

Mining in extreme squeezing conditions at the Henty mine

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Abstract

Squeezing conditions in hard rock underground mines with defined foliation/schistosity/bedding fabric are becoming more common as mines develop deeper. Often mines are finding themselves in squeezing ground without having planned to deal with these challenging conditions and can make time consuming, costly and hazardous mining decisions to keep ore drives serviceable. An understanding of what is occurring around the underground opening is critical and implementing practical yet proven ground support strategies is essential.

The Henty Gold Mine, located in western Tasmania, Australia has recent mining experience in extreme hard rock squeezing conditions. Examples of monitoring data collected at Henty Mine to manage and control squeezing ground conditions are presented. A mining drive closure classification more suited to extreme closure has been produced. The ground support methods are described and the design process used to justify the ground support methods using advanced numerical modelling techniques are discussed.

1 Introduction

The Henty Mine is located in western Tasmania, Australia and has produced gold since 1998, see Figure 1. A number of orebodies have been mined from near surface to a maximum depth of about 900m below surface for a total production of 4,690,789 tonnes at 9.1 g/t Au for 1,370,285 ounce Au (end November 2015). Production rates, mining and haulage methods have varied over the years, depending on the characteristics of the orebody being mined. Shaft haulage of ore was ceased in 2010 in preference to decline truck haulage and the paste plant was decommissioned in March 2008 due to the remaining orebodies being narrow and mined by longitudinal methods, rather than the transverse stoping methods that were used in the wider areas of the Darwin and Darwin South orebodies.

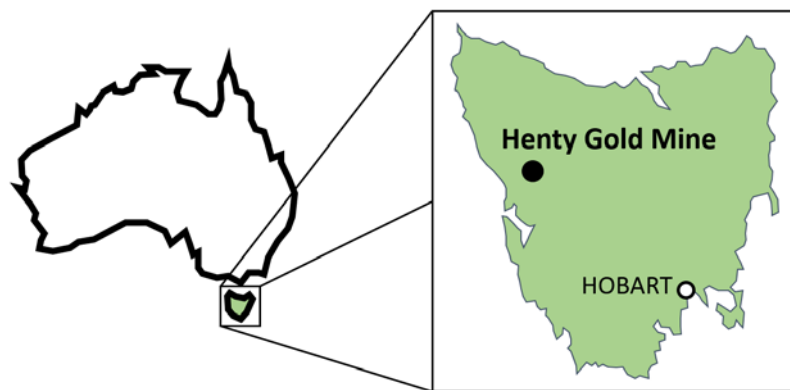


Figure 1 Location of Henty mine, Tasmania, Australia

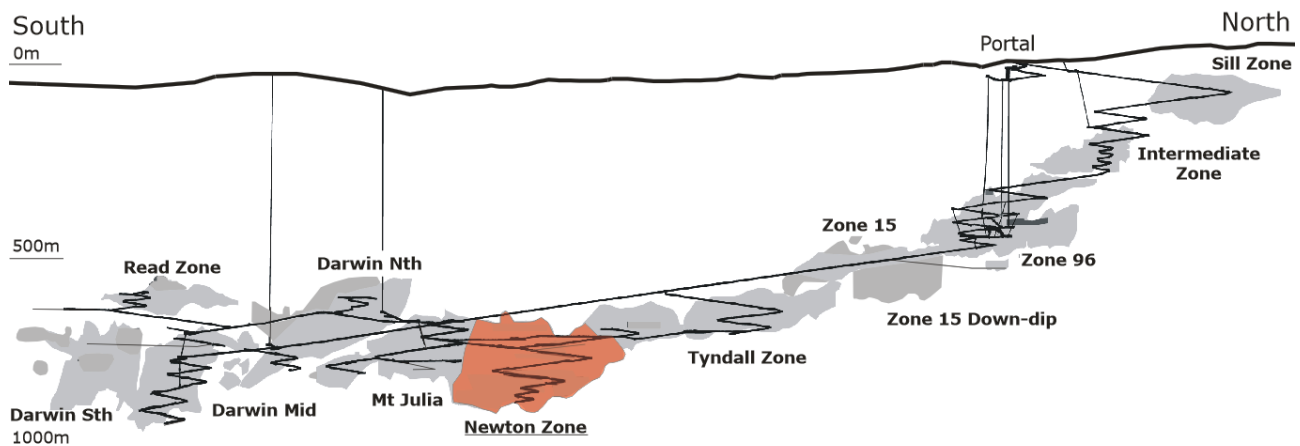
During 2014 and 2015, three stoping areas were in production, being the Read Zone (overhand cut and fill), the Darwin South Remnant Zone (longitudinal open stoping) and the Newton Zone (longitudinal open stoping).

Squeezing ground was not considered during the planning of ground support design of the Newton Zone due to side wall strains of less than 2% experienced in most Henty Mine development headings and declines. Mining conditions changed with the development of ore drives experiencing extreme squeezing in the Newton Zone.

1.1 The Newton zone

The Newton orebody is located between 650m and 800m below surface level with an approximate vertical dip and striking north-south. There are two parallel ore lenses, each about 3.5m width, with parts of each ore lens sub-economic for open stoping. The distance between the two ore lenses varies between about 5m and 8m, refer to Newton zone longitudinal section, Figure 2.

Mining development was based on a 20m level spacing and ore drive development was initially 3.6m wide, 4m high arched profile. The development was later changed to 4m width when the extent of squeezing conditions became apparent with ongoing development experience. The Newton Zone stope strike lengths were generally around 17m and stopes filled with rock fill. Narrow rib pillars were left behind to contain the rock fill.



a) Henty Mine Longitudinal Section



b) Newton Zone Longitudinal Section

Figure 2 a) Henty mine longitudinal section b) Newton zone longitudinal section

1.2 Geological setting

The Henty Mine local geology is late Cambrian Volcanogenic Hosted Massive Sulphide (VHMS) deposit that has been subsequently altered and overprinted by late stage hydrothermal and structural events.

The Newton Zone orebody at the Henty Mine is hosted within rocks locally referred to as Volcanics, with variable amounts of Sericite alteration. The Sericite alteration gives the rock a greenish appearance, is lower strength than unaltered rock and has a pronounced foliation intensity. Foliation dip varies between 75° and vertical. Foliation spacing is greater than 20 cm in the Henty Mine country rock but foliation spacing decreases significantly in the Newton Zone to as little as 5 mm to 10 mm spacing. Foliation is oriented parallel to the Newton Zone orebody and is present in both the orebody and the country rock.

Rockmass strength of the Newton Zone is influenced by the anisotropic conditions. Rock strength testing at orientations perpendicular/parallel and at about 45° to the foliation display a strength ratio of 8:1, meaning intact sample strength is 8 times stronger parallel to the foliation.

The principal stress orientation at Henty Mine is approximately horizontal and oriented east-west, perpendicular to the strike of the Newton orebody and is highly deviatoric with the ratio of $\sigma_1:\sigma_3$ measured at 3.6.

The conditions causing the extreme squeezing in the Newton Zone are described in Figure 3 and are:

- A prominent foliation feature is present with close spacing.
- Ore drive development is parallel to the foliation.
- Alteration decreases the rock strength.
- The principal stress is oriented perpendicular to the foliation.
- There are parallel ore drives. The parallel ore drives create an unconfined pillar between the two ore drives which exacerbates wall squeezing.

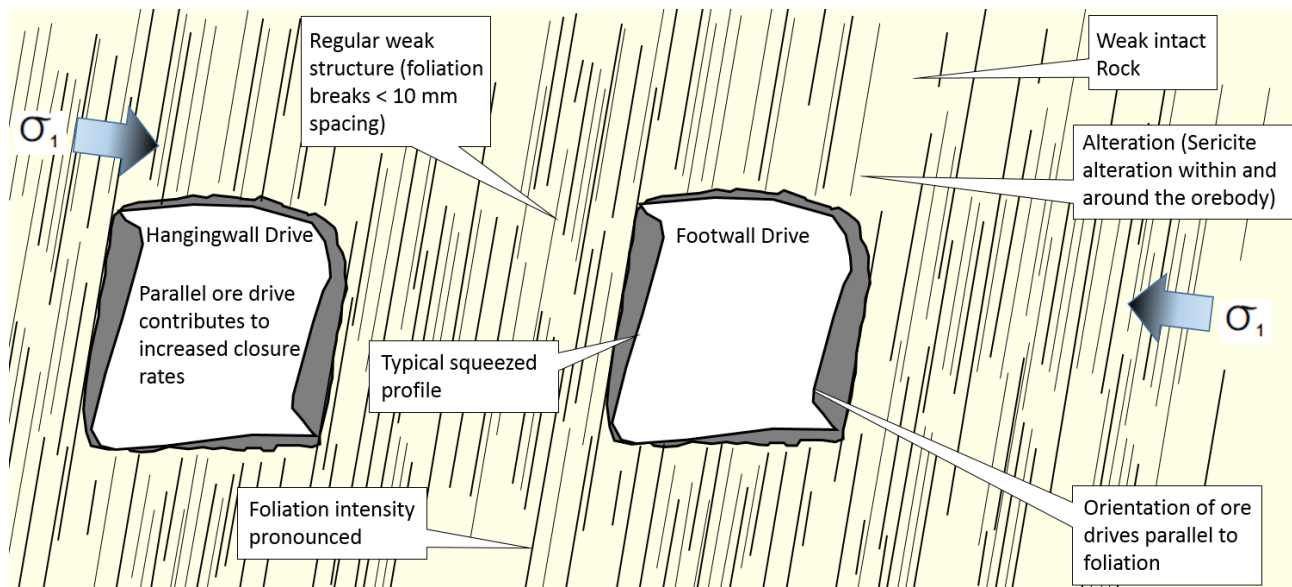


Figure 3 Contributing conditions for the development of squeezing in anisotropic rock

2 Description of squeezing conditions at Henty mine

Mine development at the Henty Mine has generally displayed less than 2% strain and in most cases mine openings do not require rehabilitation or monitoring with instrumentation during drive service life. When mining in the Newton Zone strains in excess of 50% have been recorded.

2.1 Practical definition of strain

Drive closure in squeezing ground is usually described by the amount of strain experienced between the points of maximum closure since the drive was first developed, as has been described clearly by Potvin and Hadjigeorgiou 2008. For practical reasons many mines, including Henty, monitor the drive closure between the walls at 1.5 m height above the floor. This is an accessible monitoring height, monitors the squeezing where the majority of movement is occurring (in the walls due to the near vertical foliation) and provides mine management with information regarding squeezing rate for mechanised machinery access planning.

Drive closure is practically defined as the squeezing distance divided by the original drive measurement, or as:

$$\text{Drive Closure (Strain \%)} = \frac{(A - B)}{A} \times 100 \quad (1)$$

Where:

A = Original drive width.

B = Current drive width.

When describing drive closure in areas where the drive walls have been stripped once or more, the strain should be described against the original drive width, or as:

$$\text{Post Stripping Drive Closure (Strain \%)} = \frac{[(A - C) + (D - B)]}{A} \times 100 \quad (2)$$

Where:

C = Drive width before stripping.

D = Immediate post stripping drive width.

The stability performance of the roof is associated with the total drive strain and it is therefore critical to describe the drive strain as a sum of the strain both before and after drive stripping, as shown in equation 2.

Mine management commonly require estimates of when stripping is expected and advanced warning of additional ground support installations. Estimates can be made from the drive closure monitoring results and by interpreting the results against previous mining case studies in squeezing ground.

2.2 Newton zone monitoring results

Monitoring of the Newton drive closure at Henty Mine was completed by methods including survey of points along each ore drive (drive closure monitoring), survey monitoring of points on the roof at intersections and with numerous extensometers installed along the drives in both the walls and roof (in excess of 30 extensometers installed in the Newton ore drives). Monitoring within the Newton Zone was an important part of the ground support design verification process.

Visual observation of drive performance commonly included shearing of foliation in the drive side walls leading to offsets and 'guillotining' of the rock bolts and significant drive wall closure at up to 20 mm/day but more commonly between 2 to 4 mm/day. The roof and floor bulked and heaved respectively, refer to Figure 4.



Figure 4 Typical squeezing drive in the Newton Zone

The drive closure monitoring data shown in Figure 5 describes the wall movement over time in the NW1765HWN, an ore drive positioned parallel to foliation and with a footwall drive located in close proximity to the east. This wall movement is typical of ore drives within the Newton zone. Wall strains of over 30% were experienced with only minor regression in the wall closure rate. Small adjustments have been made to smooth steps in the monitoring data, as stripping did take place along the entire length of the ore drive causing unavoidable loss of monitoring points and short term restriction of access to the drive preventing continuous drive closure survey.

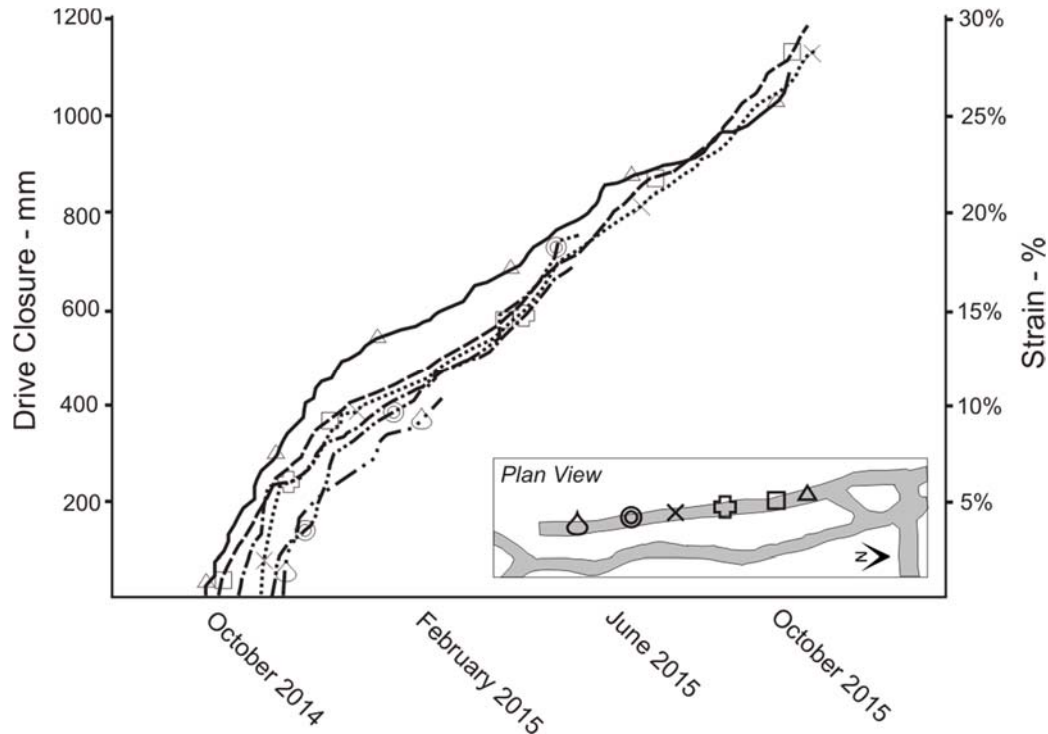


Figure 5 Wall closure monitoring in the NW1765HWS

Extensometer monitoring instruments were installed throughout the Newton Zone. The majority of extensometers were installed in the roof, to verify any longer term roof bulking and loosening. Over time,

monitoring within the walls using extensometers became less of a focus to mine management due to the following:

- The design model was verified and showed unravelling from the base of the wall was the likely failure mechanism.
- It was demonstrated through practice that the walls were stable with support and the monitoring results were predictable and consistent.
- In many cases, the drive walls were stripped with new reinforcement and support installed to allow for ongoing machinery access. This alleviated the risk of wall failure initiated by unravelling or toppling.

Monitoring data from within the walls and roof of the ore drives demonstrated consistent patterns. The first 2m of wall material showed about 80% of the total side wall strain, as shown within Figure 6. Deeper within each wall the yield zone continues but at reducing strain amounts. Between 2m and 5m depth about 10% of total strain, between 5m and 7m about 6% of total strain and between 7m and 10m about 4% of total strain.

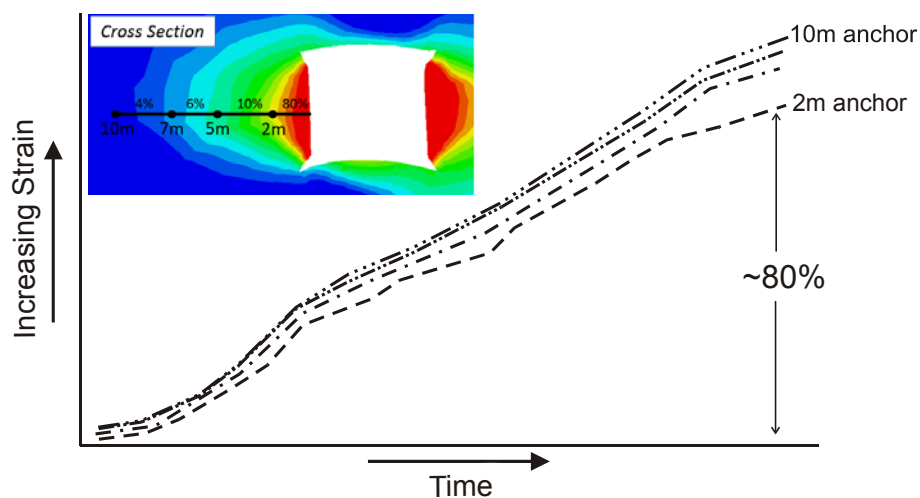


Figure 6 Typical sidewall behaviour

The ore drive roofs performed consistently and predictably, despite progressively bulking over time. The majority of ore drive roof strain occurred between 3m and 6m depth, beyond the depth of the 2.4m long roof bolts. No increase in the rate of roof bulking relative to drive closure rate was noted, even at drive closure strains beyond 20%.

Induced stress in the roof clamped the roof material in place, until roof bulking caused eventual breakup of up to 1m of roof material at the excavation boundary. This break up of material at the roof boundary occurred only when drive closure strain had well exceeded 20%. This highlights how time-dependant rock mass deterioration must be understood during ground support design and verified during mining.

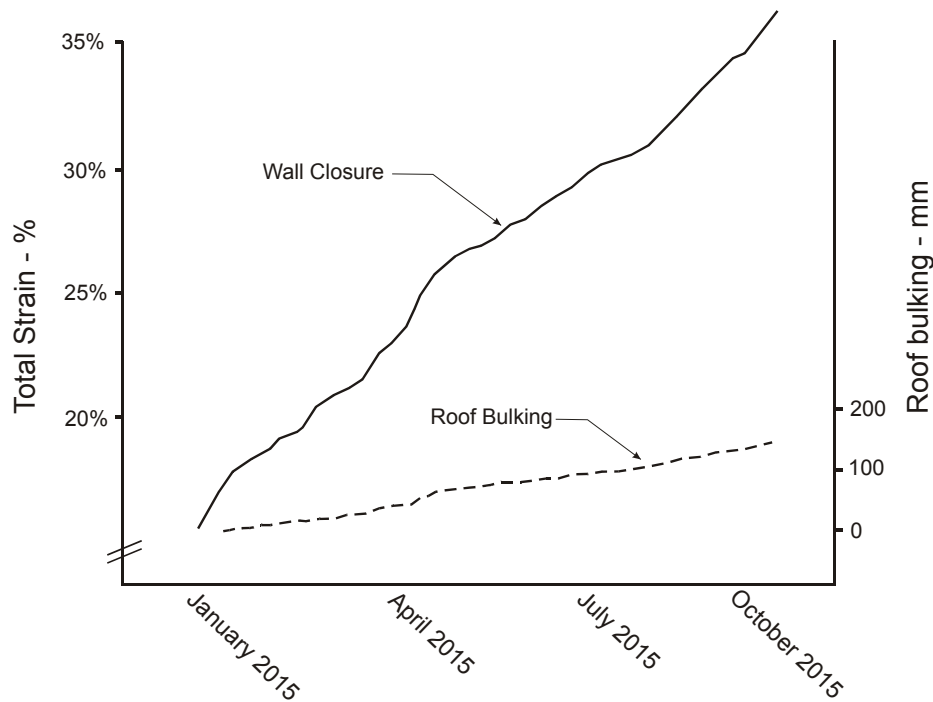


Figure 7 The relationship between wall closure and roof bulking

2.3 Newton zone intersections

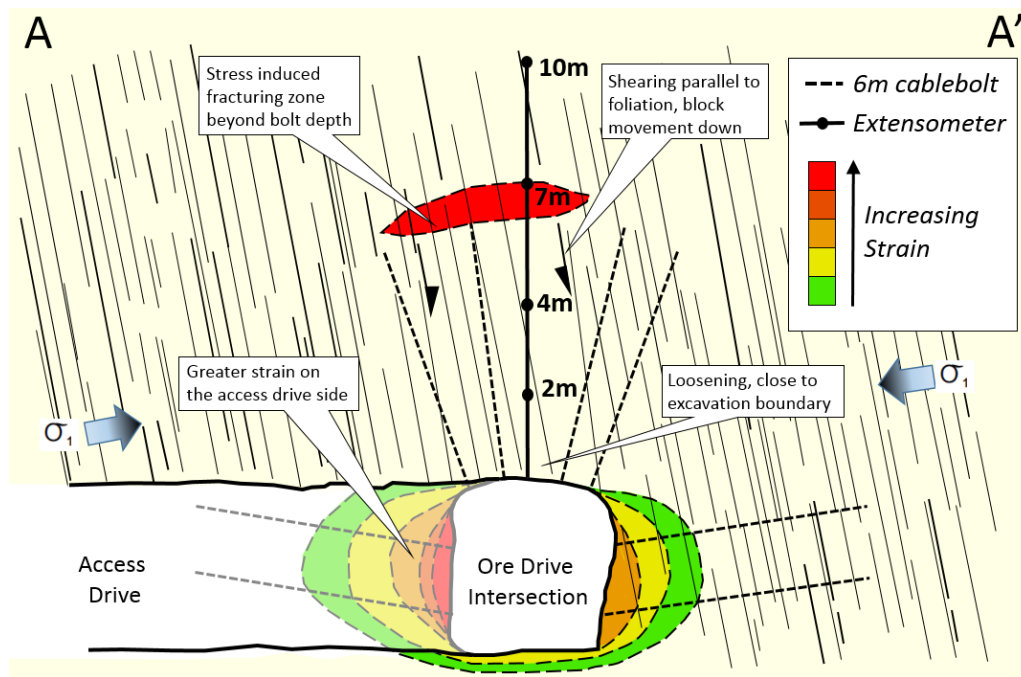
Ore drive intersections experienced more pronounced roof bulking than compared to the ore drives. The geometry of the intersections was a significant contributing factor to the roof bulking, with the ore drive access allowing for more pronounced wall squeezing in the ore drive walls adjacent to the access drive.

Cablebolts (fully grouted) in combination with the standard ore drive ground support were used as a ground reinforcement method to maintain stable conditions at deforming intersections. With detailed monitoring, Henty Mine extended the life of intersections without the need for excessive ground support rehabilitation.

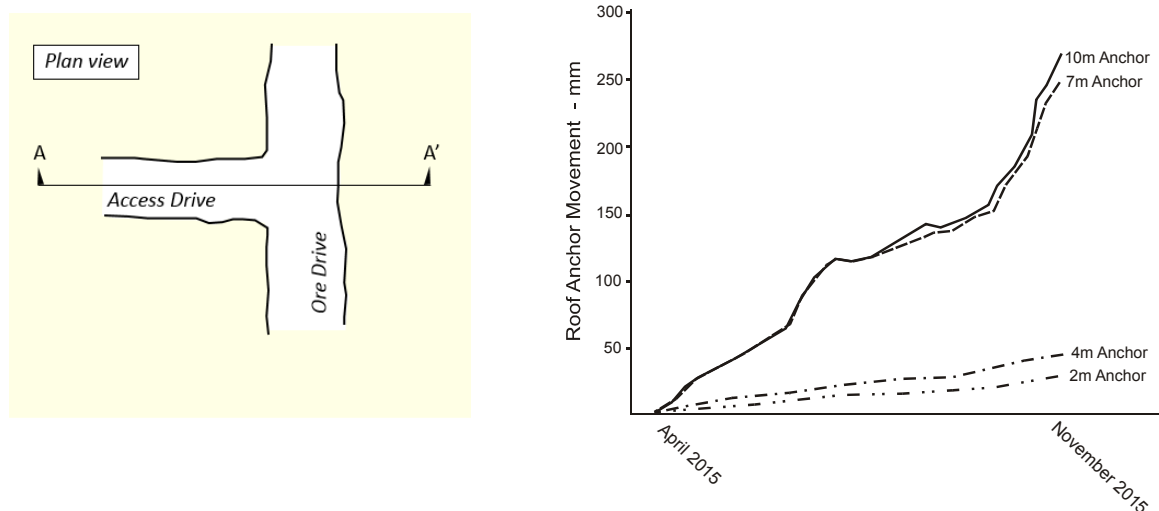
The serviceability of intersection cablebolts was limited to 120 mm of roof movement monitored by conventional survey techniques. This was based on the possible yield of the cablebolt strand beyond 120 mm of movement and that a cablebolt stretches over an assumed length due to debonding at the cable/grout interface with certain amounts of cable anchor pull out and wedge pull in at the plate.

Intersection roof bulking exceeded hundreds of millimetres in multiple Newton Zone intersection locations and all were maintained as safe and stable accesses for mining operations without the need for excessive rehabilitation campaigns. Wall cablebolts were critical for the support of ore drive intersections when the intersection was required to be serviceable for periods of greater than 18 months.

Monitoring of intersection roof bulking in Newton Zone suggests that the majority of roof movement was occurring beyond the cablebolt embedment length, which were 6m long in most instances. Cablebolting was successful in reinforcing the 6m above the intersection and holding the material together while the ongoing movement of the walls allowed the “6m reinforced block” to move into the intersection. This deeper roof movement may also be related to shearing on foliation planes and further work modelling this mechanism is required to validate these observations. Extensometers were essential in the daily management of the intersections, refer to Figure 8.



a) Observations of extreme strain around ore drive intersections – cross section



b) Plan view of cross section location c) Extensometer monitoring of the intersection roof (NW1765 Link)

Figure 8 a), b) & c) Monitored observations of extreme strain around intersections

3 Closure strain classification for extreme drive squeezing

Definition of the squeezing amounts required to cause problems to mine operators is misleading in most of the literature produced to discuss squeezing ground conditions. Many squeezing classifications used to describe squeezing ground were developed for civil tunnels e.g. Hoek 2001, Aydan et al 1993 and Singh et al 2007. Civil tunnels commonly install temporary stiff liners at a set distance from the excavated face and permanent liners within days or months of the temporary ground support being installed and this is distinctly different to the development of a temporary mining opening. Tunnelling classifications of squeezing ground are applicable to mining operations that are continuing to use fibre reinforced shotcrete as a liner, although many mine operations in Australia have discontinued this practice, some are still persisting with the use of fibre reinforced shotcrete in squeezing conditions.

The position of the yielding material at the excavation boundary is important in the classification of squeezing severity. Observations and experiences from the Henty Mine are based on a near vertical foliation with the majority of yield within the walls. In mines with anisotropy that positions the zone of greatest strain at the shoulder or roof of the tunnel, the amount of strain defined as being manageable to operations will be less, due to the walls being inherently more stable than the shoulders or roof.

An example of manageable strain within the Newton Zone 1785HWS ore drive, developed parallel to foliation is shown in Figure 9. This drive was one of the last developed in the Newton Zone and was better planned, supported and reinforced to avoid stripping of the drive prior to stoping commencing. The drive experienced strain of up to 10%. The visual change over time of what 10% strain actually looks like is shown in Figure 10 (this corresponds with up to about 400 mm of drive closure at this location). It should also be acknowledged that drives with identical amounts of strain will perform differently in terms of stability.

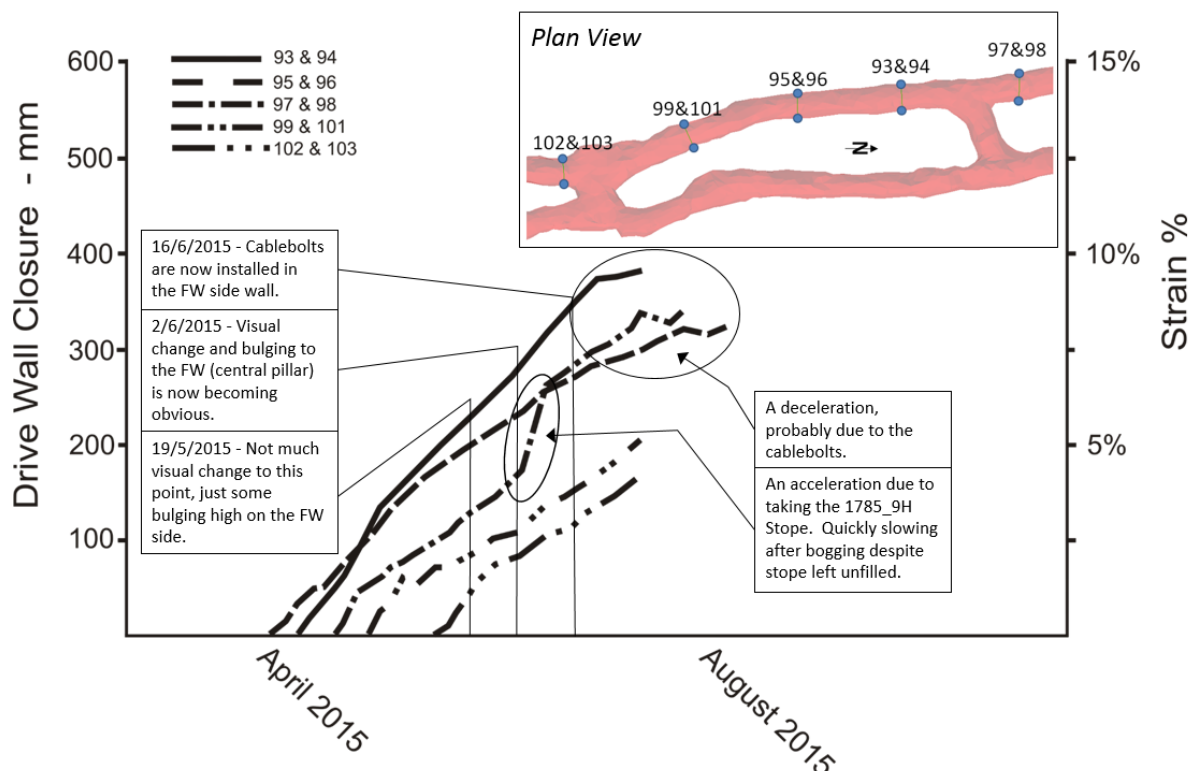


Figure 9 Closure monitoring data with observations of performance at the 1785HWS



Figure 10 Photographs of 1785HWS. Visual indications of drive change are relatively minor, despite the 10% strain being associated with about 400 mm of closure

The experience of detailed closure monitoring and observation of the Newton Zone has been summarised in Table 1. This classification of closure strain acknowledges that wall stripping cannot be avoided in some circumstances.

Table 1 Closure strain classification for mining parallel to a vertical anisotropy orientation

Drive Strain (ϵ_t)	Mine Classification	Description
$0 < \epsilon_t < 2\%$	Few Support Problems	Generally no significant deterioration of the drive.
$2\% < \epsilon_t < 5\%$	Light Squeezing	Squeezing is now noticeable at the shoulder. Ground support (with no stiff liner) requires no significant rehabilitation.
$5\% < \epsilon_t < 10\%$	Fair Squeezing	Minor requirement for replacement of failed wall friction bolts (less than 5% of wall bolts). No deterioration of the roof observed.
$10\% < \epsilon_t < 20\%$	Stripping Zone	Generally reaching the limit in terms of reliable bolt performance, wall stability and width requirements for machinery access. Stripping required.
$20\% < \epsilon_t < 40\%$	Post Stripping Zone	This essentially means that the drive has been made safe with the removal of unstable material, and re-installation of pattern ground support. The roof requires possible re-support as the material begins to break up close to the excavation boundary. Bolt warping and breakage common in the shoulders and possibly in the roof.

4 Ground support methods

Ground support in Newton Zone was designed to prevent wall failure initiated by unravelling from the base of the wall and to reinforce the roof loosened zone at the excavation boundary. Induced stresses locked the foliation structures together in the roof, meaning a relatively light ground support regime was sufficient. The walls remained stable with relatively light bolting, with flexible surface containment being most critical for stability.

Within the Newton Zone ore drives, walls were meshed floor to floor with 5.6 mm wire, 100 mm aperture galvanised mesh. The mesh was pinned with galvanised 47 mm friction bolts, 1.8m long in the walls, 2.4m long in the roof, on a 1.2 m x 1.2 m pattern. Two rows of 8 mm mesh straps were installed running along each wall to provide resistance to mesh join splitting and mesh wire strand breakage at higher strains. Cablebolts (fully grouted, 6m long twin strand and bulbed) were installed selectively at stope brow positions, where narrow pillars existed between parallel ore drives or where side wall squeezing needed to be slowed to prevent further drive stripping prior to stoping.

Other strap types were used, mainly to use up ground support stock at site. Through experience the mine developed a preference for using an 8 mm mesh strap, rather than a 1.9 mm thick w-strap. The w-strap was found to tear under load and was more susceptible to loader bucket damage.

For the ground support system to be a success in squeezing ground conditions, the following items are considered to be essential components:

- Rehabilitation of all squeezing drives is a very regular task, to replace failed bolts or torn mesh and address all issues prior to the development of a potential ground control hazard.

- Friction bolts require modification to ensure all bolt components match the friction bolt tube UTS of 18 t, as the bolts became locked in place within the walls due to shearing on foliation structures. With no consideration of the friction bolt surface connection, the bolt ring and in some cases the plate will fail at loads possibly below 5 t. This issue is solved by strengthening the surface connection of the friction bolt (both the plate and bolt ring). The plates were upgraded to meet >15 t loading and this was achieved by using a 4 mm thick modified collar plate. The bolt ring, which holds the plate against the wall, more closely resembled a friction bolt pull ring (significantly larger surface connection to the bolt than a 8mm bolt ring) to enable consistent bolt ring failure at >15 t load. Implementing these changes to the friction bolt created a bolt capable of working effectively at up to 200 mm of movement over the bolt length. Due to the foliated conditions and bolt clamping/guillotining in the walls, the full bolt UTS can be utilised.
- Flexible surface support installed to the base of each wall is essential.

Cablebolts (fully grouted and bulbed) achieved between 300 mm and 400 mm of movement over the bolt length when installed into the drive walls. This amount of movement is usually only associated with the performance of debonded cablebolts. Fully grouted cablebolts and progressive breakage at the bolt/grout interface where foliation breaks intersect the bolt (in numerous locations) still allows for some connection of the cablebolt to the rock mass at positions over the entire bolt length.

5 Ground support design for extreme squeezing ground

Considering the complexities involved with the ground conditions at the Newton zone, conventional ground support design methods and numerical modelling techniques are not able to capture the correct failure mechanism. To assist in predicting and understanding of appropriate ground support strategies, a 3D numerical model was developed for the Newton Zone utilising the IUCM method described by Vakili et al (2014). The model accounts for critical factors controlling the failure mechanism in highly stressed and highly anisotropic ground conditions, such as those at Henty Mine. The numerical modelling complimented the ground support design techniques commonly used at Henty Mine that consider the rock mass, rock structures and engineering experience.

This modelling methodology has provided reliable forecast of rock mass behaviour at number of other mine sites with similar ground conditions to Henty Mine, hence the decision to use this approach. The IUCM accounts for mechanisms, such as the transition from brittle to ductile response at various levels of confinement, dilatational response, strength anisotropy, and stiffness softening. As shown in Figure 11, this modelling method was able to forecast the rock mass response to mining with a high level of precision using the realistic input parameters obtained from lab testing and field investigations. A good correlation between monitoring data and model outputs was achieved. This model was used for optimisation of ground support design, primarily at stope brow positions and proved to provide a reliable and cost effective design method.

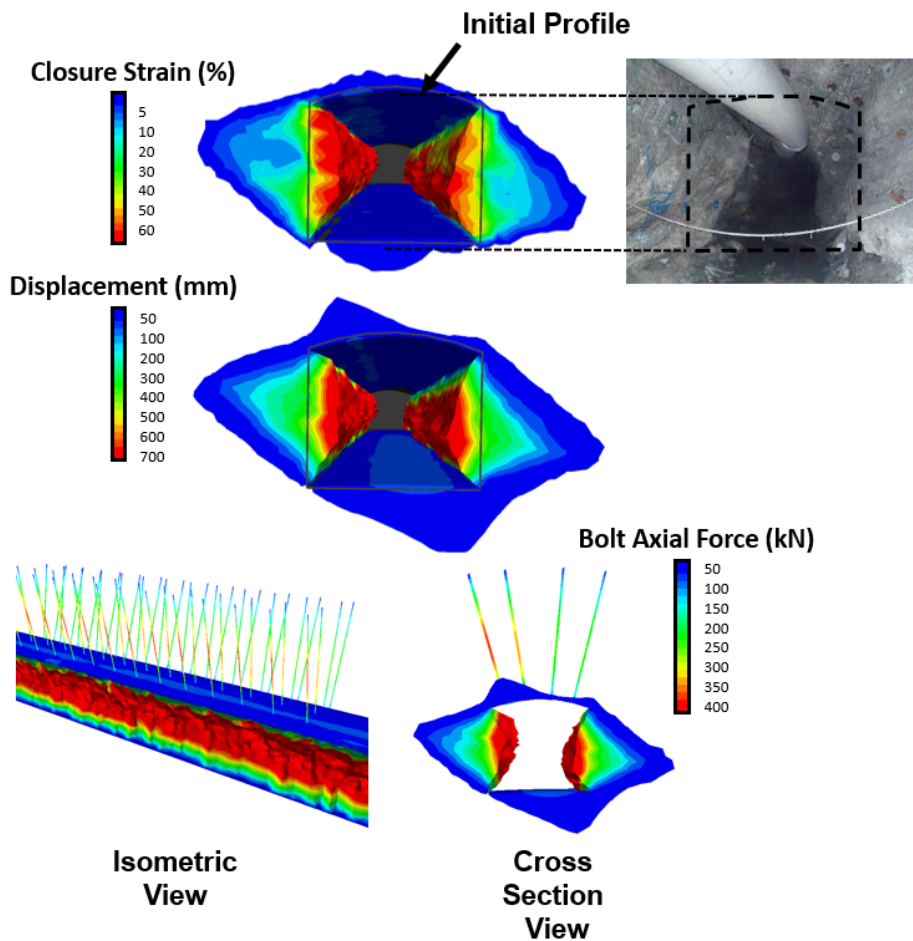


Figure 11 Newton Zone IUCM model – ore drive and stope brow bolt performance

6 Conclusions

The Newton Zone at Henty Mine was mined successfully without a ground control incident (rock fall or failure), even though the ore drives experienced strain described as being extreme. The Newton Zone ore drives experienced as much or more strain than other published squeezing ground case study locations in Canada and Australia. Monitoring data, rather than just visual observations was used to confirm the nature of the movement around the drive openings.

Detailed monitoring has confirmed the depths and extent of the movement zone around the drive. The relationship between strain in the roof and the walls was presented with no increase in the rate of roof bulking relative to drive closure rate, even at drive closure strains beyond 20%.

It was demonstrated that installed ground support can be relatively light in squeezing drives and still maintain safe and stable openings for personnel. Friction bolts with mesh and straps to floor retained the walls and friction bolts were modified to strengthen the surface connection of the bolt which extended bolt service life and reduced the need for rehabilitation of failed bolts. Intersections were maintained in serviceable condition, despite hundreds of millimetres of roof bulking and without excessive rehabilitation through better understanding of the mechanism of movement.

Ground support design for extreme squeezing conditions is a complex and difficult task. A 3D numerical model using the IUCM method assisted by predicting and understanding appropriate ground support strategies. A good correlation between monitoring data and model outputs was demonstrated to provide reliable forecast of rock mass behaviour.

Acknowledgement

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