**Delineation of large localized damage structures forming ahead of an active mining front
by using advanced acoustic emission mapping techniques**

*Hirokazu Moriya^a, Makoto Naoi^{b1}, Masao Nakatani^c, Gerrie van Aswegen^d, Osamu Murakami^e,
Thabang Kgarume^f, Anthony K. Ward^g, Raymond J. Durrheim^h, Joachim Philippⁱ, Yasuo Yabe^j,
Hironori Kawakata^k, and Hiroshi Ogasawara^k*

^a *Graduate School of Engineering, Tohoku University, 6-6-04 Aobayama, Aoba-ku, Sendai
980-8579, Japan*

^b *Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo
113-0032, Japan*

^c *Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo
113-0032, Japan*

^d *Institute of Mine Seismology, Stellenbosch, South Africa*

^e *Research Organization of Science and Engineering, Ritsumeikan University, 1-1-1
Noji-higashi, Kusatsu, Shiga 525-8577, Japan*

^f *Council for Scientific and Industrial Research, PO Box 395, Pretoria 0001, South Africa*

^g *SeismoGen cc, PO Box 1177, Carletonville 2500, South Africa*

^h *The University of the Witwatersrand, 1 Jan Smuts Ave, Braamfontein 2000, Johannesburg,
South Africa & the Council for Scientific and Industrial Research, PO Box 395, Pretoria,
South Africa*

ⁱ *Gesellschaft für Materialprüfung und Geophysik, Dieselstraße 9, 61231 Bad Nauheim,
Germany*

^j Graduate School of Science, Tohoku University, 6-6 Aramaki aza aoba, Aoba-ku, Sendai
980-8578, Japan

^k College of Science and Engineering, Ritsumeikan University, 1-1-1 Noji-higashi, Kusatsu,
Shiga 525-8577, Japan

^l Present address: Department of Civil and Earth Resources Engineering, Graduate School of
Engineering, Kyoto University, Kyoto Daigaku Katsura, Nishikyo-ku, Kyoto 615-8540, Japan.

Corresponding author: Hirokazu Moriya

Graduate School of Engineering, Tohoku University, 6-6-04 Aobayama, Aoba-ku, Sendai
980-8579, Japan

Phone & Fax: +81-22-795-7996; e-mail: hirokazu@m.tohoku.ac.jp

ABSTRACT

We applied advanced mapping techniques to 291 230 acoustic emission (AE) events as
small as around $M -4$ that were recorded over 50 days by an ultra-high resolution network close
to the active front of a tabular mining stope being advanced northward at 1 km depth in the
Cooke 4 Gold Mine in South Africa. We first applied joint hypocenter determination (JHD) to
improve absolute locations, and then applied the double-difference relative location algorithm to
the JHD output. These steps resolved the seemingly continuous, dense cloud of AEs that extend
about 20 m ahead of the stope front into several discrete, steeply dipping tabular clusters a few
meters thick and 10–30 m in dip extent, separated by quiet intervals a few meters thick. The
clusters have a strike parallel to the stope face and a dip of about 65° , resembling commonly
observed large shear fractures along the plane of maximum shear (Ortlepp shears). In general,
the activity of the clusters changed in similar ways as the stope face advanced, but each cluster

remained stationary and the gaps between clusters were impressively quiet. This study demonstrates that high-resolution AE mapping can delineate the formation of large structures of localized damage in the highly stressed intact rock mass ahead of the stope face, a process that may culminate in hazardous seismic events.

Highlights

This is the first study of acoustic emissions (down to $M_w -4$ or smaller) focusing on an active mining front at depth. A huge number of events selectively occur within large (10–30 m), steeply dipping, tabular clusters separated by clear seismic gaps, suggesting that the stope-front seismicity represents the formation of large discrete structures of localized damage, rather than microfractures occurring pervasively through the stressed volume of rock mass.

Keywords: Acoustic emission, gold mine, mining-induced fracture, joint hypocenter determination, double-difference hypocenter relocation

1. Introduction

In South African gold mines, where extensive tabular mining of subhorizontal reefs at depth creates a zone of high differential stress around the mining front [1], various types of macroscopic fractures, with dip dimensions of decimeters to several tens of meters, are observed around the stope [2, 3], posing serious hazards to mining operations (Fig. 1). The most common types of macrofractures are vertical extension fractures (type I), which form by tensile failure of rock near the stope face when confinement is removed. Together with another secondary extension fracture (type III), type I fractures degrade the integrity of the rock mass and make the stope prone to collapse. Type I and type III fractures correspond to E1 and E2 fractures in the

terminology of van Aswegen and Stander [3]. Type II fractures are steeply dipping shear fractures that can be as large as several tens of meters in the dip dimension. W. D. Ortlepp [4, 5] studied their distinct morphological characteristics and emphasized their close association with seismic events. Following van Aswegen [6], we refer to these brittle shear structures formed in intact rock as Ortlepp shears. Ortlepp shears often are the sources of violent seismic events with magnitudes between M 1 and M 4 [4–6], which cause severe rockburst damage in the stopes and beyond. Ortlepp shears form in macroscopically intact rock as far as tens of meters ahead of the stope face [4], where a similarly steeply dipping zone of elevated shear stress is present [1]. Because they occur near the active mining face where people are working, seismic events from Ortlepp shears pose a hazard comparable to that from larger events caused by reactivation of geological faults, which can reach M 5 [5, 7]. Ortlepp shears are not rare; around 20 of them were found in the East Rand Proprietary Mine (ERPM) in the wake of face advancement for about 200 m [4]. This averages one in every 10 m of face advancement.

The characteristics of these types of macrofractures are explained by the stress field induced around the stope front [3]. Indeed, almost all seismicity associated with the sub-horizontal tabular mining typical in South African gold mines is concentrated in a zone of excessive vertical compression a few tens of meters in extent along the mining front. Routine monitoring of seismicity down to M –1, as conducted in most gold mines in South Africa, commonly detects “seismic clouds” that migrate with the advancing mining front, highlighting this volume of high stress.

Very high resolution imaging of seismicity down to very small magnitudes as acoustic emissions (AE) may be able to trace the development of macrofractures in a stressed rock mass, delineating developing macrofractures as clusters of numerous, much smaller AEs. The damage structures delineated by AEs, if found and monitored, could have more specific implications for

rock mass stability than the relatively featureless volumes of elevated stress implied by conventional seismic monitoring. AEs have been mapped during projects in tunnel construction, mining, and the development of geothermal and petroleum fields [e.g., 8–14]. However, active mining faces at depth have never been covered by seismic observations with a resolution suitable for this purpose. If we seek to monitor the development of macrofractures of, for example, 10 m, the minimum requirement would be a methodology with the ability to detect microfractures (AEs) smaller than a square meter (corresponding to $M -2$ for a 3 MPa assumed stress drop) at relative location accuracies better than a meter.

This paper presents our analysis of the seismicity around an advancing mining front using AE monitoring data in the Cooke 4 Mine (previously known as the Ezulwini Gold Mine) in South Africa. Deployed as part of the Science and Technology Research Partnership for Sustainable Development (SATREPS) program [15–20], sensors have located AEs as small as -4 in moment magnitude (M_w) or even smaller. We applied the joint hypocenter determination (JHD) method [21] to these AE data to improve the absolute location accuracy followed by the double difference (DD) method [22] to improve the relative location accuracy. We have found that the seismic cloud around the stope front can be resolved into several discrete planar clusters 10–30 m across with orientations similar to Ortlepp shears. The planar clustering of this seismicity suggests that the AE activity represents the formation of relatively large structures of localized damage rather than pervasive microfracturing throughout the stressed rock volume ahead of the mining front.

2. Observation of AE events at the Cooke 4 Mine

The Cooke 4 Mine is about 40 km southwest of Johannesburg, near the town of Westonaria in Gauteng Province, South Africa. Operations at the mine commenced more than 40 years ago.

The mine is in an Archean sedimentary basin several kilometers thick that consists mainly of quartzite and shale with scattered minor volcanic units. The volume considered in this study consists entirely of quartzite, except for a lava layer near its top edge. Since 2010, ore has been mined from the upper Elsburg reef within a shaft pillar about 400 m in diameter at a depth of about 1 km. An extension of the reef outside the shaft pillar had been mined out by 2001, when the mine was temporarily closed, and was left as an extensive tabular cavity, thus the background vertical stress in the shaft pillar is high for its depth. Faces (panels) in the current mining are 20–30 m across and 1–2 m high. In the study area, the stope is subhorizontal, gently dipping about 10°WSW. Daily blasting advances the panels to the north by about 10 m per month.

We conducted AE monitoring during mining operations by using 6 three-component accelerometers and 24 single-component AE sensors installed in a volume measuring approximately 95 m (N–S) $\times$ 50 m (E–W) $\times$ 30 m (depth) [16]. Three of the accelerometers have a flat frequency response up to 25 kHz (Wilcoxon Model 736) and the other three up to 10 kHz (Wilcoxon Model 728). The AE sensors (GMuG, Bad Nauheim, Germany) cover up to 50 kHz and are very sensitive. All of the detectors were grouted into their boreholes.

Seismic signals were transmitted to the data acquisition system through coaxial cables and recorded on a computer hard disk. Waveform data were recorded on all 42 channels whenever the amplitude of an AE event exceeded a threshold at any detector. Events were acquired as digitized waveforms of 65.5 ms duration (32 768 samples) at a sampling frequency of 500 kHz. Before recording, high-pass filters with cutoff frequencies of 50 Hz and 1 kHz were applied to the signals from the accelerometers and AE sensors, respectively.

We used travel-time detection software from Home Seismometer Corp. (Japan) [23] that automatically picks the P- and S-wave arrival times and determines the source locations. We

visually inspected the travel-time readings, theoretical travel times, and observed waveforms for several hundred of these events and confirmed that obvious mistakes in readings led to erroneous hypocenter determinations in fewer than 1% of events [16]. The velocities of the P- and S-waves used in the analysis were 5700 and 3600 m/s, respectively, as estimated by transmission tests in which elastic waves from active ultrasonic sources were received by network sensors [17].

For this study, we used AE events that had at least 10 P-wave travel-time readings and root-mean-square (RMS) residuals of 0.2 ms or less, occurring in a volume measuring approximately 100 m (N–S) $\times$ 180 m (E–W) $\times$ 50 m (depth). During our analysis period from 7:21 on 12 July to 00:00 on 2 September 2011, 291 230 AE events were identified as satisfying these conditions. Their magnitudes, estimated from the spectra [16], ranged from M_w –5.3 to 1.3. Figure 2 shows the AE event rate given as the number of located events per day. From 26 July to 8 August the AE event rate abruptly decreased by more than an order of magnitude because all but five of the AE sensors were mistakenly taken offline. Thus, caution must be taken when discussing the activity during that time period. In addition, we excluded time intervals during which observations were masked by continuous noise from drilling by visually checking all the waveform records before feeding them to the automatic picking program [16]. Such noisy intervals mostly occurred during the morning shift between 9:00 and 14:00, and the exclusion sometimes amounted to several tens of percent of the shift time. However, the impact was limited because most seismicity around the stope occurred during the several hours following blasting, starting at 15:00.

3. Refinement of AE source locations by joint hypocenter determination

We used the JHD method to re-estimate the absolute source locations and analyze location errors. This method refines source locations by decreasing systematic errors, adjusting all AE events iteratively to compensate for station corrections [21]. We applied JHD to the 291 230 events whose source locations had been estimated automatically. Figure 3 shows the JHD result of 289 015 events that had RMS residuals smaller than 1.0 ms. Shown also are the contours of the “condition number”, calculated by applying principal component analysis to a matrix consisting of the partial derivatives of the travel times from the hypocenters to the observation stations [24] and taking the ratio of the largest and smallest singular values of the matrix. The condition number is useful in identifying systematic error trends that commonly appear in the AE cloud owing to the geometric relationship of the monitoring network and source locations. A lower condition number indicates a better-constrained and less-biased source location, and also indicates that the system of equations is less sensitive to noise.

Nearly all (90%) AE events occurred in a zone extending about 20 m ahead (north) of the active mining face (contour S in Fig. 3), forming what we will refer to as the stope-front cloud. The positions of the mining faces shown in Fig. 3 were calibrated by relatively large ($M_w > -1$) AEs occurring 14:00–16:00 on weekdays, which were almost certainly blasts [16], to determine the positions of AEs relative to the mining stope. The activity cloud migrated north as mining proceeded, consistent with the concentration of stress ahead of the mining front [1]. Even though the high resolution network recorded about 300 times as many events than the conventional network [16], the stope-front cloud still extended only 20 m in the face-normal direction; very few AEs occurred outside it. On the other hand, the stope-front cloud was ubiquitous across the active mining front, confirming that the activity was generally associated not with specific geological structures but with the stress field of the mining front. In Fig. 3, two contours labeled N and G enclose AE clusters that are spatially separate from the stope-front

clouds (Note that G encloses multiple planar clusters belonging to different geological structures, while N encloses only one cluster belonging to a single structure, that will be used in some later arguments). They most likely represent activity on preexisting geological faults and are discussed elsewhere [25, 26]. The RMS residuals of the travel times, calculated for all final source locations determined by JHD (Fig. 4), provided a measure of the quality of the computed source locations for a given velocity model. The RMS distribution approached a chi-squared distribution, which means that the location errors followed a normal distribution. The mean RMS residual after JHD was 0.12 ms, which corresponds to distances of 0.68 and 0.43 m, respectively, for the P- and S-wave velocities used here. Figure 5 shows residuals before and after JHD for channels 16 and 35. The asymmetric distributions of the residuals about the mean reflect systematic errors associated with un-modeled velocity structure, including its inhomogeneity (which was assumed to be homogeneous), but JHD reduced this bias in the distributions. Before JHD the channel 16 distribution had twin peaks and the mean value was biased by about 0.2 ms; after JHD the bias was compensated for and the mean approached zero. For channel 35, JHD made the residual distribution sharper, implying that random errors in the source locations were also reduced. These results show that JHD was effective in reducing both the bias (systematic error) and random errors in the estimated source locations. Station corrections ranged from -0.10 to 0.31 ms for P-wave arrivals and from -0.29 to 0.29 ms for S-wave arrivals.

4. Structure of the stope-front cloud revealed by the double-difference algorithm

4.1 Application of the algorithm

To take a closer look at the stope-front cloud, we focused on a cuboid volume of rock 20 m wide from east to west (box R in Fig. 3). Within that volume, most detectors were within a 50 m

distance, and the complete magnitude of $M_w -4$ was achieved. The low condition number (< 75) obtained for this region indicates that locations estimated by JHD were highly reliable. In addition, the face was farthest advanced here, so the stress field was mostly governed by the local face position, allowing for a simple interpretation. Figs. 6(a) and 7(a) show the AE source locations by JHD along with the mining fronts as of 21 July and 24 August 2011.

We then applied the double-difference relative hypocenter relocation algorithm (DD) [22] to improve the accuracy of the relative hypocenter locations, reducing systematic errors by using source locations corrected by JHD as input. The DD method is an iterative least-squares procedure that optimally relocates seismic events in the presence of measurement errors and velocity structure uncertainty. The fundamental equation of DD relates the residual between the observed and predicted phase travel-time differences for pairs of AE events observed at common stations to changes in the vector connecting their hypocenters through the partial derivatives of the travel times for each event with respect to the unknown locations. DD used automatically detected P- and S-wave arrival times to refine the initial source locations given by the results of JHD, and the weighting coefficient was applied to the arrival time data when the DD equation was solved.

The differences between travel times for events located within 10 m of each other were initially used for the relocation. The weighting coefficient was given by referring to the inter-event distance and was changed with each iteration, although the first 25 iterations were done with even weighting. The distance used for defining joined events was gradually decreased to 4 m. Of the 34 742 AE events in Figs. 6(a) and 7(a), DD relocated 33 288 events whose M_w ranged from -4.3 to -0.4 (Figs. 6(b) and 7(b)).

4.2 Identification of tabular structures

The DD method yielded a set of AE locations that were considerably more coherent than those from JHD alone, and the results show that the stope-front cloud can be clearly resolved into steeply dipping planar clusters. In plots of the relocated events (Figs. 7(a) and 7(b)), we can identify four clear planar clusters of AEs (Lines B, C, D, and N in Fig. 7b) separated by areas with few events. Another cluster (Line A in Fig. 7b) is also present to the south of Line B, but is less easily visible in the figure because of the small dot size and the modest density of the events.

A snapshot analysis, described in Section 4.3, confirmed that the quiet zones between these clusters are not artifacts of the time period when observations were sparse (Section 2). That is, the very large number of AEs recorded in the stope-front cloud, even the smallest events, really did occur in discrete large-scale clusters. This came as a surprise to us.

Four of these five clusters (Clusters A–D) are steeply dipping to the south (60–75°S) and are assigned to the stope-cloud S (Fig. 3). They all have a strike nearly parallel to the mining face, and Fig. 7 displays them along their strike so that they appear at their thinnest. Each cluster has dip dimensions of 10 to 30 m. The shapes and arrangements of the planar clusters resemble those of Ortlepp shears [2] to a large extent, but some differences are discussed later in section 5.1.

Cluster N has a dip of 75°N and is clearly separate from stope-front S. It is much thinner than Clusters A–D, as is apparent when it is viewed in this vertical slices 50 cm thick (Fig. 8), which virtually serve as 2D thin sections. These vertical thin sections show that Cluster N has a very small thickness (~30 cm) and is continuously and sharply defined by very densely distributed events (Figs. 8(c) and 8(d)). The continuity of these dominant traces in slice view is also good in the strike direction, and it holds over the cluster's entire extent of ~20 m [25]. These features suggest that Cluster N delineates a macroscopic fracture surface itself. Indeed, a

corresponding geological fault was identified at the outcrop during mining excavation, and therefore Cluster N was interpreted as on-fault AE activity [25].

In contrast, Clusters B–D define tabular zones of significant (2–4 m) thickness, and their AE distributions do not exhibit the degree of continuity seen in Cluster N. (Cluster A had insufficient events for detailed analysis.) More importantly, the section views (Fig. 8 a-d) of Clusters B–D lack narrow, dominant traces that likely delineates the macroscopic fracture surface of preexisting discontinuity [26]. The location accuracy of the events in Clusters B–D is almost the same as that of the events in Cluster N (i.e., better than 30 cm in the N–S direction) because they are similarly situated with respect to the observation network. Therefore, the observation that Clusters B–D have a thickness of 2–4 m must be real and not the result of location error.

Although Cluster D may have a dominant continuous trace similar to Cluster N in one thin slice taken at the position of Fig. 8(d), such is not true elsewhere along its strike. As a whole, Cluster D has a tabular distribution with significant thickness, like Clusters B and C.

4.3 Migration of microseismicity with time

Figure 9 shows the AE source locations determined by the DD method during the eight different time intervals indicated in Fig. 2. The time windows were selected based on eye observation so that the development of seismic structures can be better seen from the AE distribution. The view angle is the same as in Figs. 7 and 8. Clusters A, B, and C can be recognized in the 436 events during the first 17 hours worth of data (Fig. 9(a)). The next 24-hour interval (Fig. 9(b)) contained many more events (2190), delineating Clusters B and C even more strongly with respect to the quiet zone between them whereas activity in Cluster A ceased during this period. Clusters B and C remained active at least through 26 July, when the

network temporarily lost most of its sensors. The strong contrast between zones of activity and the gaps between them was consistently seen throughout the five time periods before the sensor problem, demonstrating that the gaps are real and not artifacts caused by the observational trouble. When the network returned to normal on 8 August (Fig. 9(g)), Cluster B activity had become much lower and Cluster C activity was still strong, and the gap between them was still present. In the last period (Fig. 9(h)), the activity of Cluster B was largely limited to its lowest part. This decrease in activity of Cluster B appears to coincide with the passage of the mining front. Cluster N started after 8 August several meters north of the stope-front cloud (Fig. 9(g)) and grew with time [25]. Cluster D, the last and northernmost cluster in the stope-front cloud, emerged only in the last time interval (Fig. 9(h)), several meters ahead of the mining front at the time. In that time interval, the mining front was a few meters behind the position of Cluster C at the stope horizon, and Cluster C was still active.

In summary, this snapshot analysis shows that the northward migration of AEs in the stope-front cloud consisted of the activation and cessation of stationary tabular clusters A–D in response to the advance of the working face. The fact that the position of each cluster remained fixed suggests that AE activity was associated with some form of physical damage in the rock, rather than with the continuously moving stress field.

5. Discussion

5.1 Type I fractures

Interestingly, we could not recognize AE activity from type I (or E1) fractures, which are by far the most common fracture type in the stope front. Fractographic patterns indicate their dynamic origin [3]. Because type I fractures form near the current working mine face, the wake of corresponding AEs, if any, should appear at the stope horizon. However, our results showed

no sign of AEs concentrated on the stope horizon.

Even at the level of the stope horizon, the quiet zones between Clusters A–D remained quiet. Moreover, the AEs in Clusters A–D were not more numerous at the stope horizon. Even assuming a minimal stress drop of 3 MPa for mine AEs [28], a 1-m rupture, which is somewhat smaller than the typical size of type I fractures, should produce an easily detectable event as large as $M -2$. The absence of AEs corresponding to type I fractures implies that the stress drop upon dynamic tensile failure of a type I fracture is probably very small. This possibility is supported by the low tensile fracture toughness of rocks in comparison with the considerable frictional resistance that has to be overcome to cause shear fractures. A theoretical estimation along this line shows that seismic radiation from tensile fractures is many orders of magnitude weaker than seismic radiation from shear fractures [29]. It is also equally likely that type I fractures all occur at the moment of blasting and cannot be picked as independent seismic events.

5.2 Relation to Ortlepp shears

The observations we have described suggest strongly that large, discrete, tabular clusters of AEs (Clusters A–D) represent macroscopically localized damage structures that formed in the highly stressed intact rock ahead of the stope face. Here we discuss the relation of these damage structures to Ortlepp shears and propose that the former could be a macroscopically quasi-static preparation process for a dynamic event that forms the latter. In this discussion we accept the hypothesis that the distinct set of fractures constituting a large (typically tens of meters in dip extent) Ortlepp shear is generated all at once during dynamic propagation of a seismic event of a comparable size [e.g., 5, 6].

The M_w of the AEs we analyzed in detail in section 4 varied between -4.3 and -0.4 , a range that corresponds to rupture diameters of 8 cm to 7 m when a stress drop of 3 MPa is assumed. Considering the uncertainties in stress drop, we cannot safely say that the rupture sizes of the largest events are smaller than the extent of the tabular clusters, which leaves a possibility that each tabular cluster is a group of aftershocks of an Ortlepp shear event spanning the entire extent of each cluster. However, this possibility is unlikely because aftershock train obeying Omori law (i.e., sudden increase and subsequent decay of AE rate) spanning over the extent of the clusters, which should be observed if such a event occurred [10], was not found (note that such aftershocks can be observed even if such a large event occurred during a data missing period), and these tabular clusters emerged gradually with time.

Many of the larger events in stope-front S or Clusters A–D were likely to be mining blasts [16]. Indeed, the events larger than $M_w -1$ (red circles in Fig. 9) were near the mining front at the time and occurred around 15:00, the typical blasting time at the mine. In addition, the lack of narrow dominant traces in the thin-slice sections of AE clusters suggests that our tabular clusters do not delineate Ortlepp shears themselves, because they would have a dominant macroscopic fracture plane no thicker than a few decimeters and continues to the cluster's extent. [e.g., 5,6].

On the other hand, the orientation, dimension, and location of the tabular clusters are similar to those of Ortlepp shears. The huge number of AEs should have left much damage, and the mechanical strength of the zone must have been degraded as the AEs accumulated. Such a weakened zone, subparallel to the zone of maximum elevated shear stress (ESS lobe), should be a good candidate site for the future nucleation and propagation of a dynamic Ortlepp shear event. Thus we propose that the tabular AE activity may serve as a macroscopically quasi-static preparatory process for a future Ortlepp shear event.

This proposal contradicts earlier studies that have considered such preparatory processes unlikely on the basis of the absence of localized damage zones around excavated Ortlepp shears. However, we note some differences between the typical configuration of Ortlepp shears and that of the AE clusters in this study. In typical cases, an Ortlepp shear nucleates at some distance ahead of the stope face and propagates toward the stope opening. If it nucleates in the hanging wall, it extends downward to the stope along the hanging-wall ESS lobe that dips toward the stope. But this dip is not consistent with the dip of the ESS lobe in the footwall, so beyond some dynamic overshoot, the Ortlepp shear continues for only a limited distance in the footwall (Fig. 10a) [e.g., 5, 6]. Likewise, an Ortlepp shear that nucleates in the footwall is mostly restricted to the footwall. The dips of Clusters A–D are consistent with a hanging-wall ESS lobe, and indeed Clusters A, C, and D appear as if they were inhibited in the footwall. However, Cluster B extends about 15 m both above and below the stope (Fig. 10b), a configuration not known for Ortlepp shears. We cannot invoke dynamic overshoot for this extension because there has been no runaway dynamic event. Perhaps the extension of Cluster B is an effect of interaction between the AE-sized cracks, a mechanism that is also called for to explain why the AEs are localized in a plane in the first place [27].

5.2 Implications for hazard assessment

In our study at the Cooke 4 mine, four large tabular clusters of AEs (A–D) occurred in a 12-m stretch in the direction of face advancement. This spacing is considerably closer than the 10-m spacing between the type Ortlepp shears observed at the ERPM [4]. One possible explanation is that the tabular AE clusters occurred less frequently in the ERPM, and each one culminated in an Ortlepp shear [6]. Another possible explanation is that tabular clusters formed in the EPRM as frequently as they did at Cooke 4, but only some of them culminated in Ortlepp shears. The

stress experienced by the rock mass at a given point increases and then decreases with the approach and subsequent passage of the mining front. If the stress level rises enough to cause tabular AE activity but not enough for a runaway rupture to form an Ortlepp shear, then the AE activity would end without causing an Ortlepp shear event. The threshold of stress for overall instability is a complicated problem that should depend on the extent of damage development, and hence is time-dependent. However, the Cooke 4 case, where none of the four tabular clusters were accompanied by a large seismic event, implies that a considerable margin can exist between the stress level that triggers damage (AE) localization and the stress level for overall instability, which may give us room to detect a catastrophe in its embryonic stage.

At this point, we cannot tell whether a large tabular AE cluster might eventually host an Ortlepp shear type event. Nonetheless, we believe that the recognition of tabular AE clusters as constituents of stope-front seismic clouds shows the great value of seismicity monitoring in mines. If stope-front seismicity merely represents a raised stress level in the volume of rock ahead of the mining front, which is the consensus interpretation today, then stress modeling suffices to fully characterize mining environments where the stress field is dominated by man-made openings. However, our high-resolution study suggests that stope-front seismicity can depict the formative stages of large hazardous events, where microfracture damages localize into a large tabular zone a few meters thick. Advanced seismic monitoring evidence thus has direct relevance to the occurrence of Ortlepp shear type events and represents knowledge that cannot be obtained by stress modeling.

6. Conclusion

We applied advanced AE mapping techniques to 50 days of seismic events triggered by subhorizontal tabular mining at the Cooke 4 Mine in South Africa and identified more than 290

000 AE events down to $M_w -4$ or smaller, more than 90% of which belong to a ~ 20 m wide seismic cloud along the advancing stope face. To compensate for systematic errors in the source locations, we first applied JHD to the AE events and then applied the double-difference relative hypocenter location algorithm to the output of the JHD.

The resulting hypocenter distribution resolved the seismic cloud into several discrete, stationary, tabular clusters a few meters apart separated by quiet zones. Each cluster had a strike parallel to the face, a steep dip of $\sim 65^\circ$, and a dip dimension of 10–30 m, all reminiscent of Ortlepp shears known to form in the high shear stress zone ahead of the stope face. The activity of each cluster started as the face approached within about 10 m and ended when the face reached the cluster position at the stope horizon, and the gaps between clusters remained quiet throughout the analysis period. AE events within the clusters were more or less randomly spread over a thickness of 2–3 m, and continuous narrow and dense traces, **in thin-section views**, suggestive of macroscopic fracture surfaces were absent except in short segments. In contrast, another AE cluster ascribed to activity of a geological fault [25] was concentrated on a thin (~ 30 cm) continuous surface over the cluster's entire extent.

We propose that the stope-front seismic cloud represents the formation of macroscopic, localized damage zones in the intact rock mass that may culminate in dynamic shear events and the concomitant formation of Ortlepp shears [4, 5, 6]. This would represent a step forward from the consensus understanding of the stope-front seismic cloud as a featureless volume of stress concentration ahead of the mining front. We could not recognize AE events corresponding to type I extension fractures, the most frequent type observed in the stope, likely because the energy radiated by these fractures is orders of magnitude smaller than the energy of equally sized shear fractures.

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References

- [1] Ryder JA, Jaeger AJ (eds.) A Textbook on Rock Mechanics for Tabular Hard Rock Mines, The Safety in Mines Research Advisory Committee (SIMRAC), Johannesburg, South Africa. 2002.
- [2] Adams GR, Jager AJ, Roering C. Investigations of rock fractures around deep level gold mine stopes. Rock Mechanics from Research to Application. Proc 22nd US Symposium on Rock Mechanics 1981; 227–236.

- [3] van Aswegen G, Stander M. Origins of some fractures around tabular stopes in deep South African mines. *The Journal of the Southern African Institute of Mining and Metallurgy* 2012; 112: 729-735.
- [4] Gay NC, Ortlepp WD. Anatomy of a mining-induced fault zone. *Geol. Soc. Am. Bull.* 1979; 90, 47-58: doi: 10.1130/0016-7606(1979)90<47:AOAMFZ>2.0.CO;2.
- [5] Ortlepp WD. Observation of mining-induced faults in an intact rock mass at depth. *Int J Rock Mech and Min Sci* 2000; 37(1), 423-436: doi: 10.1016/S1365-1609(99)00117-3.
- [6] van Aswegen G. Forensic rock mechanics, Ortlepp shears and other mining induced structures. *Proc 6th International Symposium on Rockburst and Seismicity in Mines* 2013; 1-19.
- [7] Sellers EJ, Kataka MO, Linzer LM. Source parameters of acoustic emission events and scaling with mining-induced seismicity. *J Geophys Res* 2003; 108: DOI: 10.1029/2001JB000670.
- [8] Wang HL, Ge, MC. Acoustic emission/microseismic source location analysis for a limestone mine exhibiting high horizontal stresses. *Int J Rock Mech Min Sci* 2005; 43: 1460-1465: doi: 10.1016/j.ijrmms.2007.08.009.
- [9] Becker D, Cailleau B, Dahm T, Shapiro S, Kaiser D. Stress triggering and stress memory observed from acoustic emission records in a salt mine. *Geophys J Int* 2010; 182: 933-948: doi: 10.1111/j.1365-246X.2010.04642.x.
- [10] Naoi M, Nakatani M, Yabe Y, Kwiatak G, Igarashi T, Plenkers K. Twenty thousand aftershocks of a very small (M 2) earthquake and their relation to the mainshock rupture and geological structures. *Bull Seismol Soc Am* 2011; 101: 2399-2407: doi: 10.1785/0120100346.
- [11] Young RP, Hazzard JF, Pettitt WS. Seismic and micromechanical studies of rock fracture.

Geophys Res Lett 2000; 27: 1767-1770: doi: 10.1029/2000GL011547.

[12] Young RP, Maxwell SC, Urbancic TI, Feignier B. Mining-induced microseismicity: monitoring and applications of imaging and source mechanism techniques. Pure Appl Geophys 1992; 139: 697-719: doi: 10.1007/BF00879959.

[13] Talebi S, Young RP. Microseismic monitoring in highly stressed granite: Relation between shaft-wall cracking and in situ stress. Int J Rock Mech Min Sci 1992; 29: 25-34: doi: 10.1016/0148-9062(92)91042-4.

[14] Moriya H, Fujita T, Niitsuma H, Eisenblätter J, Manthei G. Analysis of fracture propagation behavior using hydraulically induced acoustic emissions in the Bernburg salt mine, Germany. Int J Rock Mech Min Sci 2006; 43: 49–57: doi: 10.1016/j.ijrmms.2005.04.003.

[15] Yabe Y, Philipp J, Nakatani M, Morema G, Naoi M, Kawakata H, Igarashi T, Dresen G, Ogasawara H, JAGUARS. Observation of numerous aftershocks of an M_w 1.9 earthquake with an AE network installed in a deep gold mine in South Africa, Earth Planets Space 2009; 61: e49-e52.

[16] Naoi M, Nakatani M Philipp J, Horiuchi S, Otsuki K, Kgarume T, Morema G, Khambule S, Masakale T, Miyakawa K, Watanabe A, Moriya H, Murakami O, Yabe Y, Kawakata H, Yoshimitsu N, Ward T, Durrheim R, Ogasawara H. Frequency-magnitude distribution of $-3.7 \leq M_w \leq 1.3$ mining-induced earthquakes and b-value invariance with post-blast time, Pure Appl Geophys 2014: 171; 2665–2684: doi: 10.1007/s00024-013-0721-7.

[17] Kawakata H, Yoshimitsu N, Nakatani M, Philipp J, Doi I, Naoi M, Ward T, Visser V, Morema G, Khambule S, Masakale T, Milev A, Durrheim RJ, Ribeiro L, Ward M, Ogasawara H. Monitoring transmitted waves across a fault with a high potential for mining

induced earthquakes The Ezulwini gold mine in South Africa, AGU Fall Meeting 2011;
S31C-2257, San Francisco.

[18] Nakatani M, Yabe Y, Philipp J, Morema G, Stanchits S, Dresen G, JAGUARS Group.
Acoustic emission measurements in a deep gold mine in South Africa: Project overview
and some typical waveforms. *Seismol Res Lett* 2008; 79.

[19] Naoi M, Ogasawara H, Takeuchi J, Yamamoto A, Shimoda N, Morishita K, Ishii H, Nakao
S, Van Aswegen G, Mendecki A, Lenegan P, Ebrahim-Trollope R, Iio Y. Small slow-strain
steps and their fore-runners observed in gold mine in South Africa. *Geophys Res Lett*
2006; 33: L12304: doi:10.1029/2006GL026507.

[20] Ogasawara H, Takeuchi J, Shimoda N, Ishii H, Nakao S, van Aswegen G, Mendecki AJ,
Cichowicz A, Ebrahim-Trollope R, Kawakata H, Iio Y, Ohkura T, Ando M, the Research
Group for Semi-controlled Earthquake-generation Experiments in South African deep gold
mines. High-resolution strain monitoring during M~2 events in a South African deep gold
mine in close proximity to hypocentres. *Proc 6th International Symposium on Rockburst
and Seismicity in Mines* 2005; 385-391.

[21] Douglas A. Joint epicentre determination. *Nature* 1967; 215: 47-48: doi:
10.1038/215047a0.

[22] Waldhauser F, Ellsworth WL. A double-difference earthquake location algorithm: Method
and application to the Northern Hayward Fault, California. *Bull Seismol Soc Am* 2000; 90:
1353–1368: doi: 10.1785/0120000006.

[23] Horiuchi S, Horiuchi Y, Iio Y, Sawada Y, Sekine S, Nakamura H, Okada T, Nakatani M,
Naoi M. Automatic P and S wave arrival time picking compared to manually picking. *Proc.*
IUGG 2011; 3430.

- [24] Lay T, Wallace TC. Modern global seismology. San Diego, CA: Academic Press; 1995:247–248.
- [25] Naoi M, Nakatani M, Kgarume T, Khambule S, Masakale T, Ribeiro L, Philipp J, Horiuchi S, Otsuki K, Miyakawa K, Watanabe A, Moriya H, Murakami O, Yabe Y, Kawakata H, Yoshimitsu N, Ward A, Durrheim R, Ogasawara H. Quasi-static slip patch growth to 20 m on a geological fault inferred from acoustic emissions in a South African gold mine. *J G Res* 2015; 120:3: 1692-1707: DOI: 10.1002/2014JB011165.
- [26] Naoi M, Nakatani M, Otsuki K, Yabe Y, Kgarume T, Murakami O, Masakale T, Ward A, Moriya H, Kawakata H, Durrheim R, Ogasawara H. Steady activity of microfractures on geological faults loaded by mining stress. *Tectonophysics* 2015; 649: DOI: 10.1016/j.tecto.2015.02.025.
- [27] Reches Z, Lockner DA, Nucleation and growth of faults in brittle rocks, *J G Res* 1994; 99: 18159–18173: doi: 10.1029/94JB00115.
- [28] Kwiatek G, Plenkers K, Nakatani M, Yabe Y. Frequency-magnitude characteristics down to magnitude-4.4 for induced seismicity recorded at Mponeng Gold Mine, South Africa. *Bull Seismol Soc Am.* 2010; 100: 3: 1165-1173: doi: 10.1785/0120090277.
- [29] Hayashi K, Motegi S, Abé H. Characteristics of energy of elastic waves due to sudden growth of subsurface reservoir cracks for geothermal heat extraction. *Progress in Acoustic Emission IV*, 1988; 4: 265-272.

Figure captions

Fig. 1. Schematic diagram of the distribution and orientation of three types of fracture around a stope [2]. Modified after [2].

Fig. 2. Time series of the number of AE events selected daily for analysis. In total, 291 230 AEs were selected. Letters (a) to (h) denote time intervals used for a snapshot analysis (Fig. 9).

Fig. 3. Source locations of AEs determined by JHD. (a) Plan view, with contours of condition number at an elevation of 690 m above sea level (about 1 km beneath ground), and (b) NNE–SSW vertical projection viewed from the west. Black squares indicate AE detector locations. Thick cyan and red lines represent positions of the mining face on 21 July and 24 August 2011, respectively. Gray lines are outlines of the mining infrastructure. A total of 289 015 AEs were located, with their dates of occurrence indicated by the color scale. The red rectangle R is the area shown in detail in Figs. 6 and 7. Regions S, N, and G denote AE populations of different natures (see text).

Fig. 4. Distributions of residuals of travel times for all channels before and after JHD. Events before JHD with RMS less than 0.2 ms were selected for relocation by DD.

Fig. 5. Distributions of residuals of travel times before and after JHD for channels 16 and 35.

Fig. 6. Plan view of AE source locations relocated by (a) JHD and (b) DD. Only the events

originally located in region R (Fig. 3) are shown. Positions of the mining front on 21 July and 24 August 2011 are also shown.

Fig. 7. Vertical projection viewed from the WNW (N292°E) of the AE source locations determined by (a) JHD and (b) DD. Only the events originally located in region R (Fig. 3) are shown. Positions of the mining front on 21 July and 24 August 2011 are also shown.

Fig. 8. (a–d) Vertical sections of AE source locations, each covering a narrow range of 50 cm in the direction normal to the paper, at four different positions along the strike. Views are from the WNW (N292°E). (e) Plan view of AE source locations and positions of the vertical sections (a–d). Origin of x-axes is the center of gravity of the selected set of events.

Fig. 9. AE source locations determined by DD for different time intervals. The view angle and coordinates are the same as those in Fig. 8. (a) 7:23 on 12 July to 0:00 on 13 July, (b) 0:00 on 13 July to 0:00 on 14 July, (c) 0:00 on 14 July to 0:00 on 15 July, (d) 0:00 15 July to 0:00 on 17 July, (e) 0:00 on 17 July to 0:00 on 26 July, (f) 0:00 on 26 July to 0:00 on 9 August (the period when most sensors were inoperative), (g) 0:00 on 9 August to 0:00 on 17 August, and (h) 0:00 on 17 August to 0:00 on 2 September 2011. Events larger than $M_w -1$ are shown in red, all others in black.

Fig. 10. Schematic diagram showing the spatial configuration of high-ESS lobes, damage structures, and the stope. (a) Typical dynamic Ortlepp shear (OS), (b) Cluster B of this study (blue).

Figures

Figure 1

Figure 2

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Figure 8

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Figure 10