Keynote Lecture: Constraints on behavior of mining-induced earthquake inferred from laboratory rock mechanics experiments

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Keynote Lecture: Forensic rock mechanics, Ortlepp shears and other mining induced structures

G. van Asweegen

New insight into the nature of size dependence and the lower limit of rock strength

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Testing of the source processes of mine related seismic events

D. Malovichko and G. van Asweegen
INTRODUCTION

Foliation structures are widely observed in rock masses of many deep mines. Laboratory studies of acoustic emission (AE) in rock fracturing experiments using foliated rocks may therefore provide insight into mining-induced seismicity. Moreover, weak foliation planes are good analogues of seismogenic faults. Understanding foliated rock fracturing will thus contribute to better understanding of the rupture processes of earthquakes and provide a valuable framework for applications of AE monitoring to rock engineering, such as the at the predictions of rockbursts in mines and the monitoring of fractures around large underground chambers.

This paper presents rock fracture results under triaxial compression for a suite of intact rock samples with well-developed foliation structures. Some preliminary results have been reported in a previous paper by Villaescusa et al. (2009). This paper focuses on an enhanced analysis of the role of foliation in the pre-failure damage process and the evolving fracturing behaviour.

EXPERIMENTAL APPARATUS AND DATA PROCESSING

Experimental and Data Processing Techniques

All tests were performed using the 200 kN loading apparatus operated by the Geological Survey of Japan (GSJ) within the National Institute of Advanced Industrial Science and Technology (AIST). During each test, the GSJ high-speed waveform recording system was used to monitor AE and make velocity measurements (see Villaescusa et al., 2009 and Lei et al., 2000a, 2000b for details).

The following is a summary of the techniques applied:

1) Thirty-two piezoelectric transducers (PZTs; compressional mode, 2 MHz resonant frequency, 5 mm diameter) were mounted on the sample surface to record the AE signals produced by micro-cracking events and enable velocity measurements.

2) Two A/D systems were used to record multichannel waveforms. The first system is a high-speed waveform recording system (Lei et al., 2000b), which has 32 analogue input units and operates at a minimum sampling interval of 40 ns with a dynamic range of 12 bits. The second system has 16 channels with a minimum sampling interval of 10 ns and a dynamic range of 14 bits. The high-speed system works in triggering mode with a mask time of ~250 µs and buffer large enough to record ~8000 events. The second system can be operated in both triggering and continuous recording modes. In typical experiments, it was switched from triggering to continuous recording mode during the final seconds before failure. The signal is pre-amplified by 40 dB before being fed into the A/D boards.

3) Two peak detectors were used to record the maximum amplitude of two arbitrarily selected sensors, after 20 or 40 dB pre-amplification. The peak data were used for the...
calculation of event magnitudes and subsequently used for
the estimation of $b$-value in the Gutenberg-Richter
magnitude-frequency relation. The magnitude ($M$) of an
event is determined from the maximum amplitude of the
waveform ($A_{\text{max}}$) via $M = \log(A_{\text{max}}) + c$, where $c$ is a
calibration constant.

4) An automatic switching sub-system was designed to
sequentially connect each of up to 18 sensors to a pulse
generator for velocity measurement.

5) Six cross-type strain gauges were mounted on the
surface of the test samples to provide measurements of the
local strains in the axial and circumferential directions.
Stress, strain, and confining pressure were recorded at a
resolution of 16 bits and a sampling interval of the order of
milliseconds. The local volumetric strain ($\varepsilon_v$) was
calculated from the axial ($\varepsilon_a$) and circumferential ($\varepsilon_c$)
strains using the equation $\varepsilon_v = \varepsilon_a + 2\varepsilon_c$. The mean strains
of the test sample were estimated by averaging these local
measurements.

6) An interactive program was used for data processing
including 1) picking of P arrival times based on AR models,
2) hypocentre determination, and 3) integrated statistical
analysis. Location errors were estimated to be generally less
than 1–2 mm for the fine-grained samples.

These techniques allow the damage process in stressed
rock samples to be analysed in detail by monitoring the
spatiotemporal distribution of microcracking events.

The test samples, referred to henceforth as CRC samples,
were drilled along different directions (Figure 1) from a
large core and shaped into right circular cylinders with
lengths of 100–125 mm and a diameter of 50 mm. These samples
allowed us to examine the effects of foliations in rock
deformation and fracturing.

Stainless-steel end pieces were attached to either end of
each sample. The sample assembly including the attached
AE sensors and strain gauges was sealed with silicone
sealant to prevent the penetration of oil used as the
hydrostatic pressure medium.

**Experimental Procedures**

The following test procedures were applied:

1) Each test sample was initially hydrostatically confined
at 10 MPa for CRC-2, and 20 MPa for other samples.

2) Three cycles of loading and unloading were then
carried out. During each cycle, the axial stress was
increased to 50–70 MPa, and then unloaded to a value
~ 2 MPa higher than the applied confining pressure.
AE data obtained during these cycles were used for the
estimation of the field stresses the samples have previously
experienced.

3) Finally, the axial load was increased to the point of
failure.

The results of the stress estimation were described by
Villaescusa *et al.* 2009. This paper focuses on the data
obtained during the final loading step.

**DATA ANALYSIS**

**Statistics of AE Activity**

Energy released by an AE event relates to magnitude by

$$E_i \propto 10^{iqM_i},$$

where $q$ is a constant and $i$ indicates the $i$-th event. The most important cases are $q = 0.75$ and $q = 1.5$, which
yield the Benioff strain and the classical energy,
respectively. The energy release rate can be estimated by
summing (1) within a given time interval ($\Delta t$):

$$\dot{E}(t) = \sum E_i / \Delta t.$$

As is the case with naturally occurring earthquakes, the
cumulative number of AE events ($N$) of magnitude $M$ or
greater follows the Gutenberg-Richter magnitude-frequency
relationship (Gutenberg and Richter 1954) given by

$$\log_{10} N = a - bM,$$

where $a$ and $b$ are constants and $b$ is referred to as the
$b$-value. The seismic $b$-value, together with other
statistical parameters, can be interpreted as an indication of

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**Figure 1. Lower-hemisphere stereographic
projection showing sample axes, principal
stress axes, and foliation plane in CRC samples
from the Bendigo gold mine, Australia**

**Rock Samples**

The main samples used in this study were retrieved via
coring at a depth of ~856 m at the Bendigo gold mine,
Victoria Australia. The lithology of the samples is a meta-
basalt, which overlies the gold-producing dyke. The rock is
foliated at a scale visible to the naked eye. All samples are
classified by the following features: 1) a generally very
homogenous (fine-grained) lithology; 2) a strong foliation
structure; and 3) a low density of pre-existing microcracks.
the heterogeneity of rock properties and the stress level the sample experiences (Lei and Satoh 2007).

**RESULTS**

Table I is a summary of the key results obtained from selected samples of different foliation angles with respect to the maximum principal stress direction (vertical).

Overall, the meta-basalt rock samples demonstrated very brittle behaviour during the initial deformation and subsequent failure. In most samples, one or a few major faults were created. Following the creation of these major faults, large numbers of AE events were recorded. The detailed spatiotemporal distributions of AE events reveal that the foliation orientation with respect to the direction of the principal stresses affects the gross behaviour of the sample during pre-failure damage. The peak strength of the sample, precursory changes preceding the final fracture, the initiation of AE activity, the total number of AE events, and the geometry of the faulting plane all depend strongly on the foliation angle.

The samples can be divided into two broad groups according to the orientation of the foliations involved: Group I, with optimally oriented foliation (with respect to fracturing), and Group II, with poorly oriented foliations. To verify whether the foliations are optimally oriented or not, Figure 2 shows shear fracture strength as a function of foliation angle based on the Mohr-Coulomb failure criterion for specified internal friction coefficients (see DISCUSSION for details). For the standard friction coefficient value of 0.6, the optimal angle is ~20°, but for present purposes all angles in the range of 10–45° are considered to be optimal.

Below, we present detailed results for some representative cases.

**Group I: Samples of Favourably Oriented Foliations with Respect to Fracturing**

CRC-1 (Figures 3–4) yielded results characteristic of samples with favourably oriented foliations. In this sample, the angle between the foliation and the direction of the maximum axial stress is about 12° and thus falls into the range of optimal orientation (Figure 2). The peak stress was about 238 MPa under 20 MPa confining pressure and the AE rate prior to the peak stress being reached is quite low. Stress dropped from the peak stress to about 217 MPa following a very short nucleation phase (a few hundreds of seconds) producing a dynamic stress drop of 21 MPa (Figure 3). The critical nucleation zone size was about 2 cm (Figure 4). During the following sliding phase, a large number of AE events (aftershocks) occurred in the vicinity of the final fracture plane (Figure 4). The seismic $b$-value was ~1.0 prior to the dynamic fracture, dropped to ~0.5 during the nucleation process, and gradually increased to ~1.1 during the aftershocks. During and after the faulting nucleation, shear fracture mode was dominant.

The foliation angle of sample CRC-4 is about 20° and thus it too is optimally oriented. Significant AE activity was observed when the axial stress reached 210 MPa, ~90% of the strength. After the initiation of AE activity, the event rate increased according to an approximately power-law function of time to failure (Figure 5). Two shear fracture planes were created along the foliation planes (Figure 6). Many AE events occurred during the nucleation, fracturing, and particularly the sliding phases of each fault. The stress drop during the rupture of the first shear fault was ~15 MPa.

<table>
<thead>
<tr>
<th>CRC-1</th>
<th>CRC-4</th>
<th>CRC-7</th>
<th>CRC-3</th>
<th>CRC-2</th>
<th>CRC-5</th>
</tr>
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<tr>
<td>Foliation, [°]</td>
<td>12</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>$P_c$, [MPa]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>10</td>
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<tr>
<td>Strength, [MPa]</td>
<td>238</td>
<td>240</td>
<td>243</td>
<td>375</td>
<td>266</td>
</tr>
<tr>
<td>AE</td>
<td>91%</td>
<td>98%</td>
<td>82%</td>
<td>53%</td>
<td>4%</td>
</tr>
<tr>
<td>$b$</td>
<td>0.8–1.0</td>
<td>0.5–1.1</td>
<td>1.0–0.5</td>
<td>1.0–1.5</td>
<td>1–0.5</td>
</tr>
</tbody>
</table>

Table I Summary of key results for selected samples exhibiting different foliation angles, defined as the angle between the foliation plane and the maximum principal stress direction (vertical).
All Group I samples demonstrated similar fracture behaviour to well-developed natural faults, indicating that the foliation structure of fine-grained rocks can be used to approximate seismogenic faults.

Figure 2. Plots of shear fracture strength under a confining pressure of 20 MPa based on the Mohr-Coulomb failure criteria for specified internal friction coefficients. Tensile strength of 20 MPa is assumed.

Figure 3. Experimental results for sample CRC-1. Upper plots: axial stress, confining pressure, strains, AE release rate and seismic b-value as functions of time. Abrupt stress drops associated with the formation of two faults are evident. Lower plots: close-up views of the final 200 s.

Figure 4. Plots showing the migration of AE hypocentres in sample CRC-1. A typical foreshock-aftershock sequence is delineated. The foreshock phase corresponds to fault nucleation; mainshocks produce a 21 MPa drop in axial stress; and a large number of aftershocks occurs near the fault plane, which is coincident with the foliation planes of the sample. The figure at the bottom of each plot indicates the time interval (s) for which AE hypocentres are plotted.
Figure 5. Plots of axial stress, confining pressure, strains, AE energy release rate and the seismic $b$-value of AEs with time for sample CRC-4. Abrupt stress drops associated with the formation of two faults are evident. A clear phase of Accelerated Moment Release (AMR) can also be observed before the formation of the first fault. AE hypocentres that occurred in the shaded period are plotted in Figure 6.

Figure 6. Plots showing AE hypocentre migration patterns in a sample of meta-basalt with foliations oriented in a direction favourable for rupture under the experimental conditions. In this case, two major faults were created in the sample. The first, lower fault initiated migrated upwards along the foliation direction, and accommodated a $\sim 10$ MPa stress drop. The second, upper fault initiated close to the centre of the sample and its nucleation is clearly delineated by the AE hypocentres. Rupture of the second fault produced a stress drop exceeding 100 MPa.
Figure 7. Plots of axial stress, strains, AE release rate and seismic b-value of AEs against time for sample CRC-5

**Group II: Unfavourably Oriented Foliation with Respect to Fracturing**

Sample CRC-5 has a foliation angle of ~80°. As illustrated by Figure 2, the foliation planes in such cases are poorly oriented for shear failure and would weaken the rock prior to failure. Indeed, this sample showed peak strength as high as 380 MPa, the highest value of all the CRC samples analysed. AE activity initiated at relatively low stresses and occurred at a relatively low rate. The vertical (axial) strain was particularly large compared with samples of smaller foliation angles (Figure 7). Pre-failure AE hypocentres reveal some clusters of activity extending along the foliation direction. The final fracture plane has a complicated geometry with sharp bends and branches along the foliations. All these features demonstrate that badly orientated foliations affect the evolution of pre-failure damage.

None of the CRC samples had a vertical foliation and a sample taken from another mine is thus used here to examine the effects of such foliations. Figure 9 presents key results for a sample cored from the PDP site at Leinster in Western Australia, in which the foliation was almost vertical. The PDP sample is a metasediment and we use the term "foliation" here to refer to bedding planes to avoiding confusion. The stress required to initiate significant AE activity was ~100 MPa, 55% of the total strength (180 MPa; note the confining pressure in this was 5 MPa). Following the increase in AE rate, a rapid increase in dilatancy was observed. The AE hypocentre distribution is strongly affected by the vertical foliation structures. The ultimate rupture surface corresponds to a linkage of vertically extended and en echelon arrayed clusters, producing a wide shear fracture zone (Figure 9).

Figure 8. A stereographic view of AE hypocentres in a sample of almost horizontal foliations
FAULT FORMATION IN FOLIATED ROCK – INSIGHTS GAINED FROM A LABORATORY STUDY

DISCUSSION

Fault Mechanics and the Mechanism of Foliation Weakening

The failure of intact rocks can be approximated by a generalised failure envelope (Figure 10). Under the triaxial compression conditions used in this study, all samples failed with the formation of a macroscopic shear fault, indicating stress regimes of B to C as indicated in Figure 10. The shear strength in regimes B and C can be approximated by a composite Griffith–Coulomb failure envelope, normalised to rock tensile strength, $T$, with a cohesive strength, $T_C$, and a “generic” coefficient of internal friction, $\mu_i$. In regime B the macroscopic Griffith criterion (Sibson 1998) is given by:

$$\tau^2 = 4\sigma_n T + 4T^2.$$ (4)

Regime C corresponds to the linear Coulomb criterion:

$$\tau = C + \mu_i\sigma_n.$$ (5)

In both cases, $\tau$ and $\sigma_n$ are the shear and normal stresses on the surface, respectively.

For anisotropic rocks, such as the foliated rocks analysed in this study, the tensile strength depends only on the direction in which the sample was cored. CRC samples have an average tensile strength of ~20 MPa.

As indicated by our experimental results, foliation planes are indeed weak surfaces. Samples of optimally oriented foliations fractured along the foliation planes. Thus it is also worth examining the frictional instability of such foliation planes. In dry rocks, frictional instability on an existing fault or other kind of surface within the brittle regime is approximated by a criterion of Coulomb-Mohr form:

$$\tau = c + \mu_i\sigma_n,$$ (6)

where $c$ is the intrinsic cohesion of the fault, and $\mu_i$ is the static coefficient of rock friction. For most brittle rocks $\mu_i$ lies in the range 0.6 – 0.85 (Byerlee 1978). In general, $c$ is likely to be significantly less than $C$.

Figure 10. A schematic illustration showing a generalised failure envelope and failure criteria for cohesionless faults

Figure 11 shows experimental results using a Mohr diagram with a composite Griffith-Coulomb failure envelope for intact rock and shear criteria for cohesionless faults. All the data suggest intact failure. Samples CRC-1, CRC-4, and CRC-7, which have favourably oriented foliations, exhibit strengths in agreement with the composite Griffith-Coulomb failure criterion for $T = 18$ MPa, and $\mu_i = 0.75$. Samples CRC-5 and CRC3, in the group of unfavourable foliations, imply larger $T$ (30 MPa) and $\mu_i$ values (1.0). Other samples fall in the intermediate region.

As mentioned above, all CRC samples were extracted from a larger core and the major difference between these samples is the foliation angle. Therefore, our experimental results indicate that foliated rocks may be weak or strong depending on the orientation of the foliations with respect to the maximum principal stress direction. Favourably oriented rocks with respect to fracturing have the smallest strength, while poorly oriented rocks have the greatest. The difference in strength could be very large in some cases and should be taken into account in mining applications.

Foliations with Complicated Fault Geometries

Both optimally and poorly oriented foliation structures with respect to fracturing play a role in complicating the geometry of the overall faulting processes. The mesoscale
patterns of pre-failure damage and the governing role of foliations are schematically illustrated in Figure 12 and summarised below.

**Figure 11.** Generic Mohr diagram showing experimental results and a composite Griffith-Coulomb failure envelope for intact rock and failure criteria for cohesionless faults

1) **Vertical foliations:** Initial AE hypocentres are clustered vertically at many sites within the sample. Subsequent and more numerous clusters concentrate along a dipping zone, which is coincident with the surface of the most optimal orientation. The eventual shear fault is created by linkage of the en echelon array of cracks. As a result, there is no recognisable process zone such as is normally observed during the quasi-static growth of a shear fault. In the tests described here, numerous AE events were detected prior to dynamic fracture but we did not observe significant aftershocks.

2) **Horizontal foliations:** The initial AE hypocentres are clustered at some horizons within the sample. The final fracturing links these clusters and creates a geometrically complicated shear fault, which is characterised by bends, step overs, and branches. In our experiments, a large number of pre-failure AE events could be observed, but these occurred at a rate substantially lower than in case A.

3) **Optimally oriented foliations:** This case demonstrates faulting behaviour similar to that seen with natural earthquakes occurring along well-developed faults: 1) a small number of foreshocks delineating the fracture nucleation; 2) dynamic fracturing involving a stress drop of the order of a few tens of MPa; 3) a large number of aftershocks located along the fault plane and in near-fault regions. The resultant shear fault is relatively simple, but may be complicated by a staircase trajectory linking stepovers. It has been reported previously that there is a process zone at the rupture front (Lei et al. 2000b and Zang et al. 2000). The process zone is guided by the progressive occurrence of tensile cracking concentrated in the dilatant region near the fault tip, and thus may influence shear fault bending (Lei et al. 2000b). In foliated rocks, this mechanism may facilitate the rupture jumping from one weak plane to neighbours structures. Our results are in good agreement with those obtained from foliated gabbro samples cored from a depth of 3 km in Mponeng mine, South Africa (Satoh et al. 2013).

4) **Moderately well-oriented foliations:** Samples with intermediate foliation angles exhibit behaviours between those of cases A and C or B and C, above, depending on the specific angle. Foliations often deflect the evolving fracture, causing it to propagate along a “staircase” trajectory, and the overall macroscopic fault envelope is consistent with the optimal fault orientation specific by the linear Mohr-Coulomb failure criterion.

**Figure 12.** Schematic illustrations of the mesoscale patterns of AE hypocentres and fault mechanisms in foliated rocks of different foliation orientations
CONCLUSIONS

Our experimental results show that in strongly foliated rocks, the foliation orientation relative to the principal stresses plays a key role in determining spatiotemporal patterns of pre-failure damage, fracture nucleation, precursory behaviour, and aftershocks. The overall geometry of the eventual fracture plane, its complexity, and the overall failure strength of the samples, are strongly affected by the foliation angle. In our experiments, one or a few shear fractures formed in each sample. For samples with foliations optimally orientated for rupture under the experimental loading conditions, the final fracturing plane is created along a foliation plane. The fracturing processes of such samples are somewhat similar to those of natural earthquakes, displaying several characteristic features: 1) a small number of foreshocks; 2) a large number of aftershocks; 3) a fault nucleation zone that is a small fraction of the fault’s total area. Like faults, foliation planes are also weak interfaces in intact rocks. Samples of smaller and larger foliation angles exhibit rougher fracture surfaces complicated by intensive bending and step-over structures. Samples containing optimally orientated foliations have the smallest strength (here ~240 MPa under 20 MPa confining pressure), while horizontally foliated samples have the largest strength (~390 MPa under the same conditions). Vertically foliated samples have strengths close to but greater than those samples containing optimally orientated foliations.

On the basis of this work, we conclude that in mining-related hazard assessment and mine design, the orientation of foliations in host rocks and dykes are important factors that should be taken into consideration.

ACKNOWLEDGEMENTS

The authors would like to thank Osamu Nishizawa for help in carrying out the experiments. This study was partly supported by the Japan Science Promotion Society (JSPS 21246134).

REFERENCES


