Strain Energy Control for the Big Bell Longitudinal Sublevel Cave

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Abstract

The Big Bell longitudinal sublevel caving operation had a production tonnage of 1.8Mtpa prior to the onset of seismic activity in 1999. During 1999 and 2000, substantial damaging seismic events resulted in a suspension of mining operations in late 2000. Major mine redesign work such as; extraction principles, development location, ground control systems, and man access to working areas, were undertaken to develop a safe and stable seismic environment. This was achieved in mid 2002 once all design principles were implemented. Due to rising costs from the lower production rate of 0.7Mtpa the mine closed in mid 2003.

1. INTRODUCTION

Big Bell had a history of rockbursts from 1999 until mine closure in 2003. During this period the mine had to develop suitable mining front geometry, development locations, ground control systems, and automated equipment usage, to minimize the potential hazard to the underground work force.

Other papers by Player 2004a, Player 2004b, Barrett and Player 2002, Turner and Player 2000, Player 2000, Sandy and Player, 1999 describe the rockmass properties, ground response, mining environment, and mining methodology. These papers were written over a number of years when the ground response to mining changed from non-seismic to seismic. They detail the progressive understanding of strategic factors involved in combating mine seismicity.

This paper will examine the driving factor for the mine seismicity and the performance of the hangingwall cave. In particular, it updates the approach to mining the orebody published by Turner and Player 2000.

2. SEISMIC GEOTECHINCAL ISSUES

It is difficult to determine when a mine changes from a non-seismic to a seismic environment. The relative induced stress compared to the rockmass strength, and how the rockmass stores and releases the energy are some of the most important controlling factors.

How the rockmass releases strain energy from stress change is a function of; the rock matrix, discontinuities present, the regional / mine wide loading system, and the amount of work that the rock does before and after failure. The loading system is considered to be influenced by the mining front rate of advance.

Beck 2000, takes the approach, "…seismic induced events can be described from numerical modelling utilising Mohr Columb slip criterion for events on discontinuities and the relationship between $s_1 and s_3$ for seismic events not associated with deviatoric mechanisms". To undertake this work requires quality processed seismic events from the mine micro-seismic monitoring system. The method is applied as a back analysis of known mining steps and associated seismic activity. It is possible to allocate seismic criteria to future mining steps or sequences, if it can be assumed that the seismic criterion remain consistent.

Brady and Brown 1994, provide the following definitions, "Rockbursts arise from unstable energy changes in the host rockmass for mining….Energy changes in a mine domain arise from generation and displacement of excavation surfaces and energy redistribution accompanying seismic events…the strain energy changes which arise from the way in which surface forces are applied as part of the mine structure" are considered to be the dominate source of energy.

According to Brady and Brown 1994, two factors need to be considered in relation to energy changes, "increase in static strain energy occurs in areas of stress concentration (stress concentration occurs around all underground openings)….sudden excavation of a surface causes an energy imbalance in the system". This can lead to a dynamic stress component related to the volume of material that is rapidly removed / blasted. It should be noted that local rock fracturing around openings would consume some of the released energy. The rapid excavation of a mining void applies a dynamic stress to the ground closest to the excavation then spreads into the rockmass. When this encounters a static stress field concentration the sum of the stresses can result in damage to the rockmass by exceeding the rockmass strength.

For mining environments, the energy released from the excavation of the rock can be considered as an index for the potential local degradation of the rockmass. The degradation, or yielding, can either by non-violent or violent (i.e. bursting conditions). Hence the energy released by an excavation can be used as a design principle. It is better to have a consistent energy release rate from a mining geometry and sequence, rather than one which has sudden energy changes.

This can be succinctly explained by the illustration of three different excavation sequences in Figure 1 from Whittaker et al 1992. Sequences one and two have a rapid energy release during the excavation cycle. This makes the sequences more susceptible to a rockburst than sequence three, which has a regular energy release. Sequences one and two could be related to;

- a mining geometry utilising primary and secondary open stopes (with pillar removal and fill compared to a pillar less sequence with the use of paste fill),
- or a longwall mining face (that uses an arrow head rather than a flat face),
- or the release of strain energy along a fault (clamping a fault and mining towards it compared to releasing the fault and moving away).

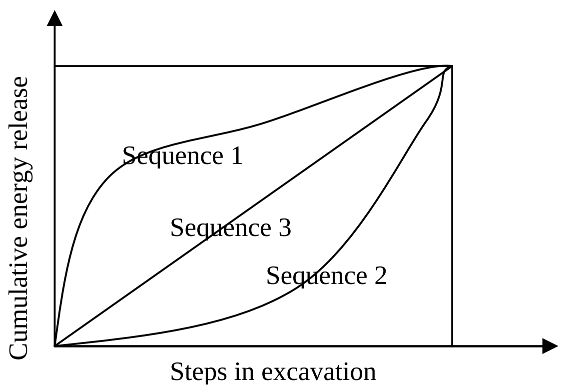

Figure 1: Example energy release rate

Strain energy release into the mine environment is controlled by the displacement of the excavation surface and the creation of new surfaces. The mechanisms will depend on the loading system stiffness and rockmass strength to stress ratios. The creation of the hangingwall cave has a very high potential energy release. The cave effectively increases the excavation size and available energy to the mining environment from the formation of new surfaces. Rather than a mining environment that has controlled displacements of the hangingwall, from fill placement or partial extraction by leaving pillars. The additional energy needs to be accounted for as part of the mine design.

The Big Bell operation utilised rapid advancing longitudinal mining front with ‘limit retreat pillars’ from 1997 to 2001, Barrett and Player 2002. The use of pillars and a flattening of the mining front, promoted a non-uniform energy release. Intuitively the performance of the hangingwall strata (particularly from rockmass variations between strata), would be expected to influence the caving process in conjunction with; mining geometry, dimension, and rate of advance of the mining front. These factors probably contributed to rapid changes in the energy release in the rockmass, similar to sequence one or two of Figure 1, rather than the gradual release of sequence three.

Brady and Brown 1994, define the potential energy of the loading system upon the rockmass as unstable, when it will lead to unstable deformation i.e. seismic events from an instability source.

There are two modes of unstable rockmass deformation that lead to instability and mine seismicity. Method One typically involves the crushing of rockmass in pillars, and around excavations at both development and stope scale. These events are modelled by $s_1 and s_3$ relationships of the monitored seismic events in a process that is explained by Beck 2000 and Wiles 2004. Method Two involves the slip of structures, which could be natural, or mining induced. Slip on a structure can be defined by the Mohr Columb criteria, Beck et al 1997. Beck 2000, assesses both modes of rockmass deformation from monitored micro-seismic events for the period April to August 2000 at Big Bell. The criterion does not describe the potential magnitude for a seismic event, but rather defined when conditions exist for a seismic event to occur. This was based on previously monitored seismic events. At Big Bell five criteria were developed for $s_1 and s_3$ and Mohr Columb modes of rockmass instability.

The above approach relies on the results of micro-seismic monitoring, stress modelling and rockmass properties. It is unlikely to be sensitive enough to provide why one location will burst within a zone that meets a criteria, as opposed to another location. However, the approach should be able to describe at which zones rockbursts won't occur. Work by Wiles 2002, and Wiles 2004, examines a combination of modelled rockmass properties, released energy and loading system stiffness, to determine conditions for rockburst occurrence from the back analysis of previous bursts.

The reliance of back analysis techniques to determine future rockburst potential implies early rockbursts will be unexpected hence good mining practices must always be applied during the life of a mine. Good mining practices should use suitable geometry and sequences that redistribute the induced stresses as uniformly as practical. This is the first step in controlling a potential rockburst problem and should be used in combination with an advance rate that controls strain energy buildup in the rockmass.

There are a number of tactical issues that need to be considered when evaluating the geotechnical needs of a mine once a strategic decision has been made to assess seismic activity;

- When does seismicity present a problem, or is there already a problem?
- Can the seismicity be represented or restricted to a rock unit, mine sequence, mine geometry or development location?
- Which personnel are available to assess the seismic activity including processing of the data, recording mine geometry change and maintenance of the seismic system?

There are specific issues relating to geotechnical properties and mine seismic that are worth further expansion (Section 2.1 to 2.3).

2.1. Rockmass, Local and Global Issues

The following list of local and global rockmass items have shown to have an that influence the geotechnical seismic potential and properties;

- Many attempts at determining a rock burst index from rock samples have been made. However, the factor that influence a potential rock burst have complexity in their geological and non-geological controls,
- Rock mass characterization across the mine environment,
- Rock mass stiffness and post peak properties,
- Rock P and S wave velocity calculation then undertaking a site survey to provide greater accuracy for the seismic system,
- Regional structures that will influence stress, can be a source of seismic activity. They could also damp seismic energy transmission from an event, and
- Insitu stress levels and background seismic activity.

2.2. Mine Sequence and Geometry Issues

The following list of mine sequence and geometry items have shown to have an influence on the geotechnical seismic potential and properties;

- The stress path from mining sequence, Beck and Sandy 2002, examines ground performance changes with different loading conditions,
- Extraction rate from areas of the mine, a number of South African reports refer to square meters exposed, some operations with an extended life have been able to develop critical benchmarks. This forms the basis of the Energy Release Rate principal that is discussed by Brady and Brown 1994, Brink et al 2000, Spottiswoode et al 2000, and Spottiswoode and Milev 2002, and
- The presence of pillars in the mine layout, and the overall geometry of the mining front. Both of these influence the hangingwall response in a sublevel cave operation.

2.3. Development Location and Support Criteria Issues

The following list of development location and support criteria have shown to have an influence on the geotechnical seismic potential and properties;

- Drive orientation and location relative to geological structure and the stress fields, both insitu and mining induced,
- Support / reinforcement installed, yieldable reinforcement, strong surface support that won't fail, quality integration of the two systems, and
- Appropriate design criteria for the determination of support and reinforcement.

3. REGIONAL STRUCTURES AND SEISMICITY

At Big Bell the examination of damaging seismic events showed that the graphitic shear acted as a dampening barrier. This observation applied for events occurring within the ore zone or the footwall amphibolite, Figure 2. It was not established whether the graphitic shears reflected energy away due to fractures, or whether the brecciated material reduced the amplitude of a wave travelling through the shear zone. Damage only occurred within the zone that the event sourced. Damage would not cross the lode graphitic shear to influence closer parallel development but rather occurred along strike, up and down dip, to effect other high stress areas.

Improvements to the seismic monitoring array in 2001 and 2002 clearly identified seismic events occurring on the graphitic shears. The implementation of additional triaxial sensors and a higher number of accepted triggers dramatically reduced the scatter in location of processed events about the lode graphitic shear. Due to the nature of the brecciated graphitic shear, it was possible that recorded seismic events occurred very small distances off the shear along parallel fractures, local splays, or rock asperities in the shear.

Far field footwall activity, often resulted in events felt on the surface. These occurred on what has been termed the Big Bell Fault. Grinceri 2002, proposed this as being the footwall contact between the granite and the mine sequence. Distinct activity was also located in the hangingwall about the granite contact. Both areas were several hundred meters to one thousand meters from the nearest workings.

4. MINE SEQUENCE AND GEOMETRY

Sequence and mine geometry effect stress redistribution around mine openings. A poor initial mining geometry and / or poor mining sequence may bring about unstable pillars, extensive linear mining fronts, or ‘pendants’ being developed. These shapes can lead to very high localised stress. If a longwall mining sequence is not correctly progressed, then an increased proportion of the mining front will be more highly stressed compared to a good geometry. Morrison and Beauchamp 2002, explore geometry and seismic proneness principals. A numerical approach can also be in conjunction with seismic data.

5. ROCKBURST HISTORY

Barrett and Player 2002, fully describe the history of rockbursts from 1999 to 2002. Damaging seismic events from 1999 to 2000 had a reduced association to specific production blasts. This most likely occurred because of a change to flatten the mining front. As a consequence of the flattened geometry any particularly firing had less influence on the stress field.

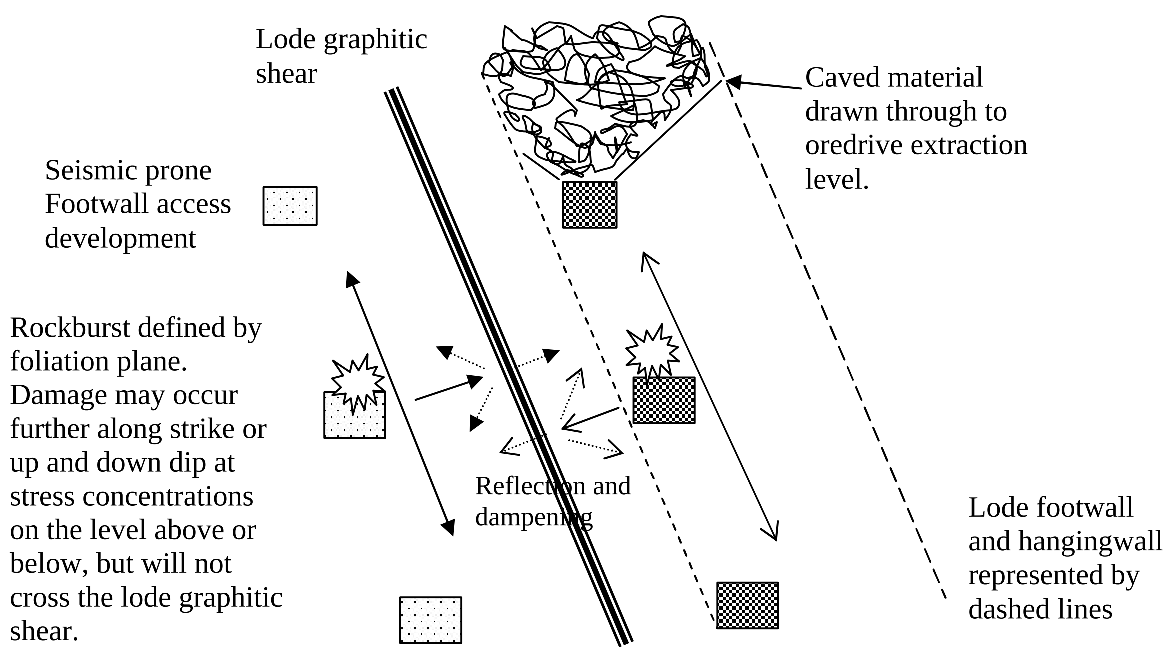

Figure 2: View in cross section showing damage transmission from rockbursts.

The flattened geometry contributed to the complete mine front becoming highly stressed rather than just an abutment stress around each production heading.

Figure 3 is a long section through the cave profile showing the damaging event locations (each event is represented by an individually shaded rectangle), and change in mining fronts from February 1999 to July 2000. Mining in the lower grade southern extension was undertaken, from September 2000 to December 2001 as shown in the right side of Figure 4. Figure 4 also shows, has the change in mining profile in the lower levels with corresponding damaging seismic events from December 2001 to July 2003. Each damaging seismic event area is again shown by individually shaded rectangles.

The principal damage morphology was similar for all moderate to significant damaging seismic events. The observed principal mechanism was shear rupture along foliation planes and intact failure of the rock on the footwall of the rupture plane. Occasionally minor damaging events exhibited different morphology.

An assessment of the principal damage mechanism indicated that a specific foliation place was not responsible for these events, rather any number of foliation planes from one meter into the hangingwall shoulder of the drive, to halfway across the drive. The breakout location was most likely controlled by local factors such as; drive orientation, the presence of the foliation plane, rock mass properties, and the stress field.

Numerical modelling of the mine geometry did not distinguish significant differences in stress concentration between the southern and northern ends of the mine. However, seismic activity and the rockburst damage were different between the northern and southern ends. The largest damaging events of local magnitude greater than 2.0 only occurred north of 3750mN.

The papers by Barrett and Player 2002, and Player 2004a provide detail on the ground control system utilised at Big Bell to control rockburst damage. Survey's of contained rockbursts showed displacements of 300mm to 700mm in the ground control system.

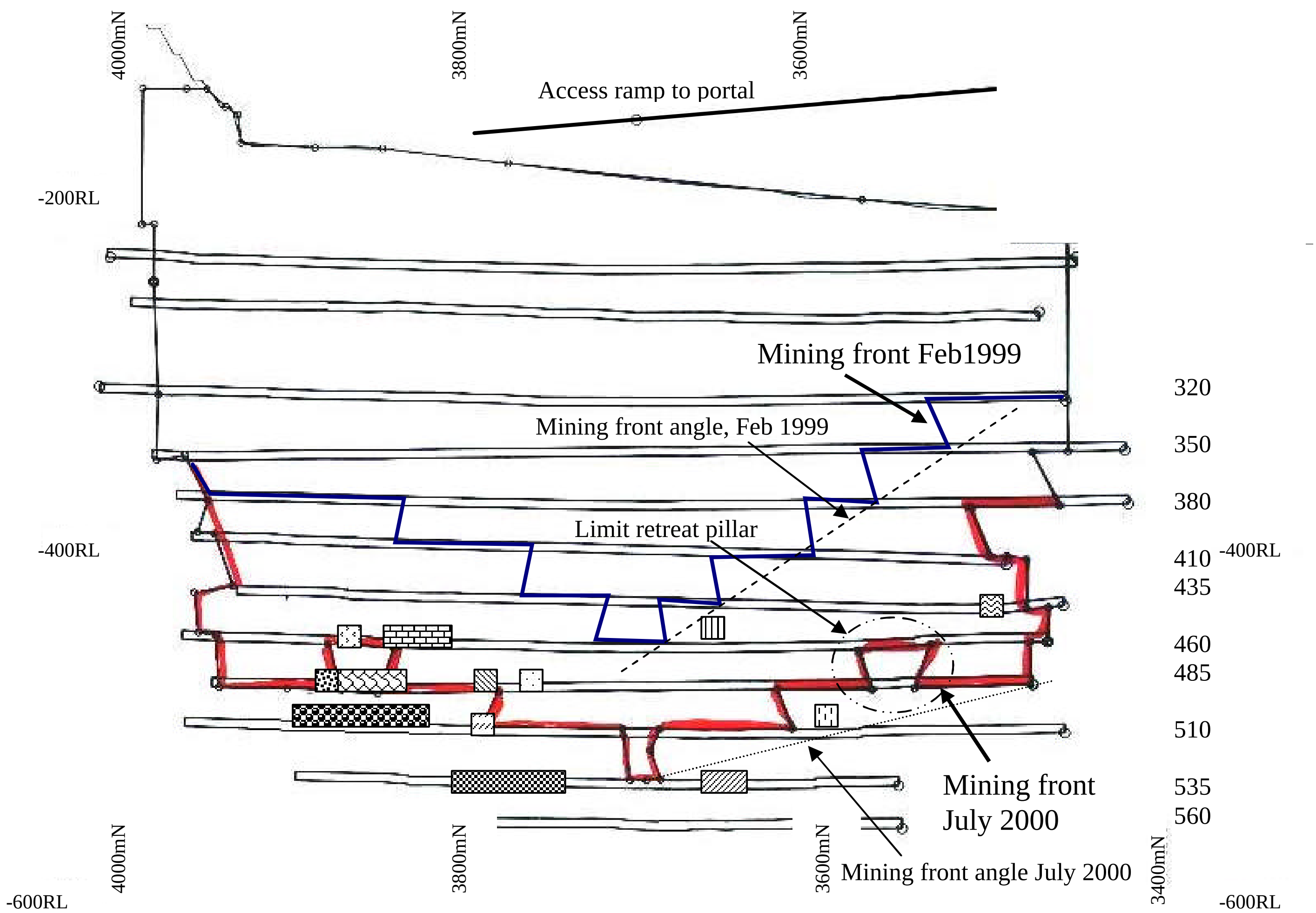

Figure 3: Change in mining front with major rockburst locations February 1999 to July 2000

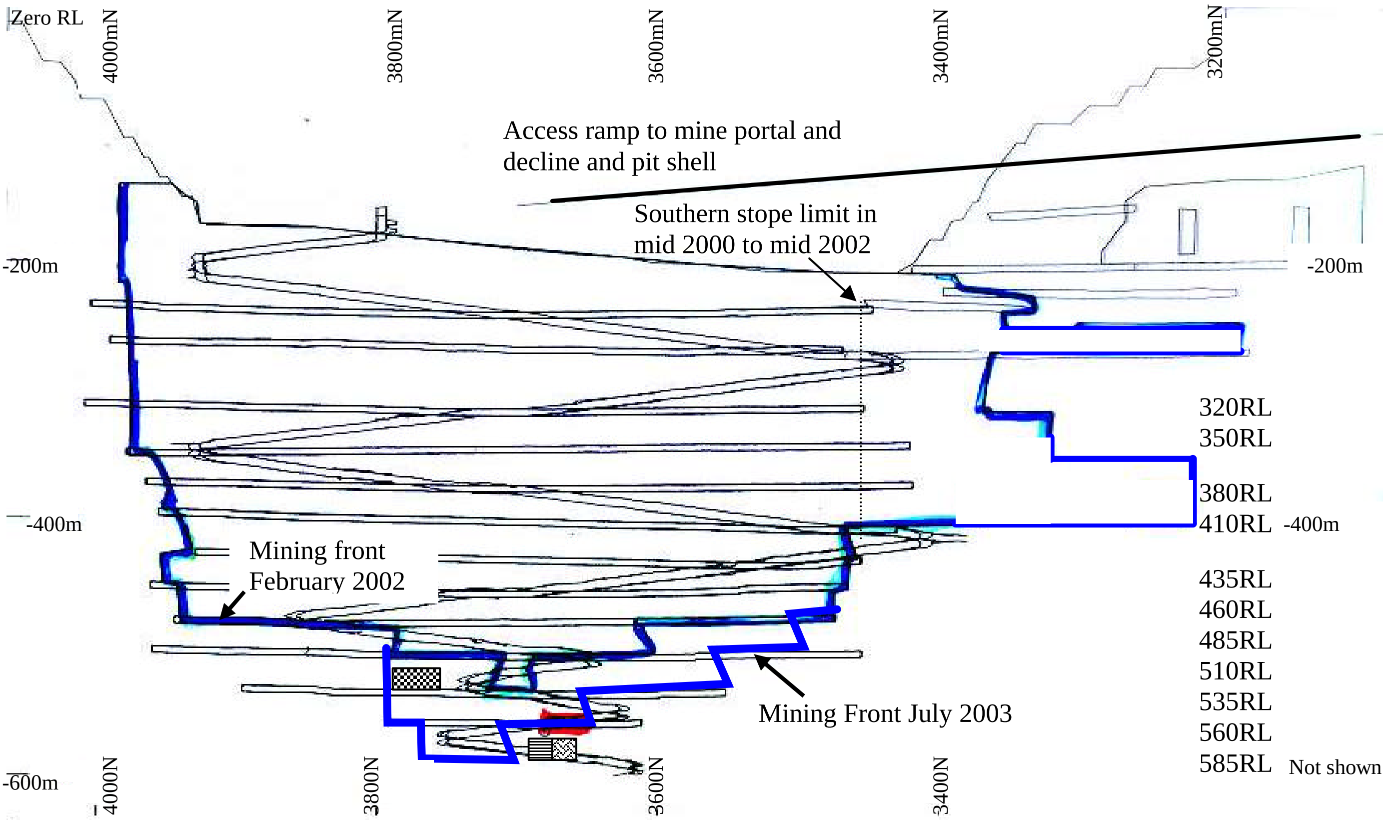

Figure 4: Change in mining front with major rockburst locations from February 2002 to July 2003

6. THE IMPORTANCE OF MINE FRONT GEOMETRY ON CAVING

During a review of access development in 2000 the mining front angle was also examined. The mining front was flattened during 1999 and 2000 due to;

- the production rate exceeding the required development rate,
- failure to open up the 535 slot in a timely fashion,
- damage from seismic events restricting development rate, and
- use of limit retreat pillars (Barrett and Player 2002) at the final cross cut location.

Limit retreat pillars are ore strike pillars from one level to the level above at the last cross cut location. Figure 3 shows an example of a limit retreat pillar. Ore strike development occurred from the crosscut to the end of the ore zone, where a slot was put up and the stope / cave was then retreated to the pillar, which was mass blasted.

The flattening of the mining front changed the mining induced stress inturn modifying the ground response and seismic activity. This change was only realised in hindsight through analysis of a sufficiently large seismic event database.

Comparative seismic activity analysis should only be undertaken on similar mining geometries for a mining operation. The changing geometry of the mining front made it difficult to correctly evaluate the changes in the seismic response to mining. Differences in the seismic response should be expected when there is a variation in the mining geometry.

With hindsight, the data processed in 2000 was influence by mining decisions that were made many months if not a year before hand.

The establishment and maintenance of a favourable mining front angle was a key criterion in the management of seismic activity for the lower levels of the mine from 2002. The planned scheduled sequence to achieve a good geometry from March 2002 is shown in Figure 5. This required a slow production rate. The established mining front and mining front angles at October 2002 are shown in Figure 6.

The schedule from March 2002 could not be maintained exactly due to ground control problems and additional tonnage draw at the northern end of 535 and 560 levels in the middle of 2002.

However, the 45° angle was maintained at the northern end of the mine as shown in Figure 6. This was due to the higher seismic activity level and magnitude that occurred at the north when compared to the south. Seismicity was considered to be strongly influenced by the hangingwall conditions. The hangingwall conditions included more competent rockmass that would have altered the local loading system and potentially stored additional strain energy from the caving process. The caving process was also likely to be less regular.

The 45° angle for mining front had been determined to be the ideal angle, for it was expected to minimise seismicity. This was mainly due to the horizontal and vertical lengths to distribute mining induced stresses being maximised.

The 45° angle was maintained at the northern end until the mining sequence required the 535 and 560 stope numbers 78 and 80 to be extracted to enable the opening of the 585 slot. As expected, this increased seismic activity and resulted in deteriorating ground conditions at the northern end of 535 and 560 levels.

The 585 level was opened slower than scheduled, due to blasting and geotechincal problems. Blasting problems, sub-optimal slot design resulted in bridging. Geotechnical, oversize development and levels less than 25m apart resulted in increased ground damage. These delays required ore from the southern side of the mining to be sourced with out excessively flattening the mining front angle.

A mining front angle of 20° was observed to be satisfactory in mid 2002, and as such mining continued with this angle. The satisfactory performance of the flatter angle was probably due to principal stress orientation (assessed as sub-horizontal and from the north east, slightly shielding the southern cave faces) and weaker hangingwall conditions (allowing softer loading system around the bottom of the cave and more regular caving). During the last months of mine operation, the extended level separation created by the 20° mining front resulted in ground deterioration and seismicity on the 560 and 585 levels, therefore efforts were being made to steepen the angle.

7. CONCLUSIONS

The principal factors controlling hangingwall cave performance include rockmass properties, mine geometry, and mine sequence. By understanding the caving mechanism in 1999, it could have been realised earlier that the more competent hangingwall promoted strain energy build up in the rockmass with the potential to generate larger rockbursts. The mining technique also allowed additional energy input into the mining environment when compared to non-hangingwall caving techniques. This is particularly important where the principal stress is sub horizontal and not parallel to the orebody.

Improved management strategies may then have included; a slowing of the advance rate, changes to the mine development layout, and the implementation of the required heavy ground control scheme. Short term pain for a long term gain.

These changes could have preserved additional levels and enabled a higher production rate than the 0.7Mtpa that was possible from 2001-2003, thereby improving the mining economics. Mining in a very high induced stress field, using longitudinal sublevel cave methods proved to be operationally and technically possible during 2002-2003.

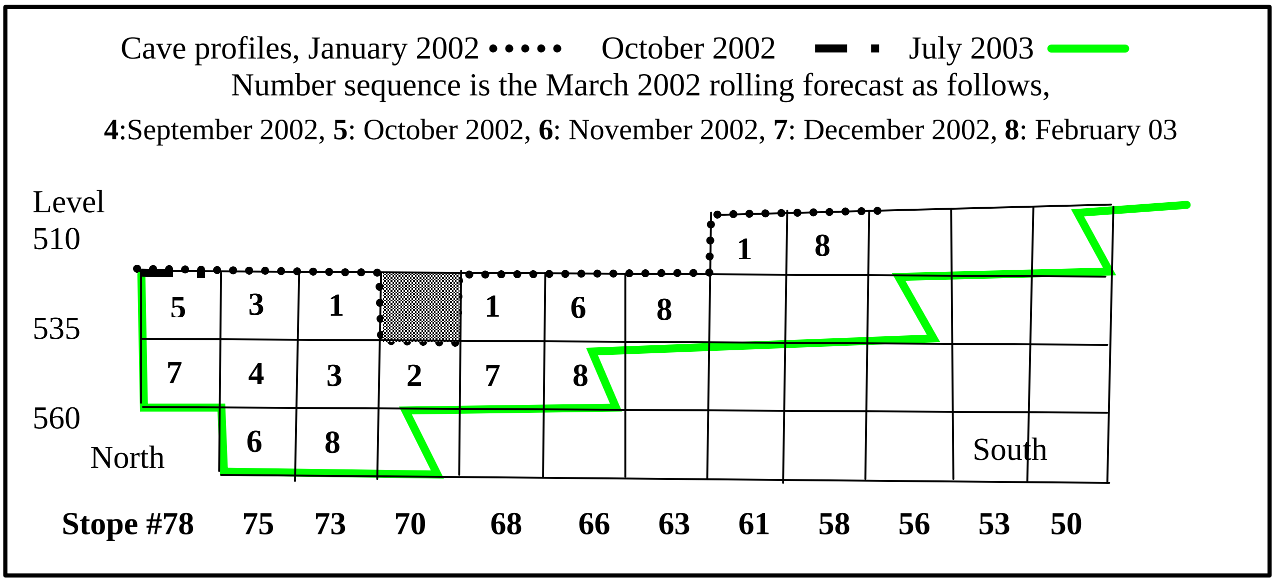

Figure 5: Sequence of stope extraction to achieve good mining front angles from

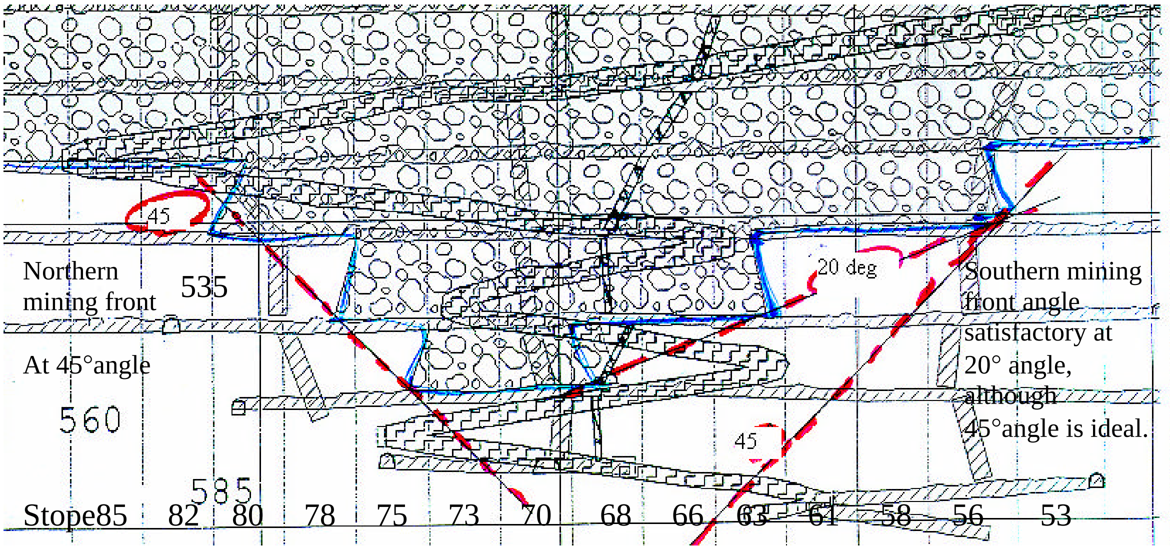

Figure 6: Base of Cave Geometry October 2002

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