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Crown pillar extraction with paste underhand stoping

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Abstract

Technical investigations were conducted for extraction of a high-grade crown pillar in the northern 3500 orebody (N3500) at Glencore's Mount Isa Mines using cemented paste backfill (CPB) underhand stoping. Several stopes have now been successfully extracted, achieving the planned recoveries with minimal dilution.

In addition to standard CPB lab testing, in situ testing was conducted in the area planned for underhand exposure. The objective was to determine the variance between actual and design CPB strengths, to ensure the strengths were suitable for the planned underhand exposure dimensions. The testing results indicated the majority of in situ CPB strengths were higher than the lab cured and design strengths, due to the arching of stresses within the fill mass and curing processes. The strength parameters obtained from the testwork were incorporated in numerical modelling assessments using FLAC3D. Model calibrations were conducted using historical vertical CPB exposures to ensure the adopted methodology and material parameters were suitable.

This paper discusses the methodology and results of the technical investigations, and how the data fed into analyses to assist with safe and efficient extraction of the crown pillar.

Keywords: *crown pillar, paste underhand, stoping*

1 Introduction

N3500 is a high-grade copper orebody situated in the northern part of the Enterprise Mine at Mount Isa Mines, located in northwest Queensland, Australia (Figure 1). Glencore's Mount Isa Mines has been in operation for almost 100 years. The current mining methods employed are sublevel open stoping with backfill and sublevel caving.

The N3500 orebody is the deepest orebody at Mount Isa Mines, with current mining at a depth of 1.4 to 2 km (Figure 2). The orebody is mined in several longitudinal panels, in a bottom up/centre-out retreat sequence, which has proven to be a successful practice to date. Stopes are filled with cemented paste backfill (CPB) then exposed vertically with the next stope in the sequence. In order to mine multiple panels at once, a crown pillar was left within the orebody from 28B to 29E sublevels, with dimensions of 100 m long (north–south), 40 m wide (east–west) and 60 m high.

To optimise extraction of the N3500 orebody, undercutting of the CPB was considered. The 29A block was identified for underhand exposure, situated in a crown pillar, underneath the 28B and adjacent 30A previously mined and filled stopes. The extraction sequence requires both vertical and underhand exposure of the paste filled stopes. Standard CPB design strengths in the area are 600 to 800 kPa from the base to 25 to 50 m, with 400 to 500 kPa for the remainder. The underhand exposures must be strong enough to prevent failure of the entire fill mass and major sloughing of the vertical and underhand exposure faces.

The planned 29A stoping block consists of seven stopes with dimensions of 20 to 30 m (L), 25 m (W) and 60 m (H) and sizes of 60,000 to 90,000 tonnes (Figure 3).

Figure 1 Mount Isa Mines is located in northwest Queensland, Australia

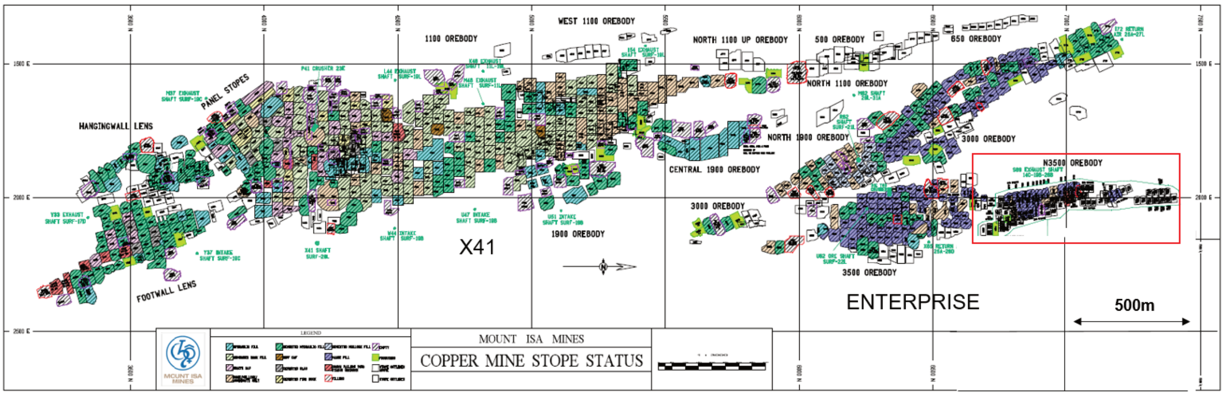
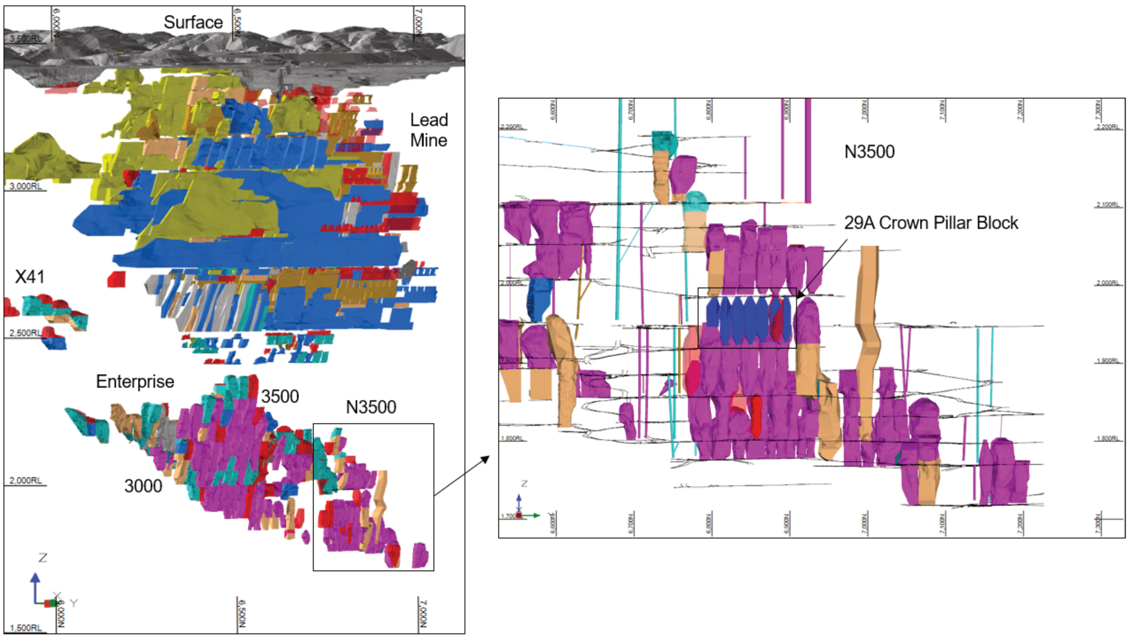


Figure 2 Plan view of Mount Isa Mines stope mine status with the N3500 orebody



(a) (b)

Figure 3 Location of the N3500 orebody and 29A stoping block with adjacent orebodies at Mount Isa Mines, looking (a) Northwest and (b) West

2 N3500 orebody

2.1 Geological setting

The N3500 orebody strikes north–south, dipping at 60 to 70 degrees to the west. It has two bounding structures which define the orebody; the basement contact zone (BCZ) which forms the lower boundary, and the footwall fault zone which forms the eastern boundary. The BCZ dips at 35 to 45 degrees to the northeast consisting of highly sheared and faulted carbonaceous mylonite of up 25 m thickness. The footwall fault steeply dips to the west exhibiting high talc concentrations and minor graphite, and moderate to strong shearing with an average thickness of 7 m.

The orebody is hosted within Urquhart shales, with rock types consisting of predominantly fractured siliceous shale with lesser irregularly brecciated shales. Rock types in the hanging wall consist of recrystallised shale and dolomitic shales. Rock types in the footwall consists of dolomitic shales, pyritic shales and slaty shales.

Several significant fault zones are also present which offset the orebody (Figure 4). The faults can be divided into two sets; the north–south (NS) west dipping faults and the north–northwest (NNW) near vertical dipping faults, exhibiting strong graphitic shearing and talcose alteration.

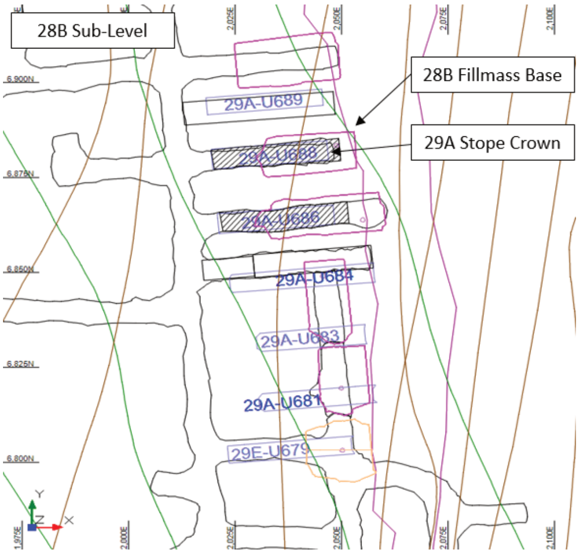


Figure 4 Plan view with 28B development, major structures, planned 29A stope crowns (blue), 28B fill mass bases (pink), north–northwest faults (green), north–south faults (brown) and footwall fault (pink)

2.2 Geotechnical setting

Rock mass conditions in the N3500 orebody are highly variable, with very poor zones of talc-altered shale, fissile graphitic shale, numerous faults and moderate in situ stress conditions, resulting in an extremely deformable rock mass. The breccia orebody outside of fault zones is extremely competent and generally massive, defined by the >2.0% copper shell.

Three main geotechnical domains have been established based on fracture frequency per metre (FF/m), talc alteration and copper mineralisation (Sainsbury & Grubb 2010) (Table 1).

Table 1 Geotechnical domains with properties

Geotechnical domain	FF/m	Talc content (%)	Rock mass rating
Hanging wall	5–10	<10.0	Fair
Orebody	0–5	0.0	Good
Footwall	>10	>15.0	Poor

2.3 Stress regime

Since the late 1960s, significant rock stress measurements have been completed at Mount Isa Mines, including in excess of 30 virgin (pre-mining) and 70 mining-induced measurements. Significant damage mapping has also been conducted in the N3500 orebody, with ample evidence of high stress spalling in the backs of the east–west crosscuts to support a north–south oriented major principle stress.

The stress magnitudes and orientations for the N3500 orebody are presented in Table 2. The 29A block is located approximately 1.7 km below surface resulting in a major and minor principle stress of approximately 64 and 44 MPa respectively.

Table 2 Pre-mining stress fields used for numerical modelling in the N3500 orebody

	Magnitude (MPa/m)	Dip (degrees)	Dip direction (degrees)
σ_1	0.037	5	176
σ_2	0.026	71	281
σ_3	0.024	18	85

2.4 Previous mining performance

Extraction of stopes in N3500 has generally been successful to date. Minor overbreak generally occurs along the west hanging wall and east walls, which is structurally controlled by the bedding planes and major structures with graphitic shearing and talc. On rare occasions, large failures from the eastern walls have occurred associated with a strong presence of talc content, which can exceed over 30% of the rock mass. The talc significantly reduces the rock mass strength and joint conditions. The north and south walls encounter little overbreak as these are oriented perpendicular to structures. The stope design methodology is to keep the walls within the high-grade orebody breccia and better ground conditions. The vertical CPB exposures can be up to 120 m high and remain stable with only minor fill dilution. This is due to:

- Adequate curing of the fill mass prior to exposure (28 days for stope firings).
- Effective blasting practices.
- A minimum 2 to 3 m skin pillar is left when blasting adjacent to the fill mass.
- Where practical, holes are drilled parallel to the fill mass rather than toeing into the fill mass.
- Boundary rings are charged with low density Sanfold explosives (a Dyno Nobel product).
- Limited cold jointing; following the capping run, CPB is continuously run for stopes in the area.
- Arching of stresses within the fill mass and curing processes increasing the in situ strength.

3 Mine design

The 29A block consists of seven stopes with dimensions of 20 to 30 m (L) by 25 m (W) by 60 m (H) and sizes of approximately 60,000 to 90,000 tonnes. The stope crowns are situated on 28B with single drawpoints on 29A. Access is gained to the top of the stope by development fill mining through the base of the previously extracted, filled and cured stope on 28B. Upholes are drilled from 29A with all downholes drilled from a single drive on 28B. A retreat sequence from north to south was adopted to assist with management of stress during the extraction of the crown pillar. Each stope is filled with CPB following completion, then vertically exposed with the next stope in the sequence.

The stopes are fired as a vertical retreat, with a single 1.1 m diameter raisebore extending the full height of the stope. The firing sequence includes a trough undercut from the drawpoint level followed by several downhole firings (Figure 5). The final firing is approximately 20 m below the 28B level.

29A-U688 was the first stope in the block to be extracted. It is positioned directly below the 28B-U688 stope, with a design CPB strength of 800 kPa (the in situ strength was found to be 1,360 kPa). The dimensions of 28B-U688 are 20 m (L), 40 m (W) and 90 m (H). To the west of the stope lies the 30A-U687 filled stope, which makes up a portion of the west footwall of 29A-U688.

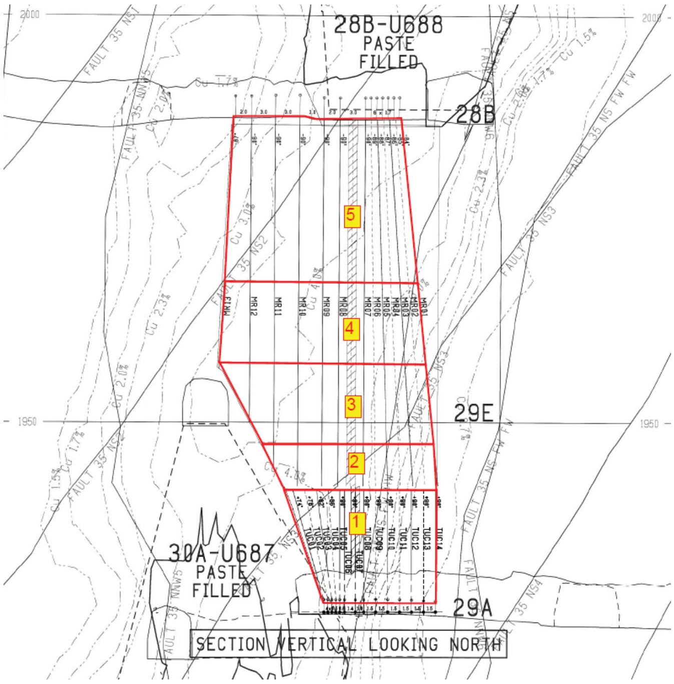


Figure 5 Cross-section looking north with the 29A-U688 stope and firing sequence

4 Technical investigations

4.1 Cemented paste backfill background

The CPB is sourced from the paste fill plant which is fed from tailings from two concentrators (copper and zinc streams). Metallurgical slags are frequently processed through the copper stream. The complexity of paste production is largely driven by the range of supply and process variations that can affect one aspect of fill quality, namely the particle size distribution (PSD). The PSD affects the rheology and strength performance of the CPB. Despite the PSD variations, these still remain within the required sizing criteria for the CPB (AMC Consultants 2012).

A second key quality parameter is that of fill slurry density. This is significantly variable relating to the successful delivery underground by gravity pipeline and due to the resulting backfill strength for a particular binder content and curing time (AMC Consultants 2012).

4.2 In situ sampling program

Bulk samples were extracted from inside the filled stope during development fill mining. The samples were taken to the site core shed for preparation and testing.

A total of 16 in situ CPB locations were sampled and tested during 2017 and 2018 from within the orebody. Inspection of each development fill face was conducted with a photo log taken to ascertain if any cold jointing or excessive layering was present. None was identified during inspections.

An example of a bulk CPB sample taken during development fill mining is illustrated in Figure 6.

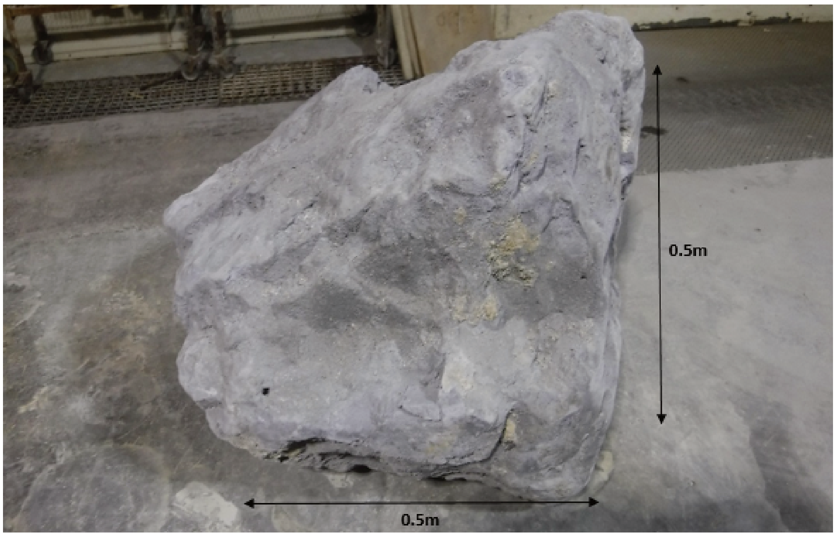


Figure 6 Bulk cemented paste backfill sample taken during development fill mining

4.3 Lab testing

The bulk samples were cored without water into cylinders of 50 mm diameter and 100 mm length in preparation for unconfined compressive strength (UCS) and multi-stage triaxial testing. Sampling numbers varied between locations due to availability of adequate bulk samples.

Examples of prepared samples ready for testing are illustrated in Figure 7.

(a)

(b)

Figure 7 In situ cemented paste backfill samples ready for (a) Unconfined compressive strength; and (b) Triaxial testing

4.4 Results

The UCS test results are presented in Table 3 and Figure 8. The design CPB strength at each extracted in situ sample location and lab CPB strength (cured in the surface lab) are also included for comparison.

The results show the in situ CPB strengths were mostly higher than both the lab cured and design strength. This can be attributed to:

- Arching of stresses within the fill mass.
- Large size and height of the stopes.
- Curing processes increasing the in situ strength, including;
  - Fast rate of filling.
  - Long travel times increasing mixing and de-hydrating.
  - High in situ temperatures.

Several results show significant increases in strength between the design and in situ CPB, thought to be due to the addition of lead slag in the CPB mix design and location of the in situ sample that was sourced from the base of the stope where the vertical stresses and arching would be the most influential.

The high strength in situ results observed could also be a function of the bulk sampling. The larger bulk samples could be higher in strength, which may result in sampling bias. In situ drilling was not conducted during the investigations; this may have led to more representative results.

Table 3 Unconfined compressive strength (UCS) results from the in situ and lab CPB testing with design UCS (standard deviation in parenthesis)

Sample #	Sample ID (location)	Design (UCS) (kPa)	In situ UCS (kPa)	# in situ tests	In situ cure time (days)	Lab UCS (kPa)	# lab tests	Lab cure time (days)
1	32D-U679 (31A)	400	424 (128)	24	>56	460 (170)	2	>28
2	32D-T681 (32D)	600	633 (131)	26	>56			>28
3	30A-U687 (29A)	500	324 (26)	2	14	310	1	>28
4	28B-U682 (28B)	600	1,380 (226)	9	>56	670	1	>28
5	28B-U682 (27A)	300	277	1	>56			>28
6	28B-U686 (28B)	700	1,030 (175)	25	>56	590	1	>28
7	30A-U685 (29A)	600	926 (47)	3	28	540 (50)	5	>28
8	30A-U687 (30A)	700	1,139 (531)	7	>56	598 (113)	5	>28
9	30A-U689 (30A)	600	1,122 (581)	2	>56	1,180	1	>28
10	33D-T719 (33D)	600	698 (223)	20	30	310 (60)	2	>28
11	33D-T719 (32D)	400	159 (70)	3	20	265 (40)	6	>28
12	30A-T663 (30E)	300	1,131 (351)	6	>56	350 (33)	1	>28
13	31A-T701 (30A)	500	2,667 (249)	3	31	1,270 (150)	2	>28
14	31A-T701 (31A)	800	973 (148)	7	31	630 (30)	10	>28
15	30A-U683 (29E)	400	1,053 (100)	2	>56	560 (90)	1	>28
16	28B-U688 (28B)	800	1,360 (300)	4	>56	600 (100)	6	>28

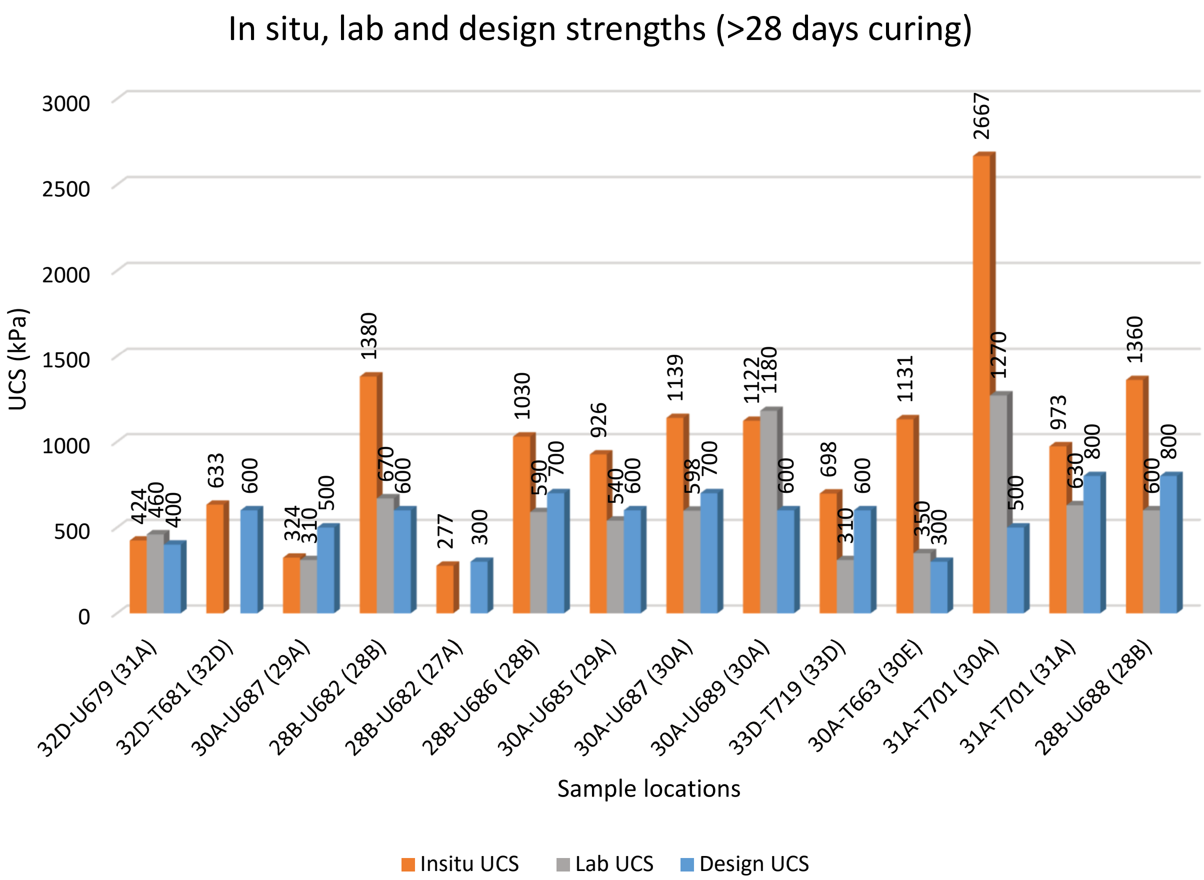


Figure 8 In situ, lab and design strengths from unconfined compressive strength testing (greater than 28 days curing)

Triaxial test results for the in situ CPB samples are presented in Table 4. The average friction angle was approximately 30 degrees, which is consistent with Brummer et al.'s (2003) hypothesis that a friction angle of 30 degrees is typical of most CPB materials. The cohesion was found to increase as a function of the UCS.

Table 4 In situ shear strength results from triaxial testing (standard deviation in parenthesis)

Sample #	Sample ID (location)	In situ UCS (kPa)	# in situ tests	Cohesion (kPa)	Friction angle (°)	Cure time (days)
10	33D-T719 (33D)	698 (223)	5	300	35.0	30
12	30A-T663 (30E)	1,131 (351)	4	400	25.4	>56
13	31A-T701 (30A)	2,667 (249)	2	475	29.9	31
14	31A-T701 (31A)	973 (148)	2	400	31.0	31
16	28B-U688 (28B)	1,360 (300)	6	250	32.0	>56

UCS data as a function of varying binder percent (general purpose coarse cement – GPC) and curing time was also investigated (Figure 9). The relationship between curing time and UCS was used to simulate the strength gain of the CPB. The numerical analyses assumed each stope was filled in 5 m high increments. The adopted strength gain relations are consistent with published early-age testing on CPB (Veenstra 2013).

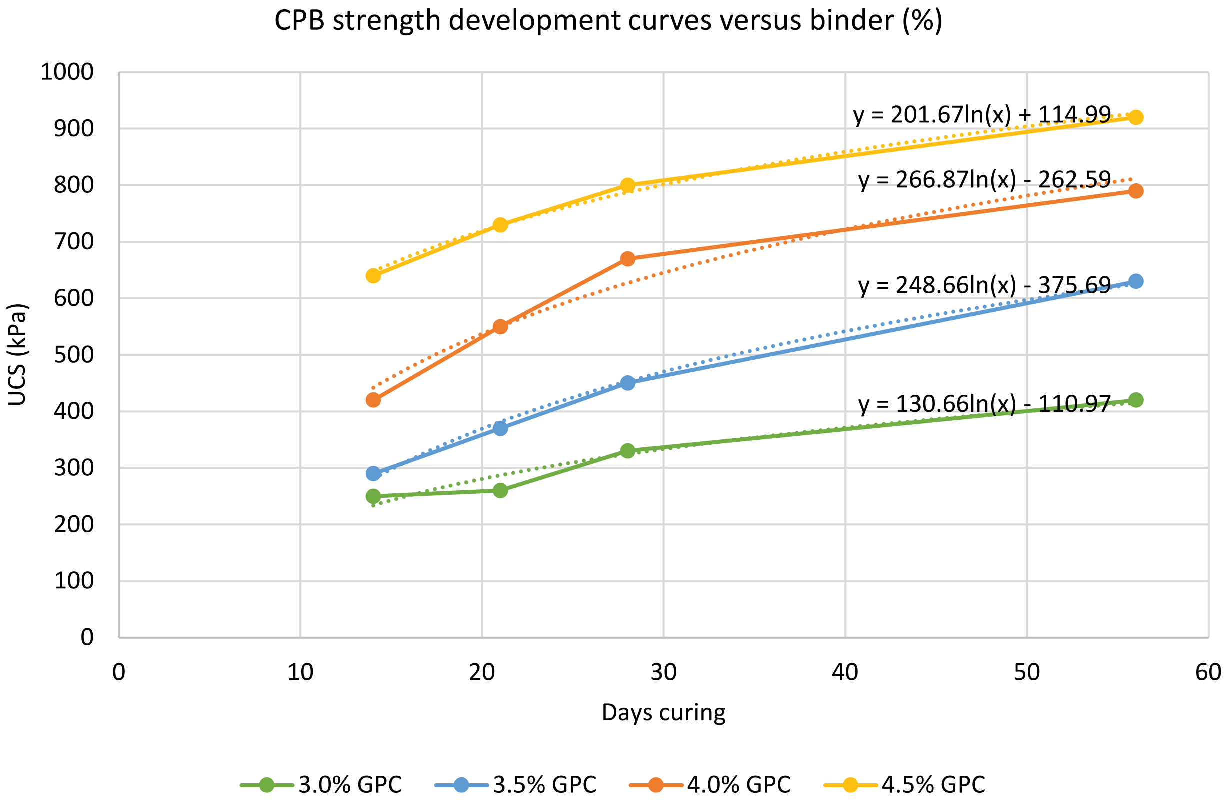


Figure 9 Lab cured strength development curves as a function of binder percent

5 Numerical modelling

5.1 Modelling approach

The underhand exposures must be strong enough to prevent failure of the entire fill mass and major sloughing of the vertical and underhand exposure faces. Paste fill exposure stability is a function of the following:

- Exposure geometry.
- Stope extraction and filling sequence.
- Hanging wall–footwall closure.
- Surrounding rock mass failure.
- Initial stresses within the fill mass.
- Internal cold joints or segregation within the fill mass.
- Dimensions of the fill mass.
- Shear strength of the fill.

The modelling approach adopted to investigate stability of the paste fill exposures included the following:

- Construction of a series of numerical models with the three-dimensional finite difference program FLAC3D. The model was constructed to simulate the historical extraction and filling sequence within the N3500 orebody. It is important to accurately simulate the filling and hydration sequence of each stope to provide a rigorous assessment of the internal stress distribution (arching) within each fill mass.

- The model was also constructed to simulate yielding and deformation within the rock mass surrounding each stope as potential fill failure mechanisms may involve failure of the yielded rock at the stope abutments.
- Calibration of previous vertical paste fill exposure performance was conducted using historic data. The calibration is critical to ensure the adopted modelling methodology and material properties that were used have a high level of confidence in predicting future underhand exposure performance.
- A series of predictive analysis was conducted to assess the performance of the underhand exposures that would be created by extraction of the planned 29A stoping block.

5.2 Model parameters

The rock mass surrounding the N3500 stopes has been simulated with a bi-linear, Mohr–Coulomb, strain softening constitutive model. The Mohr–Coulomb criterion has been used to define the peak strength of the rock mass (cohesion and friction) through a least-squares fit to the Hoek–Brown envelope developed from estimates of the Geological Strength Index (GSI), UCS (σ_{ci}) and m_i for the hanging wall, orebody and footwall domains. The Hoek–Brown parameters estimated for each domain are presented in Table 5.

Table 5 Hoek–Brown parameters for each domain

Domain	GSI	σ_{ci}	m_i
Hanging wall	55	110	10
Orebody	67	160	8
Footwall	50	95	10

The CPB properties adopted for the analyses are presented in Table 6. The adopted Poisson's ratio (ν) and friction angle (Φ) values were assumed to be constant regardless of fill strength. Based on the site laboratory testing conducted for the CPB, the remaining strength values were increased relative to the UCS. 600 and 400 kPa UCS values were adopted as a conservative measure until the method of extraction was proven.

Table 6 Cemented paste backfill properties adopted for the exposure stability analyses

Unconfined compressive strength (kPa)	200	400	600
Friction angle (degrees)	30	30	30
Cohesion (kPa)	100	160	250
Young's modulus (MPa)	14	26	41
Tensile strength (kPa)	40	80	120
Density (kg/m^3)	2,100	2,100	2,100

5.3 Model geometry

A panel scale FLAC3D model was developed to represent the typical stope geometries and sequence planned in the 28B and 29A blocks (Figure 10). The surrounding rock mass has been included in the model to simulate damage and subsequent hanging wall–footwall closure during the extraction sequence.

The stopes surrounding the 28B and 29A blocks were simulated in the model as a single mining step, while each individual stope within 28B and 29A was excavated in sequence and filled with 5 m lifts to ensure an accurate representation of the stress path with the rock mass and each fill mass.

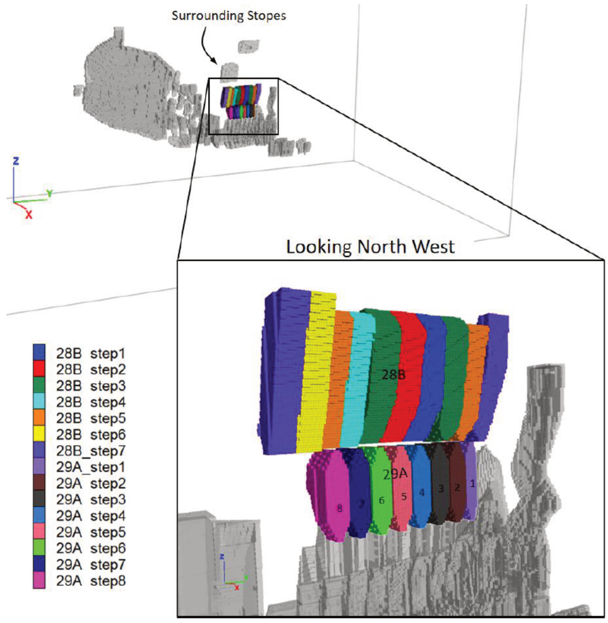


Figure 10 Regional model extents (top) and simulated stope sequence (bottom), looking northwest

5.4 Analysis of vertical exposure performance

All vertical fill mass exposures created with the extraction sequence were predicted to remain stable, with only minor damage (softening) at the perimeter of the fill masses. Figure 11a illustrates the predicted cohesion degradation (softening) and displacement after vertical exposure of a typical 28B stope (Figure 11b) and internal stresses. Although the fill mass remains stable, minor damage of the CPB can be observed.

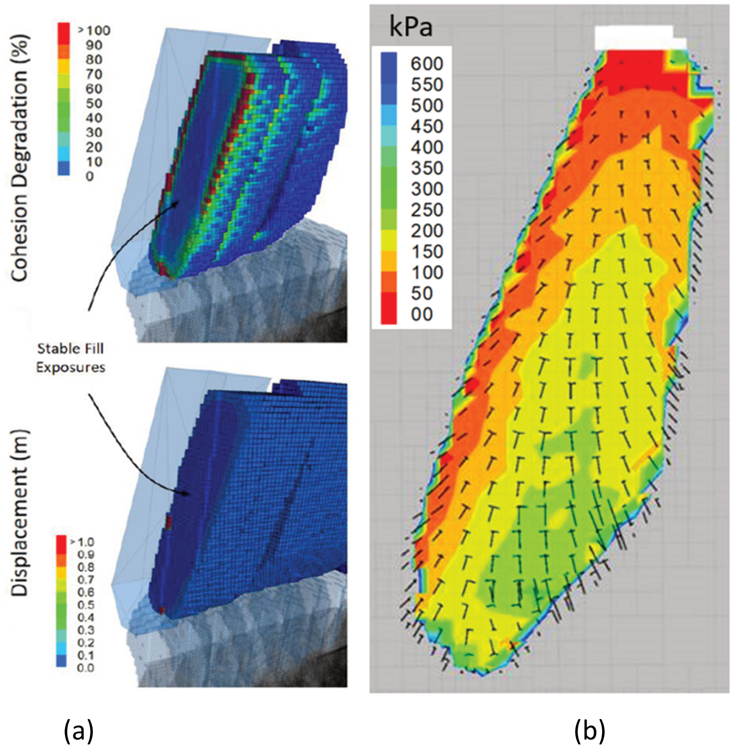


Figure 11 (a) Failure condition of the vertical exposure of a 28B stope above the future 29A block; (b) Internal stresses simulated within a 28B stope

5.5 Analysis of 29A block underhand exposure stability

Multiple analyses were conducted to determine the performance of the underhand CPB exposures created during extraction of the 29A stopes. In this case, the strength (UCS) of all CPB was 600 kPa. The CPB was assumed to be homogenous, unsaturated and with no cold joints.

Failure is defined as collapse of the adjacent vertical or horizontal CPB exposure. In the models, this is indicated by the formation of an active failure surface and continuous displacement (>1 m) of portions of the fill mass.

Figure 12 illustrates the predicted cohesion degradation (softening) and displacement of exposures created at steps 2, 6 and 8. The underhand exposures created at steps 2, 6 and 8 are predicted to remain stable. Minor, localised dilution can be expected, as illustrated in step 8.

Significant rock mass yielding was predicted within the small pillars at the base of the 28B level stopes.

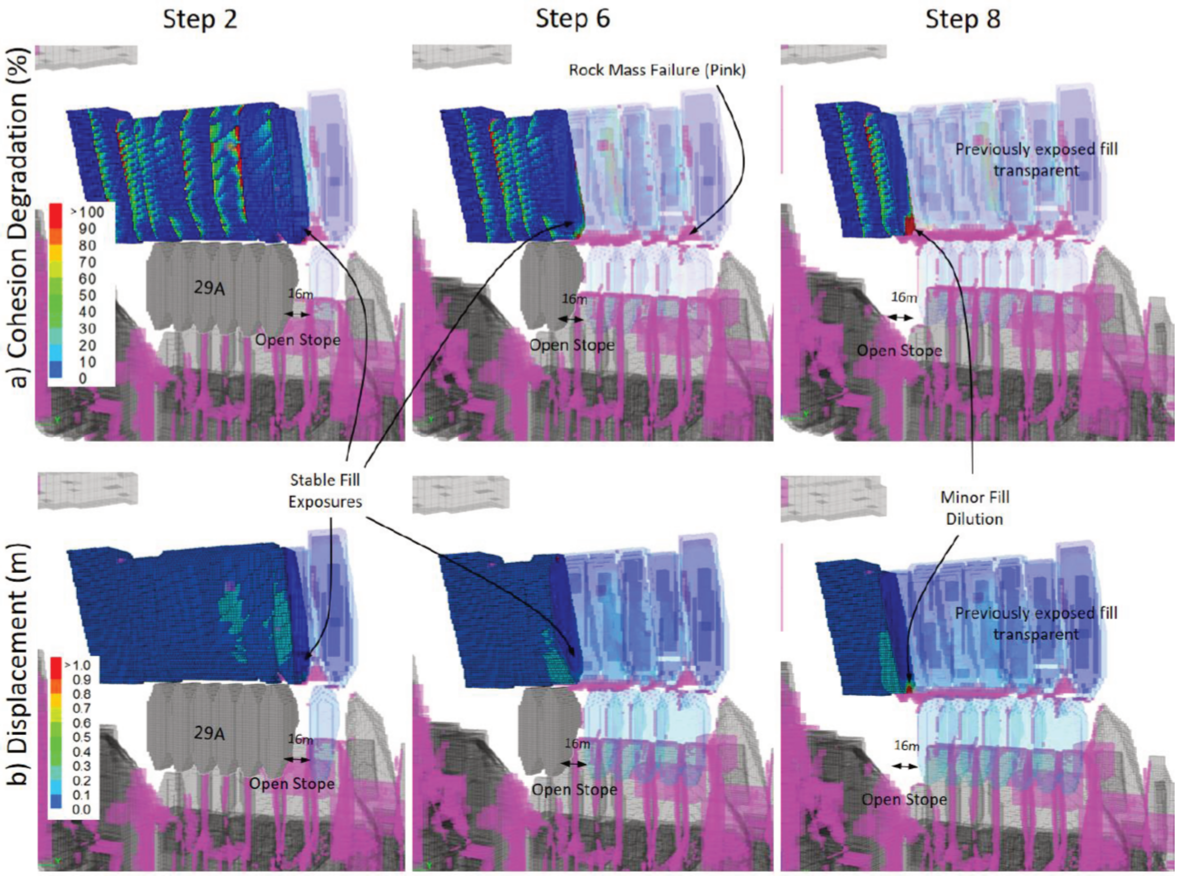


Figure 12 Failure condition predicted throughout the 29A extraction sequence. 600 kPa fill mass

An additional analysis was conducted to investigate the performance of the underhand CPB exposures of 400 kPa strength. Only a minor increase in deformation and cohesion degradation of the exposed CPB was predicted, indicating the in situ (600 kPa) 28B fill mass has a Factor of Safety of at least 1.5 to maintain stability during underhand exposure from the 29A stopes.

6 29A mining performance

Two stopes have been successfully extracted from the 29A stoping block with mining of the third stope in progress (Figures 13 and 14). The underhand exposures were both stable and achieved the planned recoveries with minimal dilution.

No additional ground support was installed in the stope crown on 28B. Difficulties were encountered during production drilling from the single downhole drill drive on 28B due to poor and damaged rock mass. The single drill drive also meant drill holes required toeing into the north and south walls. Traditional practice involves a low density boundary ring parallel to these walls which results in better recovery and less damage. A good result was still achieved, with some minor underbreak occurring on the north and south walls.

The remaining stopes in the sequence are being optimised to increase the planned underhand exposure dimensions and overall efficiency of the block extraction with a risk-based approach.

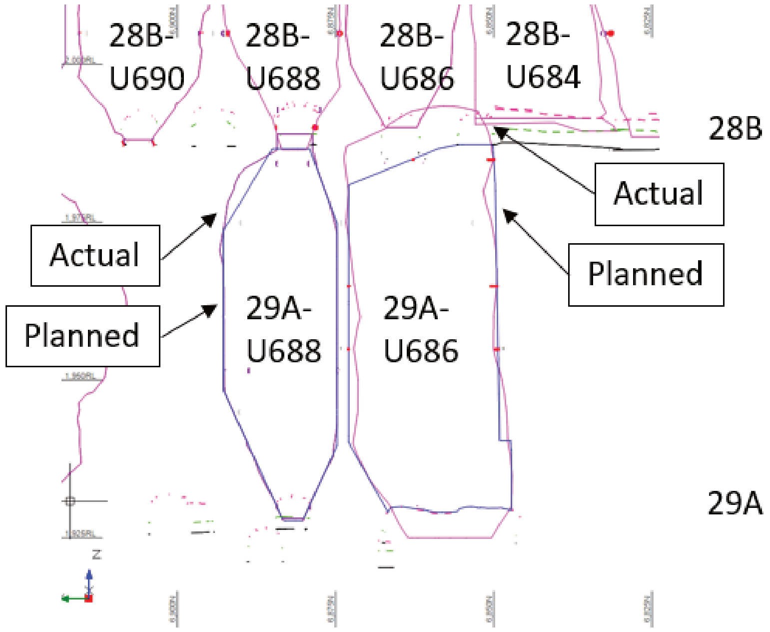


Figure 13 Long section east with planned (blue) and actual (pink) 29A-U688 and 29A-U686 extracted stopes

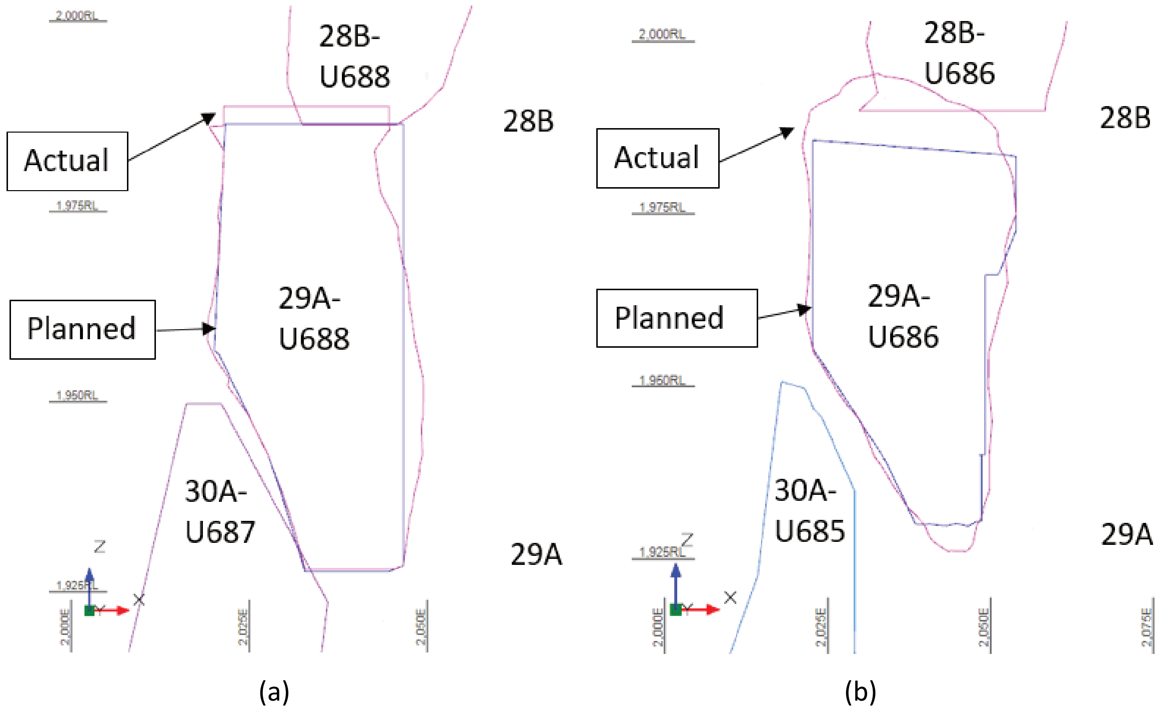


Figure 14 Cross-section north with planned (blue) and actual (pink) (a) 29A-U688 and (b) 29A-U686 extracted stopes

7 Conclusion

A series of technical investigations was conducted to establish a new method of mining at Glencore's Mount Isa Mines to extract a high-grade crown pillar underneath and adjacent to paste filled stopes.

The investigations found that the CPB cured in situ strengths were almost always higher than lab cured and design strengths. This can be attributed to:

- Arching of stresses within the fill mass.
- Large size and height of the stopes.
- Curing processes increasing the in situ strength, including:
  - Fast rate of filling.
  - Long travel times increasing mixing and de-hydrating.
  - High in situ temperatures.

The investigations confirmed and quantified the variance between design and in situ CPB strengths to ensure the underhand exposure dimensions were suitable.

The test data was incorporated into numerical modelling analyses and calibrated based on local site conditions. The refined model resulted in reliable analyses and forecasts to ensure safe and efficient extraction of stopes in the 29A block.

The modelling results demonstrated that underhand exposure of the 28B stoping block could be achieved with minimal paste dilution. The underhand exposures were both stable and achieved the planned recoveries with minimal dilution.

The remaining stopes in the sequence are being optimised to increase the planned underhand exposure dimensions and overall efficiency of the block extraction with a risk-based approach.

Further CPB in situ strength investigations are recommended, including sampling by in situ drilling, with the intent of reducing the binder content to result in lower backfill costs whilst achieving the same function.

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