Ground Support 2013 — Y. Potvin and B. Brady (eds)

doi:10.36487/ACG_rep/1304_37_Sainsbury

Analysis of extraction level performance at the Henderson Mine

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Abstract

The 7210 Level at Henderson Mine in Colorado, USA commenced production in January 2005. However, after undercutting commenced, unusual damage was noted on the western side of the drawpoint brows and entry ribs. A convergence monitoring system was developed to measure the convergence in the drawpoints as a tool to manage damage throughout the extraction level. Vertical convergence readings confirmed that substantial deformations (>5% strain) were occurring and modifications were made the drawpoint construction methodology in an attempt to limit the damage. A numerical analysis of the observed and monitored extraction level performance during the early stages of the 7210 Level has been conducted. A close match between the measured and modelled vertical convergence at multiple locations throughout the extraction level was obtained. The numerical simulation results were used to verify the modes of damage within the drawpoints and predict the performance of the modified drawpoint construction methodology over the remainder of the panel.

1 Introduction

The accurate assessment of extraction level performance is of critical importance to the planning of any caving operation. A numerical modelling methodology has been developed with the three-dimensional finite-difference code FLAC3D (Itasca Consulting Group, Inc., 2012) to simulate the complex stress redistribution, deformation and yielding that occurs surrounding an extraction level during undercut development, cave initiation, drawbell development and production. In order to provide confidence in the modelling methodology a back-analysis of the observed and monitored extraction level performance during the early stages of the 7210 Level has been conducted.

2 The Henderson Mine

2.1 Background

The Henderson Mine is located 69 km west of Denver, Colorado, at an elevation of 3,170 m above sea level. The mill is located 24 km west of the mine, on the other side of the Continental Divide, at an elevation of 2,800 m above sea level. The orebody is located 900–1,500 m below the surface, and is accessed through an 8.5 m diameter service shaft. Ore is crushed underground and transported to the mill site on three 1.2 m wide conveyor belts. A load-haul-dump (LHD) panel-caving system has been used to extract approximately 209 million tonnes of molybdenum ore since production began in 1976. Figure 1 provides a general cross–section of the mining geometry.

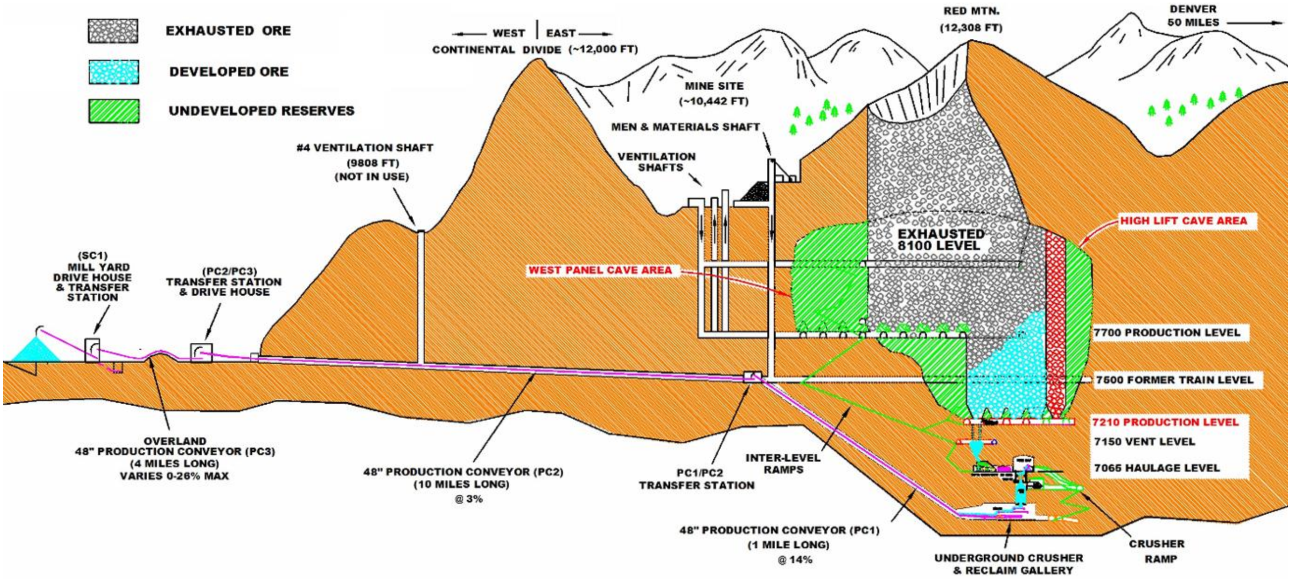

Figure 1 Schematic cross section through the Henderson Mine (after Rech, 2001)

2.2 The 7210 Extraction Level

The 7210 Level at the Henderson Mine commenced production in January 2005. A conventional (post) undercut strategy was employed whereby development of drawpoints was limited to one drawbell beyond the caved front (undercut advance). Historically, Henderson has had a four to five drawbell development lead as illustrated in Figure 2(a) (after Carlson and Golden Jr., 2008).

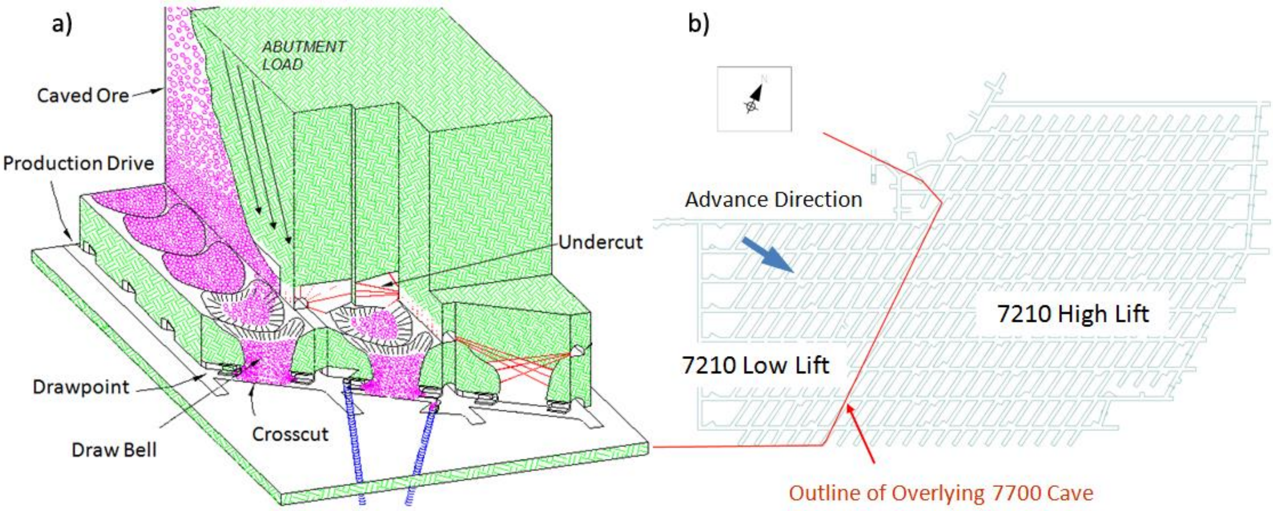

Figure 2 7210 Extraction Level layout and plan view

During undercutting of the 7210 Level, cave initiation was observed with a relatively small hydraulic radius (22 m) compared to historical value of approximately 35 m at the mine. The presence of intrusive contacts along the northern boundary of the 7210 Level Undercut has previously been reported as being responsible for premature cave initiation (Carlson and Golden Jr., 2008).

Drawpoint support on 7210 Level initially implemented a system that was similar to the previous 7700 Production Level. The system used steel arch-sets and a brow sets to act as a flow bar. Forms were placed to allow the pouring of mass concrete around the arch set system, creating the drawpoint, as illustrated in Figure 3. The length of the concrete and arch sets was varied depending on the rock mass quality.

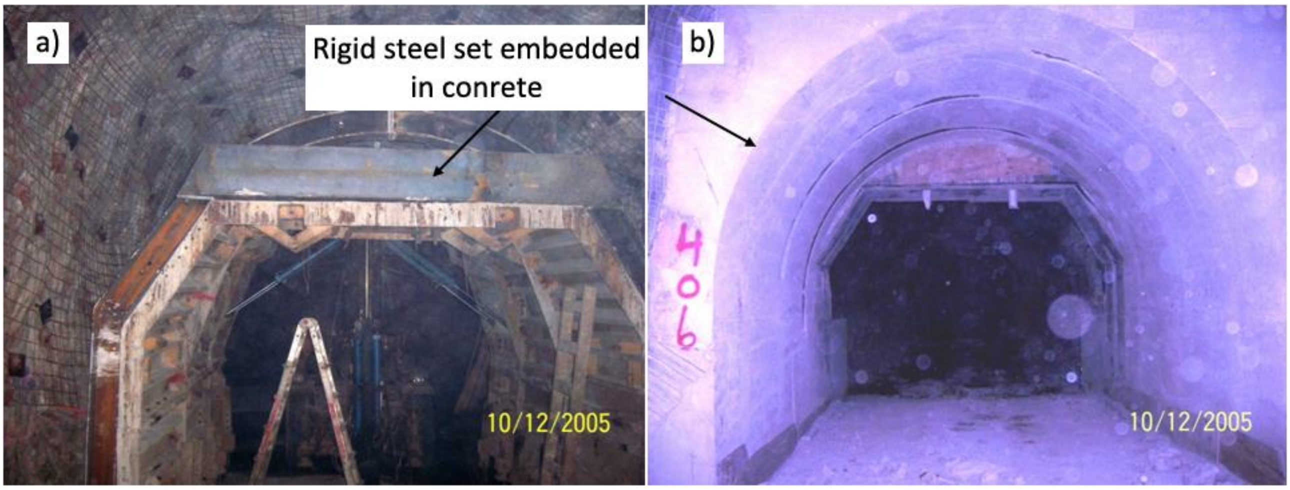

Figure 3 Conventional drawpoint support for the 7210 Level

During initial cave propagation in the 7210 area, damage was noted within the drawpoint brows and entry ribs as soon as abutment loading occurred. The steel arch sets failed and the concrete cracked and yielded to the point of creating a hazard to people and equipment, as illustrated in Figure 4. Significant repairs were required prior to production draw.

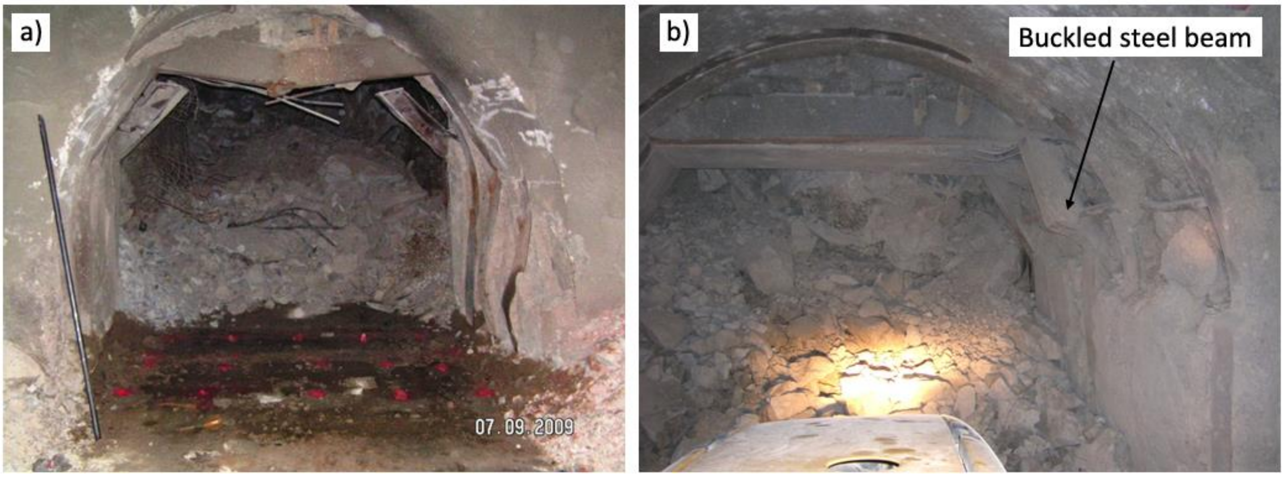

Figure 4 Typical damage observed within drawpoint brows

As a tool to manage the drawpoint damage, a convergence monitoring system was developed to measure closure strains in the drawpoints on the 7210 Extraction Level. Both horizontal and vertical closure strains were measured. Vertical convergence measurements confirmed that substantial deformation was occurring. The maximum convergence recorded was approximately 345 mm – 8% strain, with vertical convergence exceeding 150 mm – 3.5% strain in more than 50% of cases.

As a result of this damage, a more flexible cable bolt, mesh, and shotcrete arch (C-Arch) drawpoint support system was developed and tested at one location on the perimeter of the panel. As illustrated in Figure 5(a), a shotcrete arch was installed with a mechanical bolter and 1.2 m split sets and 6 m cable bolts were also installed, illustrated in Figure 5(b). Minimal damage was observed at the test location with more than 109,000 tonnes of ore drawn. The system was then implemented on drawpoints in the middle of the panel that was expected to see higher abutment loads and greater damage due to a change in the geology. The tests were again successful with only minor damage observed. Based on these trials, the decision was made to change to the flexible drawpoint support system throughout the entire 7210 Extraction Level. The new drawpoint support system reduced remediation requirements, was less labor and material intensive to install and provided the operation with significant savings.

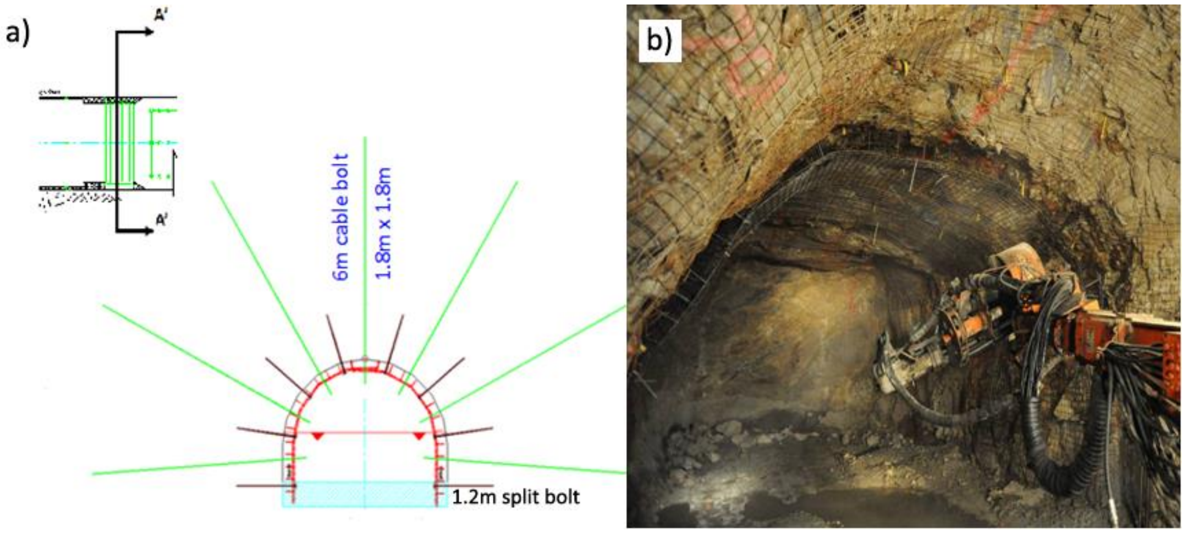

Figure 5 Shotcrete arch drawpoint construction; (a) design; (b) implementation

3 Back-analysis of the 7210 Level Extraction Level performance

In order to provide confidence in the future prediction of extraction level performance at the Henderson Mine, an analysis of the mechanisms causing the observed drawpoint damage and the magnitude of closure strains measured throughout the early stages of the 7210 Level was conducted The simulation results were used to provide guidance on the expected performance of the modified drawpoint design throughout the rest of the 7210 Panel. This could be achieved without modelling the ground support explicitly through a comparison of the simulated displacement and yielding compared to the measured closure strains and observed drawpoint damage in those locations already developed.

3.1 Model geometry and simulation of evolving cave volume

A large-scale FLAC3D model was constructed to simulate the regional extents of the Henderson Mine, as illustrated in Figure 6(a). The existing overlying cave volumes (8100 and 7700 Levels), developed prior to the 7210 Level were initialised within the model based upon historical mining records, as illustrated in Figure 6(b).

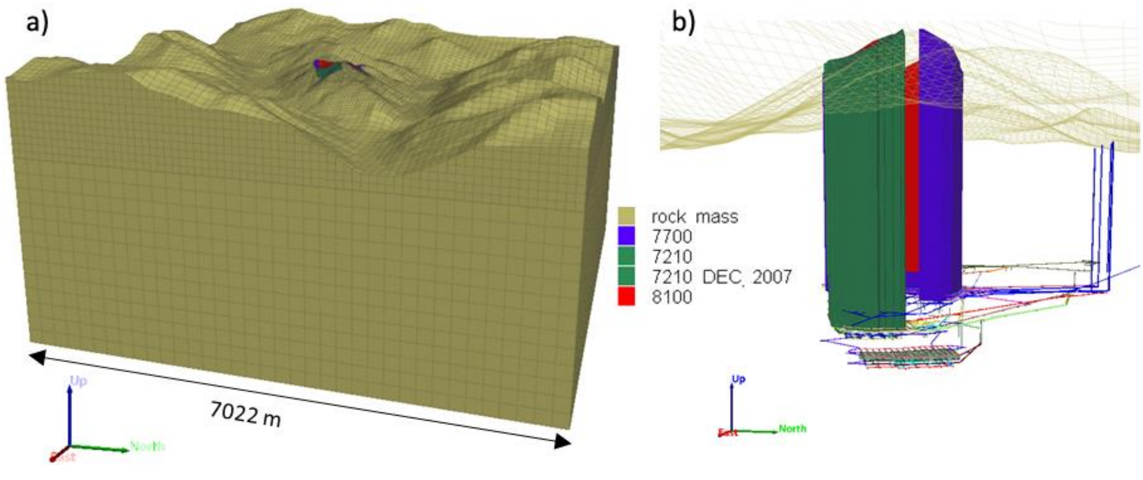

Figure 6 a) Regional extents of model; b) existing cave volumes

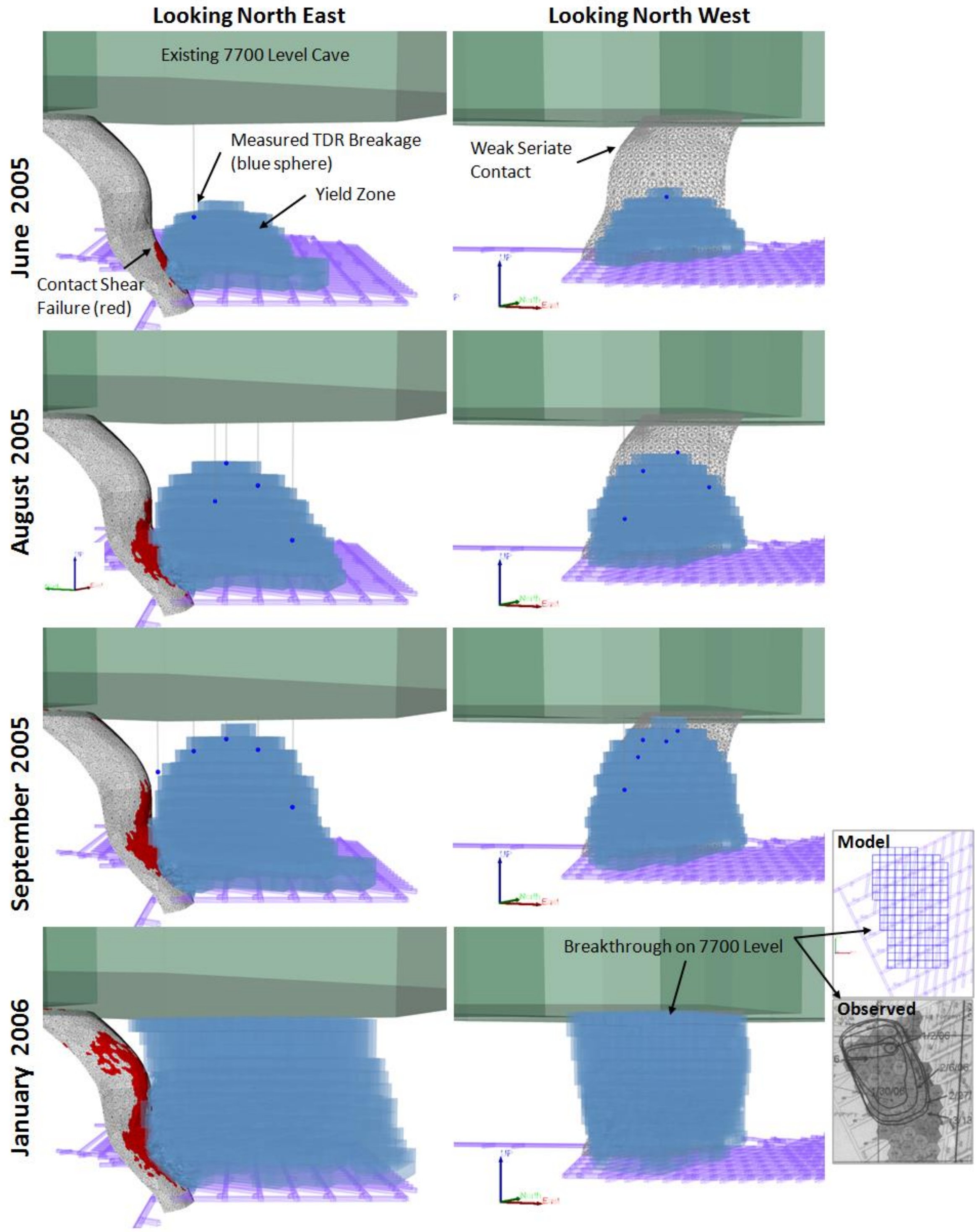

Figure 7 Evolution of cave yield zone and comparison to TDR breakages

In order simulate the evolving abutment stresses within the 7210 Extraction Level, a caving simulating was conducted using a numerical approach that has been developed over the past 12 years during the industry funded International Caving Study (ICS I & II) and Mass Mining Technology (MMT) projects. Numerical algorithms are used to represent the primary mechanisms of undercutting, draw and cave propagation within FLAC3D. Details of the modelling approach can be found in Sainsbury (2010). Back-analysis of the structurally controlled cave initiation and propagation of the 7210 Level up to the 7700 Level is described in detail by Sainsbury et al. (2011). The evolution of the model-predicted yield zone, which represents the region of new fracture or shearing on existing fractures ahead of the cave zone, is illustrated in Figure 7.

The modelled yield zone was observed to provide a close match to the time-domain reflectometer (TDR) breakages (dark spheres) monitored during cave propagation. Shear failure along the weak contact can be observed to develop along the interface coincident with vertical propagation of the yield zone. After initial breakthrough of the yield zone to the overlying 7700 Level in January 2006, the yield zone was observed to follow the weak contact, outside the northern and western limits of the undercut foot print.

To simulate the effect of the propagating cave and evolving abutment stresses on the 7210 Extraction Level, the volume of yielded rock mass predicted after each undercut/production increment in the 7210 cave propagation model were initialised within the detailed extraction level model as illustrated in Figure 8. The yielded zone was simulated with material properties equivalent to a fully-bulked rock mass.

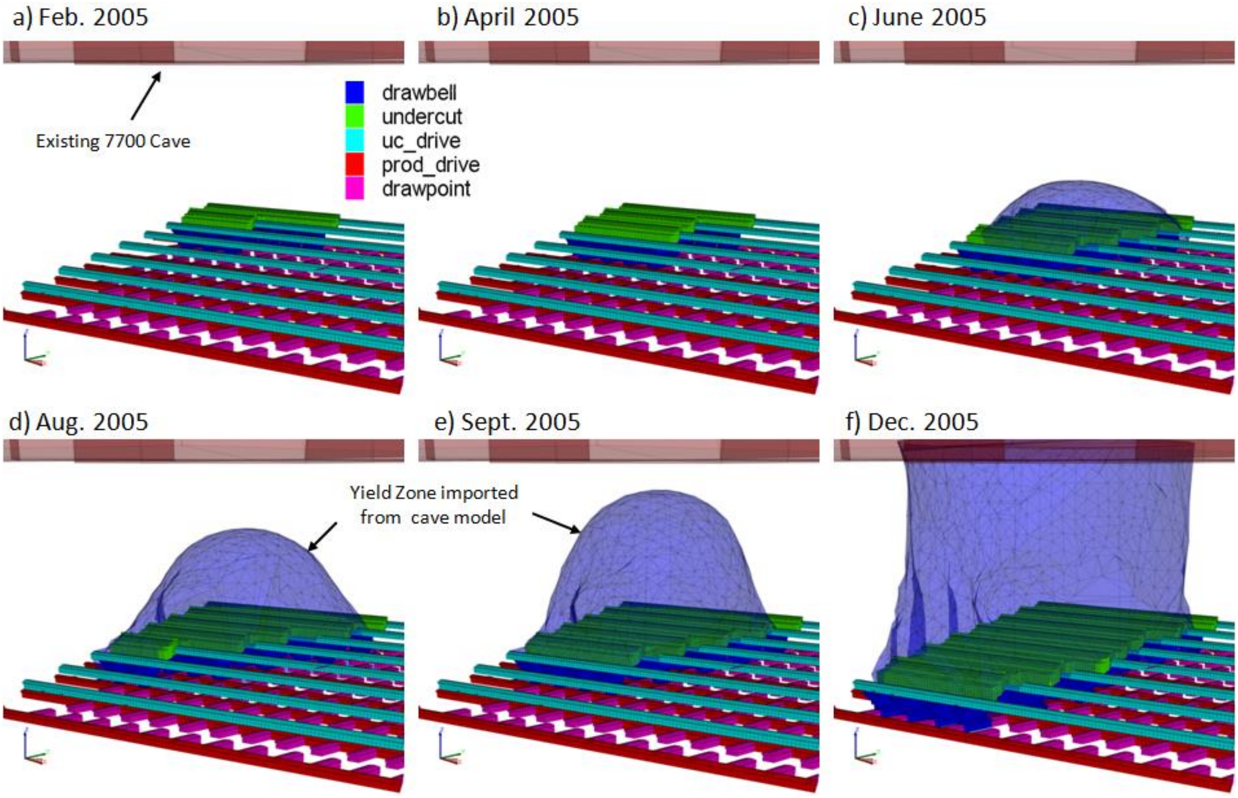

Figure 8 Simulated 7210 Extraction Level development, undercutting and cave sequence

3.2 Material properties and in situ stresses

Multiple geotechnical domains have been mapped throughout the 7210 Level. Figure 9 illustrates a plan view through the western extent of the 7210 Level.

Figure 9 7210 Extraction Level geotechnical domains

The geomechanical properties used to simulate the main rock mass domains are presented in Table 1. These material properties were derived from laboratory testing and in situ mapping. A bi-linear, Mohr-Coulomb, strain-softening constitutive model was used to simulate the rock mass response within the numerical model. Segments 1 and 2 in Table 1 refer to the bi-linear segments of a Mohr–Coulomb approximation to the Hoek–Brown failure envelope developed from the UCS, GSI and m_i values presented in Table 1. A maximum σ_3 of 15 MPa has been used for the Mohr–Coulomb fit. Softening of the peak cohesion and tension strength values has been achieved through a relationship between accumulated plastic shear-strain and GSI values as described by Cundall et al. (2005).

Table 1 Material properties derived for each domain

Domain	GSI	σ_c (MPa)	m_i	E_m (GPa)	ν_m	C_1 (MPa)	ϕ_1 (Deg.)	C_2 (MPa)	ϕ_2 (Deg.)	σ_t (MPa)
Host good	64	160	15	22.4	0.22	4.0	64	9.3	43	0.7
Host fair	55	160	15	10.0	0.24	2.7	54	7.8	41	0.4
Host poor	36	160	15	2.8	0.26	1.4	53	5.8	38	0.1
Ore good	64	118	10	22.4	0.22	3.3	48	7.3	36	0.7
Ore fair	55	118	10	10.0	0.24	2.2	48	6.1	34	0.4
Ore poor	36	118	10	2.8	0.27	1.1	46	4.5	31	0.1

The simulated response of the Ore Fair domain under large-scale (10 m high) uniaxial compression and triaxial compression loading conditions is illustrated in Figure 10. The bi-linear Mohr–Coulomb strain−softening constitutive model reproduces the general elastic, peak strength, post-peak softening and dilatancy mechanisms expected in an isotropic rock mass.

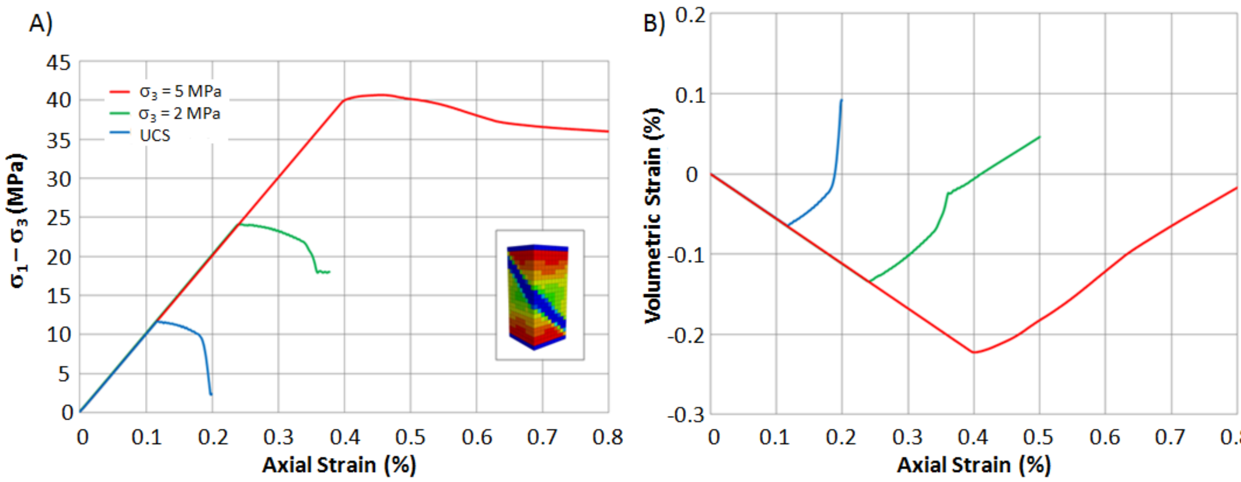

Figure 10 Simulated FLAC3D response of the Ore Fair domain

Due to the significant topographic relief and complex previous mining history at Henderson, it is difficult to estimate the pre-mining stress regime. A stress calibration exercise has previously been conducted at Henderson (Rech and Lorig, 1992), whereby nine stress measurements taken from 1970 to 1989 were calibrated determining the in situ tectonic stresses that result in a best-fit of model predicted stress to those measured by overcoring. The results of the stress calibration exercise, which indicated a major principal stress oriented at 155°, were directly applied to the back-analysis model.

3.3 Simulation results

The evolution of major principal stress and rock mass damage (expressed as percentage cohesion reduction from the strain softening process) on the 7210 Extraction Level is illustrated in Figure 11. Cohesion reduction has been used to provide an indication of the damage since it is the most direct measurement of rock mass strength in a strain–softening model. Due to redistribution of the major principal stress around the undercut and cave volume, high abutment stresses are simulated along the northern perimeter of the extraction level. After initiation of the cave, it can be seen that high abutment stresses cause moderate damage (up to 50% cohesion reduction) within the pillars along the leading edge of the undercut advance. The location of these localised high stresses and damage is consistent with the observations of damage underground and high closure strain measurements.

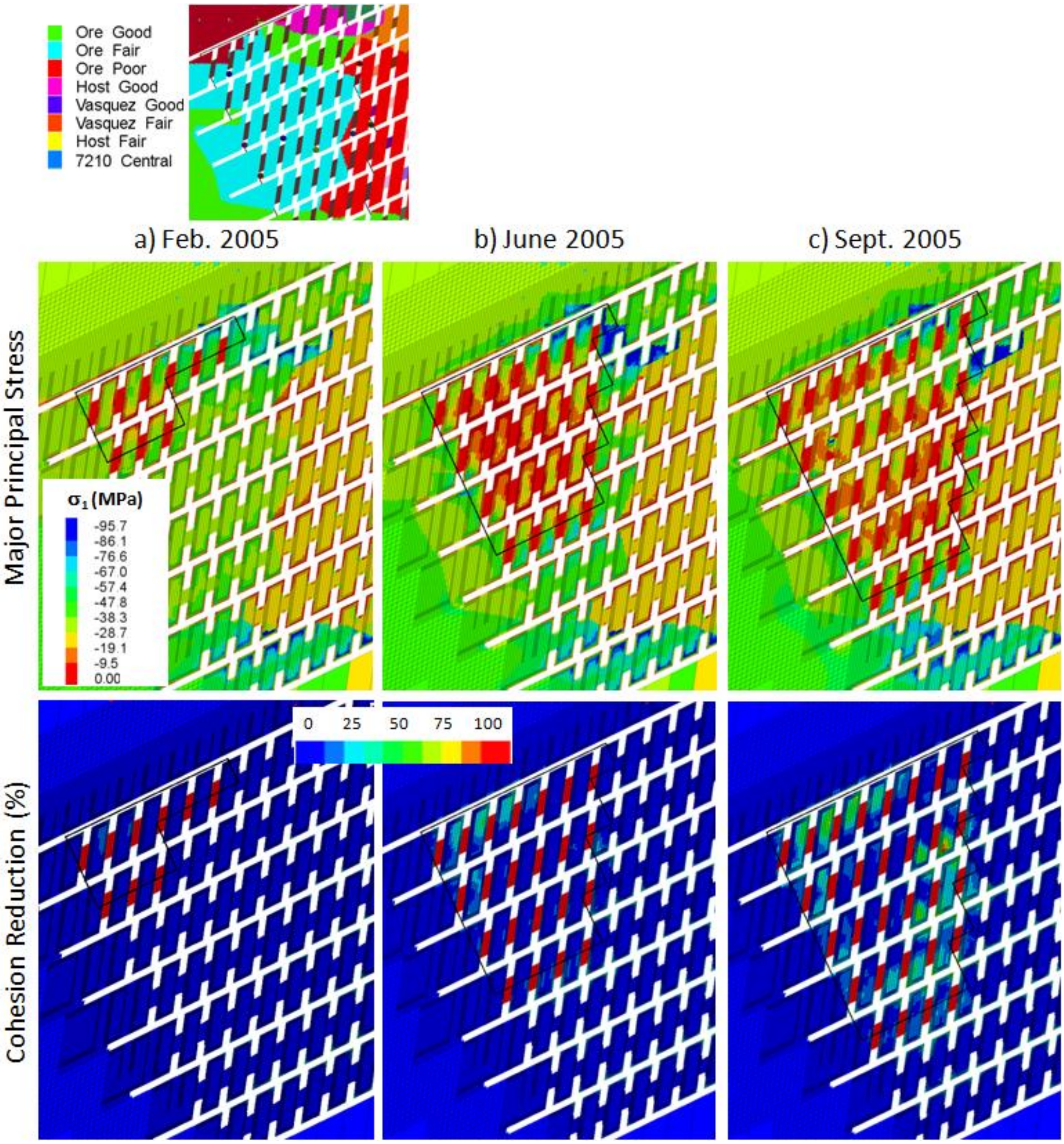

Figure 11 Evolution of major principal stress and rock mass damage (cohesion reduction)

Figure 12 illustrates a detailed view of the rock mass damage simulated at September 2005 when a change in geology within the Extraction Level was encountered. Up until this time, minor to moderate (20–50% cohesion reduction) damage within the pillars was simulated. However, as the Extraction Level entered the poor ore domain, significant rock mass damage (>75% cohesion reduction) was simulated in the bullnose locations and the western haunch of the drawpoints.

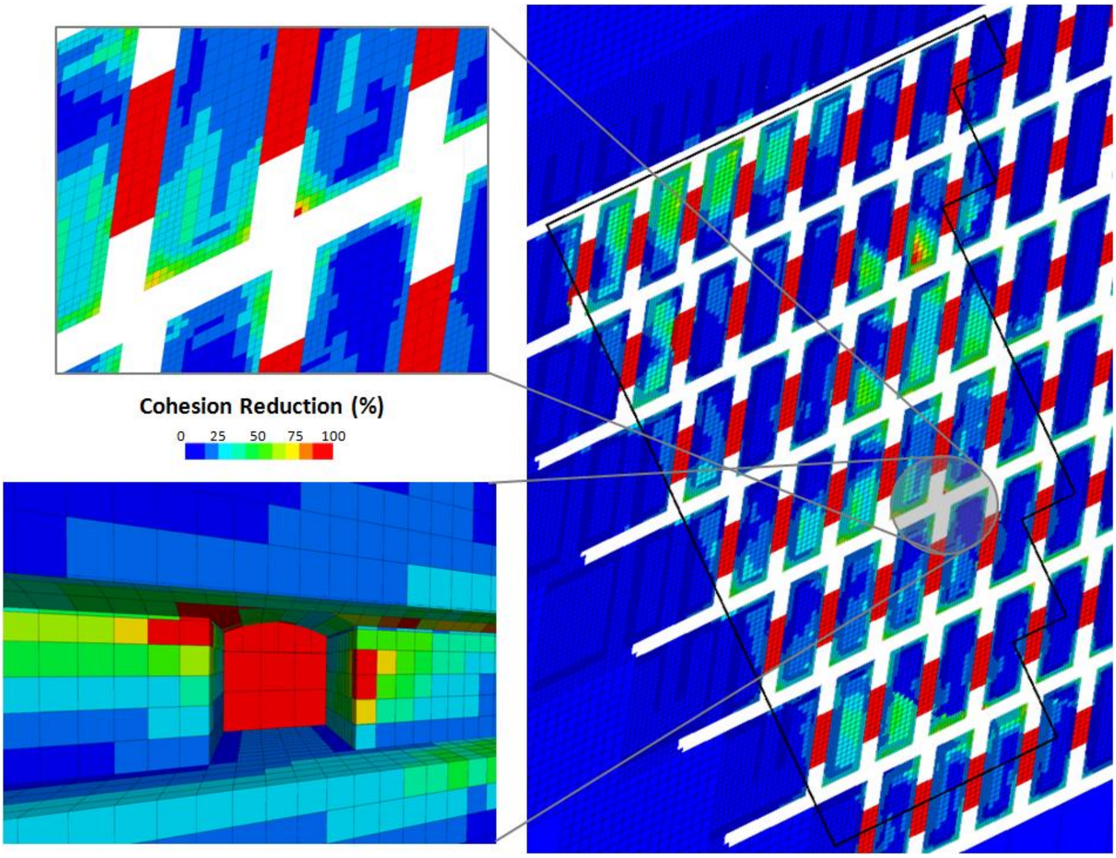

Figure 12 Typical rock mass damage predicted after September 2005

As illustrated in Figure 13, it can be seen that the depth of significant damage (>75% cohesion reduction) in the drawpoints in the poor ore domain is limited to approximately 1.5 m. This is less than the length of the bolts specified for the revised drawpoint construction procedure – resulting in a better performance.

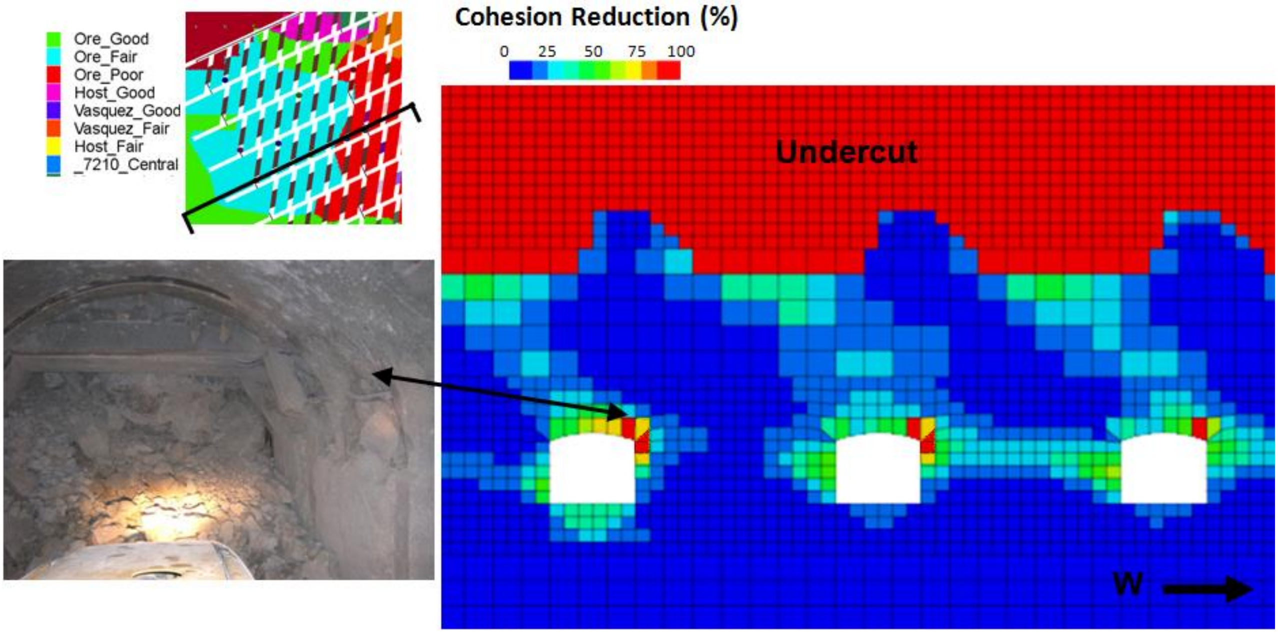

Figure 13 Rock mass damage predicted in the western haunch of each drawpoint

3.4 Comparison of measured verses modelled vertical closure

As discussed, extensive vertical convergence monitoring was conducted at drawpoint locations throughout the 7210 Extraction Level. Figure 14 illustrates the very close match between the measured and modelled vertical convergence at three separate locations. A significant increase in vertical convergence was measured and modelled within the weaker Ore Poor material as seen in Figure 14(c).

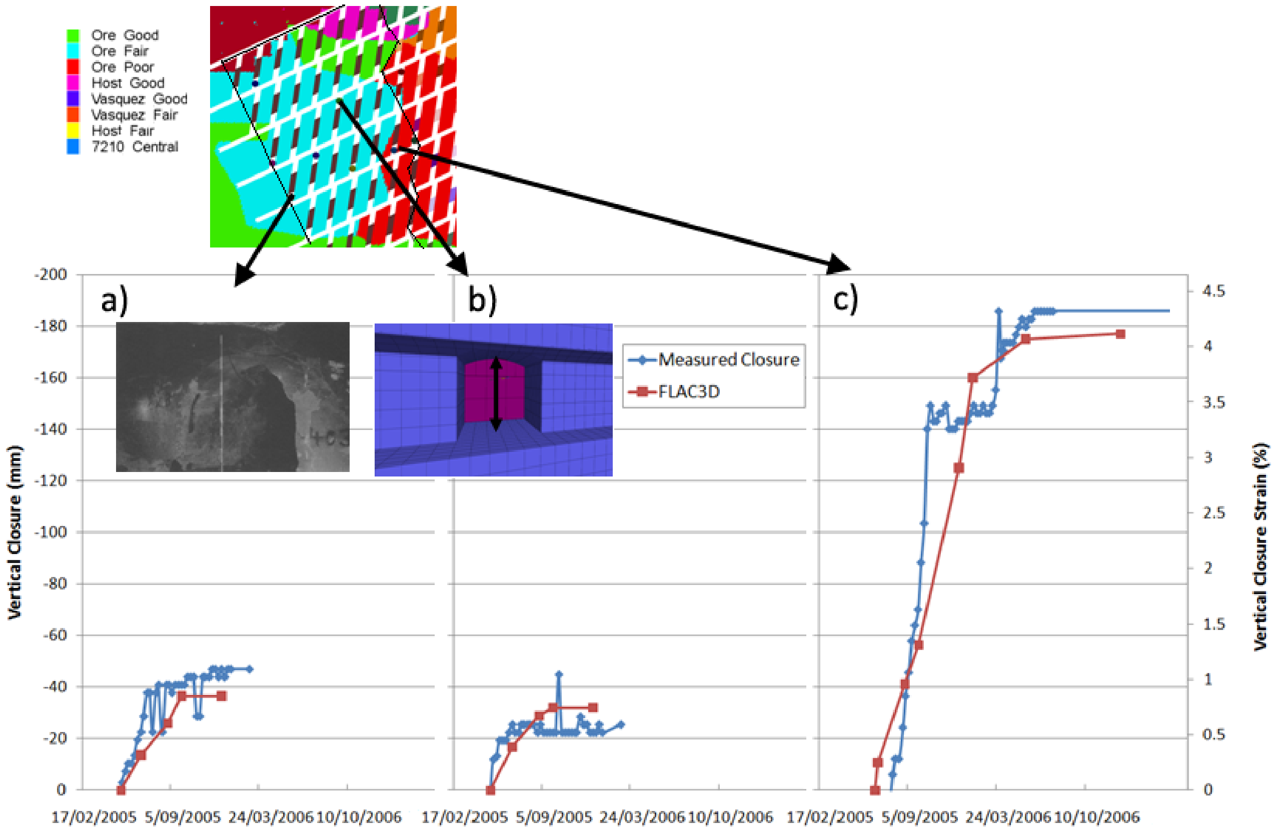

Figure 14 Comparison of measured verses modelled drawpoint vertical closure

Simulation results for the rest of the panel did not show increased closure strains or damage within the poor ore domain. As a result of the successful trial of the modified drawpoint construction method within this zone, it was deemed that the modified drawpoint construction method was acceptable for the remainder of the 7210 Panel.

4 Conclusions

Back-analysis of the extraction level performance at the 7210 Level of the Henderson Mine provides a close match to the observed and monitored rock mass damage. The numerical analysis provided information regarding the mechanisms of damage in the initial drawpoints on the level, along with confidence in the expected performance of a modified drawpoint construction methodology proposed throughout the remainder of the panel.

Acknowledgement

The authors would like to thank the management of Freeport McMoRan and the Henderson Mine for the permission to publish this work. Other contributors to this work include Mark Board and Bre-Anne Sainsbury of Itasca.

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