Caving induced by hydraulic fracturing at Northparkes Mines

A. van As
Northparkes Mines

R.G. Jeffrey
CSIRO Petroleum

ABSTRACT: This paper describes the first use of hydraulic fracturing for cave inducement in a block caving mine. As of September 1999, several hundred hydraulic fracture treatments have been performed at Northparkes and are attributed with inducing about 7 million tonnes of ore to cave.

1 INTRODUCTION

The Lift 1 portion of the E26 porphyry copper/gold deposit at Northparkes Mines is the first block cave mine in Australia and is located 30 km NW of Parkes, New South Wales.

The deposit consists of quartz monzonite porphyrys (QMPs) which have intruded into a volcanic sequence of latite composition. The deposit is characterised by a high grade, highly altered siliceous core associated with dense sheeted quartz veining, which diminishes in intensity away from the QMP. The Lift 1 block comprises several geotechnical zones which are defined as a function of the basic geology, primarily the fracture frequency and intensity of gypsum veining, both of which diminish with depth. Several in situ stress measurements have revealed a fairly low stress environment; the magnitudes and orientations of the principal stresses are provided in Table 1. The sub-vertical stress is the mininimum principal stress. The orientations of the major joint sets in the orebody are shown in Table 2.

Table 1. Stress measurement at 450 m depth.

Principal Stresses	Magnitude (MPa)	Dip (degrees)	Bearing (degrees)
σ_1	22.7	05	141
σ_2	15.0	15	049
σ_3	12.1	75	248

Table 2. Joint sets in Northparkes orebody.

Joint set	Strike (degrees)	Dip (degrees)
1	139	87
2	180	79
3	272	77
4	102	37

The Laubscher Mining Rock Mass Rating (MRMR) classification system (Laubscher 1990) was adopted to classify the Lift 1 rock mass and assess it's cavability. As illustrated in Figure 1, sustained caving was expected once the undercut development attained a hydraulic radius (the ratio of the cross sectional area to the perimeter) of between 20 to 25. The vertical bar labeled Northparkes represents the range of MRMR for different parts of the orebody. The transitional limits in Figure 1 are as they were defined at the time of mine design.

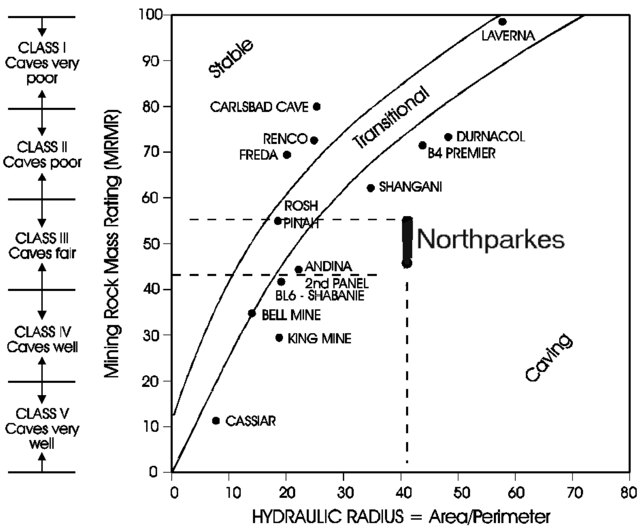

Figure 1. Laubscher's cavability diagram with the cavability of a number of mines and natural caverns, including Northparkes, included on the diagram.

Cave propagation occurred fairly rapidly as the undercut advanced, with initial caving commencing when the undercut had reached a hydraulic radius of around 23. Intermittent caving followed the advance of the undercut, however, once the entire undercut was developed (196 metres long by 180 metres wide), caving virtually ceased. On completion of the undercut, the cave had propagated to a maximum height of 95 m above the top of the undercut, yielding approximately 3 million tonnes of broken ore. Increased production rates failed to induce further caving, but, instead, resulted in an increase in the air gap between the top of the broken ore and the cave.

Hydraulic fracturing to induce caving commenced in December 1997 and was the first use of hydraulic fracturing for this purpose. Recently, hydraulic fracturing has also been successfully used to induce roof caving behind a coal mine longwall (Jeffrey & Mills 2000).

The hydraulic fracture treatments at Northparkes made use of existing exploration boreholes that were accessible from the exploration drives located midway up the lift. The treatments, which used both water and, later, crosslinked gel, were monitored with an existing in-mine microseismic system, time domain reflectometers (TDRs), wire extensometers and boreholes which intersected the cave back. In addition, the hydraulic fractures intersected nearby boreholes during some of the treatments and these intersections provided data on fracture growth rate and extent.

2 HYDRAULIC FRACTURING

The hydraulic fracture treatments were performed using a straddle packer system that was deployed on an AQ-size drill rod string in the NQ-size boreholes. The packers were inflated with water and treatments were typically conducted at 3 m spacing along the portion of the hole that intersected the ore body.

The exploration boreholes had been drilled as fans from each drill position, with holes angled up and down. Initially, the cave back was lower in elevation than the collars of the holes and the fracturing was conducted in down holes. Some of these holes had intersected the cave while others passed over the top of the cave boundary.

2.1 *Stress field and fracture initiation*

The stress field given in Table 1 is modified by the cave. Near the cave boundary, the least principal stress is oriented perpendicular to the boundary and the intermediate and maximum principal stresses are tangential to the boundary. Holes orthogonal to the cave boundary were, as a result, aligned approximately with the minimum stress direction. In these holes, hydraulic fractures can initiate at a natural fracture, flaw or stress concentration with an orientation that cuts across the hole axis. If an initiation point does not exist in the borehole, it is more common for hydraulic fractures to initiate as an axial fracture along the borehole wall at a position controlled by the stress concentrations there.

If the axis of the initial fracture is not aligned with the far-field principal stresses, the hydraulic fracture will reorient to grow perpendicular to the minimum principal stress. Breakdown of a borehole in naturally fractured rock can result in initial fractures with many different orientations, but opening mode fracture growth will result in the initial fracture reorienting to the preferred direction. Microseismic event locations associated with some of the treatments were used to establish the overall fracture orientation and size.

2.2 *Opening mode and shear mode fracturing*

Conventional hydraulic fracturing, as performed to stimulate oil and gas wells and to measure in-situ stresses, almost always results in propagation of a fracture by opening mode processes. In rock that contains pre-existing fractures, injection can pressurise and produce shearing along the existing fractures at a pressure that is below the initiation and extension pressure for an opening mode fracture.

Shear fracturing can only occur if fluid can enter the fractures and pressurise them. Opening-mode fractures will not occur if all of the fluid injected can enter pre-existing conductive fractures at a pressure lower than the magnitude of the minimum principal stress. In most conventional hydraulic fracture treatments, fluid losses into cross cutting fractures occurs and leads to some shearing on them with associated microseismicity, but the fluid injection rate is sufficiently high that an opening-mode fracture is pressurised, opened, and extended.

2.2.1 *Critical pressure*

Pine and Batchelor (1984) described and analysed shear fracture growth associated with injections of water into the fractured Carnmenellis granite near Cornwall, UK. They derived a relationship that gives the critical pressure, P_c, of a fluid in a jointed rock that will result in shear fracturing.

$$P_c = \frac{\sigma_1 + \sigma_3}{2} - \frac{1}{\alpha}\frac{\sigma_1 - \sigma_3}{2} \quad (1)$$

where σ_1 is the maximum principal total stress, σ_3 is the minimum principal total stress, and

$$\alpha = \frac{\tan\phi}{\sin 2\theta + \tan\phi\cos 2\theta}\,. \quad (2)$$

The joint friction angle, ϕ, and the angle, θ, between the direction of σ_1 and the joint strike direction must be measured or estimated, along with the stress directions and magnitudes, to calculate P_c. When the stress directions do not align with the natural fracture directions the critical pressure for shear fracturing can be considerably less than the pressure for opening mode hydraulic fracture extension. The pressure required to extend a hydraulic fracture is slightly greater than the magnitude of σ_3.

The before mining stress state at Northparkes has been measured by overcoring at a depth of 450 m (Table 1) and by micro-hydraulic fracture tests. The hydraulic fracturing work to induce caving was undertaken at a depth of 250 to 300 m and near the existing cave. Figure 2 shows the result of a calculation of the critical pressure, P_c, for stress conditions near a spherical cavity in a uniform compressive stress field of 12.2 MPa, the mean horizontal stress at a depth of 300 m.

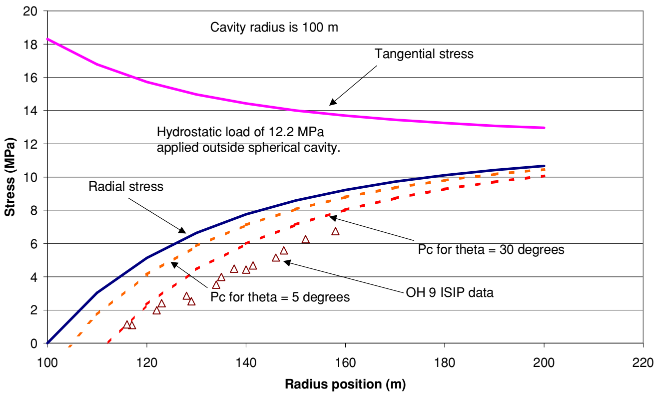

Figure 2. The tangential and radial stress around a spherical cavity, of radius 100 m, in a uniform compressive stress field of 12.2 MPa.

The critical pressures for shear fracturing were calculated by substituting the tangential stress for σ_1 and the radial stress for σ_3 in equation 1. The friction angle of the joints was taken as 40^0 and a range of orientations of the joints with respect to σ_1 was considered (Table 2). The extension pressure for hydraulic fracturing is greater than or equal to the radial stress in this stress field. For this assumed stress state and joint strength, P_c is always lower than the hydraulic fracture extension pressure, implying that shear fracturing is favored.

The bottom-hole ISIP data from borehole OH 9 is also shown in Figure 2. The OH 9 shut-in pressures lie below the lowest shear fracturing critical pressure line. More accurate calculations of the tangential and radial stresses for non-hydrostatic far-field stress may improve the match.

The joints must have some conductivity before the fluid can enter and pressurise them, leading to shear fracture growth. The amount of shear fracturing that occurs will then depend on the competition between pressure required to extend a hydraulic fracture and the rate of fluid loss into natural fractures. Shear events are detected around most hydraulic fractures and these events can be used to map the direction and geometry of the hydraulic fracture (Warpinski et al. 1995).

The gypsum filled joints at Northparkes are not typically permeable except where deformation from mining is significant. Shear fracturing is expected to occur near the cave where the rock is partially failed and the joints have been opened by these large deformations.

2.3 *Fracture treatments*

Fracturing campaigns were carried out at Northparkes starting with the first trials in December 1997 and followed soon after with 2 weeks of work in both January and February 1998. During this three month period, 127 treatments, using 750 m^3 of water, were performed in 10 boreholes. During each treatment, the injection rate and pump pressure were logged to a computer. Microseismic monitoring was active and events were recorded throughout this period. An estimated 2 million tonnes of ore caved during these three campaigns.

A hydraulic fracturing system was then purchased by Northparkes and commissioned in June 1998. This system has been used by the mine to continue hydraulic fracturing from underground and surface boreholes. In March 1999 chemical additive pumps were purchased that allowed treatments using borate crosslinked gel fluid. The crosslinked gel has an apparent viscosity that is about 1,200 times that of water and was found useful in promoting caving near the cave back. Overall, more than 1,500 fracture treatments have been conducted in the E26 orebody at Northparkes.

2.3.1 *Treating pressure response*

Injection pressure, rate and the instantaneous shut-in pressure (ISIP) were measured and recorded for each fracture treatment. Figure 3 shows a typical injection pressure history for a treatment close to (in this case 15 m from) the cave back, and for comparison, Figure 4 contains an injection record in the same hole and on the same day, but located about 30 m from the cave back.

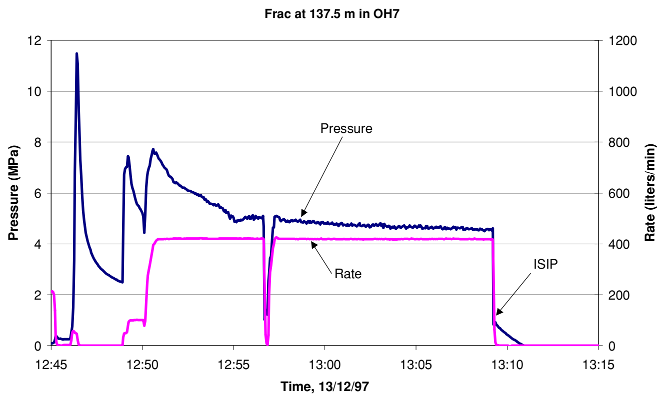

Figure 3. Pump injection pressure and rate for the fracture treatment located 15 m from the cave in hole OH7.

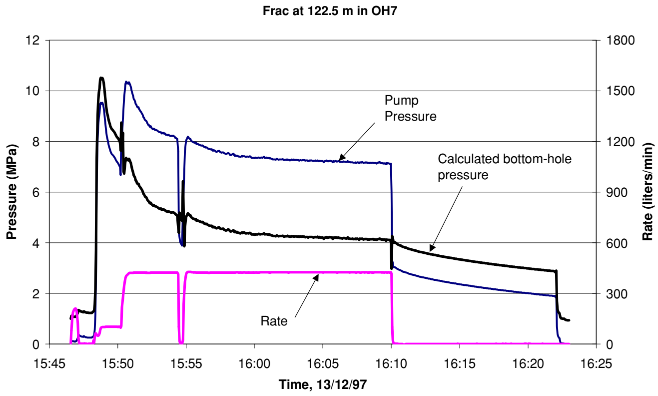

Figure 4. The record for a fracture treatment in OH7 located 30 m from the cave.

Neither interval accepted fluid until after breakdown. The breakdown response was typical for initiation of a fracture in intact rock. The treatment located 30 m from the cave had a higher treating pressure and a higher instantaneous shut in pressure (ISIP). Based on these pressures, the normal stress across the fracture at this location is higher by about 2 MPa than the normal stress at 15 m from the cave back.. The increase in ISIP (and stress across the fracture) was noted in every borehole as treatments were performed progressively from near the cave back to distances up to 100 m from the cave.

The measured ISIP data in borehole OH 7, corrected to give bottom-hole pressures, as a function of distance to the cave back are plotted in Figure 5.

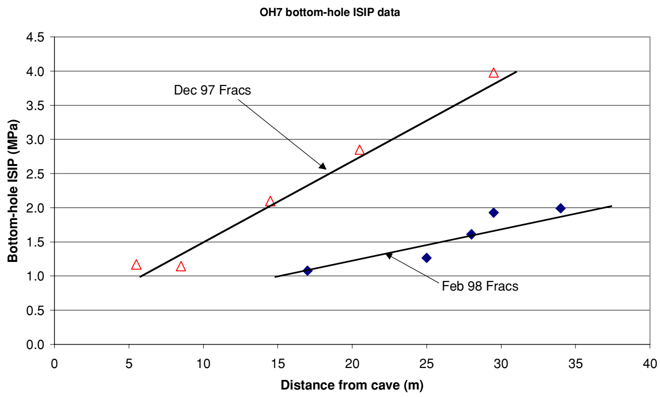

Figure 5. Bottom-hole ISIP values increase with increasing distance from the cave back.

The ISIP measurements indicate that the closure stress across the fracture increases with distance from the cave. Furthermore, the treatments in December 97 produced ISIPs that were higher in magnitude and increased more with distance away from the cave than the later re-fracture treatments in February 98. These trends indicate changing stress conditions with distance from the cave and with time in this borehole. Hydraulic fracturing treatments carried out in the rock mass around the cave serve to weaken and soften the rock. One effect of the softening is to reduce the stress in the rock that has been treated. Similar ISIP tends were obtained from treatment data in other boreholes.

A numerical hydraulic fracture model has been used to match the pressure history for this treatment (Figure 6). The model assumes a radial, planar fracture geometry and, despite these simplified assumptions, was able to match the recorded pressure very well. A permeability of 0.2 md, a rock Young's modulus of 60,000 MPa, a rock fracture toughness of 1,000 kPa$\sqrt{m}$, and a closure stress of 2,800 kPa were used to produced the match shown. The model predicted that the fracture grew to a radius of 34 m, which is consistent with data from microseismic events and fracture growth through adjacent boreholes.

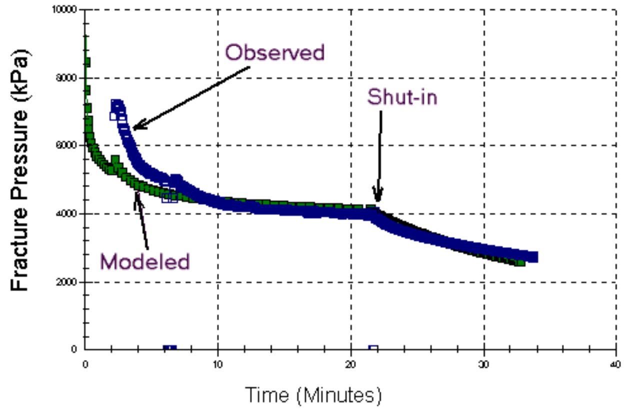

Figure 6. Pressure data from the treatment at 122 m in OH7 compared to data from a numerical fracture model simulation of the treatment.

A log-log Nolte-Smith plot of the treatment at 122 m in OH7 is shown in Figure 7. The net pressure shown is the bottom hole treating pressure minus the closure pressure and the time is elapsed time since the start of injection. The slope of the curve over most of the treatment time is –1/4, which is consistent with growth of a radial fracture (Nolte & Smith 1981).

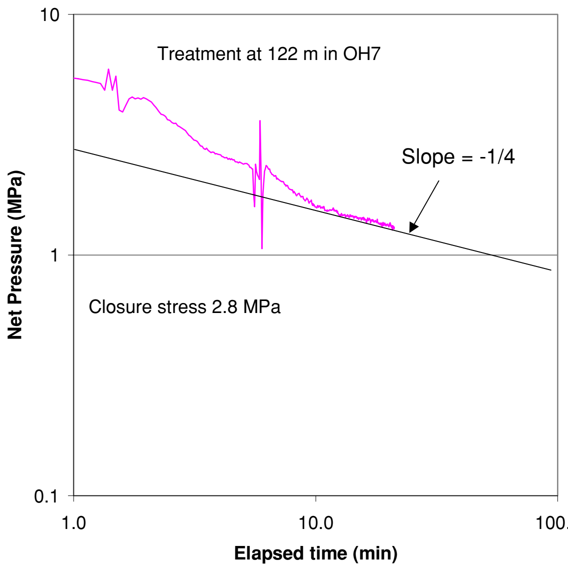

Figure 7. Nolte-Smith plot of the treatment at 122 m in OH7.

2.3.2 *Fracture growth through nearby boreholes*

Several of the treatments intersected adjacent boreholes. The main evidence for these intersections consisted of water flowing from the offset borehole during or shortly after the injection.

In several cases, the offset borehole was instrumented using a packer and pressure transducer which then allowed measurement of the arrival of the fracture at that borehole in subsequent treatments. Some boreholes could not be sealed and these holes acted as fluid loss points to the fracture when they were intersected.

An example of data collected during an intersection event is contained in Figure 8.

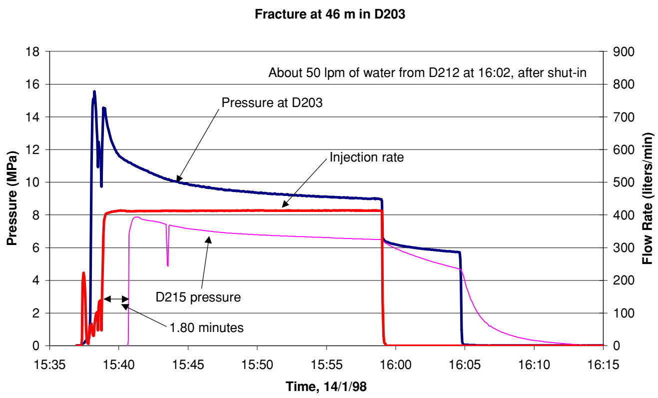

Figure 8. D215 was intersected by the treatment in D203 at 46 m below the collar. D212 was also intersected, but no pressure monitoring was possible at this hole.

Hole D215 was drilled at an angle to D203 and passed within about 15 m of it at depth. D212 was drilled parallel to D203 and more than 27 m distance from it. The treatment in D203, using water injected at 412 litres/min, intersected D215 after 2.3 minutes (0.5 min breakdown and 1.8 min of treatment) of injection time and had also grown through D212 by the end of the 20-minute treatment. The pressure transducer in D215 was located at the collar of the hole at the same relative elevation as the pressure transducer at the pump. Figure 9 is a plot of the modeled hydraulic fracture growth for the treatment in D203.

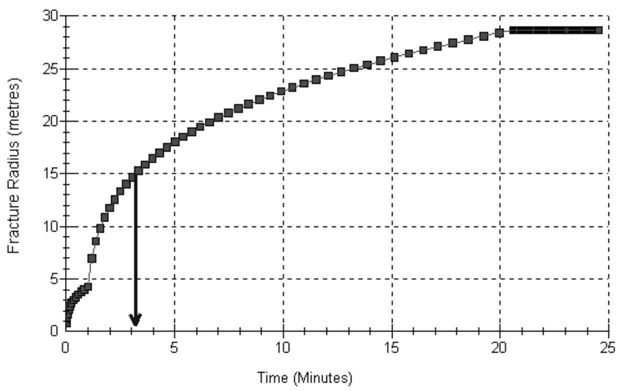

Figure 9. Growth of the radius as predicted by a numerical model for the treatment at 46 m in D203. The fracture intersected D215, 15 m away, after about 2.8 minutes of injection.

The radial fracture is predicted to grow to 15 m in about 3 minutes which is not far from the observed intersection. The fracture also is predicted to grow to a size greater than 27 m, allowing it to also intersect hole D212. No time of intersection for hole D212 is available.

The surface pressure recorded at the collar of D215 and at D203 show the same trend of decreasing pressure with time. After shut-in, the pressure at D215 dropped more rapidly than at D203, suggesting that the fracture closed very soon after shut-in occurred. Treatments in other boreholes that intersected adjacent holes were monitored. The pressure falloff at the intersected hole was found to track the falloff at the treatment hole in several of these cases. In D203, closure was accelerated by losses occurring into D212.

The pump transducer is affected by the fluid friction in the injection lines between the pump and the hole collar (and between the collar and the straddle section). This friction pressure is removed at shut-in, causing the sudden drop in the treating pressure record there.

2.3.3 *Microseismic monitoring of treatments*

Figure 10 contains a plot of micro-seismic event locations, superimposed on the cave outline, associated with hydraulic fracture treatments in OH 7 performed during February 1998.

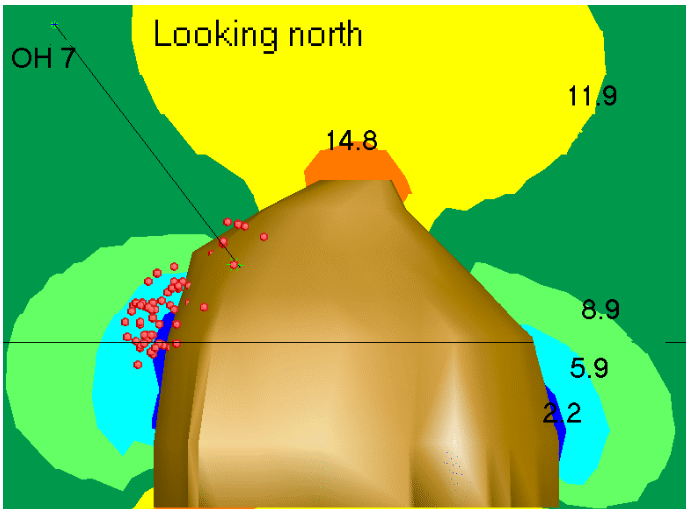

Figure 10. The cave back as of November 97 with stress contours (in MPa) on an east-west vertical plane passing through the centreline of the cave. Microseismic events associated with fracturing in borehole OH 7 during Feb. 98.

The stress shown contoured in Figure 10 are the 3D stresses (σ_{h1}=15, σ_{h2}=9.9, and σ_v=8 MPa) resolved onto an east-west plane. Only the east-west normal stress component is contoured.

The east-west normal stress is a maximum at the crown of the cave and minimum on either side of the cave boundary. The east-west stress is zero at the east and west cave boundaries. Microseismic events recorded during the 5 treatments carried out in one day's work on OH 7 are shown. Figure 11 contains a plot showing contours of σ_1 for the same far-field stress conditions.

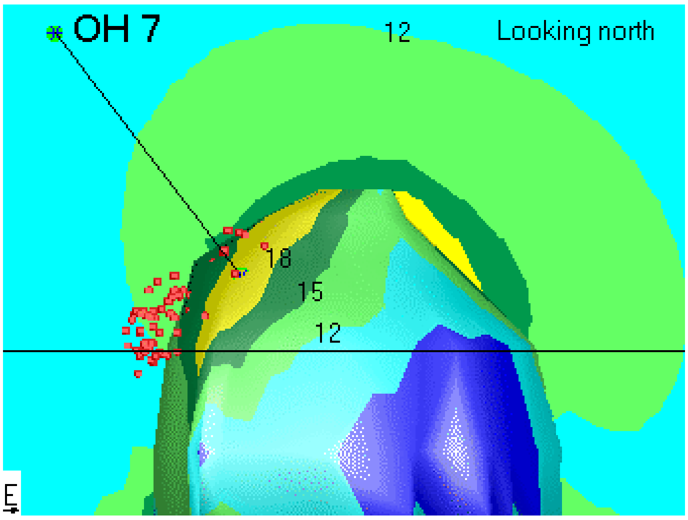

Figure 11. Contours of the maximum principal stress around the cave.

The cluster of event locations in Figure 11 just west and below the borehole should probably be located centred around the hole axis. The rock seismic velocity data used in the event location calculations is based on a pre-mining calibration of the accelerometer array and the cave development is believed to have modified these velocities, introducing a systematic error. The seismicity shown is in a region of high tangential stress (σ_1) and low radial stress (σ_{E-W}) which is consistent with generating shear on existing fractures.

The directional trends of the microseismic events recorded for two treatments in borehole D201 (Figure 12 and 13) have been obtained by fitting a plane, using the least squares method, to them. The trend planes were found to strike N28E and dip of 46^0 to the NW for the treatment at 82 m from the collar and strike N47E and dip 48^0 to the NW for the treatment at 97 m. The orientation of these planes do not coincide with any joint sets listed in Table 2. At the time of these treatments, the cave back was located 16 m down the hole from the treatment at 97 m. Borehole D201 has a bearing of 91^0 and a dip of 47^0.

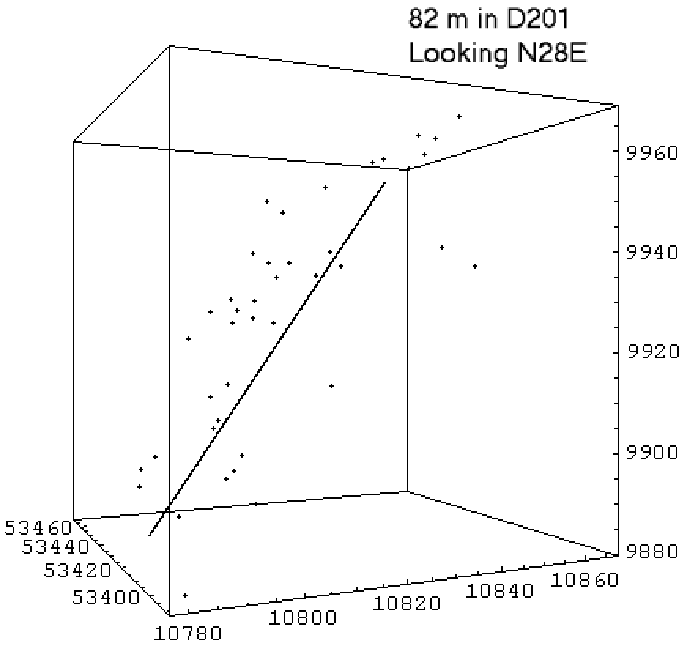

Figure 12. Microseismic events associated with the fracture treatment at 82 m in borehole D201.

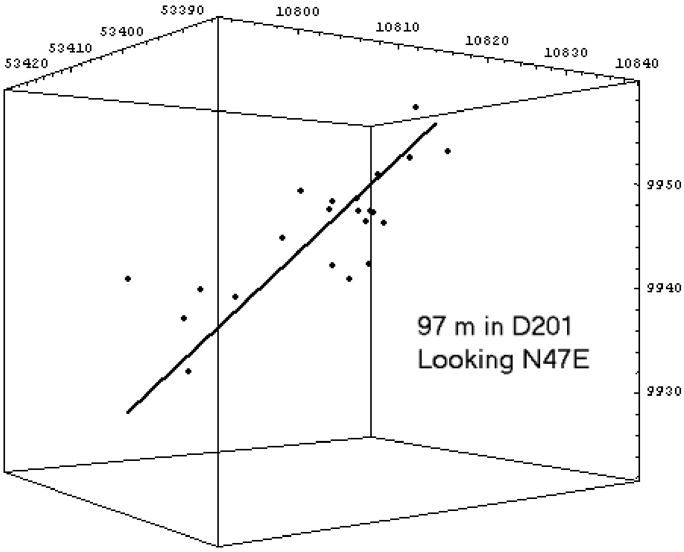

Figure 13. Microseismic events associated with the fracture treatment at 97 m in borehole D201.

Only the microseismic events occurring during the injection portion of each treatment are shown in Figures 12 and 13. In both cases shown, the seismicity is contained within a flat ellipsiodal volume 40 to 50 meters in size on its long axis and 10 to 20 m across its short axis. The ellipsoids are aligned more or less tangential to the cave boundary with their long axis similar to the fracture radius as predicted by the fracture modeling.

17 of the 127 treatments (about 13 percent) performed during the first three campaigns at Northparkes produced 3 or more seismic events, allowing planes to be fitted through the event locations. A stereo plot, showing contours of the poles to all 17 planes obtained in this way, is contained in Figure 14. The majority of the planes strike NE and dip to the NW.

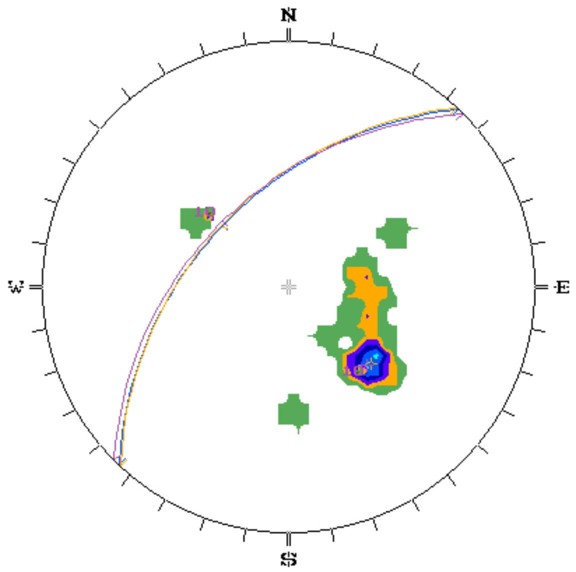

Figure 14. Contours of the poles to the planes fitted through the microseismic events recorded for 17 of 127 fracture treatments.

During the injection period, most treatments either produced no detectable seismic events or produced less than 3 events. However, seismic events usually continued to occur for some time after each injection. Caving events often occurred hours or days after treating a particular part of the orebody.

The stereo plot in Figure 15 contains contours of the poles to the 4 major joint sets mapped in the orebody. By comparing Figure 14 with Figure 15, it is clear that the microseismic event locations recorded during the treatments do not coincide with any of the pre-existing joint set directions.

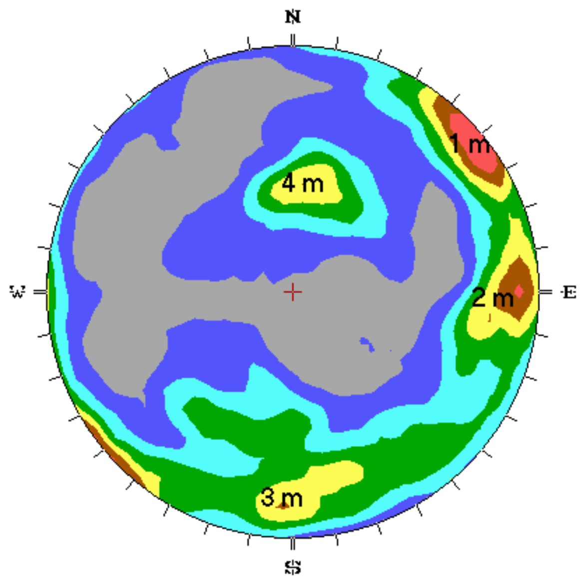

Figure 15. Contours of the poles to the joint sets at Northparkes E26 mine.

2.3.4 *Discussion*

Block caving is a low cost underground mining method that is ideally suited for mining marginal massive deposits. In the past the only orebodies considered suitable for caving were those comprising a fairly weak and well jointed rockmass. At present there is an enormous interest in the mining industry to further develop the method as an effective means of mining more competent orebodies. The major risks experienced with caving relatively competent rock masses relate to cavability and the resulting fragmentation size.

Hydraulic fracturing not only offers an extremely cost effective means of cave inducement but has the potential to significantly reduce the risks associated with caving hard rock orebodies through preconditioning. In essence, by hydraulic fracturing a virgin mining block the rock mass strength and primary fragmentaion size can be substantially reduced through the introduction of new fractures and the opening of existing discontinuities. Thus the major benefits anticipated from rock mass pre-conditioning include increased cavability and reduced primary fragmentation, both of which equate to substantial reductions in mining costs.

Hydraulic fractures introduced for preconditioning should be oriented with respect to the pre-mining stress field. If fracturing is required later in the mine life, to induce caving, the fractures produced then will be affected by the mining induced stress field and will consequently orient themselves with respect to it.

Monitoring activity indicates fracture growth of more than 40 meters from the packed off borehole. The ISIP data collected after each hydraulic fracture treatment shows an increasing closure stress magnitude with distance from the cave. The closure stress magnitude in boreholes that were re-fractured a few weeks after their initial treatment was systematically reduced. Hydraulic fracturing softens and weakens the rock mass. The fractures placed some distance from the cave act to weaken that rock and to reduce the stress magnitudes and stress gradients in it. The softening of the rock may not be desirable for inducing caving. An alternate strategy involves concentrating more fracturing effort nearer the cave. This zone of concentrated hydraulic fracturing may serve to weaken the rock near the cave while preserving higher stresses outside the zone. The higher stresses act to drive the failure. Additional analysis of the data collected is being undertaken to investigate this option.

The data suggests that most of the treatments performed more than about 20 m from the cave back were opening mode fractures. Some shearing occurred around these fractures as they grew into the rock and as fluid was lost into the surrounding rock mass. In addition to inducing caving, these treatments served to pre-condition the rock for caving by the introduction of new fractures.

The fracture treatments that were located very near the cave back responded, in many cases, as would be expected for shear dominated treatments.

The packed off intervals for these treatments accepted fluid before breakdown at low pressure and a distinct breakdown of the hole did not occur. Bottom-hole treating pressure was low and microseismic activity was higher than average for these treatments.

3 CONCLUSIONS

Hydraulic fracturing is a proven method to induce caving of ore in block caving mines.

The treatment data from Northparkes is consistent with growth of opening mode hydraulic fractures at treatment sites more than 15 to 20 m from the cave back. Shear fracturing is thought to be more dominant in the treatments conducted within about 20 m from the cave back..

Although treatments performed at locations near the cave back may initiate as opening mode fractures they generally act to pressurise the rock mass, reducing the normal stress across existing fractures and promoting shearing.

There is significant potential for the use of hydraulic fracturing to pre-condition the ore blocks so as to weaken the rock mass and reduce fragmentation size.

4 ACKNOWLEDGMENT

We thank Northparkes for permission to publish this paper and for continued support of the trials of hydraulic fracturing in Lift 1. We especially appreciate and acknowledge the support, given from the early days of this new initiative, by both Michael House and Ross Bodkin.

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