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Rock Mechanics Design and Practice for Squeezing Ground and High Stress Conditions at Perseverance Mine

By M A Struthers [1], M H Turner [2], K McNabb [3] and P A Jenkins [4]

Abstract

Mining of the Agnew nickel deposit commenced in 1970 using a variety of underground mining methods, though with mixed success due to the difficult ground conditions. WMC Resources Ltd acquired the operation in 1989, and commenced nickel production with an open pit. In 1995 all production reverted to the rejuvenated underground mine, using exclusively SLC (sub-level caving) methods. Currently the mine produces 1.4Mt per annum, at an average grade of 1.74%Ni.

Underground mining of the Perseverance orebody has always presented significant challenges due to the difficult ground conditions in the weak and altered ultramafic rocks. The range of problems include areas of swelling minerals, intense and extremely weak shear zones, relatively high in situ stress, and in other areas very brittle rocks. Under these conditions rock mechanics input has been and remains a critical element of the mining strategy.

Severe ground behaviour difficulties down to a depth of 500m below surface prompted a review of the mining strategy for the large disseminated nickel orebody, including evaluation of alternative mining methods. However, sub-level caving was ultimately selected as the preferred method, and a re-design of the SLC cross-cut layout followed.

A selection of rock mechanics investigations of interest are described, including complex virgin stress measurements, detailed ground behaviour monitoring, and the use of non-linear stress analyses to re-design the mine layout. Subsequent ground behaviour, support design and production scheduling are also described.

Introduction

The Perseverance Mine is located 15km north of Leinster and 370km north of Kalgoorlie. Perseverance was initially mined for 10 years by the Agnew Mining Company, using a variety of underground mining methods but with mixed success in difficult ground conditions. The mine was placed on care & maintenance in August 1986 at a time of depressed nickel price. After purchase in 1989 WMC Resources (then Western Mining Corporation) established an open cut above the existing mine workings. Underground development and rehabilitation continued in parallel with the open pit, in preparation for commencing full-scale underground mining on pit completion, which reached a final depth of 190m in 1995.

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Most of the nickel in the Perseverance resource is contained in an ultramafic-hosted disseminated orebody which, apart from remnant mining around old stopes, WMC has mined exclusively by SLC (sub-level cave) methods. This paper describes some specific aspects of mining geomechanics at Perseverance, whilst a companion paper (Wood P, Jenkins P, Jones I, 2000) describes the evolution of mining strategy, details of mine design, and operating practices.

Geology

The Perseverance nickel deposit occurs within the Archaean Yilgarn Block of Western Australia. The orebody occurs within ultramafic rocks in the intensively deformed eastern part of the Agnew-Wiluna greenstone belt. This belt is mainly composed of metamorphosed volcanics and sedimentary rocks. The nickel mineralisation occurs in massive and disseminated sulphides hosted by dunite-serpentinite lithologies.

The ultramafics in the mine form a lens-shaped body, and the bulk of the economic nickel mineralisation is disseminated. The orebody, delineated by the 1% Ni boundary, is typically 80 metres wide (east-west), 150 metres along strike (north-south), and extends to at least 1,100m below surface. The dip of the ore is essentially vertical down to the 10,100m Level (420 metres below surface), where an inflection or "roll" to the west occurs in which the dip can be as shallow as 45°. The orebody once again becomes sub-vertical at and below the 9,900m Level (620 metres below surface).

The hangingwall rocks comprise metasediments and metabasic volcanics, with the dominant rock type a quartzo-feldspathic gneiss. The hangingwall contact with the ultramafic body is marked by a very prominent shear zone containing a mixed assemblage of extremely low shear strength metamorphic minerals (e.g. tochillonite, antigorite). The shear zone is a regional feature that extends to the north of the disseminated orebody to form the hangingwall contact of the Hangingwall Limb and 1A orebodies. It thickens in the inflection area of the disseminated orebody.

Ground Conditions

A great deal of effort has been directed at understanding the distribution of different ground conditions domains, and the key factors governing rockmass responses to mining. Ground conditions were demonstrated to get progressively worse below 10,100m Level (420m below surface), with the very worst conditions known to occur around 10,030m and 10,000m Levels, in the centre of the inflection zone.

Overall the distribution of poor ground in the ultramafic orebody is related to, or controlled by the inflection zone. Within this broad zone of dilation and shearing late-stage alteration has affected both the rockmass and discrete structures. Where the ultramafic dip increases again below the inflection zone there is a corresponding gradual improvement in ground conditions, largely due to the hangingwall shear zone which reduces in width.

Other features which negatively influence ground conditions to varying degrees, depending on the depth or structural setting, are zones of intense brucite alteration in the immediate footwall (causing swelling ground conditions), a suite of near strike-parallel very weak shears within the ore, and late recrystallisation at depth (resulting in very brittle ultramafic rockmass conditions that are prone to strain bursting).

Geotechnical Database

Detailed rock mechanics investigations have been conducted at Perseverance Mine since its inception nearly 25 years ago, by both mine owners and a range of consultants. Consequently a substantial geotechnical database exists which includes all traditional forms of hardrock mine site characterisation.

The Q-System (Barton and Grimstad, 1994) and RMR (Bieniawski, 1974) rockmass classification schemes were adopted by the mine at an early stage as a means of characterising ground conditions from core prior to development on a level. Diamond drilled core of the orebody, drilled from hangingwall drives, is logged geotechnically using the Q System and converted to Rock Mass Rating (RMR). The RMR is plotted as per the standard RMR increments of 20 (0 to 20 for very poor conditions, 20 to 40 for poor, etc). Level plans for each current and planned production level in the disseminated orebody include RMR as interpreted from borehole logs (Figure 1). The interpreted location of brucite zones are also plotted as this mineral swells on exposure to water and contributes significantly to cross-cut closure. The locations of weak tochillonite shear zones and discrete faults are adjusted on plans as face mapping data becomes available during cross-cut development. Exposure of the face during development is the only opportunity for mapping of the rockmass, due to the required total coverage of fibrecrete for stability. The detailed information that results forms the basis for many design decisions during the life of a level.

Figure 1 – ***Plan of 9,900m level showing RMR and major features***

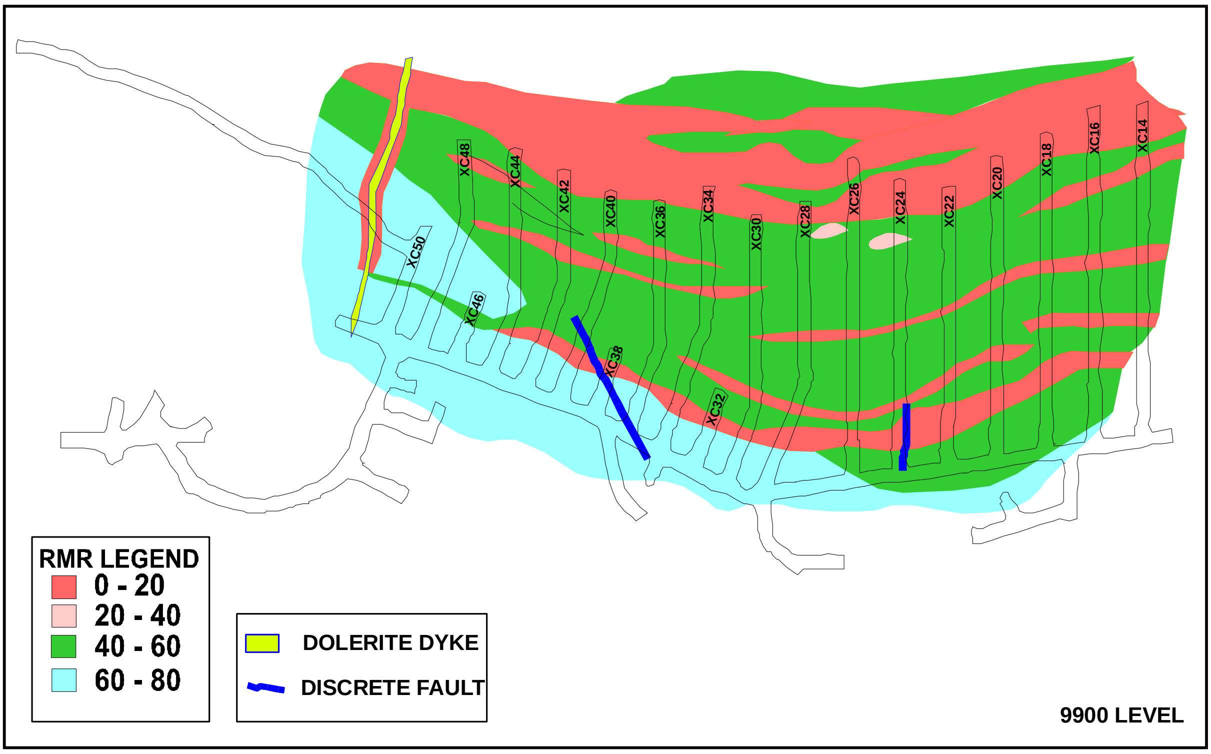


Figure 1 is an example of a sub-level plan for 9,900m Level showing RMR data (also reference Wood P, Jenkins P, Jones I, 2000). The wider hangingwall shear zone in the south is characterised by very low RMR due to fracturing and shearing within the metavolcanics and low grade ultramafics adjacent to the disseminated orebody. In this area the ultramafics contain abundant shears up to 1.0m thick with tochillonite and other very weak infills which, if allowed to unravel, spontaneously cave, undermining the stability of adjacent more competent rock. Away from major shears the disseminated orebody has moderate RMR (40-60), but also contains thin, low shear strength joints which can result in rockfalls if not supported immediately. The immediate footwall has similar conditions to the orebody, but there are zones containing swelling minerals within 10-20m of the ore boundary.

Additional studies have attempted to correlate geomechanical features with other physical attributes, such as the distribution of low-friction alteration mineralogy (e.g. brucite, antigorite etc), with some success. The presence of extremely brittle rocks at depth, prone to strain bursting behaviour, has also prompted specific, non-standard rock property testing.

Table 1 provides a summary of the mechanical properties of the main rock type groups. Table 2 details the virgin stress field which is now considered to be generally applicable to both the hangingwall and ultramafic rocks. Investigations of the virgin stress field are described in a subsequent section below.

Table 1 - ***Summary intact rock properties***

Rock Type	UCS (MPa)	E (GPa)	Comment
Metasediments	150 (± 65)	74	Prone to strain bursting at depth
Ultramafics (Olivine-Serpentinite)	126 (± 28)	80	
Ultramafics (Serpentinite-Talc)	90 (± 23)	40	Majority of the orebody
Ultramafics (Talc-Chlorites)	46 (± 17)	34	Subject to slaking / swelling when containing Brucite

Note: Rockmass strength properties are substantially weaker than intact rock, especially in the altered ultramafic rocks where strength and behaviour are largely controlled by the intensity of small-scale structures.

Table 2 - ***Average in situ stress on 9,920m Level (approximately 600m depth)***

Principal Stress	Magnitude (MPa)	Dip / Dip Direction (from Grid North)	
		HW Metasediments	Disseminated orebody
σ_1	39	22° / 112°	45° / 160°
σ_2	22	28° / 010°	45° / 025°
σ_3	15	52° / 234°	24° / 276°

Ground Behaviour History

Deterioration in Mining Conditions

SLC extraction on the upper levels (above 10,075m Level, 445m below surface) had generally progressed satisfactorily, with ground behaviour problems limited mostly to shear failure in the corners of longitudinal SLC drives, and minor sidewall closure, directly beneath the active cave.

However, development mining on intermediate levels in the mine, between 10,075m and 10,000m Levels (445-520m below surface), experienced some very serious ground control problems mostly associated with a large number of very weak shears which both sub-parallel and cross the orebody. The difficulties were pronounced within and close to the hangingwall shear zone, and especially in the southern half of the orebody, on each level. The main problems were very high rates of sidewall closure (up to 25cm per week) and floor heave, which led to premature failure of the intensive support systems and in a few cases loss of access to the SLC development. The adverse behaviour commenced prior to sub-level cave extraction on a particular level, but increased dramatically once caving progressed downwards. This behaviour conflicted with the objective of mining level development sufficiently far in advance to meet production targets.

Various mining strategies were trialled on the intermediate levels, in an attempt to alleviate some of the difficulties. This included reversing the SLC retreat direction towards the footwall, on 10,077m Level and below.

Various practical difficulties, such as long tramming distances, problems with creating blasting slots, and areas of swelling ground on the footwall ultimately led to rejection of footwall retreat as an option.

10,030m Level was recognised as especially difficult, due to the extremely poor ground conditions and the legacy of previous development (most of which had collapsed). A similar situation prevailed on 10,000m Level, though there was less prior development. In most cases the old development had been left in such a poor state for so long that recovery of it was impractical and hazardous.

The operation responded to the progressively deteriorating conditions with a series of technical studies, culminating in a comprehensive strategic mining review of the substantial remaining disseminated resource below 10,030m Level. A range of mining options were assessed, including block caving and variations of sub-level open stoping (Wood P, Jenkins P, Jones I, 2000). This review concluded, based on the information available at the time, that the net benefit to the mine in persisting with increasingly difficult conditions immediately below 10,030m Level was insignificant compared to the advantages of re-establishing a new sub-level cave ≈80m below, in better ground conditions. The 'Drop Down' strategy was therefore adopted (Wood P, Jenkins P, Jones I, 2000). It was anticipated that the temporary crown pillar thus formed between 10,000m and 9,920m Levels would be recovered via the new SLC on and below 9,920m Level.

9,920m Level Ground Behaviour

It was recognised there were some risks involved in establishing a new SLC beneath a crown pillar, but it was considered that the advantages outweighed the disadvantages.

Subsequent ground behaviour on 9,920m Level was however much worse than anticipated, due largely to the unexpectedly high virgin stress field. It transpired that beneath the inflection zone stress conditions within the orebody were different, partly due to the improved ground conditions, and more narrow hangingwall shear.

The recommended extraction strategy on 9,920m Level was to develop SLC cross-cuts at the south end first (in the poorer ground), and advance SLC extraction from south to north. Early difficulties with southern cross-cuts however led to cross-cut development occurring concurrently in the north and south, in an attempt to adhere to development targets. Since the primary objective on 9,920m Level was to simply undercut the crown pillar above, the accelerating deterioration in ground conditions over much of the level quickly led to a decision to reduce ring-height in the cross-cuts to only 10-15m, dramatically reducing the production yield from the level as a whole. What was essentially a pillar 'wrecking' operation eventually proved successful, albeit at times very difficult.

The ground behaviour on 9,920m Level was sufficiently severe to lead to abandonment of some production cross-cuts prior to starting SLC extraction. Figure 2 shows the advanced stages of ground behaviour in a cross-cut, with severe (3m) sidewall closure, over 1m of floor heave, and (not surprisingly) progressive failure of the support systems. Figure 3 is a view of the southern-most cross-cut on 9,920m Level (i.e. at the south abutment of the orebody), showing a marked asymmetry in ground behaviour which developed gradually on most of the level. The few cases of cross-cuts lost in this way were wrecked as much as possible from the level below.

Figure 2 - ***Cross-cut 27 - 9,920m Level (5 months old)***

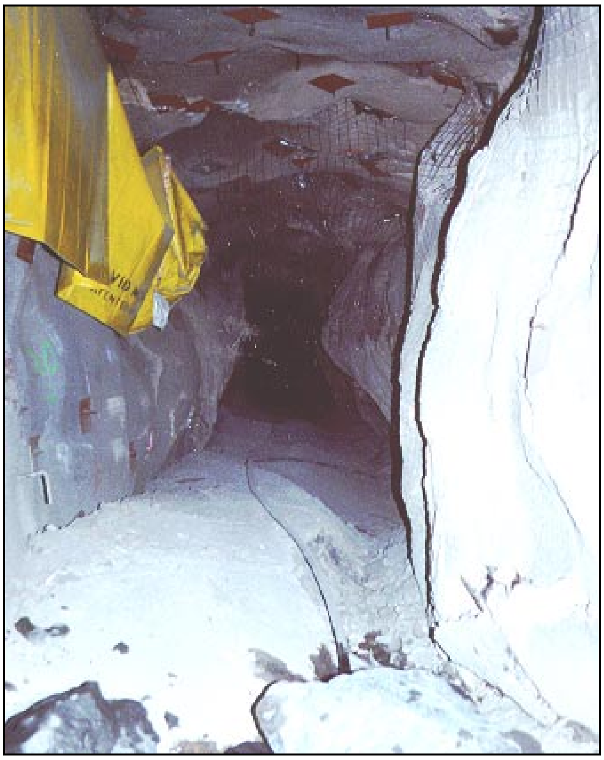
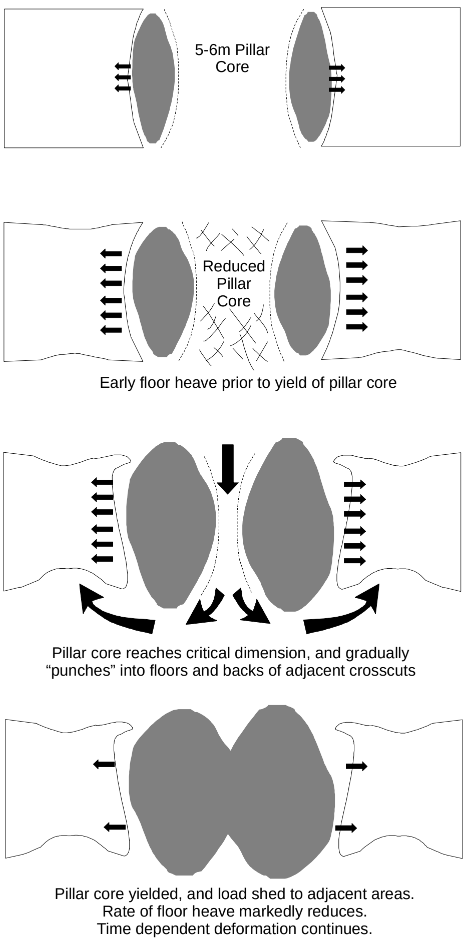


Figure 3 - ***Cross-cut 15 - 9,920m Level***

Figure 4 - ***Conceptual ground behaviour model of SLC cross-cuts***



Ground Behaviour Model

Early observations of 9,920m Level ground behaviour, particularly the depth of 'rubble zone' in the pillar walls and the rate of floor heave, led to a postulated model of cross-cut pillar behaviour, as shown in Figure 4. Though the relative timing between the different stages of failure along cross-cuts varied, depending on local conditions, the basic sequence of failure was generally the same throughout. Interestingly, it was possible to crudely infer the failure state of cross-cut pillar cores by monitoring the rate of floor heave at that point, in each adjacent cross-cut. When the rate of floor heave passed its peak and reduced, it was reasonable to assume the pillar core at that location had yielded, with consequent load transfer to adjacent areas with intact pillar cores. The rate of floor heave in cross-cuts adjacent to the latter would then increase, and the cycle repeat. This behaviour could be traced across a level. Physical monitoring of pillar core behaviour was very difficult, owing to the intense rubblisation of the pillar margins.

Development Strategy

The SLC method limits design flexibility regarding the location of stoping development. Nevertheless, the limited life of ore cross-cuts at Perseverance, due to very high rates of deformation, requires each excavation be carefully considered during detailed planning. In addition, an integrated development-support cycle has been critical to successful mining at Perseverance. The timing and stiffness of different support elements is crucial. Intensive ground control measures were established when mining through the inflection zone:

- Fibrecrete (dosage 50kg/m^3 steel fibre) has been a critical support element of the development cycle at Perseverance. A 75mm layer is applied immediately after cut is fired and bogged. The initial fibrecrete layer is followed within 8-12 hours by weld-mesh over the whole profile (including the face, as an additional safety precaution), installed with Split Set bolts.
- 4.6m long spiling bars are installed ahead of faces in weak ground, prior to drilling and charge-up.
- A second layer of fibrecrete (50mm thick) is sprayed immediately after the next cut has been fired and mucked, at the same time as the initial layer is sprayed for the second cut.
- Installation of 3m long grouted and partly-debonded rebars in the sidewalls, and plain grouted rebars in the back, follows within 10m of the face. 5m long cablebolts replace the rebars in the backs in weaker ground and shear zones.
- Struthers and Keogh (1996) provide more details on the support strategy, together with other remedial support measures. A continued focus on the quality of initial development reduces the likelihood of subsequent support rehabilitation.

Rock Mechanics

It is beyond the scope of this presentation to describe in detail rock mechanics investigations that have spanned nearly 20 years. Rather, the paper focuses on three selected aspects of interest: The challenges associated with virgin stress measurements, and the evolution of understanding of *in situ* stress; re-design of the SLC cross-cut layout using numerical modelling; and the application of extensive convergence monitoring to production forecasting.

Virgin Stress Measurements

The virgin stress field has been measured, reported and reviewed on a number of occasions. Essentially the stress field in the hangingwall meta-sediments is consistent and well defined with depth. The maximum principal stress (σ1) dips gently east, normal to foliation, with a magnitude of 42 MPa at 9,920m Level (610m below surface) and a stress ratio (σ1: σ2: σ3) of 2.6:1.6:1.0. In contrast, stresses within the ultramafic disseminated orebody are much more complex, difficult to measure, and of variable magnitudes. These are discussed further below.

A series of stress measurements within the ultramafics in 1996, on 10,030m and 9,760m Levels, used a combination of CSIRO hollow-inclusion (HI) cells and hydraulic fracturing (HF). This was necessary due to often severe core discing, which when present rendered the HI cells ineffective. Though conditions at each site were difficult, some satisfactory overcores and HF results were achieved. In addition, HF test intervals were also overcored, which together with the use of a borehole camera helped resolve the hydraulically-induced fracture orientations and positions of borehole breakout. The combination of measurement data and field observations (particularly of borehole breakout) resulted in a high confidence in the general orientation of the orebody virgin stress field at each site.

On 9,760m Level a drive was mined specifically for virgin stress measurement within very brittle (Young's modulus ≈ 78GPa), re-crystallised ultramafic rocks. Four boreholes of different orientations were drilled at the face. Various combinations of HI and HF methods were used, though eventually the required jacking pressures for HF measurements were deemed too high for the available equipment.

The performance of the non-rejected strain gauges in the HI cells was good, but a number of gauges were lost due to de-bonding, mainly from core discing. Two cells yielded a total of 22 acceptable strain gauge responses, and the stress tensors were derived from these. Where biaxial tests were not possible due to discing, samples were collected for separate laboratory strength tests. Temperature tests were conducted on all cores, to ensure any temperature effects were properly accounted for.

The calculated maximum principal stress (σ1) dipped steeply (60-70°) to the south-east, with a measured magnitude on 9,760m Level of 111 MPa. Though remarkably high, it proved difficult to fault the quality of the HI cells results, and a back-analysis of borehole breakouts indicated secondary principal stresses of at least 70 MPa.

Initial mining of the stress drive experienced strain bursting and moderate local seismicity, and finely-spaced stress fractures were evident "wrapping" around the drive profile. A few months later, the drive having been abandoned and undisturbed, its condition had deteriorated dramatically. The apparent contradiction between the original drive condition and the extremely high measured stresses can be attributed to instantaneous development of a zone of intense micro-fracturing which shed stresses away from the profile. It took some time for these fractures to open, interconnect, and become more obvious to the naked eye.

It became clear that stress magnitudes and probably orientations within the ultramafic rocks were variable, and were influenced by local major structures, tectonic history, and rock types (properties). Subsequently, simulations of stresses within the hangingwall and ultramafic rocks using stress analysis codes (MAP3D) (Wiles T, 1997) has demonstrated that variable stress concentrations can occur within the ultramafics depending on the local setting (e.g. proximity to the hangingwall shear), whilst the stress magnitudes are similar to those in the hangingwall. Nevertheless, understanding of the mine-scale stress environment is likely to continue to evolve as mining progresses deeper.

Core Discing

Discing was extremely common when overcoring a previous E-sized borehole. This phenomenon has been reported previously by Obert & Stephanson (1965), and Puillet and Kim (1987). Prominent discing (i.e. complete separation of discs) was much less common in solid core (E-size or H-size), but "incipient" discing (hairline fractures, not fully formed) was common, especially in H core. Incipient core discs were normally perpendicular to the core axis but in some cases discs were inclined at 70^{o} to the core axis. The causes of the latter are unknown, but may relate to drilling rates and local changes in the stress field. The majority of discs had a relatively flat surface, which normally indicates a low level of anisotropy of stresses in the plane normal to the borehole (e.g. Stacey and Harte, 1989). Discing and the measured stresses on 9,760m Level are however not consistent with this. Discs were flat in shape, but the measured maximum stresses in the borehole normal plane were at a ratio of 2:1. There were also no obvious changes in disc geometry in horizontal holes drilled in different orientations.

Axial fractures, though poorly developed, were observed in combination with discs in some overcored intervals, outside of the hydrofracture test sections (Figure 5). Orientations of the overcores, and borehole camera evidence, suggested these fractures were steeply dipping. The cause of these is not well understood, but may reflect stress anisotropy in the normal plane, and/or subtle local variations in rock properties.

Figure 5 Axial Fractures Outside HF Test Sections

Redesign of SLC Cross-cut Layout

Following adoption of the ‘Drop Down’ decision (Wood P, Jenkins P; Jones I, 2000), development mining proceeded on 9,920m Level using the same SLC design as on levels above, i.e. 5 x 5m cross-cuts at 13.5m centres, on 23.5m sub-levels. If development on any level is considered as a horizontal slice through the orebody, then the development extracts a certain proportion of the ‘footprint’. This is termed here the Development Extraction Ratio (DER), and is based on the principles of tributary area theory. The design DER for the original layout is 37%.

From an early stage in the level development it became clear mining conditions were much worse than expected, even prior to any SLC extraction (and hence creation of an 80m crown pillar above). In practice development overbreak (caused largely by rubblisation of the pillar margins) commonly resulted in pillar widths of only 7.0-7.5m (DER » 45%). A survey of SLC operations worldwide confirmed there were none achieving such a high DER under such adverse ground conditions.

There was clearly a fundamental problem with the SLC layout, and it was beyond the capacity of any support system to control ground behaviour. The severity of the conditions prompted a review of the SLC design, and ultimately its modification for 9,900m Level.

In order to provide a rational basis for any new design it was essential to back-analyse behaviour on 9,920m Level, and calibrate any models accordingly. The nature of this behaviour, as outlined in Figure 4, required the use of non-linear models to simulate the load shedding and time dependent nature of the failure process. A non-linear version of the popular three-dimensional MAP3D code (MAP3D-NL) was selected as the preferred tool. Two-dimensional codes were less suited to the situation, and on the scale of the problem the rockmass behaved as a pseudo-homogeneous material, rendering distinct element formulations unnecessary and inappropriate.

The back analysis involved two steps:

1. Parametric studies to develop a realistic suite of material properties, including the effects of reinforcement, residual elastic properties, and changing rockmass strength;
2. selection of appropriate "time" increments, by following failure progression through a number of stages, and adjusting visco-plastic increments to suit.

After this analysis the model reasonably represented the general sequence of pillar failure, the varying rate of floor heave, and the approximate depth of failure into pillar walls. A series of mining steps were assessed ranging from development only, to full SLC extraction of both 9,920m and 9,900m Levels. An alternative layout modelled for 9,900m Level comprised 5 x 5m cross-cuts at 17.5m centres, giving a designed DER of 29%. The model development geometry is shown in Figure 6. The orientation of cross-cuts, originally established to parallel the maximum principal stress, was also re-aligned to east-west (Figure 6) since it was recognised the actual stress field orientation varied significantly across a level, and a truly orthogonal layout avoided other practical problems.

Table 3 - ***MAP3D linear elastic material properties***

ZONE	E (GPa) $E_{Peak} = E_{Residual}$	Poisson's Ratio $\nu_{Peak} = \nu_{Residual}$
Far-field Ultramafic	60.0	0.20
Pillar Core	60.0	0.20
Reinforced Zone	60.0	0.20

Table 4 - *MAP3D non-linear material properties*

ZONE	Peak UTS* (MPa)	Residual UTS (MPa)	Peak UCS* (MPa)	Residual UCS (MPa)	Peak ϕ^* (°)	Viscous Modulus G_n (MPa)	Viscous Modulus G_s (MPa)
Far-field Ultramafic	0	0	50	50	35	42,000	42,000
Pillar Core	0	0	50	25	35	42,000	42,000
Reinforced Zone	0.5	0.5	52.7	12.5	35	42,000	42,000

Tables 3 and 4 list the material properties used in the linear elastic (first stage of analysis, time step ‘zero’) and non-linear analyses. Figure 7 shows the series of material zones modelled around SLC cross-cuts.

The viscous moduli Gn and Gs were used to control the creep or time increments of the analysis. It is essential these are calibrated against field measurements, and the convergence data and other field observations were used. In the reinforced zone two parameters were important: The peak compressive strength (UCS) was increased to 52.7MPa (based on work by Grasso et al, 1996), and the tensile strength (UTS) to 0.5MPa, to approximate the strengthening effects of reinforcement. As failure progressed however the residual strength of this zone was reduced to 25% of the original undisturbed UCS, to reflect the intense fracturing of the ‘rubble zone’.

Figure 6 - *Development model geometry*

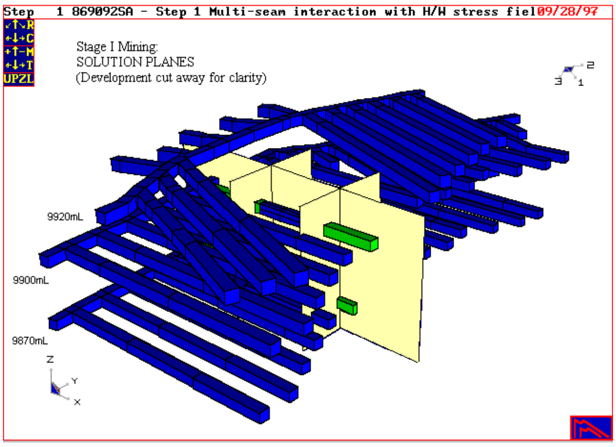
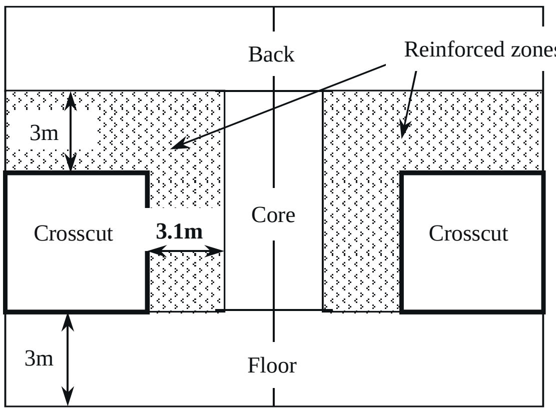


Figure 7 - *Material zones around cross-cuts*



The floor and back have the same properties as the far-field ultramafic rocks

A process of experimentation concluded the best indicators of pillar behaviour were the maximum and minimum stress and the maximum shear strain in the pillar core.

Figures 8 and 9 show a stage in pillar failure for the ‘old’ layout at which pillar core stresses have reached their peak, just prior to the core failing in shear. This would coincide with a peak in the rate of floor heave. Figure 10 compares the shear behaviour between the two layouts, quantifying the benefits of the increased pillar size. Note the marked increase in pillar shearing in the original 9,920m Level layout after Stage 4, and the reduction in the final stage when the core is fully yielded and the stresses have been shed elsewhere.

Figure 8 - *Maximum principal stress - Stage 4 - 9,920m Level*

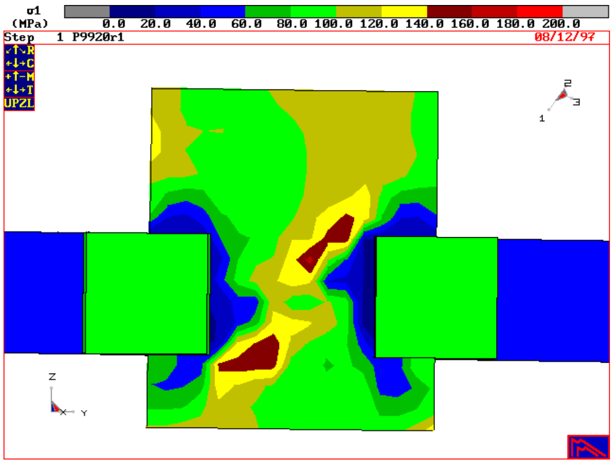
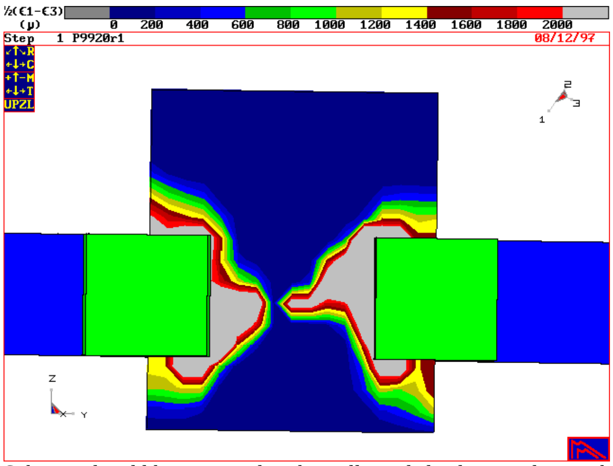
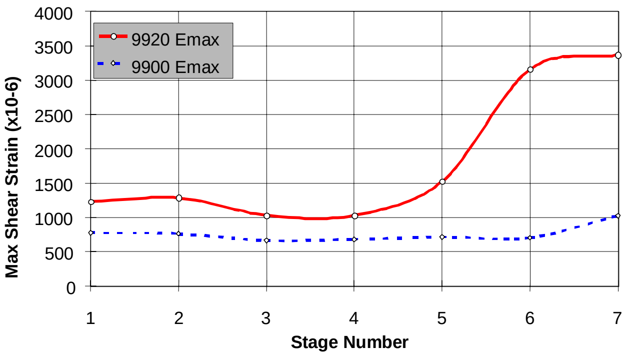


Figure 9 - *Maximum shear strain - Stage 4 - 9,920m Level*



Substantial yield has occurred in the walls, and slowly extending to the pillar core. At the next step the core fails in shera.

Figure 10 - ***Pillar core maximum shear strain***



The main conclusions from the study were: (i) The revised layout was a substantial step towards more stable SLC development, but (ii) even isolated cross-cuts away from any other influences would still experience a degree of 'rubblisation' or pillar skin failure.

The layout for 9,900m Level and subsequent levels was therefore changed to 5 x 5m drives at 17.5m centres, but with a strong focus on continuous improvement in development drill and blast practices. Rapid progress in the latter, together with even greater emphasis on ground support standards, enabled the layout to be changed to 4.5 x 4.5m cross-cuts (finished) on 17.5m centres, corresponding to DER = 26%, and this became the new standard.

An enhanced non-linear version of MAP3D was developed during the course of the investigations. A new flow rule now allows the *in situ* rockmass behaviour to be more accurately defined, simulating the transition from a competent rockmass to a much weakened fractured material. Previous modelling involved a deformation driven response, with loss of strength occurring along with rock dilation. Although with a calibrated model good agreement was achieved with actual rates of pillar degradation, it was not possible to predict the actual rate of deterioration. The new model uses true time-dependence, allowing the coupled strength-dilation response to evolve with time, so long as stresses exceed the residual or long-term strength.

Subsequent numerical studies have modified understanding of the virgin stress state within the ultramafics, recognising the role of major structures, zones of weakness, and other features on local stresses. Though the local-scale assessments of development stability have not been modified, later work has concentrated on sequencing interactions between levels, and explored the benefits of de-stressing options.

SLC development on 9,900m Level and below has confirmed the suitability of the layout, though a number of minor instabilities have occurred (Wood P, Jenkins P, Jones I, 2000). The results presented here do not include consideration of any impacts on SLC recovery and dilution, though it was judged at the time that the new layout remained within precedent elsewhere, and that SLC draw performance would not be significantly affected. Subsequent experience has generally proven this to be the case.

Ground Behaviour Monitoring

Monitoring

The principal ground behaviour monitoring technique in the orebody at Perseverance is convergence monitoring. Results from rod extensometers have in the past been erratic, apparently due to shear movement across the rods. Monitoring of convergence (closure) across development excavations commenced in the disseminated orebody in late-1996, with closure measured weekly using a digital tape extensometer. Convergence monitoring pegs are installed at regular (20m spacing) intervals 1.5m above floor level during development of cross-cuts and hangingwall access drives. The cumulative closure and closure rates are contoured using Surfer.

The final cumulative closure for much of 9,920m Level within the orebody exceeded 100cm (Figure 11). Closure on 9,900m Level, however was more manageable, with only a 20m section close to entrance of 22 and 24 cross-cuts with a cumulative closure greater than 100cm (Figure 12).

Figure 11 - ***Convergence monitoring data for 9,920m Level to December 1997***

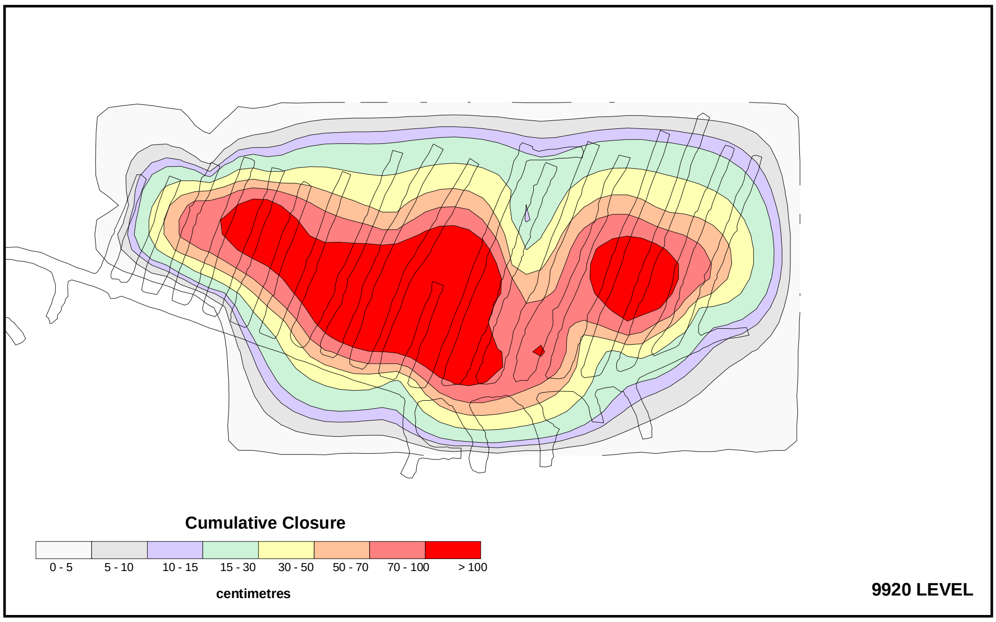
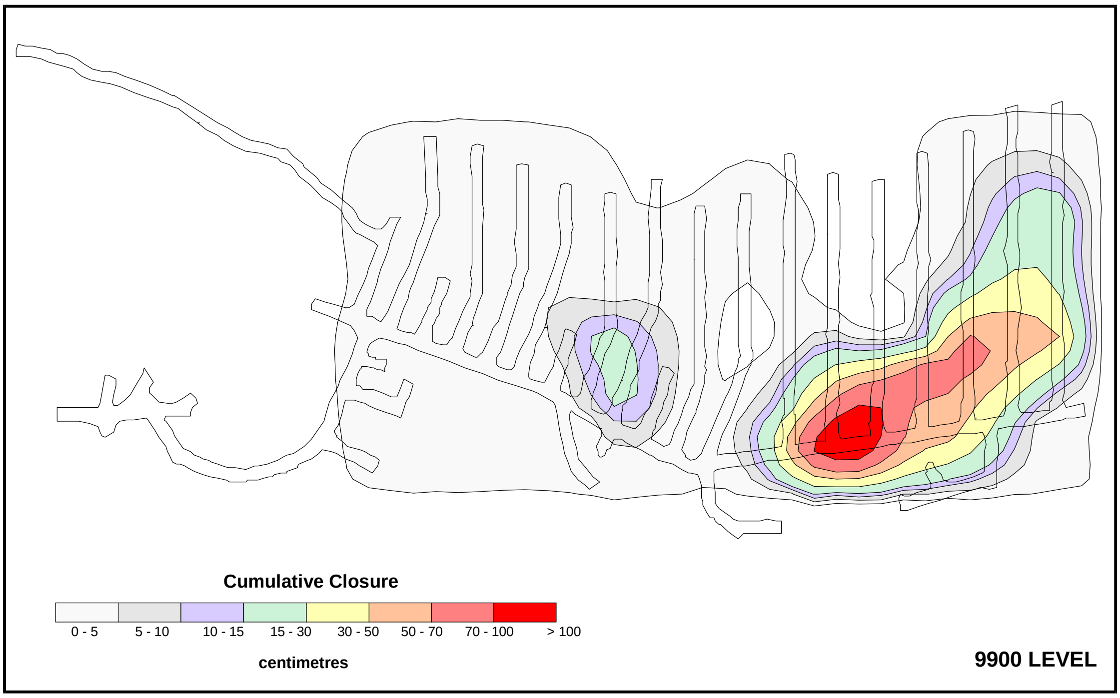


Figure 12 - ***Convergence monitoring data for 9,900m Level to April 1999***



Cross-cut closure rates are related to stress levels and rock mass quality. The monitored closure on 9,920m and 9,900m Levels was assessed using MAP3D and the stress component most closely related to closure rates in the orebody was determined to be the vertical stress in the pillars. This was confirmed with both elastic and non-linear MAP3D modelling. The non-linear MAP3D model was also calibrated to relate time steps to deformation using the convergence data, enabling predictions of closure rates for deeper levels.

The variation in total, cumulative convergence on the levels can generally be related to rock mass strength as the abutment stresses from the level above move across the whole level. Weaker shear zones exhibit increased deformation and the location of these zones as determined from drill core is critical for estimating closure. Thicker shear zones, areas with shear zones close together, western sections of cross-cuts (which remain open longer) and sections with reduced pillar widths are all more susceptible to severe closure. These areas can be pre-determined from rock mass rating plans and during development. The RMR plans for 9,900m Level (Figure 1) and for 9,920m Level (Wood P, Jenkins P, Jones I, 2000) are examples showing the distribution of the weaker structures and zones throughout the orebody.

Closure Monitoring in Planning

The modelling results confirmed that vertical pillar stress on levels from 9,900m Level and deeper was greatly reduced compared to 9,920m Level due to the levels being overmined (de-stressed). Stress magnitudes for at least the following few levels (9,870m and 9,860m Levels) were determined by modelling to be similar to 9,900m Level. Closure monitoring results for 9,900m Level could therefore be used for predicting closure in these levels, in general and around major shear zones. The calculated closure results for 9,870m and 9,860m Levels were used to determine the time available from development up until 100cm of closure occurs, at which stage expensive rehabilitation would be required to widen the cross-cuts for LHD access and safety clearances. The available working life calculated for cross-cuts varied from 16 to 24 months, these figures being used in conjunction with other cave draw limitations for optimising tonnage draw limits.

MAP3D modelling of deeper levels including 9,760m and 9,400m Levels using the current 17.5m cross-cut spacing indicates that stress magnitudes will rise to those experienced on 9,920m Level. The rock mass generally improves with depth and the expected closure are expected to be manageable. Localised peaks in stress along the hangingwall shear will, however, result in problem sections and possible increases in cross-cut spacing and/or expected working life.

Rock mass rating projections for deeper levels have been used to estimate cross-cut closure and hence excavation life. These limits on excavation life have been used as restrictions in the cave drawdown strategy.

Conclusions

That the mine remained operational, and even increased throughput, during such a difficult period in its history in the mid-1990’s is testament to the skill of all those involved, especially the operations staff who dealt with severe mining difficulties on a day-to-day basis.

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References

Barton, N., Grimstad, E., 1994. The Q-System following twenty years of application in NMT support selection, in *Felsbau* 12 (6), 428-436.

Bieniawski, Z T, 1974. Geomechanics classification of rock masses and its application in tunnelling. in *Advances in rock mechanics*, 2(a), 27-32, Washington DC Nat Acad Sci.

Grasso, P, Rossler, K, Muccan, S, Xu, S, 1996. The construction, ground reinforcement and monitoring of a large cavern in poor rockmass in NW Italy, in *Eurock'96*, AA Balkema, Rotterdam.

Obert, L, and Stephanson, D E, 1965. Stress conditions under which core discing occurs, *SME Transactions*, September.

Paillet, F, and Kim., K, 1987. Character and distribution of borehole breakouts and their relationship to *in situ* stresses in deep Columbian River basalts, J. Geophys Research, 92, B7, June.

Stacey, T R, and Harte, N D, 1989. Deep level raise boring - prediction of rock problems, in *Proceedings International Symposium Rock at Great Depth*, AA Balkema, Rotterdam.

Struthers, M and Keogh, J., 1996. Performance of mesh and fibre-reinforced shotcrete under high ground pressures in: *Shotcrete - Techniques, Procedures and Mining Applications*, Kalgoorlie, 1996.

Wiles, T, 1997. 'MAP3D User Manual', Mine Modelling Ltd, Victoria, Australia.

Wood, P, Jenkins, P, Jones I, 2000. Sub-Level Cave Drop Down Strategy at Perseverance Mine, Leinster Nickel Operations, in *Proceedings MassMin 2000*, pp517-526 (The Australasian Institute of Mining & Metallurgy:Melbourne).