The mechanism, optimization and effects of preconditioning

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Synopsis

An extensive research programme to address the issue of rockburst control has been undertaken over a number of years. This paper discusses the development of preconditioning techniques to control face bursts, for safer mining in seismically hazardous areas. Preconditioning involves regularly setting off carefully tailored blasts in the fractured rock immediately ahead of a mining face, so as to encourage slip on pre-existing fractures, in order not to allow the accumulation of high strain energy density in the rock mass.

Two different preconditioning techniques have been developed, namely face-perpendicular preconditioning and face-parallel preconditioning. Both have prevented face bursting in areas to which they have been applied, even though several large seismic events have occurred close to the faces in some areas. In addition, minimal overall damage was observed in the preconditioned panels following these events, compared to similarly exposed unpreconditioned panels. Preconditioning has also provided some protection to the face area from distant events, through the capacity of the preconditioned ground to absorb energy. An improvement in hangingwall stability and productivity has also been noted in preconditioned areas.

In order to determine the optimum blast parameters for achieving the most effective preconditioning, an extensive optimization study was carried out for the face-perpendicular preconditioning technique. While optimum values for parameters such as hole length, diameter and spacing were determined, it was ultimately concluded that the differences in results obtained by varying the preconditioning parameters were less significant than the clear positive differences observed when comparing preconditioned areas with non-preconditioned areas.

Introduction

Preconditioning, or 'destressing' as it was initially called, was first introduced as a means of ameliorating rockburst conditions in deep mines by the management of the East Rand Proprietary Mines (ERPM) in the early 1950s with the co-operation and guidance of the CSIR (Roux *et al.*[1957]). The principle on which destressing was based at that time was that '*The occurrence of rockbursts might be reduced or their violence decreased by increasing the depth of the fracture zone at the face of the working stope*'. The argument for this was based on the concept that, if the holes drilled at right angles into the face were blasted, they would advance the depth of fracturing and in so doing transfer the high stress zone further away from the face into the solid. Furthermore, should sudden failure occur in the high stress zone, only limited damage would result, because of the cushion effect of the 'destressed' zone ahead of the face.

Field trials were carried out by ERPM in the 1950s to assess the feasibility of destressing, or preconditioning, as a safety measure to reduce the incidence of rockbursts. The results of these trials were encouraging. For example, the incidence of rockbursts per area mined was reduced by 36 per cent; the number of severe rockbursts was reduced by 73 per cent, and the frequency of on-shift rockbursts dropped to almost zero. However, despite these apparent benefits, preconditioning was not generally accepted by mines as a viable and safe mining method. To address this problem, the Chamber of Mines Research Organization (COMRO) initiated a programme to re-investigate preconditioning as a viable, safe mining method in the late 1980s.

COMRO's (later CSIR / Miningtek) involvement in preconditioning began in 1987. An extensive Rockburst Control research programme has been carried out since then. In order to develop preconditioning techniques to enable mines to operate safely in areas which are at risk from seismicity and resulting rockbursts, a number of field trials at various mines was performed.

Preconditioning mechanism

The development of a conceptual model of the rock mass surrounding a deep-level stope was based on many years of detailed mapping of

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mining-induced fractures. Of prime significance in this model is that the rock surrounding the stope has failed prior to its excavation. Depending on mining geometry and stress conditions, these fractures can develop many metres ahead of an advancing stope face. The fractured rock mass ahead of the stope face is subjected to extremely high stresses, resulting in the complex fracture patterns observed underground. Once the fractures have been created, stress can continue to increase as long as confinement is maintained. Slip on the fractures results in the deformation of the rock mass and convergence of the hangingwall and footwall.

It seems that both slip and the inhibition of slip along the abundant fractures immediately ahead of the face could account for the complex rock mass behaviour that is observed in and around stopes underground. Owing to this complex geometry, if slip along fractures is inhibited, strain energy will be allowed to accumulate at various positions in the rock mass. This energy can be relieved when the confinement at the face is reduced by the advance of that face. If sufficient energy was present immediately ahead of the face, the resulting energy release could take the form of a face burst.

The stress fields and gas pressures generated by preconditioning blasts remobilize the blocks defined by mining-induced fractures, by shearing through asperities that are responsible for the 'lock-ups' on the fractures. In the process, strain energy release is facilitated by stable sliding of blocks past each other, thus reducing the risk of occurrence of face bursting during the production shift. Preconditioning results in the redistribution of stress away from the working face (Figure 1), thus reducing the risk of a face burst. The resulting less stressed ground is then also less prone to allow sudden slip on asperities when excited by incoming stress waves from distant events. In this way, it may be possible to control the size and timing of seismic events at the face, and to influence the extent and severity of damage that may occur as a result of distant events.

Since it is only the state of stress that has changed (rather than the rock mass being physically 'softened'), it is likely that, if the confinement were to be re-established in a previously preconditioned zone, the preconditioning effect could be reversed. It has been shown, both by underground observation and by computer simulation, that this is possible. Under certain circumstances, it is possible that stress can be transferred back towards the face area. This could happen either through the effects of large seismic events near the face or of poorly positioned preconditioning holes, or through the regeneration of lock-ups due to time-dependent deformation of the rock mass.

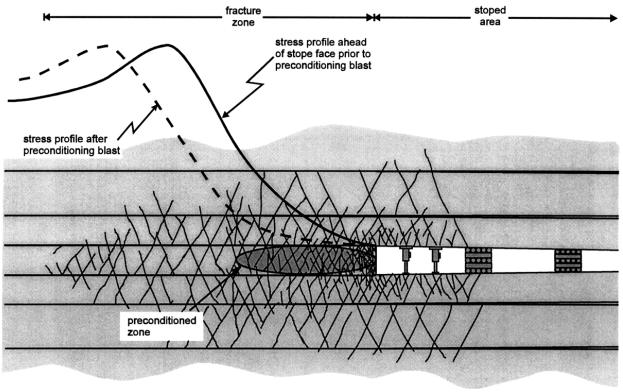

Figure 1—Stress redistribution due to preconditioning

Influence of stress waves and gas pressurization

As stated by Daehnke[1997], the interaction between a rock mass and detonating explosives is a complicated process which involves non-linear material behaviour, dynamic fracturing and gas dynamics in the form of hot combustion gases streaming into propagating fractures. These processes take place in a very short time interval: the detonation of the explosive and full borehole pressurization are effected within a few milliseconds and the subsequent development of radial fractures due to gas pressurization is completed within a few hundred milliseconds. Clearly, it is difficult to assess such complicated short-term processes quantitatively, especially when they take place within a non-uniform material such as rock and particularly when considering the underground environment.

Daehnke[1997] investigated stress wave- and gas pressure-induced fracturing in transparent material (PMMA) using high-speed photography, by means of which the spatial evolution of the stress waves and blast-induced fractures at discrete time intervals could be studied. While this work was focused on gaining understanding of the mechanisms by which blast-induced fractures are formed and propagated in rock, it also offered some valuable insight into the probable mechanism by which a preconditioning blast in pre-fractured material might achieve its effect.

Blast-induced fracturing

The detonation of an explosive charge in a borehole liberates combustion gases, which expand and suddenly pressurize the borehole cavity. The immediate vicinity of the borehole is then highly strained and borehole breakdown can result. This involves non-linear material behaviour, including fracture initiation. The rapid borehole pressurization gives rise to stress waves which propagate into the surrounding medium. The nature of these stress waves is governed largely by the charge geometry.

Column charges do not detonate instantaneously in practice. Instead, the detonation front proceeds at a finite speed—the velocity of detonation (VOD)—along the charge length. At a VOD of less than or equal to the P-wave speed in the material (but greater than the S-wave speed), a substantial proportion of the total energy is present in the form of S-wave energy. Owing to the high VOD (between 2000 and 6000m/s) of most commercial explosives, the borehole is rapidly pressurized, after which the pressure decay takes place comparatively slowly, due to the additional volume formed by fracturing and due to thermal quenching.

Immediately after detonation, radial fractures driven by tensile tangential stresses can realistically be assumed to propagate at a maximum velocity of about half of the Rayleigh wave speed of the material. This initial fracture speed rapidly decreases to less than 10 per cent of the P-wave speed, so that borehole de-pressurization occurs at a comparatively slow rate. It has been found that the borehole

pressure decay rate has a limited influence on the dynamic stress field, but that prolonged pressure decay has important implications in terms of the static stress field and results in more extensive gas-driven fracturing.

The initial amplitudes of the stress waves (typically, hundreds of MPa) are rapidly attenuated as the waves expand away from the borehole, so that fragmentation due to the stress waves is usually limited to the immediate vicinity of the borehole. The dynamic tensile stresses act for a comparatively short time before converging to the quasi-static stresses induced by borehole pressurization, which are then responsible for the majority of the dense network of radial fractures surrounding the borehole. The stress waves rapidly outpace the fractures, which propagate at a much slower rate, so that the fractures extend mainly due to pressurization by the combustion gases rather than under the influence of the stress waves. Interestingly, Daehnke saw no evidence of significant fracture deflection due to multiple stress wave reflections within the PMMA blocks.

Post-blast observations of the near-borehole zone typically reveal a narrow annular region of crushed rock, which has failed due to the high radial and tangential compressive stresses acting in the vicinity of the borehole wall. Beyond the region of crushed rock, a dense system of radial and circumferential cracks extends for about 3,5 hole radii from the borehole centre. The radial cracks form due to tangential tensile stresses induced by the quasi-static borehole pressurization superimposed by tensile stresses associated with the trailing tail of the tangential stress pulse component, while the circumferential cracks form due to the very high stress gradient associated with the rapid transition from compression to tension induced by the radial stress pulse. It is only within this zone that cracks remain open after blasting. Two intermediate zones are formed outside this zone by the extension and kinking of the radial cracks which formed in the innermost zone, while, in the outermost elastic zone, the comparatively few cracks are driven by pressurization by the combustion gases. The specific borehole cracking pattern strongly depends on the blasting condition and configuration, and on the degree of coupling between the charge and the borehole wall (increased damage is produced by increased coupling).

Daehnke considered the case of a free surface intersecting the borehole. It was found that, upon reflection of the conical S-wave front at the free surface, the material is subjected to high stresses at the reflection point. For the case of a VOD between the P- and S-wave speeds in the material, the dynamic tensile stresses acting in the vicinity of the reflection point are likely to initiate fracturing along the free surface. For the case of a stemmed charge intersecting a plane of weakness orthogonally, Daehnke found that, when gas-driven fractures intersect the plane, gaseous detonation products enter the plane and the sides of the interface separate due to the gas pressurization. During the initial stages, when the fractures are propagating rapidly due to high stress wave and gas pressure loading, the main fractures appear to continue propagating without change in direction across the interface. As the gases driving the fractures penetrate the interface and the gas pressure separates the sides of the plane, all subsequent fractures terminate abruptly at the interface. At later times, the interface de-lamination and radial fracture propagation outwards from the borehole occur at the same rate.

A quasi-static treatment of stresses and rock displacements is generally considered appropriate for explosively induced gas-driven fractures, as most of the stress waves occur on a very brief time scale compared with that of the late-time gas fracturing phenomena. Also, the speed of the gas-driven fractures is small in comparison with wave speeds in rock, so that the gross features of the surrounding stress field are nearly quasi-static: the effect of the blast-induced stress waves on the fracturing is separated in time from the gas-driven fracturing. Daehnke used a combined analytical/numerical procedure to simulate the gas-driven fracturing associated with column blasting in competent rock confined by uniform compressive stresses; no attempt was made to model the gas leak-off as pressurized cracks interact with pre-existing voids.

During the reaction of the explosive, the detonation front pressure (acting in a localized area for a very short time) is of the order of GPa's. Owing to the effects of charge de-coupling and borehole expansion and fracturing, the actual borehole pressure driving the fractures is orders of magnitude lower than the pressure at the detonation front. In reality, gas flow is not isothermal, and convective and conductive heat transfer from the hot combustion gases to the fracture walls and into the surrounding bulk material reduces the gas energy. In addition, with increasing gas seepage into the exposed fracture walls due to rock permeability and porosity, the final fracture length decreases; for highly pre-fissured rock, this is likely to be the main mechanism restricting fracture growth.

Application to preconditioning

Clearly, the results of investigations into the mechanisms of blast-induced fracturing conducted in a homogeneous material under controlled laboratory conditions cannot be directly applied to explain the mechanism by which a precon-ditioning blast in a pre-fractured rock mass achieves its effect. However, the improved understanding of the interaction between stress waves, gas pressurization and the fracturing host material gained by Daehnke[1997] and other workers in related fields can be extrapolated to derive a likely scenario for the processes active during such a precondi-tioning blast, as outlined below.

When the preconditioning blast is set off, the borehole is rapidly pressurized and the rock in the immediate vicinity of the borehole is pulverized due to the action of the high compressive stresses on the borehole wall. The stress waves generated by the borehole pressurization are initially of sufficient magnitude to produce a zone of intense radial fracturing close to the borehole. The stress waves then propagate outwards and their amplitudes are reduced by the effects of geometric and intrinsic attenuation. Thereafter, the blast gases act to extend the fractures outwards from the borehole wall into the surrounding rock mass.

When the propagating fractures intersect pre-existing fractures in the surrounding rock mass, the blast gases enter the existing fractures and pressurize them. The sides of the fractures are forced apart, reducing any clamping stresses and allowing the rock to slip across the fractures in response to the prevailing mining-induced stresses acting on them,

thus relieving the stress acting on the stope face as a whole. The diversion of blast gases into existing fractures reduces the number and size of new fractures, compared with what might have resulted from a blast in previously unfractured rock.

The action of the stress waves in the pre-fractured rock mass depends on the type of stress wave (whether longitudinal or shear) and on the orientation of the pre-existing fractures with respect to the direction of propagation of the stress waves. The stress waves, by introducing rapid fluctuations in time of clamping or tensile stresses, might therefore act either to increase the clamping across locked fractures, or might add to any stress tending to cause slip on the fractures, perhaps overcoming the clamping and allowing slip to take place. The local stress concentrations formed by reflections of stress waves at discontinuities in the rock mass are likely to contribute to the action of the propagating stress waves in the rock mass, as well.

While the effects of stress wave-induced remobilization of fractures can probably not be divorced from remobilization under the influence of pressurization of blast gases in practice, it would seem that the role of the blast gases in achieving the preconditioning effect is very significant. Given that gas pressurization has been shown to be the more important mechanism driving fracture growth at some distance from the blast in unfractured rock, it is likely that it is also the more important factor in terms of the remobilization of existing fractures.

The effect of preconditioning on stress wave transmission through discontinuous rock

Underground observations have indicated that preconditioned stopes are generally less prone to damage due to seismic events occurring at some distance away from the stope face. A possible mechanism contributing towards the reduction in damage is associated with the extension of fracture zone as well as existing discontinuities being mobilized, by the preconditioning blasts.

Stress waves, initiated due to the sudden rupture of fault and dyke interfaces, propagate towards the stope. In homogeneous, intact rock the amplitudes of the stress waves attenuate inversely proportional to the distance propagated (geometric attenuation). In discontinuous rock, however, the incident wave energy is reflected and refracted (transmitted) at the discontinuity interfaces. The amplitude of the stress wave which interacts with the excavation surface is thus significantly reduced in amplitude due to (i) geometric attenuation, as well as (ii) energy reflection. In a highly discontinuous rock mass more energy is reflected, and the refracted portion which is finally transmitted to the excavation surface is reduced in magnitude.

Daehnke[1997] investigated in detail the reflection and refraction characteristics of various discontinuity types. A non-cohesive frictional interface model is used to investigate the wave interaction with rock mass discontinuities ahead of the stope face. By means of an analytical formulation of the problem, it is shown (Daehnke,[1997]) that the amplitudes of the reflected and refracted waves depend on the angle of wave incidence, Poisson's ratio, and the coefficient of friction between the joint surfaces. Two boundary conditions need to be satisfied, depending on whether the joint sticks or slips. The transition from stick to slip depends on the angle of wave incidence and the coefficient of friction. During the slip process energy is dissipated, and hence the cumulative wave energy of the reflected and refracted pulses is not equal to the incident wave energy.

Preconditioning blasts generate new fractures in the reef horizon and mobilize and extend the existing discontinuities ahead of the stope face, and hence, compared to non–preconditioned stopes, the excavation is more effectively shielded from incident stress waves. This results in reduced peak particle velocities in the immediate excavation vicinity, and potentially less structural damage to the rock mass.

Optimization and effects of preconditioning blasts

In order to optimize the face-perpendicular preconditioning technique with respect to blast parameters (e.g. hole length, hole diameter, hole spacing, explosive amount, etc.), an optimization experiment was carried out at the project site. The effects of varying the lengths of preconditioning holes were investigated using the available drill-steels at the mine (i.e. 2,4m, 3,2m and 3,8m). Each of these drill-steel lengths was used for a minimum of two weeks for the drilling of preconditioning holes. Initially, these holes were drilled with a 36mm bit, but, after the initial six week period, the bit size was changed to 40mm. This was done to examine the effect of changing the hole diameter (and hence the amount of explosive) on the effectiveness of preconditioning. Various measurements were used to examine and quantify the effects of the various preconditioning scenarios.

Seismic activity

During the optimization work, the seismic data was recorded by the Portable Seismic System (PSS) from the vicinity of the project site. The seismicity was clustered into distinct spatial groupings associated with the area of active mining.

The slope of the linear portion of the frequency-magnitude graph yields the b-value, which gives an indication of the relative proportions of larger and smaller seismic events (e.g. a lower b-value indicates that more seismic energy is being released via a relatively large number of larger events). A b-value of about 0,5 is fairly typical of deep-level longwall mining environments. The minimum recorded magnitude (M_{min}) was -0,79 which indicates that seismic events of magnitude smaller than this are not reliably detected by the system. The seismicity rate was fairly uniform during the optimization period.

As was described earlier, the preconditioning optimization experiment passed through four stages, each characterized by the use of different drill-steel lengths and/or drill-bit diameters in the drilling of the face-perpendicular preconditioning holes. Some 21 large (M>1) seismic events were recorded from the site during the period. Two of these events occurred virtually simultaneously. One of the events occurred ahead of the face of an unpreconditioned panel and resulted in extensive damage to the panel (production had to be stopped for over a week for rehabilitation), while the other occurred close to a preconditioned panel and resulted in very minor damage. Production activity recommenced in this panel on the following working day. No injuries were reported due to this incident.

Four other large seismic events occurred in close proximity to the preconditioned panel during the period of the optimization study, none causing noticeable damage to the panel. Another evidently significant result which has emerged from this study is that no seismic activity was recorded from the vicinity of the preconditioned panel between 20:00 and 04:00 during the period of the study. This suggests that the preconditioning blasting was effectively destressing the rock mass ahead of the panel face, and that this destressing remained in effect for some time following the production blast (i.e. that the panel was made safer, at least for the period during which the night shift was present in the stope).

Certain source parameters determined for the seismic data recorded during the period indicate that the preconditioning of a panel was having a positive effect on the conditions of that panel compared with those of the unpreconditioned panels in the project site. Unfortunately, the seismic data recorded during the period was insufficient to allow for discrimination among the different phases of the optimization study.

Rock mass fracturing and hangingwall profiles

Five distinct mining-induced fracture groups were identified at the project site based upon their spatial orientation (dip and strike). The fractures mapped at the site, after the initiation of preconditioning, populated the same five groups identified in the stope before preconditioning was initiated. However, the abundances of the fractures within these groups differed between preconditioned and unpreconditioned (normal) areas.

Following the inception of preconditioning, there was a noticeable change in the appearance of the stope. This resulted from a change in the fracturing of the rock mass around the stope. Despite this change, no new groups of fractures formed. Rather, the relative abundances of the existing groups changed (Figure 2). There was a significant increase (25 per cent) in the number of steeply dipping fractures, whilst shallowly dipping fractures showed a 61 per cent decrease in abundance in preconditioned areas. Fractures with an intermediate dip did not show much variation in abundance between preconditioned and unpreconditioned (normal) areas. In normal areas, fractures with an intermediate dip made up approximately 21 per cent of the total, compared to 27 per cent in preconditioned areas. It can therefore be deduced that, in terms of dip orientation of fractures, preconditioned stopes have steeper dipping fractures when compared with normal stopes.

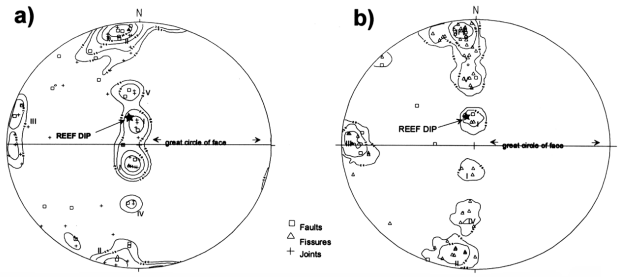

Figure 2—Schmidt-net (lower hemisphere projection) of poles to all fractures mapped in the preconditioning project site. a) Prior to preconditioning and b) after preconditioning

During the optimization phase, minor variations in the fracture pattern were observed with the various depths of preconditioning and various bit diameters. These differences, while measurable, are less significant than those observed when ground conditions in the preconditioned and unpreconditioned panels are compared.

From the fracture mapping data, it would appear that the 3,2m drill-steel (with a 40mm bit) is the most effective scenario at remobilizing the fractured rock mass within the reef horizon, whilst restricting the extent of damage to the hangingwall.

One of the beneficial side effects of preconditioning is an improvement in the quality of the hangingwall conditions. These effects were quantified by measuring profiles of the hangingwall. With increasing drill-steel length, and subsequent change in bit diameter, the quality of the hangingwall was seen to improve. The smoother hangingwall at preconditioned panels results from the combined effect of fewer fractures in the hangingwall and of decreased penetration of those that do occur, compared with unpreconditioned areas.

Ground penetrating radar surveys

Ground penetrating radar (GPR) was used to determine the effect of preconditioning on the rock mass as well as the optimum spacing of preconditioning holes. The electromagnetic pulse emitted by the GPR antenna is reflected strongly by fracture planes, particularly if the fractures are open and the sides of the fractures are coated with the residues from the blast gases. As a result, it was possible to look at the depth and intensity of fracturing ahead of the face and, thus, to define the zone of influence of the individual preconditioning holes. The fracture pattern ahead of a preconditioned face was also compared with that ahead of an unpreconditioned face.

The GPR work proved very successful in delineating the extent of re-activation of fractures ahead of a preconditioned face. Figure 3 shows annotated radar scans (superimposed with the positions of mapped preconditioning holes) and clearly illustrate the zones of influence of the individual preconditioning blasts. Analysis of the GPR data indicated that the effective zone around each preconditioning hole extends for about 2m in radius. A spacing of greater than 4m between adjacent holes resulted in an unpreconditioned zone between two preconditioning holes. Figure 3 shows that two of the preconditioning holes were not drilled on the previous day and, hence, none of the pre-existing fractures were opened up at those positions.

A significant difference in the nature of fracturing ahead of preconditioned faces from that ahead of unpreconditioned faces was detected from the GPR scans. In unpreconditioned areas, the depth of open fractures ahead of the face extended to approximately 2,5m, whereas, in preconditioned areas, the zone of rock ahead of the face with open fractures was up to 4m deep. The density of open fractures was also much higher in preconditioned areas.

Face advance

In addition to the safety aspects of preconditioning, a

significant increase in the face advance rate, consistent with the improved fragmentation noted earlier, has also been noted. This is mainly due to opening and extending the pre-existing fractures in the reef by the preconditioning blast. In addition to this, the face dilation and resultant shearing along the reef/hangingwall and reef/footwall contacts, caused by preconditioning, also contribute to the ease of face breaking. During the optimization work, the face advances were measured daily at the test panel from fixed points. The results of these measurements are summarized in Table I.

The effect of preconditioning on face advance rates appears to be significant. The greatest face advance was achieved when the preconditioning holes were drilled with a 3,2m drill-steel and 36mm bit. During preconditioning, the average face advance rate increased by almost 50 per cent compared with unpreconditioned periods, which decreased the mining cost per centare.

Drilling rates

The drilling rate should be affected by the state of stress in the rock. The initial study into the time required to drill one 3,0m long preconditioning hole established that the average drilling time was approximately 12 minutes. The panels at the project site were, on average, 17m long and, for each panel, two drilling teams were allocated to drill about 60 production holes in total. Since six preconditioning holes should be drilled in such a panel, it was thought that each drill crew would need to drill for an extra 45 minutes. Thus, when preconditioning was initiated on a particular panel, it was considered, among the workers, as work in addition to their daily responsibilities.

The timing of the drilling of both preconditioning and production holes was undertaken at the project site. The results of these timing studies are tabulated in Table II and Table III. As the hole length increased, so did the drilling time. However, this increase was not uniform. It took one minute longer to drill 3,0m holes than 2,2m holes (an extra 0,8m) and two minutes longer to drill 3,6m holes than 3,0m holes (0,6m extra). This was most likely due to the increased stress encountered further ahead of the face, which would make it more difficult to drill. The best drilling rate was achieved with a 3,2m drill-steel and 40mm drill-bit. Although the area to be drilled was increased by 23 per cent, the additional button on the 40mm bits compensated for this. The increase in the amount of explosive (and resultant fracturing) also contributed to the improved drilling rate for subsequent holes. It is important to note that the drilling of preconditioning holes as deep as 3,6m was not an impossible task and could be completed in less than 15 minutes.

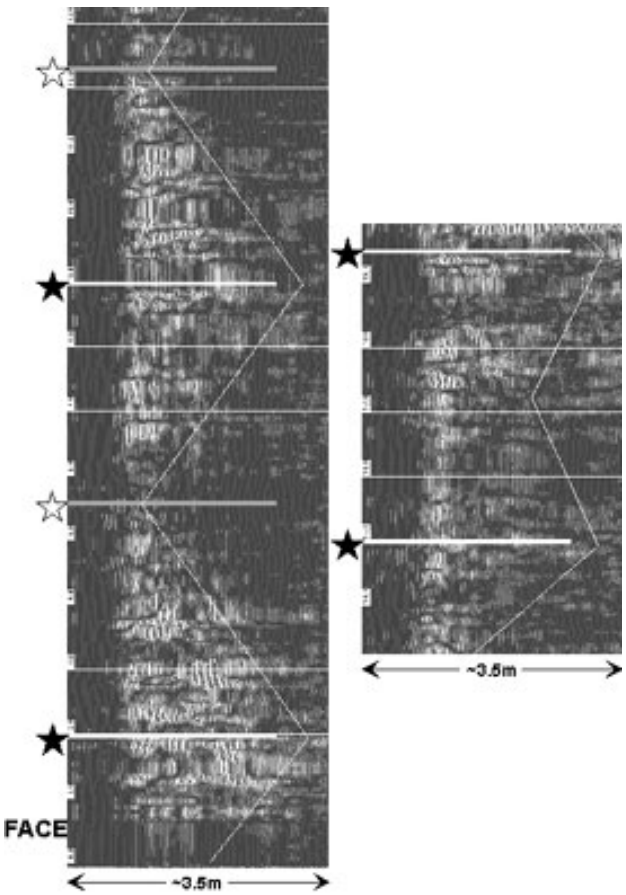

Figure 3—Ground penetrating radar scan (range setting of 70 ns). The solid white bars (and black stars) represent the positions of preconditioning holes, while the solid grey bars (and white stars) show where preconditioning holes should have been drilled, but no such evidence could be found

Table I

Comparison of face advance rates in adjacent panels in the 87–49 stope

Scenario*	Face advance (metres per blast)		
	Minimum	Average	Maximum
Unpreconditioned	0,55	0,70	0,85
Preconditioning (2,4m, 36mm)	0,80	1,06	1,60
Preconditioning (3,2m, 36mm)	0,80	1,16	1,50
Preconditioning (3,8m, 36mm)	0,90	1,14	1,35
Preconditioning (3,2m, 40mm)	0,90	1,03	1,20

**Preconditioning holes are described by drill-steel length and bit diameter*

Table II

Comparison of drilling rates of preconditioning holes

Scenario*	Minimum	Average	Maximum	Average (metre/minute)
Preconditioning (2,4m, 36mm)	10′00″	11′38″	12′59″	0,19
Preconditioning (3,2m, 36mm)	10′30″	12′37″	14′16″	0,24
Preconditioning (3,8m, 36mm)	12′59″	14′31″	15′55″	0,25
Preconditioning (3,2m, 40mm)	8′36″	10′45″	12′35″	0,28

**Preconditioning holes described by drill-steel length and bit diameter*

Table III

Comparison of face drilling rates of production holes for adjacent preconditioned and unpreconditioned panels.
Drilling times decrease with increased drill-steel length and drill-bit diameter

Scenario*	Minimum	Average	Maximum	Average (metre/minute)
Unpreconditioned	4′34″	5′08″	5′51″	0,21
Preconditioning (2,4m, 36mm)	3′56″	4′48″	5′50″	0,23
Preconditioning (3,2m, 36mm)	3′00″	3′57″	5′10″	0,28
Preconditioning (3,8m, 36mm)	2′30″	3′05″	3′55″	0,36
Preconditioning (3,2m, 40mm)	1′56″	3′14″	4′31″	0,34

**Preconditioning holes described by drill-steel length and bit diameter*

The effect of preconditioning on improving the drilling rate of production holes is significant (Table III). This has a favourable impact on the actual time the drilling team spends in a shift. All of the preconditioning scenarios have higher drilling rates than the unpreconditioned case, the best drilling rate being 0,36m/min. If the total drilling times are compared in unpreconditioned and preconditioned panels, it can be seen that less time is actually spent drilling in preconditioned panels, despite drilling more metres.

Safety implications

The primary objective of preconditioning is to reduce the risk of potential face bursts and minimize the damage caused by any seismic event that occurs in the vicinity of the face. During the preconditioning experiment (about 21 months), no face burst has been reported from a preconditioned panel. However, some slight injuries were associated with the incorrect or ineffective application of preconditioning.

Table IV shows the centares mined per reportable injury (classified as related to seismicity and falls of ground) in the project site during the experimentation. A clear improvement can be seen after the introduction of preconditioning. During the diagonal mining period, the deteriorating safety record can be attributed to the poor face configuration (with respect to joint orientations) and the formation of highly stressed areas adjacent to the stability pillar. After the faces were re-established for up-dip mining, there was a significant improvement in the safety record.

Fragmentation

Each preconditioning blast hole is initiated just prior to neighbouring production blast holes, so that existing fractures are opened up and extended, thus reducing the stress near the face. The production blast should then break the face much more efficiently and a preconditioned panel should show better fragmentation of the material coming off the face than an unpreconditioned one.

Although some sophisticated techniques of image processing of fragmented rock are available, it was possible to use simple two-dimensional photographic images of blasted rock to quantify the differences between fragments in preconditioned and unpreconditioned panels. Photographs of preconditioned and unpreconditioned rock piles were taken at the stope face prior to cleaning. Then photographs from each of the two panels were examined and the edges of the rock fragments were detected and traced manually, since the contrast in a pile of broken rock was not sufficient for an automated process. The area of each fragment was calculated using a digital planimeter and the dimensions (i.e. long and short axes) were measured.

The analysis on the averages of calculated areas of the fragments show that the fragment area is smaller in preconditioned panels. A reduction of nearly 50 per cent in the average area of fragments was observed in the preconditioned panel. This improved fragmentation from a production blast results in about 30 per cent smaller sized particles and a more uniform particle size distribution, thus improving material handling efficiency.

Conclusions

The effect of preconditioning is localized both in space and time. As the mechanism of preconditioning is one of stress transfer resulting from induced deformations in the fracture zone ahead of the face, rather than one of actually modifying the material properties of the rock, the zone that is preconditioned is still capable of carrying high loads. After a face has been preconditioned, it is possible that subsequent mining of that face or of adjacent faces will result in the transfer of stress back onto the preconditioned rock mass, if nothing is done to prevent this from happening.

Of practical significance is that stress transfer is a dynamic, ongoing process. The stress is redistributed in the rock mass in response to both mining and preconditioning. The preconditioning process must be integrated into the production cycle in a controlled, sequential manner. This sequence must be engineered to ensure that the most favourable stress distribution for maximum face stability is maintained at all times.

Preconditioning has prevented face bursting in areas to which it has been applied correctly, even though several large seismic events have occurred close to the faces. In addition, minimal overall damage was observed in the preconditioned panels following these events, compared to similarly exposed unpreconditioned panels.

The main purpose of preconditioning is to prevent face bursts. Indirectly, it can affect the rock mass in the vicinity, through the stress transfer resulting from the blast. Although preconditioning might be beneficial in providing some

Table IV

Safety record for the project site during the preconditioning experimentation

	Safety record (centares mined/injury)		
	Up-dip	Diagonal	Combined
Preconditioning	2 553	981	1 430
Non-preconditioning	735	377	562
Combined	937	528	741

protection for the face area from distant events, it is not possible to influence the source of such events. Preconditioning cannot control the large-scale behaviour of the rock mass (manifested, for example, in the form of instabilities on geological structures or in pillars). It can, however, provide some protection to the face area from distant events, through the capacity of the preconditioned ground to absorb energy that might otherwise lead to in-stope damage.

An improvement in hangingwall stability has generally been noted in preconditioned areas. Fracture mapping results have indicated that a reduction in the prevalence of adversely-oriented fractures was probably the major contributing factor to this improvement. The mechanism of preconditioning is one of opening up pre-existing fractures ahead of the stope face, so as to dissipate strain energy by enhancing shear mobilization of the discontinuities and the breaking of asperities. In the process, blast gases can also penetrate the distinct bedding plane that overlies many reefs, weakening or even delaminating this plane. Any fractures that have a tendency to grow in the preconditioned zone will not be able to penetrate this weakened bedding plane. Under these circumstances, production blast fractures will truncate before they cause damage to the hangingwall. However, preconditioning experimentation to date has generally taken place in areas with a reasonably strong and competent hangingwall, with a relatively narrow stoping width. It is possible that large preconditioning blasts may have a detrimental effect on the stability of weaker hangingwall strata. It is expected that future implementation of preconditioning in different areas will provide more insight in this regard.

In addition to the safety aspects of preconditioning, a significant increase in the face advance rate, consistent with the improved fragmentation, has also been noted. During preconditioning, the average face advance rate increased by almost 50 per cent compared with unpreconditioned panels, which decreased the mining cost per centare.

The effect of preconditioning on improving the drilling rate of production holes was also significant. This has a favourable impact on the actual time the drilling team spends in a shift. When the total drilling times were compared in unpreconditioned and preconditioned panels, it was seen that less time is actually spent drilling in preconditioned panels, despite drilling more metres. Higher drilling rates were achieved when the amount of explosive in the preconditioning holes was increased.

The differences in results obtained by varying the preconditioning blast parameters were less significant than the clear positive differences observed when comparing preconditioned areas with non-preconditioned areas. However, in order to maximize the effectiveness of preconditioning, it is advisable to optimize the blast parameters when preconditioning is implemented in new environments. Practicality and suitability should be the major concerns: compromising the optimal preconditioning application somewhat is preferable to disrupting the mining activity unnecessarily.

When considering drill-steel lengths, optimal results were achieved for preconditioning holes drilled with 3,2m drill-steels. These drill-steels yielded the best face advances, if only marginally better than those from 3,6m drill-steels. The latter drill-steels did yield slightly higher drilling rates, but required longer manoeuvring times. The relative practical merits of using the 3,2m drill-steels in the confined space of a stope face also outweighed whatever improvement in preconditioning effect might have been derived from the longer drill-steels. The use of 2,4m drill-steels is not recommended, although preconditioning even with the shorter drill-steels is more beneficial than not preconditioning at all.

The use of a larger diameter drill-bit (40mm, compared with the standard 36mm bit used for drilling the normal production holes) with the 3,2m drill-steels yielded somewhat improved results. However, potential practical problems that could be encountered when using drill-bits of two different sizes in the stope may outweigh the potential gains of using the larger bits. Therefore, the use of drill-bits of the same diameter as those used to drill the normal production holes is recommended for drilling the preconditioning holes, to facilitate the successful integration of preconditioning into the production routine.

Analysis and interpretation of the GPR data indicated that the effective zone around each preconditioning hole extends 2m along the stope face. Thus, a maximum spacing of 4m between preconditioning holes is recommended for effective preconditioning of the whole length of the stope face. This should prevent the formation of hard patches of locked-up fractures ahead of the face, which could attract stress concentrations, leading to an increased risk of face bursting. In practice, the spacing between adjacent preconditioning holes is influenced by the spacing between packs at the face, but it is important that this should not be allowed to result in increasing the hole spacing to beyond the recommended maximum.

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