Fracturing around a Preconditioned Deep Level Gold Mine Stope

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Abstract: The mining faces of the highly stressed tabular stopes in South Africa's deep level gold mines are prone to a type of rockburst termed face-bursts. As a means of ameliorating these face-burst conditions, a destressing technique termed preconditioning has been employed. Part of the studies into the quantification of the effects and mechanisms of preconditioning was a detailed investigation of the fracture pattern around unpreconditioned and preconditioned stopes. Techniques included mapping of the fractures exposed in the mined areas of the stope, measurement of profiles of the stope hangingwall and the use of Ground Penetrating Radar (GPR). Fracture mapping of discontinuities and subsequent geostatistical analysis indicates that the same groups of fractures occur in preconditioned and unpreconditioned areas. Profiling of the hangingwall also showed that even though the conditions in the stope improved significantly with the introduction of preconditioning, the same pattern of fracturing could be discerned. GPR was used to delineate the areas of fractured ground in the rock mass ahead of the stope face. It was found that the depth of fracturing ahead of the stope face within the plane of the reef increased in preconditioned areas. All of these studies indicate that preconditioning does not produce new sets of fractures and stress redistribution ahead of the face occurs by reactivation of specific pre-existing fractures, thereby reducing the potential for face-bursting.

Key Words: deep mines, preconditioning, fracture pattern, GPR

Introduction
The deep level gold mines of South Africa are subjected to a large number of rockbursts. These rockbursts have caused approximately 100 fatalities per year for the last few years and are likely to remain a serious problem as the mines reach greater depths. The CSIR Division of Mining Technology has, for several years, been undertaking research to prevent these incidents. One of the most successful techniques is preconditioning - initial analysis of accident data shows a definite decrease in the incidence of rock related accidents with the introduction of preconditioning. Preconditioning is specifically aimed at reducing the incidence of rockbursts which occur at the stope face (face-bursts). This is achieved by detonating explosives ahead of the face at the same time as the production blast. Numerical modelling has shown that this technique results in the reduction of stresses in the area of the face – thus reducing the potential for face-bursts (Kullmann et al 1996). However details of the mechanism of stress-transferral were not known.

Fracture growth is controlled by the orientation and intensity of the stress field in the vicinity of the fracture tip. Thus investigation of the fracture pattern around the stopes can reveal details of the stress changes. As such a detailed investigation into the fracture pattern around both preconditioned and unpreconditioned stopes was
undertaken. The experimental site was located on a gold mine, at a depth of approximately 2700 m below surface, on an orebody dipping towards the south at 20°, known as the Venterdorp Contact Reef (VCR). The VCR is a tabular deposit of gold-bearing conglomerate, of about 2600 Ma in age. The footwall in this area is a slightly argillaceous green quartzite and the hangingwall an andesitic (occasionally amygdaloidal) lava, with a UCS of around 250 MPa. Mining was carried out in an overhand updp configuration.

Detailed fracture mapping, hangingwall profiling, as well as GPR studies were carried out to determine the nature of the fracture pattern. The data used in the analysis of unconditioned areas was collected over a period of several months prior to the initiation of preconditioning. Once preconditioning was started, data was collected from the preconditioned panels as well as the adjacent panels, which at that stage were not subject to preconditioning.

**Collection of fracture pattern data.**

Data regarding the fracture pattern were collected using various techniques. The information gathered using these different techniques tend to confirm and complement each other, as well as strengthen the conclusions that have been drawn from these data about the mechanisms of preconditioning. The three principal techniques are discussed in detail below.

**Fracture mapping**

A data set of some 1100 fractures mapped around the deep level stope was gathered. Approximately 600 of these were mapped in unconditioned areas and the other 500 were mapped in preconditioned areas. For each fracture (or set of fractures) data was gathered on its orientation, frequency, displacement, surface characteristics and persistence. Fractures were classified into three types on the basis of their appearance, namely faults, fissures and joints. Faults were recognised as those fractures with visible movement indicators such as gouge or slickensides, whilst those with a significant dilational component were termed fissures. Those discontinuities with no discernible movement were termed joints. These terms encompass both fractures of geological origin as well as the mining induced (blast and stress) fractures. By far the most common fracture type was joints (69% of the total), whilst faults made up about 30% of the total. Not surprisingly fissures were virtually non-existent in this deep level stope. Five distinct fracture groups were recognised on the basis of their orientation (Figure 1). These were termed Groups I to V and their characteristics are summarised in Table 1. Because of the presence of a large number of metallic objects (such as mechanical props and drill steels) it was not possible to measure the absolute orientation of the various discontinuities using a compass – rather their true dip and their strike relative to the mining face were measured.

The majority of the fractures mapped were face parallel and steep dipping (Group II). Most of the fractures of this group occurred at the face, within the plane of the reef, and it is thought that they represent short, relatively intense mining induced fractures. There was also a group of shallowly dipping face parallel fractures (Group I); these were however restricted to the lava hangingwall. Many of these shallow dipping fractures are actually late stage extensional features, without significant dilation, that
developed sub-parallel to pre-existing joints after excavation of the reef. Thus, even though on a local scale they appeared to be abundant, they actually had a very low persistence. Group III fractures are thought to predate mining activities and were recognised as part of a well-defined joint set within that area of the mine. Underground these were seen as either joints or faults filled with a white gouge of crushed material.

Table 1: Summary of characteristics of the various fracture groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Shallow dipping face parallel joints (and occasionally faults)</td>
</tr>
<tr>
<td>II</td>
<td>Steep dipping, face parallel joints</td>
</tr>
<tr>
<td>III</td>
<td>Steep dipping face perpendicular joints and faults</td>
</tr>
<tr>
<td>IV</td>
<td>Moderately dipping (towards face) face parallel joints</td>
</tr>
<tr>
<td>V</td>
<td>Moderately dipping (away from face) face parallel joints</td>
</tr>
</tbody>
</table>

Group IV and V fractures were much less common than the other face parallel fractures and were only recognised as distinct groups after a large amount of data had been collected. Figure 1 shows that these fractures form two distinct sets dipping at approximately 100° to each other. These low persistence joints form last, as interconnections between the shallow and steep dipping face parallel fractures.

![Figure 1: Contoured Schmidt-net (lower hemisphere projection) plot of poles to all fractures mapped in (a) unpreconditioned and (b) preconditioned areas. The stereonets are orientated so that the mining face is to the North. Reef dip (20/180) is indicated by the star and the numbers 1 to V refer to the fracture groups described in Table 1 and the text. Note that the same five groups of fractures can be seen on both stereonets.](image)

**Hangingwall profiling**

One of the beneficial side effects of preconditioning (where the main objective is to reduce the incidence of face-bursts in highly stressed stope) is an improvement in hangingwall conditions. Underground it can clearly be seen that conditions improve (Figure 2), however it was necessary to quantify these differences. Hangingwall profiling was used to quantify this change, as well as determine the area of influence.
of the preconditioning holes. Several profiles of the hangingwall in preconditioned and unpreconditioned areas were taken. The profiles were measured underground by stretching out a measuring tape over a particular length and measuring the distance between the tape and the hangingwall at various points along the tape. The dip of the tape and average dip of the hangingwall were recorded, as well as the position and orientation of each profile. Two types of profiles were measured underground. Initially, only the peaks and troughs in the hangingwall along several 10 m long profiles were measured. However, it was realized that this irregular data set could not be analysed using more sophisticated methods such as fractal and spectral analysis. Both of these methods require a more periodic data set, and so measurements were taken every 2 cm along a series of 5 m profiles.

Figure 2: Photograph of the hangingwall taken sitting at the face looking back down the panel once preconditioning had started. Width of view is about 1.5 m. Note the much smoother conditions in the preconditioned area (closer to the camera).

Ground penetrating radar studies
Both the fracture mapping and hangingwall profiling strongly suggested that the fracture pattern ahead of the face was being altered by the preconditioning blast. To confirm this, ground penetrating radar (GPR) studies were carried out using the SIR-2M radar system developed by the CSIR: Division of Mining Technology and Geophysical Survey Systems Inc. (GSSI) specifically for use underground (Figure 3).

Figure 3: Photograph showing GPR in use underground. A 500 MHz antenna is being dragged along the face to collect data on the fracturing ahead of the face.
The penetration depth of the radar signal is dependent on the transmitted wavelength, which results in a loss of detail with an increase in depth of penetration. To account for this, each of the surveys consisted of several scans of the face using a 500 MHz antenna set at various ranges. Table 2 gives the number of scans and the approximate penetration depth for each range setting. From this table it can be seen that the majority of the scans penetrated to a depth of about 3.5 m, thus allowing detailed examination of the area of influence of the preconditioning holes (which extend into the face approximately 2 to 2.5 m beyond the production blast).

Table 2: GPR range settings and approximate penetration depths.

<table>
<thead>
<tr>
<th>Range (Ns)</th>
<th>Depth (m)</th>
<th>Number of scans</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>1.75</td>
<td>3</td>
</tr>
<tr>
<td>50</td>
<td>2.5</td>
<td>7</td>
</tr>
<tr>
<td>70</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>5.0</td>
<td>1</td>
</tr>
<tr>
<td>150</td>
<td>8.0</td>
<td>6</td>
</tr>
</tbody>
</table>

Analysis of fracture pattern data

Change of the fracture pattern with preconditioning

Following the onset of preconditioning there was an appreciable change in the conditions underground due to a change in the fracturing of the rock mass around the stope. This change was not however due to the appearance of new groups of fractures, but rather a change in relative abundance of the existing groups (see Figure 1 and Table 3). There was an increase (20%) in the abundance of steep fractures, whilst the shallow dipping Group I fractures decreased in abundance by 42%. The fractures of Groups IV and V (both with an intermediate dip) did not show much variation. In unpreconditioned areas fractures with an intermediate dip comprised 21% of the total and in preconditioned areas they made up 27% of all the fractures. Thus, in terms of dip, preconditioned areas have more steeply dipping fractures than unpreconditioned areas. This suggests that the fractures are formed further ahead of the face, where the maximum principal stress is more steeply dipping. Of importance also is the position of these steep dipping fractures – within preconditioned areas the majority of the fractures occurred within the plane of the reef, whereas in unpreconditioned areas there was a large number of fractures within the hangingwall.

The same five groups of fractures were found to occur within preconditioned and unpreconditioned areas. The orientation (mean strike and dip vector) of each of the groups in the two areas was found to be very similar (Table 3). Although the strike-vector azimuth of Groups II IV and V appears very different in preconditioned and unpreconditioned areas, they are more or less 180° apart and are thus in fact sub-parallel. The spherical variance of the groups is two orders of magnitude lower than that of the entire database, indicating that the groupings identified are realistic.

As a result of preconditioning, the fractures of Group I decreased in abundance. In unpreconditioned panels these joints and faults accounted for approximately 26% of the fractures, whereas in preconditioned areas they made up less than 15% of the total. There are two potential reasons for this reduced abundance. It is possible that, because preconditioning reduces the stress at the face, these stress fractures are not
able to develop deep into the lava. Secondly, the preconditioning blast may weaken the contact between the reef and the lava hangingwall by shearing and or dilatation. This weakened contact would result in less penetration of the production blast into the hangingwall and hence less fracturing. As a consequence of the reduced number of these fractures, the hangingwall quality is better in preconditioned areas. This difference was quantified by measuring profiles of the hangingwall.

Table 3: Characteristics of the fracture groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plunge (unpreconditioned.)</td>
<td>4°</td>
<td>85°</td>
<td>75°</td>
<td>41°</td>
<td>60°</td>
</tr>
<tr>
<td>Plunge (preconditioned.)</td>
<td>8°</td>
<td>85°</td>
<td>78°</td>
<td>47°</td>
<td>48°</td>
</tr>
<tr>
<td>Angle to face (unpreconditioned)</td>
<td>10°</td>
<td>2°</td>
<td>99°</td>
<td>15°</td>
<td>18°</td>
</tr>
<tr>
<td>Angle to face (preconditioned)</td>
<td>27°</td>
<td>178°</td>
<td>86°</td>
<td>176°</td>
<td>164°</td>
</tr>
<tr>
<td>Percent (unpreconditioned)</td>
<td>26%</td>
<td>38%</td>
<td>21%</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Percent (preconditioned)</td>
<td>15%</td>
<td>47%</td>
<td>24%</td>
<td>11%</td>
<td>5%</td>
</tr>
<tr>
<td>Spherical Variance (unpreconditioned)</td>
<td>0.8°</td>
<td>0.6°</td>
<td>0.2°</td>
<td>0.5°</td>
<td>0.2°</td>
</tr>
<tr>
<td>Spherical Variance (preconditioned)</td>
<td>0.1°</td>
<td>0.6°</td>
<td>0.2°</td>
<td>0.3°</td>
<td>0.1°</td>
</tr>
</tbody>
</table>

In contrast to this decrease in abundance of the shallow dipping Group I fractures, the steeply dipping face parallel Group II fractures showed an increase in abundance (see Figure 1). In certain cases, the fractures changed character from only joints (in unpreconditioned areas) to gouge-filled faults and joints. It is suggested that preconditioning does not cause the development of new fractures in this orientation, but rather extends and opens pre-existing fractures. This is because the preconditioning blast occurs within a zone with abundant pre-existing fractures and micro-flaws (equivalent to the “starter defects” of King and Sammis (1992)). This apparent increase (actually merely a change in the character and extension of pre-existing fractures) led to an improvement in face-advance, with the normal production blast causing the fractures to be further opened and extended.

The steeply dipping face perpendicular Group III joints show almost no variation in abundance between preconditioned and unpreconditioned areas. This is because they formed much earlier than the other (mining induced) fractures in the stope, thus preconditioning could not have an influence on the stresses that caused their formation. The lack of any gouge or crushed material on Group IV and V fractures suggests that they were formed as extensional features. It is thought that they formed when Group I and II fractures were temporarily locked against each other, but due to the lowered minor principal stress of the area could form in extension. In preconditioned areas this is thought to occur further ahead of the face.

**Hangingwall fracturing changes**

Several statistical and mathematical techniques were used to analyse the changes in the pattern of the fracture pattern in the hangingwall as determined by the hangingwall profile measurements. As mentioned previously two types of profiles were measured underground—namely irregular and periodic profiles. The analysis was thus also separated into periodic and irregular techniques. Periodic data were also, however, analysed using the successful techniques described for irregular data. The successful irregular data analysis techniques were: determination of the profile length, its average
gradient and the average deviation of the points along the profile from the mean. Determination of the correlation coefficient and the cumulative size of the steps in the profile were also tested but these techniques proved unsuccessful. The profile length was determined by calculating the distance between successive points along the profile and summing these distances. The straight-line profile length between the first and final point was subtracted from this total. It was found that the profiles measured in the preconditioned areas were significantly shorter (Figure 4) indicating a smoother hangingwall. Profile gradients were calculated by dividing the absolute differences of the x co ordinates of successive points by the absolute differences in the y co ordinates of these points. It was found that the average gradient of preconditioned areas was 0.84, whilst the unpreconditioned areas have a steeper average gradient of 1.15 (Figure 4). The absolute average deviation (a measure of the variation of x with respect to y) in preconditioned areas was found to be almost half of that of profiles measured in unpreconditioned areas (11.6 versus 21.0).

![Graph](image)

Figure 4: Average gradient of hangingwall profiles and the length of the profile exceeding the minimum theoretical straight-line distance is plotted. Preconditioned gradients and profile lengths are significantly lower than those of unpreconditioned areas, indicating a smoother hangingwall.

Periodic data analysis techniques included examination of the moving average of the height of the profile with increasing window length, spectral analysis and the determination of the fractal dimension of the profile. The moving average of the heights was useful for determining the minimum length of profile necessary to include all the major steps in the hangingwall. Unfortunately it was not possible to fit a meaningful fractal dimension to the hangingwall profiles, but research is continuing as the fracture pattern appears to show scale invariance.

One of the most interesting observations came from the spectral analysis of the periodic data. Figure 5 is a plot of the average spectra from periodic profiles measured in both preconditioned and normal areas. Several important conclusions can be drawn from examination of these spectra. Firstly, there is a distinct separation of preconditioned and normal hangingwall spectra. The different groups show the
same trend, indicating that the wavelength (that is fracture spacing) is similar in the two areas. There is, however, a major difference in the amplitude of the spectra, with the unpreconditioned areas having significantly higher amplitudes than preconditioned areas. This indicates that depth of the (equally spaced) fracturing is greater in the unpreconditioned areas.

![Figure 5: Log-log plot of the averaged spectral data from all periodic profiles. Wavelength varies form 5 m (left hand side of the x-axis) to 0.04 m (right hand side of x axis). Note the lower amplitude of the preconditioned profiles.](image)

The decrease in the roughness of the hangingwall is important for support performance. Both backfill and elongate support performs best with smooth hangingwalls, as a more even loading of the support occurs. In addition, a smoother hangingwall indicates less fracturing and hence a more intact beam. The less breaks within the hangingwall beam the further apart the support units can be placed (all other factors being constant).

**Changes in the fracture pattern ahead of the face**

By using GPR it was possible to examine the fracturing ahead of the mining face in preconditioned and unpreconditioned areas. The greater the intensity of fracturing and dilation of individual fractures, the stronger the reflection of the electromagnetic wave transmitted from the antenna. Bearing this in mind, it was possible to examine the general fracture pattern ahead of the stope face. It was found that the depth, intensity and dilation of the fractures ahead of the mining face were greater in preconditioned areas (Figure 6).

The fractures which were detected with the radar were most likely steep dipping and at a sub-parallel to the face, as fractures in this orientation would be the best reflectors of the electromagnetic pulse. This correlates well with fracture mapping data, which indicated an increase in the number of Group II (steep dipping, face parallel) fractures within the plane of the reef. When the radar-scans were examined, it was found that
the area of fracture extension and dilation did not extend beyond 3 m after the production blast ahead of the face. If one takes into account the fact that the production blast results in an average face advance of 1 m, it suggests that the preconditioning blast does not have a major influence on the rock mass further than 4 m ahead of the face. This zone of fractured rock is however able to absorb significant amounts of seismic energy, thereby reducing the potential of a face-burst during a seismic event.

![Figure 6: Radar scan of unpreconditioned (left) and preconditioned (right) panel faces. Note the increase in the depth, intensity and dilation of the fractures in the preconditioned face (indicated by lighter colours). Range setting is 70 ns, depth of penetration (down the page in this view, with face at top) is 3.5 m. Approximately 5 m of face is shown in each scan.](image)

**Conclusions**
Preconditioning has been found to be a successful technique for reducing the incidence of face bursting in deep, highly stressed stopes. In this paper several different measurement and analysis techniques have been presented as ways of quantifying the differences in the fracturing in a deep level tabular excavation due to preconditioning. All the methods are independent of each other, but the observations are complementary.

Significant insight into the rock mass behavior, and hence almarso the effect of preconditioning has been gained from these studies; the most important observation being that preconditioning does not appear to cause the development of new fracture sets. Rather, the relative abundance of pre-existing fracture sets is modified. This is evidenced by the fact that no new fracture groups were mapped within the preconditioned areas when compared to areas of similar depth and mining conditions. Fracture mapping indicated that the top reef contact of preconditioned stopes was weakened by shearing, thus preventing fractures from penetrating deeply into the hangingwall. Spectral analysis of hangingwall profiles confirmed this, with the profiles in preconditioned areas having the same trend but lower amplitude than those in unpreconditioned areas. Hence preconditioned stopes typically have much better quality hangingwall and are less prone to falls of ground. Whilst there was a decrease in the intensity of shallow dipping fractures in the hangingwall, there was also an increase in the abundance of steep dipping face-parallel fractures within the reef horizon. This was seen as an increase in the Group II fractures. GPR work showed that this increase was not restricted to the immediate face area, but that the area of fractured rock ahead of the face actually also increased. It should be remembered that
the apparent increase in the abundance of these fractures was due to extension of pre-existing weaknesses within the rock mass. Small pre-existing flaws are extended and enhanced by the preconditioning blast (see Figure 7).

Figure 7: Sketch diagrams to show the reason for apparent increase in abundance of Group II fractures. I) An idealized section through the rock mass ahead of stope face. Note that line a-a' only intersects one fracture II) The same area ahead of the face, but after a preconditioning blast has caused extension of pre-existing fractures. Now line a-a' intersects four fractures. Note the change in dip of fractures as they pass through the reef horizon. Certain fractures can interconnect to form a continuous surface.

These different studies allowed specific values to be assigned to a complex pattern of fracturing, thereby allowing scientific comparison of the changes in the rock mass behavior as seen by different conditions underground.

In conclusion it may be said that the combination of fracture mapping, hangingwall profile measurements and GPR work gives a clear picture of the type, abundance and distribution of the discontinuities developed in a preconditioned stope. When compared with similar data obtained from unpreconditioned areas they provide details of the mechanism of stress transferral by the rock mass in response to preconditioning.

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References