Mining the South Reef at Doornkop

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ABSTRACT: The South Reef, exposed at Doornkop Gold Mine between 1600 m and 2000 m below surface, is a tabular ore-body mined at 1.2 m stoping width in a predominantly quartzite environment, typical of South Africa's Witwatersrand system. Generally conditions are favourable with continuous hangingwall broken up by occasional steeply dipping joint sets, dykes and sills. The continuous host rock has allowed for rapid haulage development and generally favourable stoping conditions. The stopes are supported with a combination of timber packs mine poles and roof-bolts with temporary jack support used in the face area during the day shift. The support pattern, designed to carry a tensile zone of 6 m above the stopes has proved effective in inhibiting back-breaks across spans in excess of 200 m however; rapid deterioration of the hangingwall in some face areas has necessitated a study of the behaviour of extension fractures and further engineering the rock-mass to prevent large falls of ground.

This paper describes an investigation into the nature of hangingwall fracturing in our face areas and a strategy adopted to reduce their potential danger.

1. INTRODUCTION

Doornkop is an intermediate depth gold mine situated on the northern side of the Witwatersrand System 30 km west of Johannesburg. A number of gold bearing reefs exist within the lease area at different depths, however, currently most of the development and stoping activity is taking place on the South Reef, a tabular orebody between 1600 m and 2000 m below surface, mined in a series of mini-longwalls at a stoping width of 1.2 m.

To expose the South Reef, raise lines are developed on the dip of the reef, spaced 175 m apart from which 30 m panels are breasted north and south, each with their own strike gully. Generally, with the bottom panels leading a mini-longwall of about 10 panels a side form a Christmas tree pattern when viewed on plan. A stope plan showing one side of the layout used to achieve a mini-longwall is presented in Figure 1.

Virgin stress on the reef is typically about 50 MPa and the mine has been laid out so the field stresses should not exceed 140 MPa in access ways or working areas. Panels are supported with a combination of timber packs and mine poles with tendon support in the hangingwall and temporary jack support installed in the face area during the morning shift.

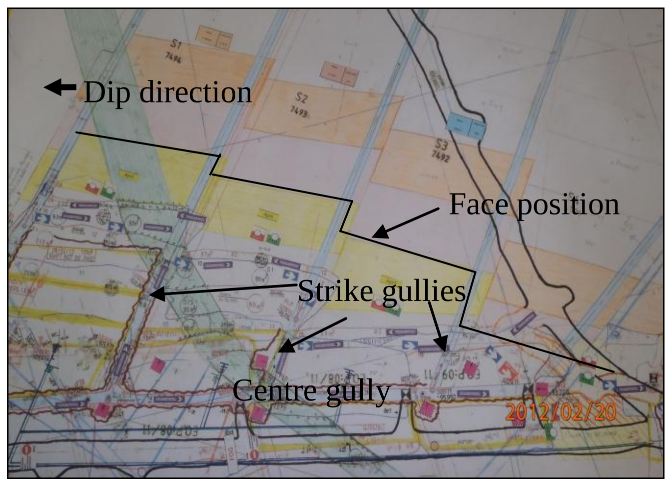

Figure 1: A stope plan showing south side panels forming one side of a Christmas tree pattern

2. STOPE SUPPORT

Taking into account numerical modeling, rock mass rating and best practice from neighboring mines at similar depths, the support pattern was designed to support a tensile zone above the stopes not exceeding 6 m. The chosen support pattern provides a support resistance of 170kN/m^2 and has proved effective in preventing rapid in-elastic closure across stoping spans, some exceeding 200 m. A copy of the support pattern is presented in Figure 2.

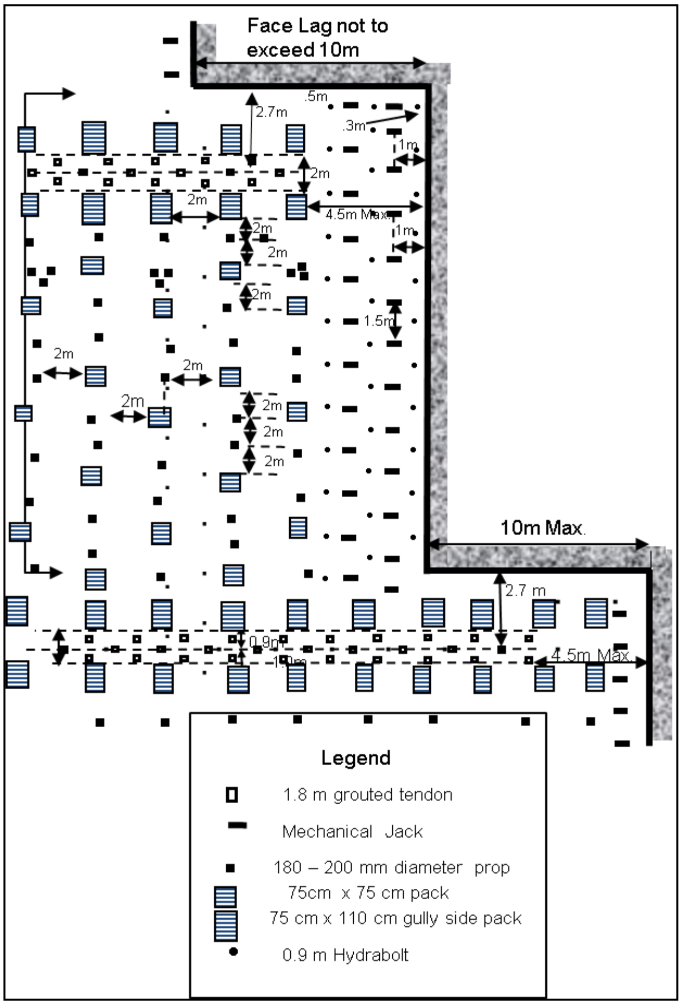

Figure 2: Stoping support plan.

Typically, good hangingwall conditions are present in the face area as illustrated in Figure 3.

Figure 3: Two lines of temporary support provide a safe working environment between the permanent pack support and the face.

3. FALLS OF GROUND

Over a period of about 30 months, a number of fall-of-ground (FOG) have been recorded in the face area.

A typical FOG report would include the following observations:

- 180 tons of rock collapsed into the face area.
- The FOG covered the area between the front row of permanent pack support and the face along half the length of the panel, an area of about 50 m^2.
- The hangingwall was found to have intense stress fracturing dipping towards the face which was further destabilized by a bedding plane 1.5 m above the original plane of the hangingwall.
- The fall occurred immediately after the blast, probably brought on by the removal of the temporary support prior to the blast, the increased span following the blast and the S-wave elastic energy released by the blast.
- The fracturing contained a combination of extension and shear fractures which intersected each other.
- No one was in the stope at the time.

A photograph showing a face area FOG is presented in Figure 4. The protruding and missing roof-bolt support indicates the thickness of the FOG.

Figure 4: A 180t FOG in the face of a panel.

A diagram explaining the cause of the FOG is presented in Figure 5.

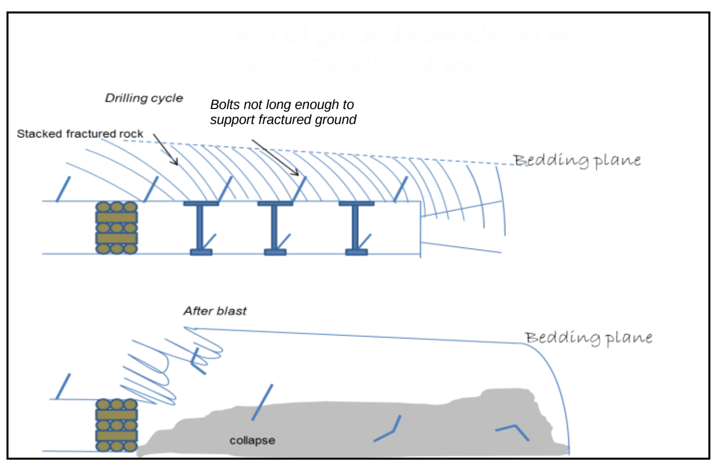

Figure 5: Sequence of events leading up to the FOG.

Other observations common to many FOG investigations include:

- A fall out thicknesses of one to three metres.
- FOG's always occurred after the blast fortunately with no-one in the stope at the time, but with the potential for multiple fatalities should the fall have occurred during the shift.
- The FOG is cut off either by the first line of permanent support, a bedding plane, or a steeply dipping fault plane, or a combination there-of.

Taking into account the danger to personnel, disruption to production and cost implications to the mine of a large face area FOG, an investigation to understand the nature of FOG's was required. In addition, an immediate strategy was required to protect workers exposed to fractured hangingwall rock in their work environment while the investigation continued.

4. A PROCEDURE TO DEAL WITH HIGHLY STRESSED PANELS

Auditing of the stopes revealed that by February 2011, approximately half of the panels mining towards the north already had some stress fracturing in their hangingwalls. A procedure was therefore adopted in all stopes in accordance with the mines code of practice. The following entry examination and stope preparation procedure was enforced.

(i) Before entering a panel, check for availability of two escape ways.

(ii) Working from a point of safety, bar down and make safe.

(iii) More than one person to bar an area at any time.

(iv) Check for geological features, including faults bedding planes and dykes, mark off and support them.

(v) Check angle of fractures, low angle fractures must be supported immediately after barring.

(vi) Install temporary jack support and pre-stress.

(vii) Establish a line of permanent support not more than 2.5 m from the face and pre-stress. (This is closer to the face than the 3.5 m pack to face distance required by the stoping standard).

(viii) Install longest possible roof-bolts with large end-plate.

(ix) Damaged support to be replaced. Examine the hangingwall taking particular note of intrusive geological features and bedding planes.

(x) Barricade off potentially unsafe areas.

(xi) Install face area netting.

The strict implementation of the above procedure proved effective in controlling the rock-mass during the shift, however, FOG's accompanying the blast continued to occur. The investigation into the cause of stress fracturing continued.

5. INVESTIGATION INTO THE CAUSE OF HANGINGWALL FRACTURING IN THE FACE

The following outlines the investigation procedure:

5.1 Discussion

Fall of ground meetings created a forum where Production personal and Rock Engineers could discuss their understanding of the problem.

5.2 Numerical modeling

Map3D, a three dimensional, boundary elements numerical modeling program was used to simulate the stress around a number of stopes affected by stress fracturing. An example is presented in Figure 6 where the stress levels surrounding N4 panel on 197 S1A stope are projected on a grid plane placed perpendicular to the plane of the stope. At the time of modeling N4 panel had recorded a 2.5 m thick FOG and the exposed hangingwall had been mapped revealing extension fractures curving backwards over the stope, relative to the direction mining. The FOG had occurred as a result of the fractured rock separating from the solid rock above.

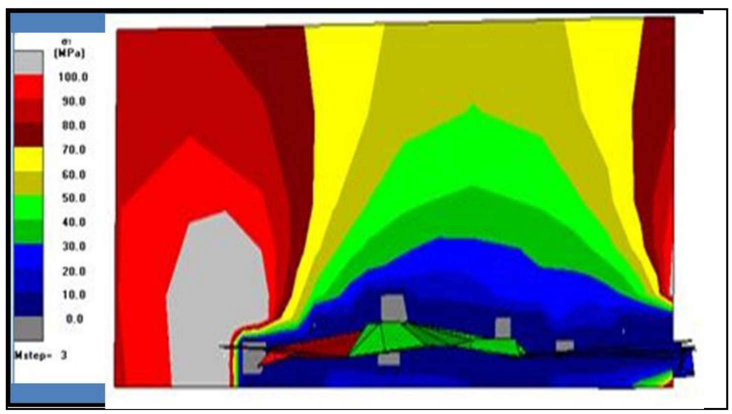

Figure 6: A numerical model showing a section through the highly fractured N4 stope.

The model showed stress levels on the face did not exceed 110 MPa. Clearly a rock mass with a Uni-axial compressive strength (UCS) in excess of 250 MPa would not fail in compression at these stress levels. The nature of the fractures is therefore more likely to be extension and shear fracturing initiated ahead of the face by a combination of blast pressure and field stress [1].

Observations from boreholes drilled into the advancing faces of deep-level tabular excavations suggest that fracturing initiates some distance ahead of the face (up to 10 m) depending on the field stress leve1. Computer simulations of narrow openings that are created suddenly in an un-failed medium indicate that failure is initiated at the edges of the openings where extreme stress gradients exist [2].

Using a computer model known as DIGS (Discontinuity interaction and growth simulation) Napier simulated stress propagation ahead of a highly stressed stope face. In his study, two basic modes of fracture are distinguished, namely extension fractures and shear fractures [2]. Whereas shear fractures would require the relaxation of stress across a fault plane, extension fractures can be formed by a combination of field stress and percussion from an explosive detonated ahead of the face.

The primitive horizontal-to-vertical stress ratio controls the orientation of fracturing in monolithic (unlayered) material near the edges of slot-shaped openings. As the horizontal stress is increased, shear fractures initiating from the edges of the openings curve back over the opening to form domical structures, as reflected in physical modelling [2]. At zero horizontal stress, shear fractures tend to grow in a vertical orientation with respect to the horizontal opening [2]. The most common fracture pattern encountered after FOG's at Doornkop curve back over the stope indicating the presence of a high horizontal stress as illustrated in Figure 7.

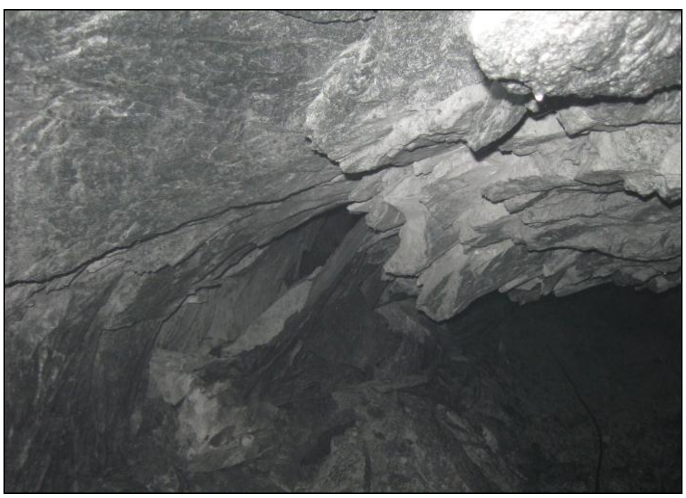
Figure 7: Fracture patterns lean backwards above the panel from the direction of face advance.

5.3 Fracture mapping

From mapping of sites where FOG's had occurred it was found that bedding and fault planes form cut planes against which the extension fractures cut off and that the shape and orientation of extension fractures is consistent with the DIGS modeling undertaken by Napier et al. Shear fractures, which form during the blast are therefore enveloped by pre-existing extension fractures and cut off against them, further breaking up the rock-mass.

A typical model of exposed fracture patterns following a FOG investigation is presented in Figure 8.

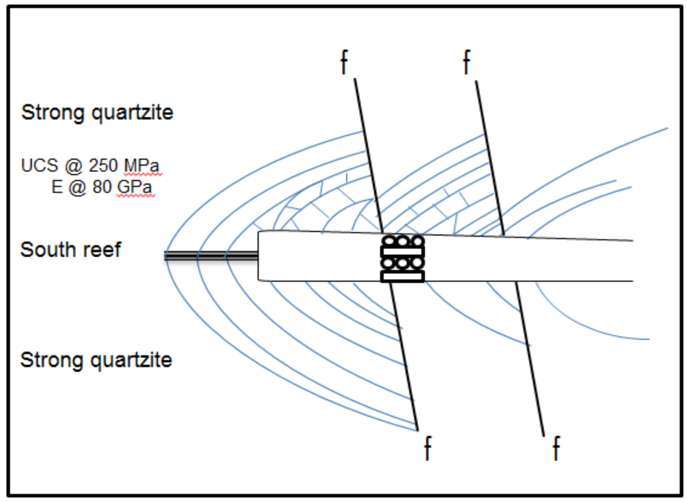

Figure 8: An observed fracture pattern around a north face.

Parting planes can play a role in allowing extension fractures to initiate in the solid region above the edge of a tabular opening. In particular, the mobilization of parting planes can allow regions of strong tensile stress to be formed on the lower side of the parting-plane interface, which can encourage the nucleation of extension fractures dipping forward at about 80 degrees in the hangingwall [3].

A photograph showing extension fractures dipping towards the face is presented in Figure 9. The photo also shows how extension fractures cut off against a reef parallel parting plane 1.7 m in the hangingwall.

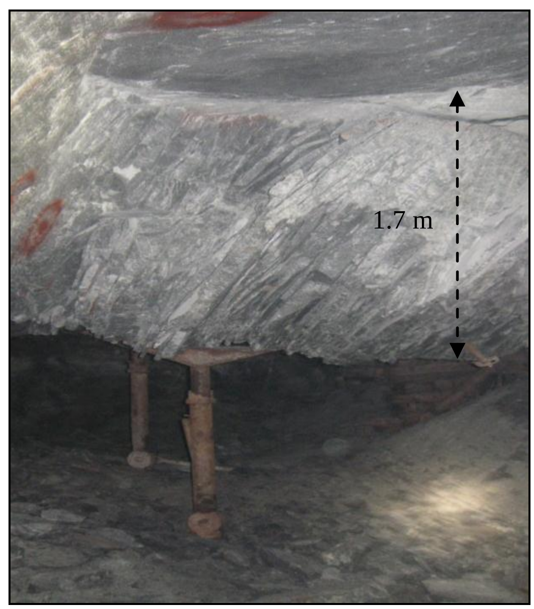

Figure 9: A FOG reveals fracture patterns in the hangingwall dipping steeply toward the face (to the left of the picture).

The implication is that a second source of fracture patterns is present in our hangingwall, namely extension fractures generated by the mobilization of parting planes in our hangingwall.

5.4 Understanding the orientation of the field stress

The contrast between the highly fractured and often damaged north panels and the relatively stable hangingwall conditions typical of south panels, suggests an asymmetrical stress field. Determining the magnitude and orientation of field stress in broken rock has proved unreliable in the past; however, observations made elsewhere in the mine have provided useful evidence about the orientation of the South Reef field stress. Generally, our cross-cuts are orientated parallel to the dip of the reef, breaking away from the main haulage some 30 m below the reef plane and are continued until reef intersection. The cross cuts are therefore orientated parallel to the stope faces which will later be developed on the plane of the reef above them. Occasionally dog-earing forms on the top south corner of the cross-cut tunnels as illustrated in Figure 10.

The implication is that the field stress in the vicinity of the South Reef is orientated some 30° north of vertical.

Figure 10: Dog earing on the top south corner of a crosscut.

Numerical modeling shows a stress field plunging from 30° north of vertical would favor the propagation of extension fractures on our north panels and suppress their growth on the south panels.

Figure 11 presents a model showing an asymmetrical stress field and the resulting extension fractures around the north face area. Further underground measurements will be required to determine the values of σ1 and σ3.

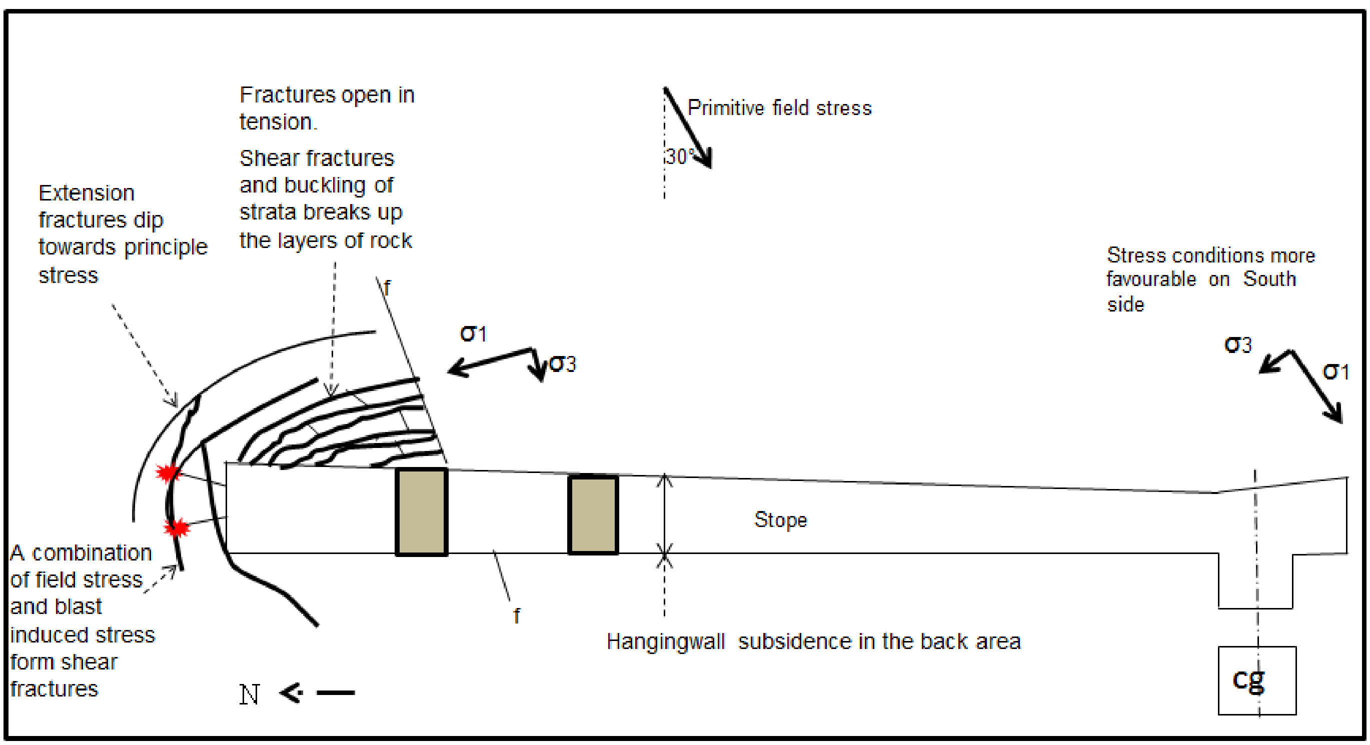

Figure 11: An asymmetrical stress field and the resulting fracture formations on the north panels.

Mobilization of parting planes near the stope face can form a barrier to the growth of shear fractures, depending on the orientation of the fractures. Fracturing in the solid region ahead of the current face is strongly affected by the horizontal stress parallel to the direction of mining known as a clamping stress. If this stress is reduced over an 'effective' stope width larger than the physical mining height, shear fractures can be formed ahead of the actual stope face [3]. The leaning back nature of extension fractures above our panels confirms a well-established horizontal component of the South Reef field stress.

5.5 The effect of explosives

A strategy which may also be useful to control the stability of the fracture zone is the rate of stope face advance. The speed of extraction, combined with an appropriate viscous constitutive law, should provide some guidance as to how to determine safe values of extraction rate and better control of the fracture zone [2]. While Doornkop uses low gas - high percussion emulsion based cartridge explosives on the face, the interaction of blast induced elasto-dynamic waves and gas-driven stress loading on existing fractures needs to be minimized. It has been established from fracture geometry that a high proportion of the ‘bow-wave’ fractures in conditions of high stress, are due to the combination of high field stress and the superimposed transient blast stresses [4].

6. A STRATEGY TO MINIMIZE STRESS FRACTURING ON THE FACE

An important aspect of excavation design is to control the incidence of adverse fracturing to improve the stability of the opening. Low angled-fractures and other discontinuities can break the hangingwall into semi-detached key-blocks which enhance the possibility of FOG’s. In addition, stress transfer onto the face can cause sudden and generally, unpredictable failure of the face.

6.*1 Preconditioning*

Preconditioning involves the detonation a one metre charge at the back end of a three metre hole drilled perpendicular to the face at three metres intervals along the length of the face, with the first two metres of the hole to be tamped. The rock breaking shot holes should not exceed one metre in length. The effect is to create a zone of crushed rock two metres ahead of the face and hence shift the peak stress away from the face. The shear fractures, which would normally form at the end of the blast hole, will now form two metres ahead of the face and be clamped by the un-mined rock-mass behind them.

To achieve satisfactory results from preconditioning it necessary to choose the optimal interaction between the distressing cycles, the production blast cycles and the time dependent relaxation of fracture zone discontinuities.

6.2 Use short jumpers and blast the face daily

Current research into this topic suggests that the speed of fracture zone development is not only dependent on material properties, but also on the mining rate. Different face advance rates can alter the stress concentrations near the stope face [3]. Generally, increasing and regulating the frequency of blasting, restricts fracture development.

6.3 *Use long roof bolts with end plates*

When properly installed at right angles to the strata, stiff bolt support will inhibit the growth of extension fractures and bind the hangingwall into a more stable beam.

6.4 *Keep stiff support close to the face*

Stiff mine pole support placed beneath extension fractures will bear the weight of the broken rock-mass and apply a clamping force to extension fractures. In one stope with many closely spaced flat dipping fractures in the hangingwall of its north facing panels, a row of pre-stressed mine poles was placed no more than one metre from each face before the blast. Although some of the poles were blasted out, the majority survived the blast in-situ and in so doing provided stiff support to the hangingwall immediately behind the face, an area that is usually unsupported after the blast. It was found that by repeating this practice daily, the fractured hangingwall became more manageable and the danger of FOG’s was somewhat mitigated.

6.5 Hydraulic props

Active support, in the form of blast-on hydraulic props has since been adopted by the mine for this application; However caution is advised when removing active support from beneath a broken rock-mass where the load exerted by the prop when activated, may itself destabilize the hangingwall. Figure 12 shows two lines of hydraulic props with the front row 1.5 m from the face before the blast barricade is installed.

Figure 12: Two lines of hydraulic props, front row 1.5 m from face

Hydraulic props also allow for better grade control: Stoping width control is improved and, with barricades, sweepings are kept closer to the face. Figure 13 shows a blast barricade on the first row of props 1.5 m from the face.

Figure 13: Blast barricades on front row of props

6.6 *Keep a straight face shape*

A straight face will eliminate pockets of stress build-up on the face.

6.7 *Maintain a 2.7 m gully siding*

Many FOG investigations showed a concentration of stress patterns next to the gully when no siding had been developed. Gully sidings are used to move adverse stress patterns away from the gully. Figure 14 presents a photograph of adverse stress fracturing in the hangingwall of a gully where no siding had been cut.

Figure 14: Stress fracturing above a gully.

Gully sidings will position the strike gully in destressed rock, thereby reducing hangingwall deterioration in the access way [5]. A model for improving ground control around a gully is presented in Figure 15.

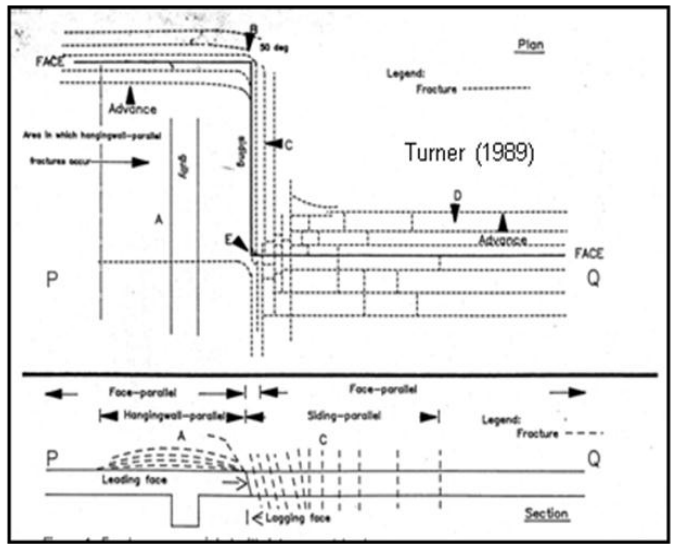

Figure 15: Maintaining a gully siding will moves stress patterns away from the strike gully [5]

6.8 *Keep leads and lags between four and ten metres.*

Maintaining a regular face pattern within the mini-longwall method of mining will eliminate cross fracturing at the toe of the panel and the formation of blocky ground [5]. A photograph of a highly stressed toe of a panel is presented in Figure 16.

Figure 16: The highly stressed toe of a panel where leads and lags were out of standard.

A model showing the formation of fractures at the toe of the panel is presented in Figure 17.

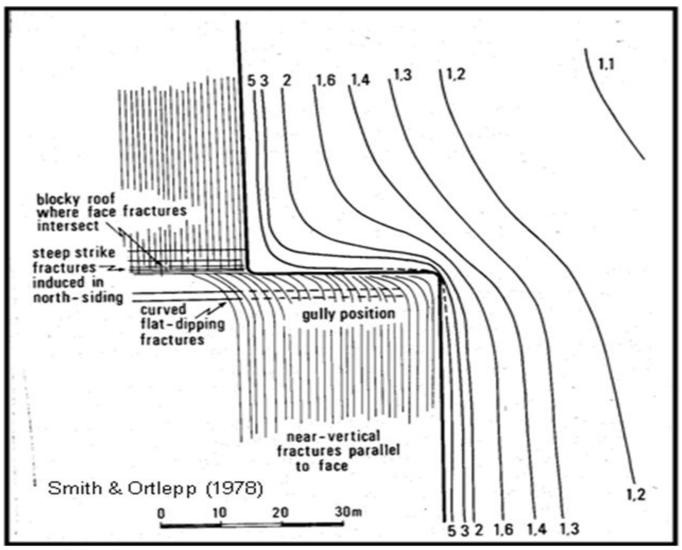

Figure 17: Long leads and lags will create adverse joint intersections at the toe of the panel.

7. DEVELOPMENT

While stress fracturing has affected many of our north facing panels, generally our footwall tunnels have only moderate ground control problems with almost no evidence of bow wave fracturing, typical of tunnels developed in highly stressed ground. Scaling of the hangingwall is most common in our north-west oriented tunnels, indicative of a high horizontal field stress in this area. Figure 18 presents a photograph of hangingwall scaling in a north-west orientated tunnel. The protruding tendon support indicates scaling of about 20 cm across the entire width of the tunnel.

Figure 18: Stress related hangingwall scaling in a north-west orientated tunnel.

Generally ground control problems are more easily dealt with in tunnels where long anchors, thin sprayed liners and mesh and lace have proved effective in containing FOG's. A photograph showing mesh with temporary lacing is presented in Figure 19.

Figure 19: Mesh and temporary lacing used in tunnels.

8. ANALYSIS

By adhering to the strategy listed in items 6.1 to 6.8 above the mine is to attempting to inhibit the formation of fracturing in the rock-mass ahead of our panels.

In addition some success has been achieved with limiting the density and growth of adverse shallow angle fractures common at FOG sites by keeping stiff support close to the face.

The success of the strategy and the effectiveness of the support design is illustrated by an example of normal elastic closure occurring in the back area of a north facing panel with no hangingwall deterioration. Figure 20 presents a photograph showing gully packs originally 120 cm high now crushed to 60cm high as a result of elastic closure. The packs when photographed were 45 m behind the face. The hangingwall above the packs showed no visible sign of deterioration.

Figure 20: 60 cm of elastic closure on 120 cm high packs with no evidence of inelastic closure 45m behind a face.

9. CONCLUSIONS

Potentially dangerous FOG's have forced Doornkop Gold Mine to investigate the nature of extension and shear fracturing in stope hangingwalls and to review its strategy for dealing with them.

The support standard, although suitable for providing support during the day shift, did not provide clamping forces to the hangingwall between the new face position and the front row of permanent support following the blast. This created a tensile zone suitable for the extension of fractures in our hangingwall.

It was found that by engineering the rock-mass ahead of the face and applying stiff support close behind the face, the damaging effect of fractures could be reduced.

FOG records show that since the implementation of our fracture control strategy the frequency of recorded FOG's in the face area and the size thereof has been reduced. Where FOG's have occurred, investigations have revealed several deviations from the support strategy.

10. REFERENCES

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