Introduction

Deep mining facilities provide an excellent opportunity to observe earthquakes at the closest proximity possible (e.g., Nicolaysen, 1992). Deep mining in South African gold mines can occur down to depths of 4 km. Stress changes near the mining face that has been advancing for a couple of years may exceed tens of megapascals (MPa) (COMRO, 1988). Non-local stress redistribution induced by relatively large-scale mining causes relatively large earthquakes of up to $M \sim 3$ on preexisting weak planes or discontinuities, such as faults or dyke contacts (Gay *et al.*, 1984; Gibowicz and Kijko, 1994). Since 1994, Japanese and South African researchers have carried out a series of experiments within the framework of the SeeSA project (Semi-controlled Earthquake generation Experiments in South African mines) (Iio and Fukao, 1992; Ogasawara *et al.*, 2002a) in which various kinds of sensors have been installed in the close proximity of the source region of forthcoming earthquakes. A number of notable results have been obtained using sensitive Ishii strainmeters (Takeuchi, 2005; Naoi *et al.*, 2006) and several-kHz frequency-band seismometers (Yamada *et al.*, 2005, 2007).

Another dimension has been added to the SeeSA experiments with the recent collaboration of German researchers on a new project called JAGUARS (Japanese-German Underground Acoustic Emission Research in South Africa) (Nakatani *et al.*, 2008). The main objective of JAGUARS is to capture ultra-small brittle failure events in geological settings where a relatively large earthquake is anticipated. An obvious motivation for such research is that many laboratory results indicate intriguing relations between very small events (acoustic emission, AE) and macroscopic failure (Reches and Lockner, 1994) or frictional sliding (Yabe *et al.*, 2003). As described below, by deploying sensitive high-frequency (up to 200 kHz) AE sensors, we were able to observe a large number of aftershocks, most of which are presumably very small, following an M_w 1.9 earthquake that occurred in our AE network.

2. Observations

A 30-m thick gabbroic dyke (called the Pink and Green (PG) dyke) within quartzite host rock was identified at a depth of ∼3.3 km in the Mponeng gold mine (owned by AngloGold Ashanti Ltd.) (Fig. 1). The attitude of the dyke

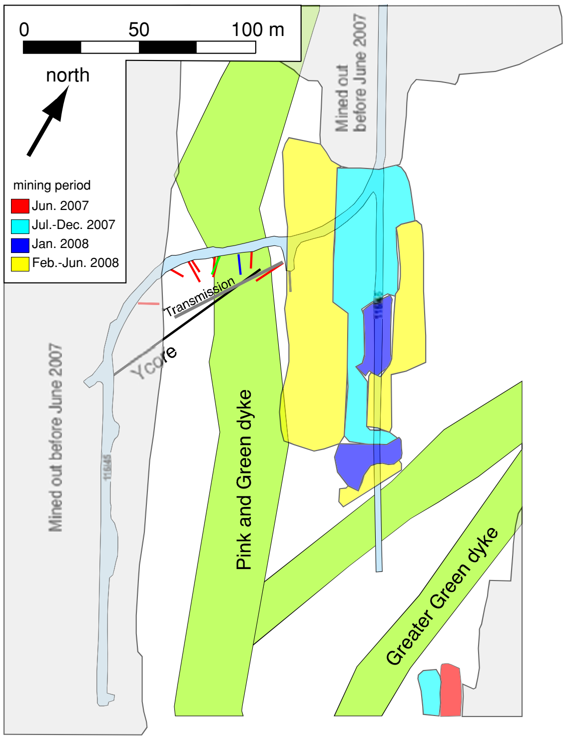

Fig. 1. Map of observation area. Narrow light-blue zones and wide green zones represent horizontal access-tunnel and dykes at a depth of 3268 m, respectively. Red and green lines show boreholes in which the AE sensor and triaxial accelerometer, respectively, were installed. Thick gray line labeled 'Transmission' represents a borehole along which the transmitter was used. Black line labeled 'Ycore' indicates a 20°-inclined borehole drilled after the M_w 1.9 earthquake to go through the main shock rupture. Grey: Mined out by the end of May, 2007. Red: Active panels of June, 2007. Light-blue: Mined out in an interval of July–December, 2007. Blue: Active mining panels of January, 2008. Yellow: Mined out in an interval of February–June, 2008. The reef, which is several tens of centimeters thick, is 90 m above our network and dips shallowly to the SSE. It intersects with the western access-tunnel at the southern end of the tunnel.

(strike N30W, dip 70–85W) is known from numerous exploration drillings and extends at least 2 km along the strike and 1 km along the dip around our network.

A horizontal access-tunnel that crosses the dyke at a depth of 3268 m was chosen as the JAGUARS site. We installed various sensors in short boreholes (depth: 6–15 m) drilled from this tunnel to avoid the high attenuation zones near the tunnel wall. Eight AE sensors and one accelerometer were used to locate the events presented in this paper.

Tabular gold reef (several tens of centimeters in thickness) dipping 26.5SSE has been mined since early 2007 at and around this site, but the PG dyke is to remain unmined as a dip pillar. Our sensors were installed beneath the pillar. The reef is 90 m above the location of our sensors; as such, our network is situated in solid rock that has not been damaged by stoping, but it is still close enough to mining activities to expect the occurrence of relatively large earthquakes due to the non-local redistribution of mining-induced stress. Indeed, several events with a local magnitude >2 occurred along the PG dyke prior to our commencing with observations in June 2007. These events were presumably affected by earlier mining activity at shallower levels to the NNW of our site. This experimental setup and location are ideal for observing the behavior of more or less "natural" geologic structures, even if stressing is artificial. That the rock in the area is of good quality is also evidenced by prior observations of local attenuation properties based on the results of transmission tests within the network (Naoi *et al.*, 2008) and on those from the spectral analysis of events at further distances (Kwiatek *et al.*, 2009). The AE sensors used in this project have a piezoelectric disc element enclosed in a waterproof brass sonde. They cover a frequency range from 1 to 200 kHz, with moderate resonances at about 70 and 130 kHz. Acoustic coupling to the rock was secured by pushing the sensor face against the flattened bottom (GMuG MA-Bl-70s) or smooth sidewall (GMuG MA-Bl-70w) of the boreholes. Vacuum grease was used as a coupling agent following a technique successfully applied for similar types of AE sensors installed in German salt mines (Spies and Eisenblaetter, 2001). In-hole preamplifiers of 30 dB were installed within 30 cm of each AE sensor.

The tri-axial accelerometer (ISS 3A25k) consists of three Wilcoxon-736T transducers packaged in a stainless steel sonde to be grouted in a borehole. The sensitivity of the 736T accelerometer is flat from 0.002 to 25 kHz. We used waveforms observed by the accelerometers to calibrate complicated characteristics of AE sensors due to the resonances, although amplitude information is not presented in this report.

Preamplified waveforms from the AE sensors and the accelerometer are fed to a 16-channel GMuG acoustic emission monitoring system. After band-pass filtering (1–180 kHz for the AE sensor and 0.05–25 kHz for accelerometer) and 20-dB amplification, the waveforms are digitized at a sampling frequency of 500 kHz with a resolution of 16 bits.

When waveform amplitude exceeds a threshold level specifically prescribed for each channel, P- and S-wave arrivals are automatically picked to perform in-situ hypocenter determination. All of the automatic pick results are stored in daily summary files. Waveform data of 65.536 ms (32,768 samples) are also stored on a local hard disk, although this is only for events satisfying prescribed conditions in order to avoid the disk being filled up quickly by too many working noises.

Since the in-situ location uses a simplified algorithm and poorly constrained seismic wave speeds, we show the hypocenters relocated by post-processing, although the arrival times used in the hypocenter determination are picked by the in-situ algorithm. To avoid local minima, the post-processing algorithm attempts to determine location with 100 different initial hypocenters, ultimately choosing the best result for each event. We use seismic wave speeds determined by in-situ transmission tests (Naoi *et al.*, 2008) in which a piezoelectric ultrasonic transmitter is used on a shot-and-run basis all along a long borehole (Fig. 1). Waveforms received by AE sensors are stacked for 8192 times and stored on the PC. The obtained P-wave speeds are 6.00 and 6.90 km/s for the host rock and the dyke, respectively; the respective S-wave speeds are 3.65 and 3.92 km/s. The transmitted wave indicated a good signal-to-noise ratio in the frequency range of 1–40 kHz, which coincides with the frequency band at which most of the observed AE events have a significant amplitude (Plenkers *et al.*, 2009). Since there is some ambiguity about the exact position of the dyke contacts, we use average seismic speeds of 6.45 km/s for the P-wave and 3.79 km/s for the S-wave.

3. AE Distribution After an M_w 1.9 Earthquake in the PG Dyke

A relatively large event of M_w 1.9 occurred very close to our site at 15:20:52 on 27 December 2007 (the local time in the Republic of South Africa). The hypocenter located by the mine-wide seismic network operated by ISS International Ltd. (referred to as the ISS network hereafter) was only ∼30 m above the center of our network (Fig. 2).

Because the event occurred in the midst of a long holiday period, there were no working noises, which allowed the data to be analyzed using picks made by in-situ program. We were able to locate more than 20,000 AE events within the first 150 h following the main shock. Among these, 15,488 events in the volume shown in Fig. 2 satisfied the following conditions; (1) at least four P-arrivals were picked, (2) at least four S-arrivals were picked, (3) at least ten arrivals in total were picked, and (4) the root mean square (RMS) residual of arrival time was <0.2 ms. We refer to these events as well-located events.

The distribution of the hypocenters of the well-located events is shown in Fig. 2. These formed clusters (encircled in the figure). Cluster T extends along the horizontal access-tunnel, presumably representing activities related to excavation damage. Cluster M is within a solid rock mass of the PG dyke and consists of more than 13,000 events (86% of the well-located events). The hypocenter of the main shock lies on this cluster. Moreover, as seen from the lower left panel viewed from the SSE, this aftershock cluster is planar. Therefore, we have little doubt that this cluster has delineated the rupture plane of the main shock. Note that at least the lower and northern half of cluster M resides in the zone where localization by our network is very reliable. However, cluster M will not be discussed in detail here because the hypocenter of each event is currently still based only on in-situ automatic picking. A moment tensor solution of the main shock is not yet available due to the many obvious inconsistencies in the orientation information of the ISS network. Waveforms of the main shock by our AE network were all saturated at the first pulse of the P-wave. Cluster N is on the northern extension of the main shock fault (cluster M), but the distribution is clearly separated from cluster M. In the near future, we would like to investigate in detail whether or not cluster N belongs to the main shock rupture plane.

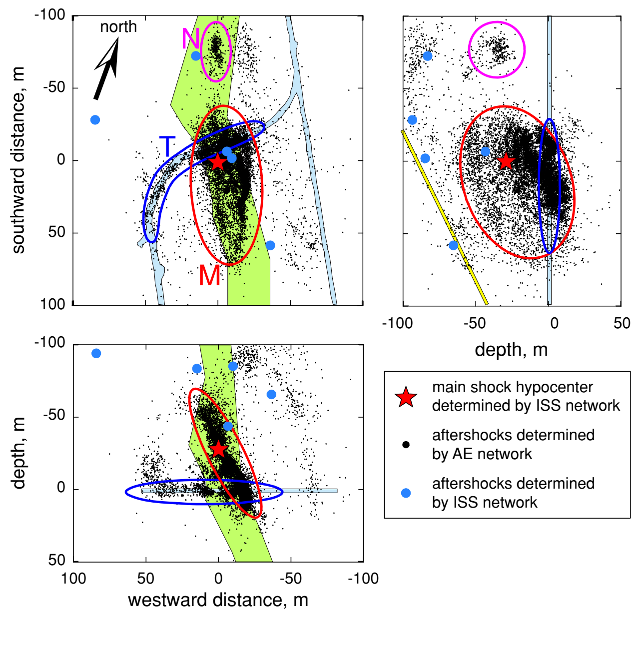

Fig. 2. Hypocenter distribution of the well-located AE events (black dots) in the first 150 h following the M_w 1.9 earthquake on 27 December 2007. A red star indicates the hypocenter of the M_w 1.9 earthquake located by the ISS network. Blue solid circles represent earthquakes located by the ISS network during the first 150 h following the main shock. The epicenter of the main shock is taken as the origin of horizontal distances. Depths are measured relative to the ceiling of the access-tunnel (3264 m in depth). Narrow light-blue zones and wide green zones represent the access-tunnel and dykes at a depth of 3264 m, respectively. Yellow zone in the right panel indicates gold reef.

4. Discussion

It has been occasionally pointed out that aftershock activity is not very distinct for mining-induced earthquakes, even for relatively large ones. Generally fewer than about ten aftershocks of each M 2–3 class earthquake that occurs in a mine are detected by the mine's routine seismic monitoring (e.g., Spottiswoode, 2009). Ogasawara *et al.* (2002b), for example, installed a more sensitive network consisting of accelerometers covering up to 10 kHz and subsequently detected about 100 aftershocks of an M 2 main shock. However, these aftershocks did not show a planer distribution indicative of delineation of the main shock rupture, presumably because the spatial resolution was not adequate. The present array is very dense, and many of the aftershocks are very close to the sensors. It is also evident that our success in detecting so many aftershock events has been the application of sensitive high-frequency sensors. We discuss a very rough estimation of the detection threshold of the present observations system in the following paragraphs.

The ISS network detected only five earthquakes in the volume shown in Fig. 2 during the first 150 h following the main shock. By examining the ISS catalog of the area, we were able to confirm that the detectability of the ISS network for the area decreases from ∼100% at M 0 to ∼0% at M −1. If we assume a unity b-value for the Gutenberg-Richter's relationship, which was also confirmed down to M 0 by the ISS catalog, the fact that our network detected ∼3000 times more events means that we probably detected many events as small as M −3.5 to approximately −4.5. If a 3-MPa stress drop is assumed (Sellers *et al.*, 2003), the source dimension of an $M \sim -4$ earthquake is about 0.1 m, which comes into the range of typical laboratory samples. Such a dimension is also consistent with the shortest range of pulse width (Nakatani *et al.*, 2008) observed for many events.

Because no large earthquake was located within the main rupture area (cluster M) by the ISS network before the M_w 1.9 earthquake, this earthquake is thought to have occurred on a newly generated fault. However, the static stress drop estimated by a routine analysis by ISS from the corner frequency and DC level of the P-wave spectrum recorded by the ISS network is 2 MPa. This is in the range of the stress drop of natural earthquakes and mine earthquakes that occur on pre-existing faults.

Near-horizontal breakout was observed along the near-fault portion of the Ycore hole (Fig. 1) drilled 1.5 years after the main shock, indicating a vertical-compression field. Note that mined-out areas did not differ very much between the time of the M_w 1.9 earthquake and the time of Ycore hole observation. The main rupture fault suggested by the aftershock cluster M dips 30° off the vertical. This is optimally oriented for the vertical-compression field, if a typical laboratory value of a frictional coefficient of ∼0.6 is assumed. Also, the spatial extent of cluster M (100 m along strike and 80 m along dip) is reasonable for M_w 1.9 earthquake.

5. Conclusion

By deploying a sensitive seismic observation network covering up to 200 kHz at a depth of 3.3 km in a South African gold mine, we have successfully captured a large number of AE events that followed an M 2 earthquake occurring in a solid rock mass. The detectability limit of our network is estimated to be $M \sim -4$, whose source dimension may be comparable to the size of typical laboratory samples.

A 100×80-m^2 fault plane dipping 60° has been delineated by a planar distribution of AE events. This plane is optimally oriented for nearly vertical compression, which is suggested by the borehole breakout observed in the area. In other words, the present case is a clear demonstration that the presence of mining stress allows 100-m scale rock fracture experiments to be performed during which small fractures on the centimeter-scale can also be observed at the same time in association with macroscopic failure occurring in a more or less natural environment.

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