Pit wall failures on 'unknown' structures

by P.M. Dight*

Synopsis

A number of impending and actual pit wall failures have been observed and documented, which have been interpreted to initiate on newly generated structural features. This infers failure through intact rock. Failure mechanisms have been postulated resulting from circumferential stress, extensional strain and brittle flexure. These will be discussed in the context of the failures and the associated monitoring. The implications of failure initiating on 'unknown' features has a significant impact for deep open pit mines where designs are based on the expected structural regime. Being able to anticipate such failures is important for design. Equally important is management of such changes as they arise. In this context, monitoring using high resolution microseismic techniques will be discussed as a means of providing early warning of such failures.

Introduction

The classical geotechnical approach to open pit design in hard rock is to examine the potential for kinematic failure on existing structures and/or rock mass failure.

This paper focuses on failure on structures and through intact rock.

The structural regime around mineralized systems is often complicated by the tectonic events preceding mineralization which pre-condition the rock mass, and subsequent events interpreted to be associated with mineralization.

Understanding of such systems provides additional insight, to the orientation of structure to be expected.

Data for analysis and interpretation of geotechnical failure potential is typically obtained from oriented drill core, downhole geophysics, outcrop mapping, face mapping and/or structural geology interpretation.

In all mapping, allowance for bias is essential; this is particularly the case for interpretation of defects sets from orientated diamond drill core. Recent publications using tectogenesis such as Bogacz 2004 have also helped identify whether weakly represented structure orientations in the database are significant and should be given more emphasis in analysis. This arises from the interpretation of tectonic evolution (i.e. prior to mineralization) or tectogenesis (tectonic events contemporaneous with mineralization) and the associated structures that should exist when examining the fracture patterns in a rock mass.

Geotechnical issues in open pits arise, however, when failures occur on inferred structures, which have not been captured in the database.

This paper will present examples of such occurrences. It will provide guidance as to why they have occurred and how to anticipate such issues in design and to monitor for the potential onset of failure on 'new' or 'unknown' structures.

In this paper: Geotechnical failure is defined as a failure that is statistically expected based on the defect orientations and their intersection with the pit slope. It typically occurs during mining and scaling but often does not significantly impede mining. Such events can be catastrophic if personnel are seriously injured or death results. Generally, however, as a result of low exposure times, such events tend not to be catastrophic for personnel, equipment or financially.

A mining failure is defined as one which occurs subsequent to creating the slope face, and can create significant disruption to mining. While these are also 'geotechnical' failures, the timing of the failure is the important issue.

* *Coffey Mining a Division of Coffey Geosciences Pty Ltd), Australia.*

Case study A

This open pit mine was developed on a sequence of siltstone and sandstone. A view of the south wall of the pit is shown in Figure 1. Originally the south end of the pit was mined with 20 m high batters at 71.5°, 5 m berms and a design probability of geotechnical failure of 15% and a depth of 120 m.

Following completion of mining in the south pit, the owners felt that the actual percentage of geotechnical failures was unacceptable (actually <10% of the exposed batter face) and requested that the northern pit wall be reinforced with cable bolts to reduce the incidence of batter scale failures. The resultant design comprised 12 m long twin strand, 15.2 mm diameter prestressing cables, post tensioned to 5 tons. The bolt spacing was 2.5 m by 2 m. As a consequence of the reinforcement, this lowered the design probability of failure of a 30 m high batter (triple stack) to 2%. No consideration was given at the time to failure greater than a batter height because, at the time of the design, no structural interpretation was available and there were no structures interpreted to be that long based on detailed scanline face mapping, and the rock mass had an MRMR of 55 interpreted from the available drill core.

Hence the pit design comprised 71.5° batter angles over 30 m with a 5 m berm and an overall slope angle of 59.7°.

Shortly after commencing mining the company changed the batter angle to 76.5°.

A consequence of the change was the creation of a convex wall.

Figure 2 shows the wall 24 hours prior to failure. Large cracks had opened up on the face; the ground had been experiencing audible cracking after blasting (locally called 'booting') for several months, and the rock mass strength had dropped from 27 MPa to 5 MPa. Failure was imminent.

The failure was witnessed by the site geotechnical engineer who described it as '*son et lumiere*' as the barrel and wedge anchors were stripped off the cables. The failure measured 200 m along strike, approximately 10 m deep and 80 m high. The back scarp appeared to follow the trace of the thrust line created by the oversteepening.

Figure 3 shows the wall after the failure and after a large windrow had been constructed through the pit.

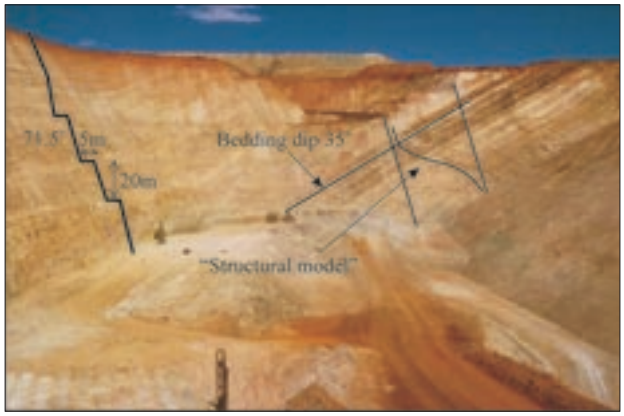

Figure 1—Mine A: looking south in the South Pit

There are several interpretations of the failure mechanism but the one favoured by the author comprises toe failure resulting from inadequate rock mass strength (Coates and Yu, 1998) and shearing through intact material.

The back scarp followed a step-path comprising structure 5, which was sub-parallel to the thrust line due to oversteepening (Figure 4). This set had an up-dip continuity of 1 to 2 m and terminated on bedding. Note that all the rock mass on the pit side of this line would be totally stress relieved 'in tension'.

Figure 5 shows a cross-section through the failed rock mass. The failure scarp is plot deep (<10 m).

The failure mechanism therefore could be interpreted using Baczinski's step path model (Baczynski 2000) as shown in Figure 6. However, there is not sufficient explanation of the initiation of shearing at the toe.

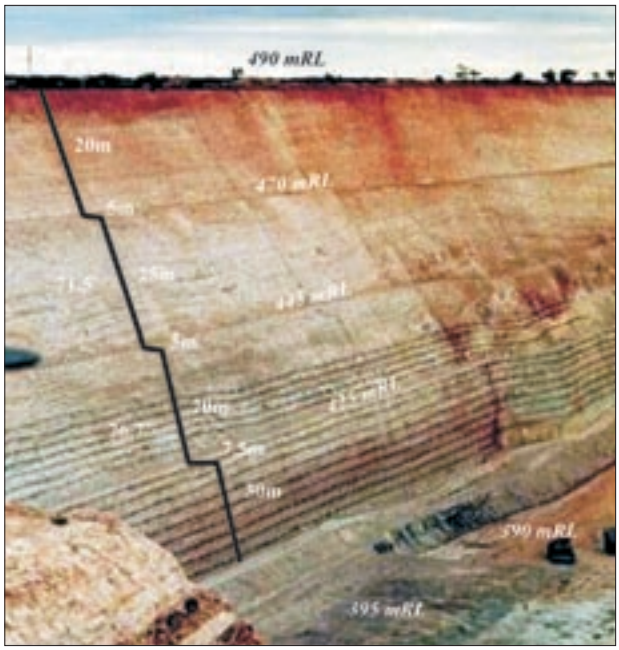

Figure 2—Mine A: highwall just prior to failure

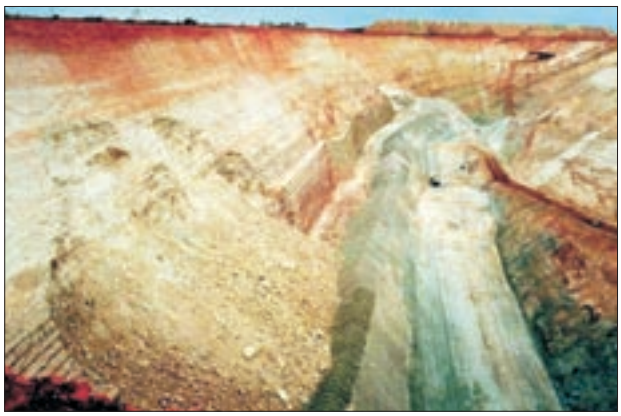

Figure 3—Mine A: showing extent of highwall failure. Windrow in centre of pit built afterwards

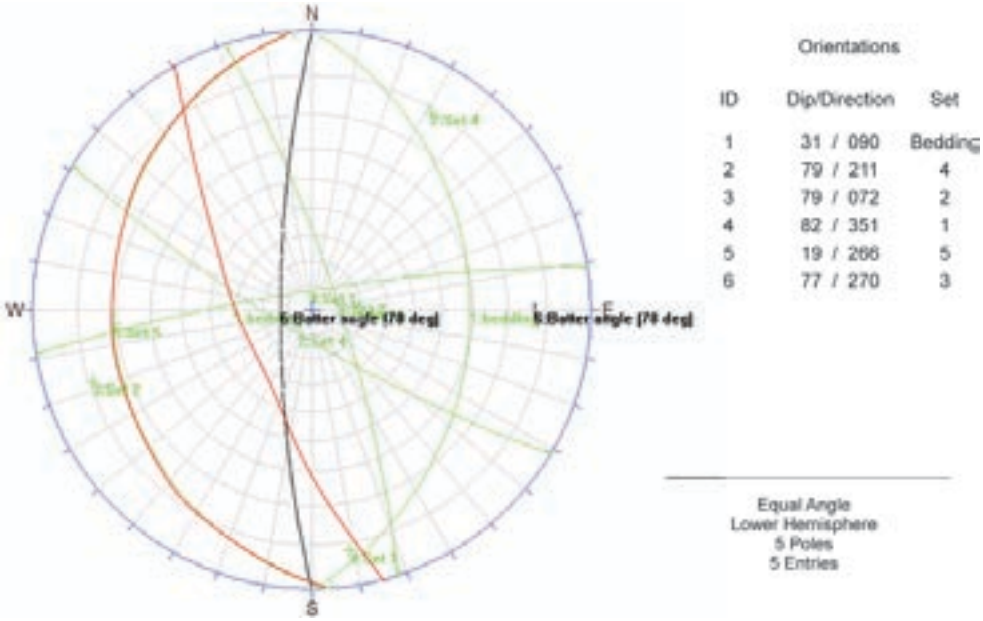

Figure 4—Stereonet showing major defect orientation Mine A

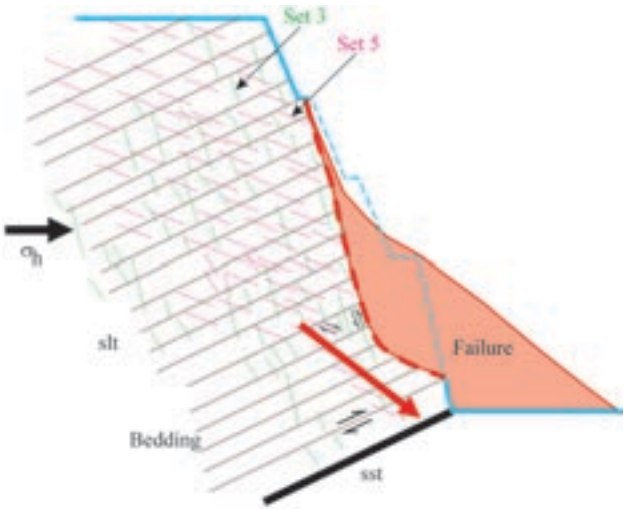

Figure 5—Failure scarp and shape of rill. Note failure occurred adjacent to change in rock type

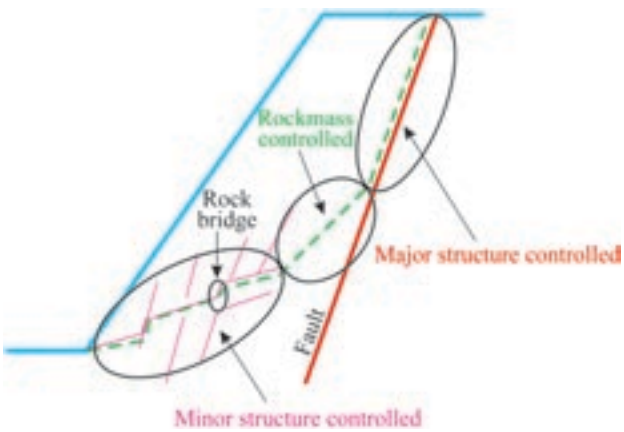

Figure 6—Step path failure after Baczynski, 2000

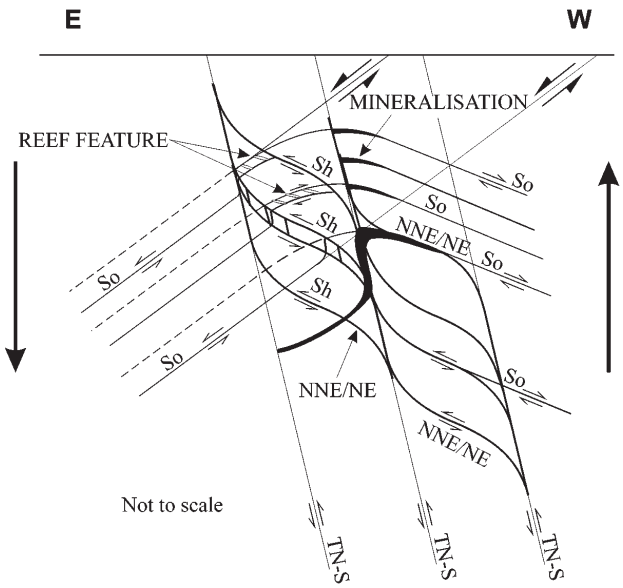

Figure 7—Tectogenetic Model after Bogacz, 1998

Subsequently, a detailed structural model of the mine was developed by Bogacz (1998). Shown on Figure 7 is a schematic 'structural interpretation' as projected onto the south wall of the pit. Of note are the steep 'shears' which traverse obliquely across the bedding. These shears 'parallel' the cross bedding structures (Set 5) identified in the pit wall exposures, but due to the bias in the mapping were not recognized/identified features. The typical spacing on these features is between 20 and 50 m. Structurally they could be considered as part of a fractal set. Use of the structural model in geotechnical design would have warned against steepening the pit wall and as a consequence a probable reduction in the size of the failure.

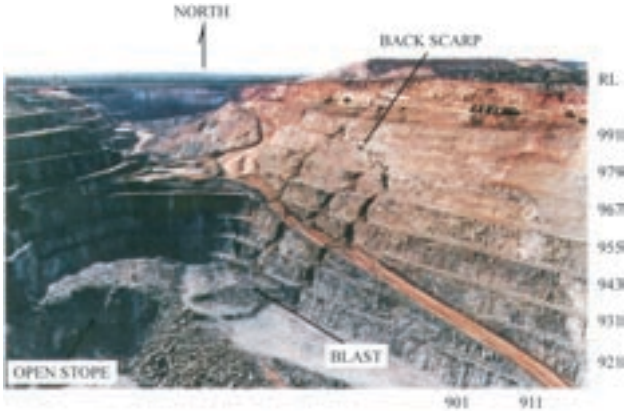

Figure 8—Mine B: looking north with failure on east wall

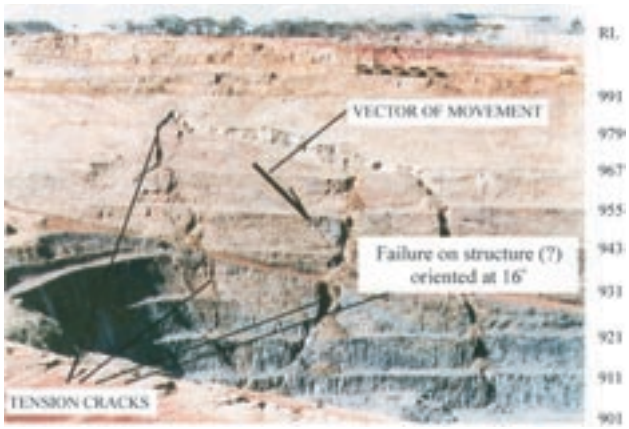

Figure 9—Mine B: looking at failure. Vector of movement was 16°

Case study B

This mine was developed in a sequence of amphibolites, a highly foliated, steeply dipping quartz biotite schist and high magnesian basalts.

A failure occurred on the east wall of the pit affecting the main access to the pit (Figure 8 and Figure 9). The failure occurred rapidly.

The only slope monitoring undertaken prior to the instability was visual inspection. Immediately the failure initiated, prisms were installed to provide a history of displacement.

The movement that occurred immediately after the failure initiated (Figure 10) suggested that the failure was accelerating (in particular up to 100 hours after the prisms were installed) and that the pit would have to be abandoned until a new access was established. The equipment had already been evacuated (within 18 hours of the initial observation). Subsequently the movement rate slowed down (as seen in Figure 10) suggesting that the driving force for the failure had been exhausted.

Examination of the movement vectors showed the failure was inferred to be occurring on a structure dipping at 16° towards the south-west. However, there were no features mapped in the pit that correlated with this direction.

The owners of the mine commissioned an extensive geotechnical investigation to establish the cause of the failure.

In the course of the investigation, it was identified that two adjacent pits had experienced failures in geometrically similar positions to the one described here. In addition, the mine had experienced an earlier failure in exactly the same position on a previous cutback. This observation was made by examining a photograph of the previous pit located behind the mine secretary's desk! This earlier failure was interpreted to be one through the rock mass.

This later failure was interpreted to be the result of buckling in the quartz biotite schist, followed by flexural failure and sliding on the 16° plane. Figure 11 shows the stress analysis undertaken at that time. Once the lateral stress was relieved, then the driving force for the failure dissipated and the rock mass reached equilibrium.

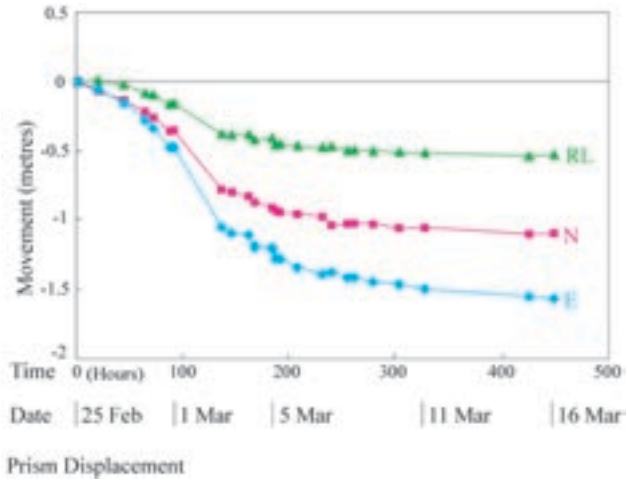

Figure 10—Mine B: displacement profile developed with time

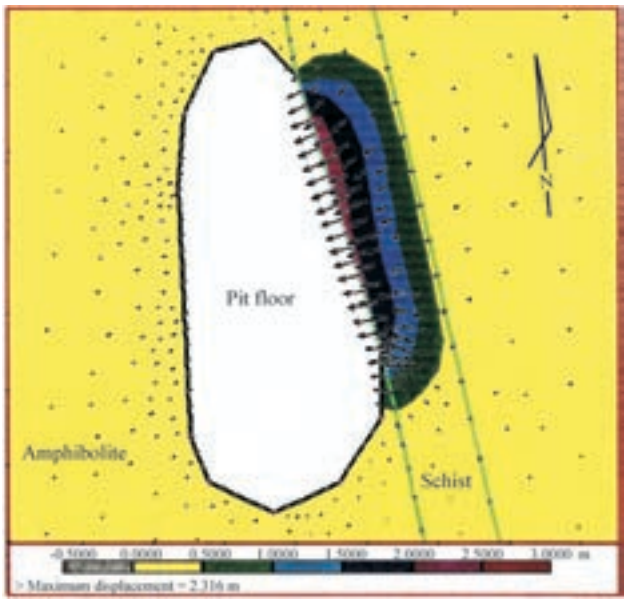

Figure 11—Mine B: showing displacement concentration in schist

Subsequently the east wall of the mine was cut back. The design recognized the potential for another failure but laid the slope back to minimize the extent. During mining, another failure did occur. With the confidence built up from the previous experience, rather than cease mining, the company continued, safe in the knowledge that the very strong amphibolite at the toe would buttress the quartz biotite schist. The strategy was successful.

Case study C

This potential failure initiated within an ultramafic rock mass. As can be seen in Figure 12 there has been an earlier failure characterized by shearing and rock mass failure within a highly weathered felsic/dacitic unit. Initially the failure was attributed to a rock mass failure as a result of the slope being too steep for the rock mass strength. The original design assumed a base of weathering extending to 100 m below surface. In fact the depth of weathering extended considerably further (140 m). On closer inspection, however, this failure involved shearing on steeply dipping faults. As depicted in Figure 12, this suggested that the failure was located in a zone of compression as indicated by the Kirsch equations (Figure 13). It is a coincidence but an earlier cutback of this same mine also experienced a failure in a similar location within that pit. As with case study B, this appears to be a signature of stress induced failures in open pits.

The author believes the stress model inferred from this failure was confirmed when later a toppling failure occurred in the region of low stress as predicted by the Kirsch equations (as shown in Figure 14) in the same rock unit.

The interpreted 'stress regime' also agrees with a structural interpretation of the stress regime presented to the mine some 8 years prior to the initiation of these failures.

The design location of the switch back in the haul road was moved off the south wall to the position shown in Figure 12. The pit wall shown below the switch back was instrumented with 120 m long SMART Extensometers (Hoek *et al.* 1995). When the wall was approximately 90 m high below the switch back, visual observation showed that the face was deteriorating with the formation of large shallow slabs.

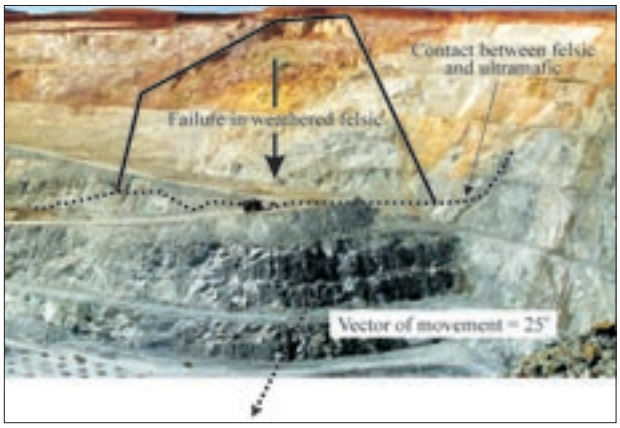

Figure 12—Mine C: showing extent of failure in scale from bottom of pit to switchback 90

Movement was also detected on the extensometers, coinciding with displacement along the contact between the felsic and ultramafic approximately 100 m behind the face. A review of the prism monitoring showed that the vector of movement was at an angle of 25° towards the pit.

A review of the extensive defect mapping database does not reveal any structures that would singly or in combination form a step path with this orientation. It was considered that the most likely mechanism comprised toe release of the face and local dilation This allowed a change in failure mode for the mass behind the face to develop into an active wedge.

This item caused the ultramafic to respond in flexure and generate an initial 'tensile' crack at an angle of 20° to 25° resulting in a step-path angle (combining with the 70° foliation in the ultramafic).

Based on this interpretation it was decided:

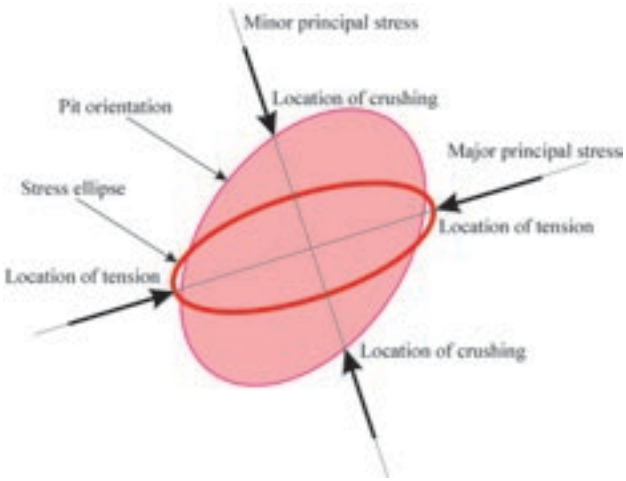

Figure 13—Mine C: showing Kirsch stress interpretation

Figure 14—Mine C: toppling failure located in 'tension' zone as interpreted using Kirsch equations

- To install deep depressurization holes to relieve any excess pore pressure behind the slope, and
- Cease mining at the toe of slope and 'temporarily' abandon the ore until the next mining cutback.

As soon as mining stopped at the toe of the slope, the movement also ceased.

Discussion

The three case studies demonstrate that stress has a significant influence on generating new structures. Stacey (1981) postulated that when the extensional strain exceeded 0.0004, new cracks could be initiated. The equation for the extensional strain is:

$$\varepsilon_3 = 1/E\left(\sigma_3 - \left(\sigma_1 + \sigma_2\right)\right)$$

This approach was examined also by Stacey *et al.*(2003) and Lynch *et al.* (2005) at the Navachab mine in Namibia. This latter study was very well documented, and one of the first case studies to be published on the use of microseismicity in open pit studies. The host rock for the mineralization is a calc silicate, a very hard brittle rock.

In this study the contours of extensional strain shown in Figure 15 do not comprehensively demonstrate the initiation of a new failure surface as noted by Lynch. This may, in part, be due to the assumptions relating to the local stress field, and the simplifying assumptions which arise from the 2D modelling, which can often ignore major structure effects. In the case of Navachab, the instability apparently occurred adjacent to a major pegmatite dyke (Figure 16). A preliminary structural analysis of the published data suggests that a major influence on the local stress regime (and possibly associated with the mineralization events) can be traced to a granotoid intrusion located to the north-east of the mine.

Making an allowance for this event, a different model of extensional strain can be interpreted, as shown in Figure 17, which is closer to the expected basal plane.

Hoek (1968) published a paper describing uncontrolled crack initiation in glass when the ratio of σ_3/σ_1, fell below 0.05. This approach has been examined for Case A, Case C and Navachab.

The contours of σ_3/σ_1 show that this method also can provide guidance to the initiation of new cracks. It has geotechnical merit in open pits over the extensional strain approach for the following reasons:

- It is independent of the elastic properties of the rock mass,
- σ_3 will reduce as the mine is excavated, and
- σ_1 will rotate and increase as the mine is developed.

A new method of examining crack initiation has also been trialled. This is based on the premise that all cracks initiate in tension and then coalesce into shear behaviour. This is reinforced by the measurement of microseismicity in mines (Lynch and latterly ACG). While the measurement of tensile cracks is difficult due to their high acoustic frequency, high attenuation and limited extent, they may provide a significant warning to the subsequent development of

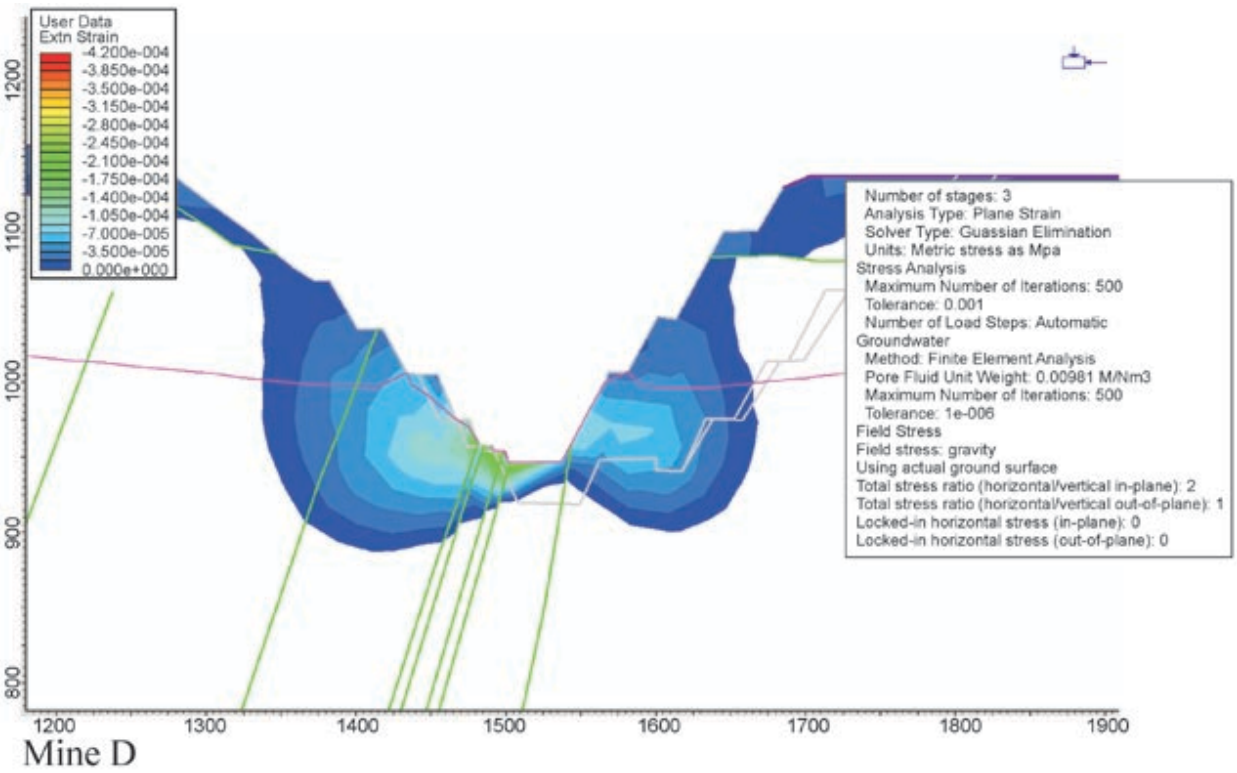

Figure 15—Mine D: showing contours of extension strain. Failure angle is quite shallow

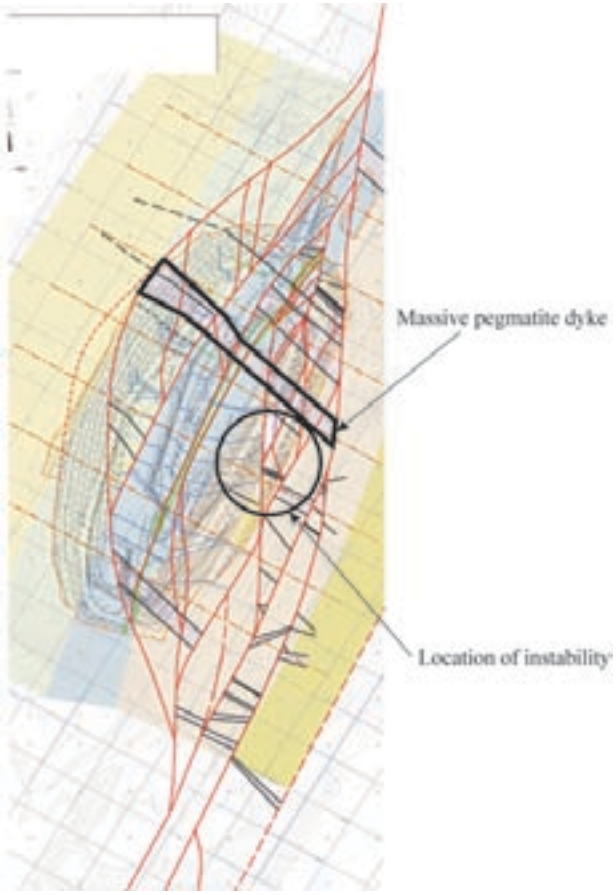

Figure 16—Mine D: showing location of instability adjacent to pegmatite dyke

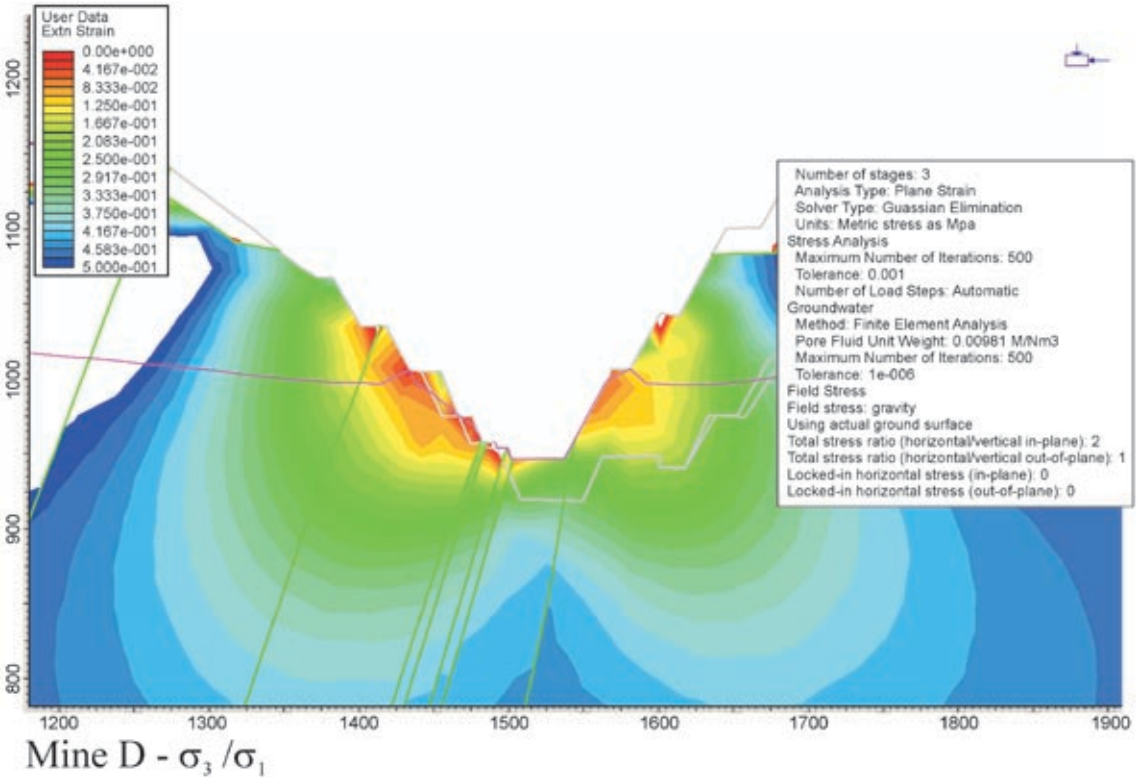

Figure 17—Mine D: shows contours of σ_3/σ_1; failure occurs at a shallow angle

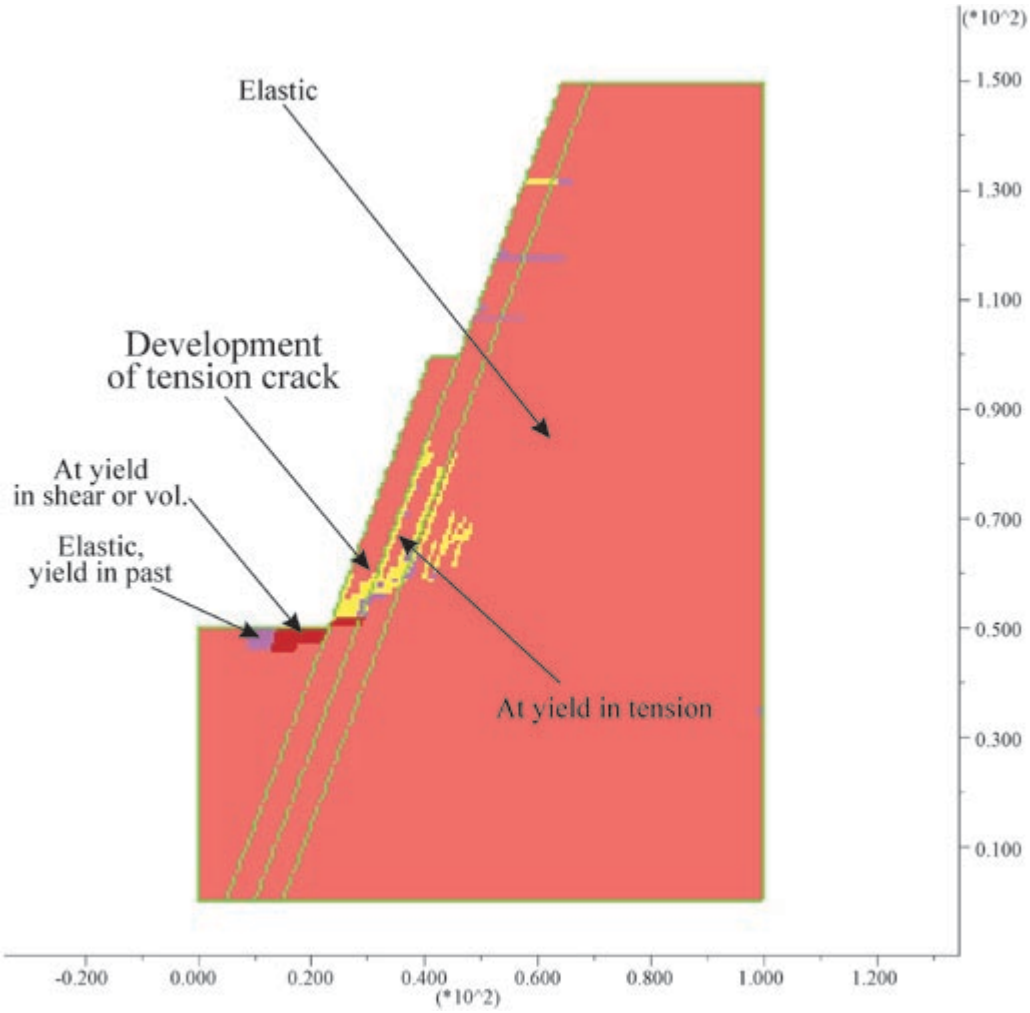

Figure 18—Development of tensile cracks which initiate through flexure

shearing. Figure 18 shows the development of tensile cracking resulting from rock flexure. The angle is surprisingly similar to that generated by σ_3/σ_1 and extensional strain.

The approach is being examined further.

Acknowledgements

I wish to acknowledge the support of the many clients who have provided the opportunities to undertake these investigations, including BHP Billiton, Newmont Australia, Sons of Gwalia, Anglo Gold Ashanti and Kalgoorlie Consolidated Gold Mines.

I also acknowledge the support of my colleagues at Coffey Mining.

Dr Vic Bogacz has been a constant source of inspiration and valuable friend.

References

BOGACZ, V.W. *The Tectogenesis of the Telfer Gold-Copper Ore System in the Proterozoic Paterson Orogen, North Western Australia*. Archon Resource Technologies. 2004.

BOGACZ, V.W. *Telfer Tectogenetic Model. Implementation of the Structural Model for Main Dome*. Archon Resource Technologies, Adelaide, 1998. pp. 1–9.

HOEK, KAISER, P.K. and BAWDEN, W.F. *Support of Underground Excavation in Hard Rock*, 1995. Rotterdam: Balkema

COATES, D.F. and YU, Y.S. Block Flow Slope Stability. Canmet Report 78–10 June 1978.

HOEK, E. *Brittle Fracture of Rock in Rock Mechanics in Engineering Practice* Stagg and Zienkiewicz, (eds.), London: Wiley, 1968. pp. 99–124.

LYNCH, R.A. WUITE, R., SMITH, B.S., and CICHOWICZ, A. 2005. Microseismic Monitoring of Open Pit Mines in RaSIM6—Controlling Seismic Risk. 2005. pp. 581–592.

STACEY, T.R., TERBRUGGE, P.J., KEYTER, G.J., and XISNBIN, Y. Extension Strain—A New Concept in Open Pit Slope Stability, and its use in the explanation of Two Slope Failures. *AuSIMM – Fifth Large Open Pit Mining Conference*. 2003 pp. 259–266.

STACEY, T.R. A simple extension strain criterion for fracture of brittle rock. 1981. *Int. J. Rock Mech Min Sci* 18: pp 469–474.

BACZYNSKI, N.R.P. STEPSIM4 Step-path method for slope risks. Geo Eng 2000, *Proceedings of the International Conference on Geotechnical and Geological Engineering*, Melbourne, 2000. pp. 6 ◆