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Unearthing the Black Rock orebody with sublevel caving

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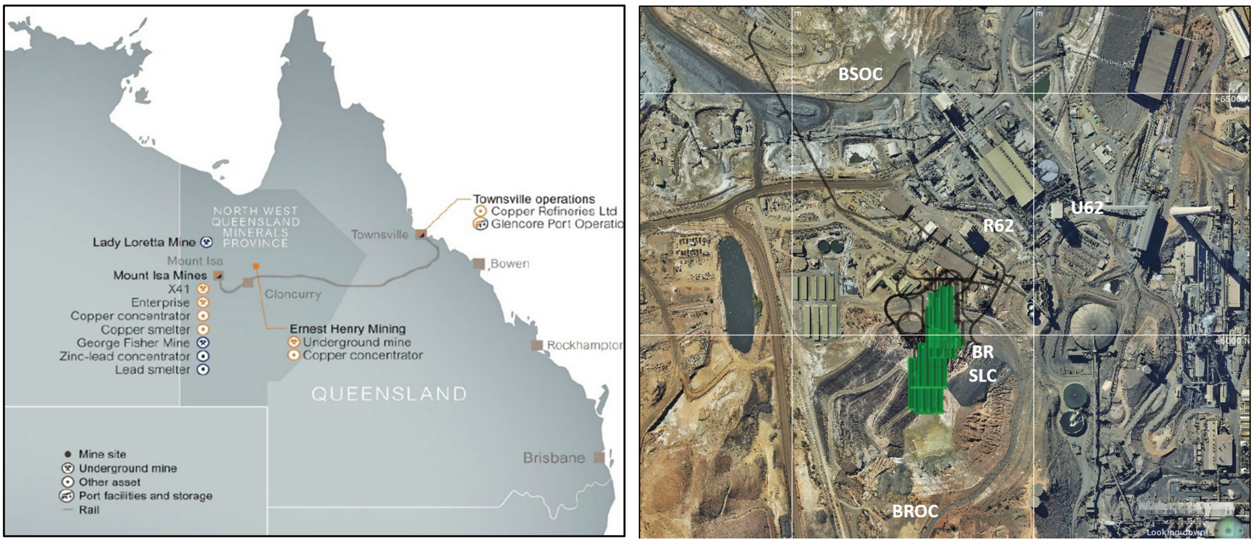
Abstract

The Black Rock orebody is located at Mount Isa Mines, in northwest Queensland, Australia. Owned and operated by Glencore, the mine has been in operation for almost 100 years. The orebody was last mined as an open cut from 1957 to 1965. It was closed due to two major wall failures and ongoing stability issues one bench short of completion, leaving behind a large quantity of high-grade ore. The remaining orebody is being extracted using the sublevel cave (SLC) mining method. The orebody is located in extensively altered and weak kaolinic shales, with zones of hot and reactive ground. Other challenges include naturally occurring and historic voids, and mining proximity to fixed surface infrastructure. The small SLC has a planned draw of approximately 1.5 million tonnes at 4.5% copper over four years, which commenced in September 2020. This paper discusses the work completed during the project phase and the key learnings during the initial execution phase. This includes geotechnical characterisation, caveability and subsidence assessments, fragmentation testing, cave flow and rock cutter trials, and development of a real-time instrumentation system to monitor surface infrastructure.

Keywords: *sublevel caving, weak and poor rock mass, rock cutting, subsidence, cave flow*

1 Introduction

The Black Rock orebody is located at Mount Isa Mines, in northwest Queensland, Australia (Figure 1). Owned and operated by Glencore, the mine has been in operation for almost 100 years. The Mount Isa orebodies span over 4 km in strike to a depth of 2 km, illustrated in Figure 2.



(a) (b)

Figure 1 (a) Mount Isa Mines location in northwest Queensland, Australia; (b) Plan view of surface topography with projected Black Rock SLC (green)

The remaining Black Rock orebody is being extracted using the SLC mining method. The SLC is a continuation from the historic Black Rock Open Cut (BROC). Extracting the remaining ore via open pit and block caving methods was considered; however due to high capital requirements relocating surface infrastructure associated with the pit option, and irregular orebody geometry, variable cave flow and propagation, and stability risks associated with the block cave option, the SLC method was ultimately chosen. The SLC method allowed drilling and blasting of all the ore, ensuring that it mobilised with a higher chance of recovery. The SLC also started in the highest-grade material, which meant more metal tonnes early and it did not have to travel as far to be recovered. The drawpoint brows would also have a short service life to combat poor and weak ground conditions.

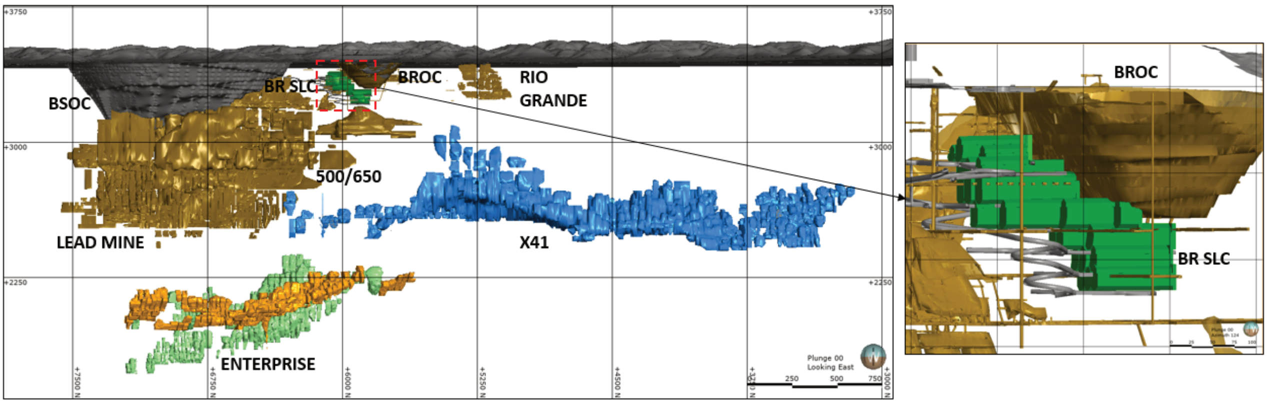


Figure 2 Long section east with Mount Isa Mines mined orebodies and Black Rock SLC (green)

The SLC operates within an extremely challenging and complex setting, both technically and operationally. The orebody is hosted within extensively altered and weak kaolinic shales, with zones of hot and reactive ground. Other complexities include naturally occurring and historic mining voids, and proximity to fixed surface infrastructure.

2 Historic mining

The Black Rock orebody was discovered in 1923 by prospectors Campbell Miles and Bill Simpson. Mining commenced in 1931 using a combination of room and pillar, and cut-and-fill stoping (Berkman 1996). The BROC was closed due to two major west wall failures and ongoing stability issues one (12 m) bench short of completion.

Approximately 5 million cubic metres of waste material was placed against the west, north and northeast walls in an attempt to stabilise movements impacting fixed infrastructure. Caving of the 500 copper orebody commenced in 1963 vertically below the west wall, which was likely a factor that affected its stability (Edwards 1967).

3 Geological setting

3.1 Mineralisation and alteration

The Black Rock orebody is the shallowest copper mineralisation at Mount Isa Mines. The mineralisation has been altered and enriched by weathering processes, resulting in a range of copper minerals. These include but are not limited to native copper, copper oxides (malachite, chrysocolla, and cuprite) and copper sulphides (chalcocite, covellite, and chalcopyrite). The mineralisation is contained within two main weathering and leaching domains that sit above and below the base of complete oxidation (BOCO) respectively.

The high-grade chalcocite ore is the primary focus for extraction (below the BOCO) with the SLC. The orebody is irregular in shape, although roughly concordant with the bedding dip of 60 to 70 degrees west, striking north–south (Rosengren 1968). The chalcocite ore occurs within the pyritic shale units adjacent to the main mineralised alteration zone, locally referred to as the silica dolomite halo; in which the original siltstone/shale may have been either silicified and/or dolomitised with varying degrees of brecciation.

3.2 Lithology

The Black Rock area exists within two main lithology zones; the Kennedy-Spears siltstone and Urquhart shale units, illustrated in Figure 3 and described below.

3.2.1 Kennedy-Spears siltstone

Present to the west of the SLC, this lithology zone is comprised of well-laminated sequences with medium to coarse beds of dolomitic siltstones. The siltstones within Black Rock are extensively leached with formation of montmorillonite on the bedding and joint planes (Rosengren 1968).

3.2.2 Urquhart shale

This zone consists of well-laminated and graded sequences of siltstones, mudstones, pyritic shales, dolomitic, volcanic and graphitic shales, fine grained dolomite and tuff. The Urquhart shales within Black Rock are extensively leached to form a soft earthy material, which also retained its original bedding (Rosengren 1968).

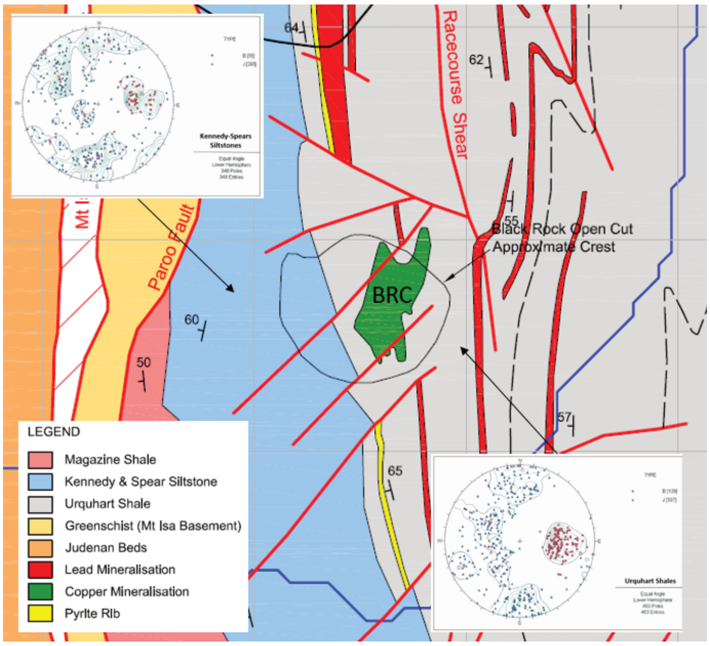


Figure 3 Mount Isa Mines geological setting with the Black Rock SLC (BRC) (after PSM 2015)

3.3 Weathering and leaching domains

The two main weathering and leaching domains are described below and illustrated in Figure 4.

3.3.1 Base of complete oxidisation

The BOCO is generally found at depths between 75 to 100 m below surface, and is highly variable in nature with strength ratings of weak to medium strong. Joint surfaces range from slightly altered through to complete breakdown of the rock fabric to an engineering soil. The lower strength zone is typically found closer to the ground surface, with the deeper zone typically higher strength.

3.3.2 Base of moderate and strong leaching (BOML and BOSL)

An extensive network of faults is responsible for the extensive leaching in the Black Rock area, reaching depths of up to 800 m, extending for a strike length of approximately 900 m and typically 200 to 250 m wide. Extensive leaching of the carbonate and sulphide minerals has occurred in these zones.

The effects of leaching include reduced rock strength and a much higher frequency of rock mass scale discontinuities. The leached zone comprises the majority of the SLC and development.

In the dolomitic zones of stronger leaching, cavities of variable sizes are common.

The jointed and permeable shale rock mass within the Black Rock orebody has resulted in a fairly consistent leaching profile, whereas the silica dolomite is highly variable in leaching degree, and subsequently rock mass strength and joint condition.

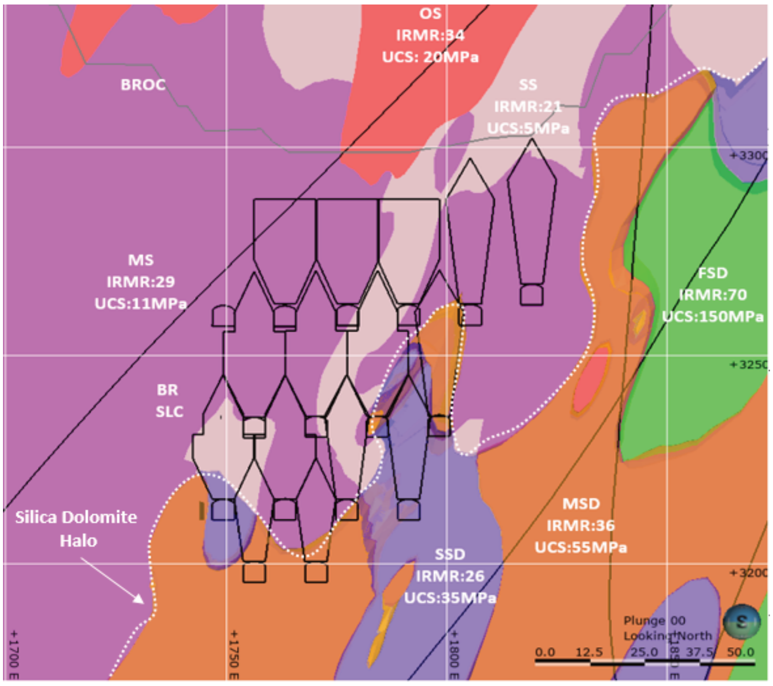


Figure 4 **Cross-section north at 5850N with the geotechnical domains and data; Black Rock SLC (black), BROC (grey), oxidised shale (red), moderate leached shale (purple), strong leached shale (beige), moderate leached silica dolomite (orange), strong leached silica dolomite (blue), fresh silica dolomite (green) and major structures (black)**

3.4 Structures

3.4.1 Major structures

Four major structural orientations occur in the Black Rock area (Campbell 2017):

1. Northeast striking faults which dip steeply towards the northwest.
2. Northwest striking faults which dip steeply towards the southwest.
3. East–west striking, sub-vertical faults.
4. North–south striking, bedding parallel shearing around the margins of the silica dolomite halo.

3.4.2 Minor structures

Typically, two to three joint sets exist around the bedding plane in the shales. The bedding is an important weakness plane in the shales. The most prominent joint set orientations are:

1. East–west striking, steeply dipping north.
2. North–south striking, moderately dipping west.

Bedding is present but not a prominent weakness plane in the siltstones (Rosengren 1968). In addition to the north–south striking joints seen in the shale, an additional set of near vertical joints with strike ranging from east–west to northwest/southeast is also present in the siltstones.

4 Geotechnical setting

4.1 Stress regime

The Black Rock SLC is sited at shallow depths ranging from 75 to 230 m, with subsequently low in situ stresses. Around the abutments of the historic BROC, some minor increases in stress were noted during initial mining of the SLC. The major principle stress direction is perpendicular to the orebody and incline of the bedding plane, described in Table 1. The orebody is dry with de-watering taking place with historic mining.

Table 1 Pre-mining stress fields for the Black Rock orebody

	Magnitude (MPa/m)	Dip (degrees)	Dip direction (degrees)
σ_1	0.037	30	90
σ_2	0.029	0	0
σ_3	0.025	60	270

4.2 Geotechnical domains

The geotechnical domains for the Black Rock area have been established based on rock type, mineralised alteration and degree of weathering/leaching, described in Table 2.

The rock mass within the SLC is predominantly weak with isolated zones of medium strong and has a high degree of jointing. The rock mass exhibits strong anisotropy due to the presence of bedding. The in situ rock mass rating (IRMR) for the orebody and hanging wall domains is poor (IRMR values of 21 to 29).

Table 2 Black Rock SLC geotechnical domains with unconfined compressive strength (UCS) and rock mass classification

Code	Domain	Subdomain (leaching degree)	Region	UCS (MPa)	FF/m	IRMR	IRMR rating
FS	Shale	Fresh	Footwall	100	7	55	Fair
MS		Moderate	Orebody, hanging wall	11	8	29	Poor
SS		Strong	Orebody, hanging wall	5	14	21	Poor
OS		Oxidised	Waste	20	10	34	Poor
FSD	Silica dolomite	Fresh	Footwall	150	4	70	Good
MSD		Moderate	Footwall, orebody	55	8	36	Poor
SSD		Strong	Footwall, orebody	35	18	26	Poor
FST	Siltstones	Fresh	Hanging wall	75	7	52	Fair
MST		Moderate	Hanging wall	60	12	39	Poor
F	Fault/residual soil	Total	All	1	99	19	Very poor

5 Geotechnical design

5.1 Basis of design

The Black Rock SLC consists of eight sublevels vertically spaced at 20 to 25 m with 14 to 15 m drawpoint centres. Sublevels extend from 4C (75 m below surface) down to 7C (230 m below surface). On several levels the vertical and horizonal spacing was governed by historic voids. Although narrow cave draw was expected, the adopted drawpoint spacing was required for layout stability due to the poor and weak rock mass conditions. Recent work by Campbell (2022) indicates that total ore recovery has no significant correlation with drawpoint spacing.

The decline profile measures 6.0 m high and 5.5 m wide with accesses and drawpoints 4.5 to 5.0 m high and 5.0 m wide. A typical sublevel is approximately three to five drawpoints wide (42 to 70 m) and 150 m long, with a design hydraulic radius (HR) of 16 to 23 m (Figure 5). The SLC has a planned draw of approximately 1.5 million tonnes at 4.5% copper over four years, which commenced in September 2020.

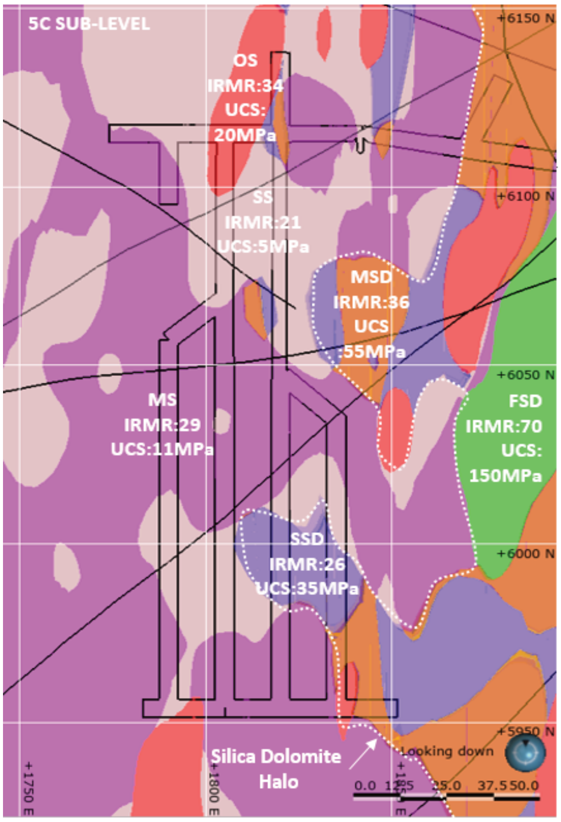


Figure 5 Plan view with typical sublevel layout on 5C with the geotechnical domains and data; oxidised shale (red), moderate leached shale (purple), strong leached shale (beige), moderate leached silica dolomite (orange), strong leached silica dolomite (blue), fresh silica dolomite (green) and major structures (black)

A number of additional controls are employed during extraction of the SLC, these can include tele-remote mucking, remote drilling, building up floor heights, height and distance based controls for working around drawpoints, standing up and supporting drawpoint rills, all supported by trigger action response plans (TARPs) and visual observations.

The presence of historic and natural voids has also affected the drill and blast, and cave flow of the SLC due to several levels having irregularly spaced drawpoints on consecutive levels. Over-broken voids required either extensive support or backfilling which increased dilution during caving.

Stability issues have been observed in the drawpoints generally when the cave has approached major fault zones, effectively managed with additional support and rehabilitation.

5.2 Ground support

A number of ground support systems were trialled in the initial stages of development. Due to the poor and variable conditions, most of the standard industry rockbolts were difficult to install and did not achieve the required capacity. Typical ground support used at Black Rock includes:

- In-cycle 75mm fibre-reinforced shotcrete (FRS).
- 2.4 m pre-grouted friction bolts.
- 4 m bulbed cable bolts.
- Weld mesh.

In strong faults and rubble zones additional support includes:

- 6 m spiling bars (self-drilling anchors).
- 150 mm FRS rib arches.
- Osro straps.

After approximately 18 months of development stand-up time, it was found the highly corrosive nature of the leached zone (reactive and hot ground) significantly shortened the service life of the pre-grouted friction bolts. Primary support was upgraded to include 4m bulbed cablebolts in all development.

Drilling for development faces and ground support generally uses air-mist drilling (minimal water), retractable drill bits and drill bits of various sizes for ground support due to hole instability in poor ground.

A typical SLC drawpoint face in the leached shale domain with drill and blast pattern is illustrated in Figure 6. Development conditions through the leached shale and leached silica dolomite contact is illustrated in Figure 7.

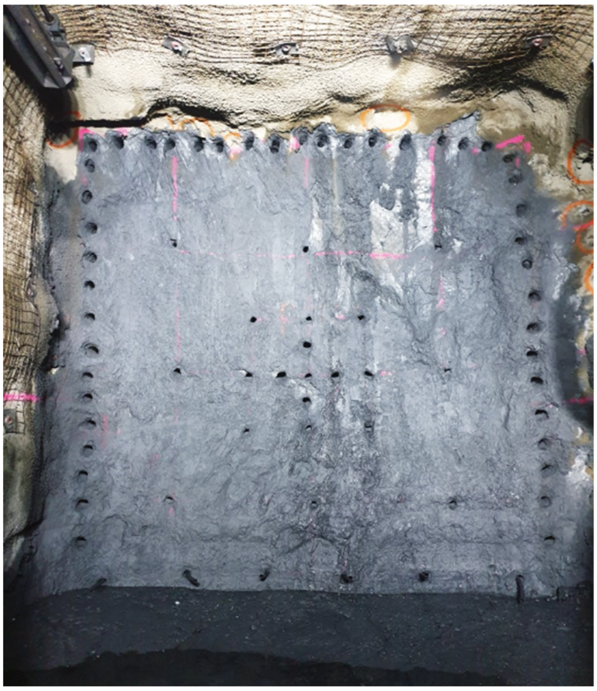


Figure 6 Typical SLC drawpoint face with development drill pattern in the leached shales on 6C sublevel

Figure 7 Development conditions through the leached shale (left side of face) and leached silica dolomite contact (right side)

5.3 Caveability

Two methods were used to assess caveability; empirical analysis using Laubscher's mining rock mass rating (MRMR) caveability assessment (Laubscher 2000) and numerical analysis with Abaqus 3D. Both methods confirmed caving would occur early in SLC production. The presence of the overlying BROC, poor quality rock mass and low confining stresses was expected to promote caveability. The failure mode in the crown was expected to be in a slumping and chimneying manner rather than traditional caving due to poor rock mass quality. Based on the mean and upper MRMR values for the orebody and hanging wall domains, a minimum HR of 8 and maximum of 14 m was required for continuous caving, circa 35 to 60% of the 6C undercut level (HR of 23 m). Caveability was achieved into the open pit at an approximate HR of 10 m, illustrated in Figure 8.

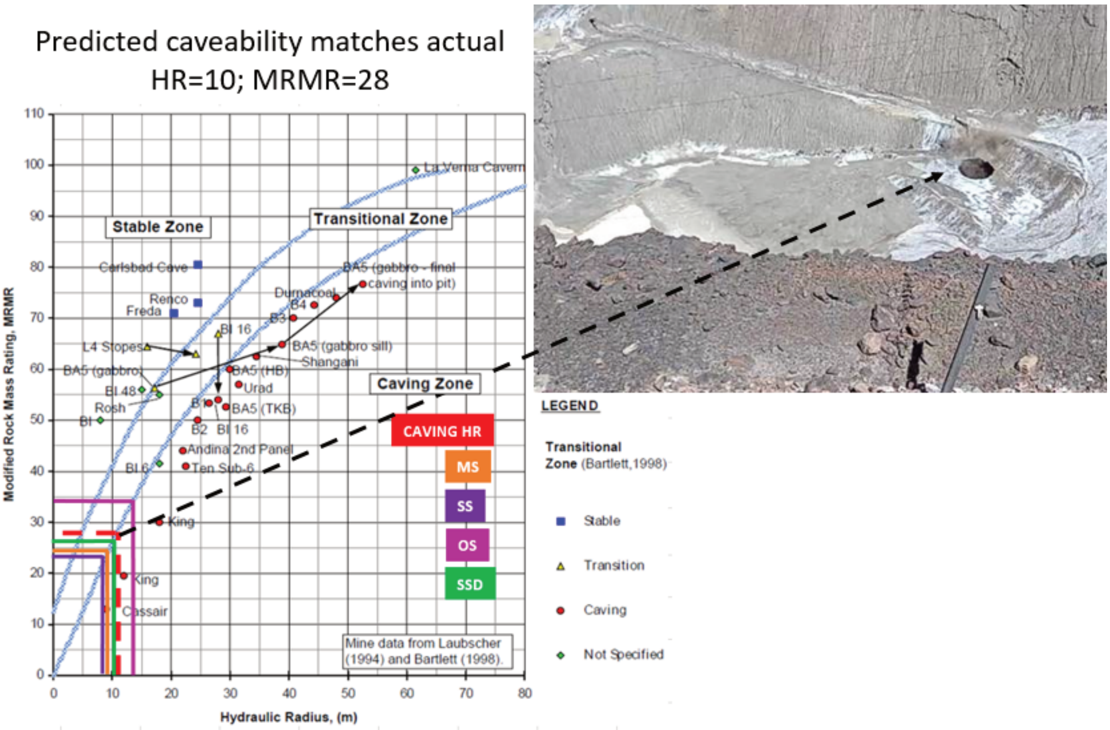


Figure 8 Caveability forecasts using the MRMR system and BROC cave breakthrough location

5.4 Sequencing and draw strategy

The cave extraction sequence progresses from south to north retreating away from BROC. The inclusion of a pillar between the SLC and BROC focused on increasing primary recovery, slowing pit fines ingress and reducing dilution. The sequence also aims to maintain a relatively flat cave face with minimal ring lag to promote interactive draw, reduce hang-ups and control chimneying.

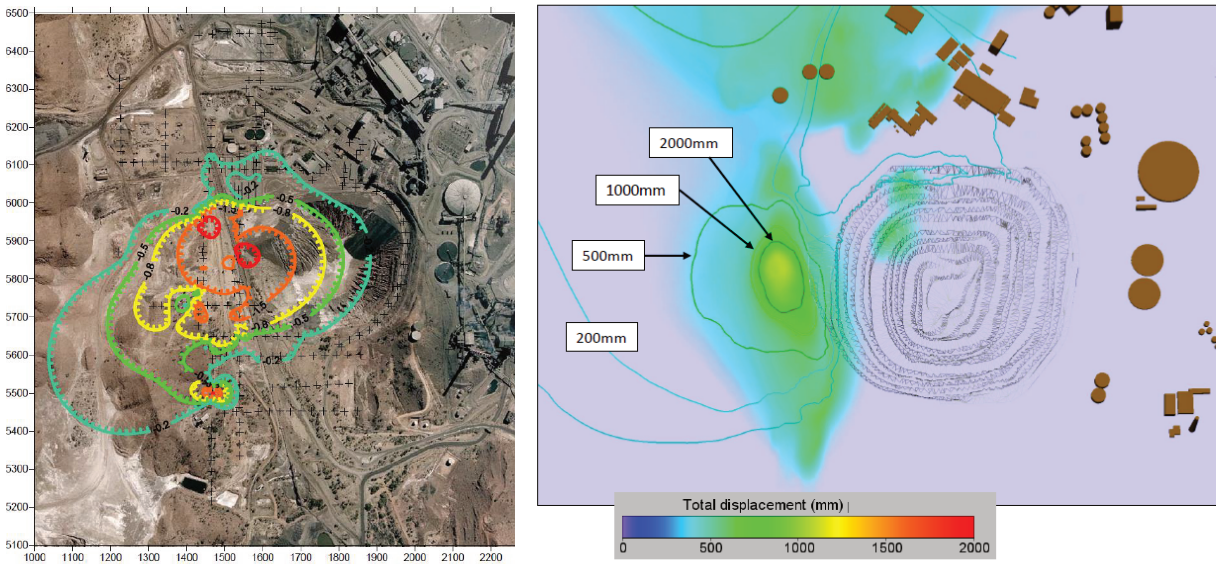
The SLC draw strategy has been optimised using cave flow modelling software Power Geotechnical Cellular Automata (PGCA). A fixed draw of circa 60%, 90% and 120% was planned over the first three levels until caving was achieved, then the draw was optimised using PGCA.

5.5 Numerical modelling

Finite element analysis with Abaqus 3D was completed for the extraction of the Black Rock SLC by Beck Engineering in 2019.

A discrete fracture network was developed using the mine scale structural model, historic mapping within the R62 shaft and nearby open pits. The bedding planes were explicitly built, with anisotropy achieved by modelling as a discontinuum and the rock mass as a continuum between the bedding planes (Beck Engineering 2019).

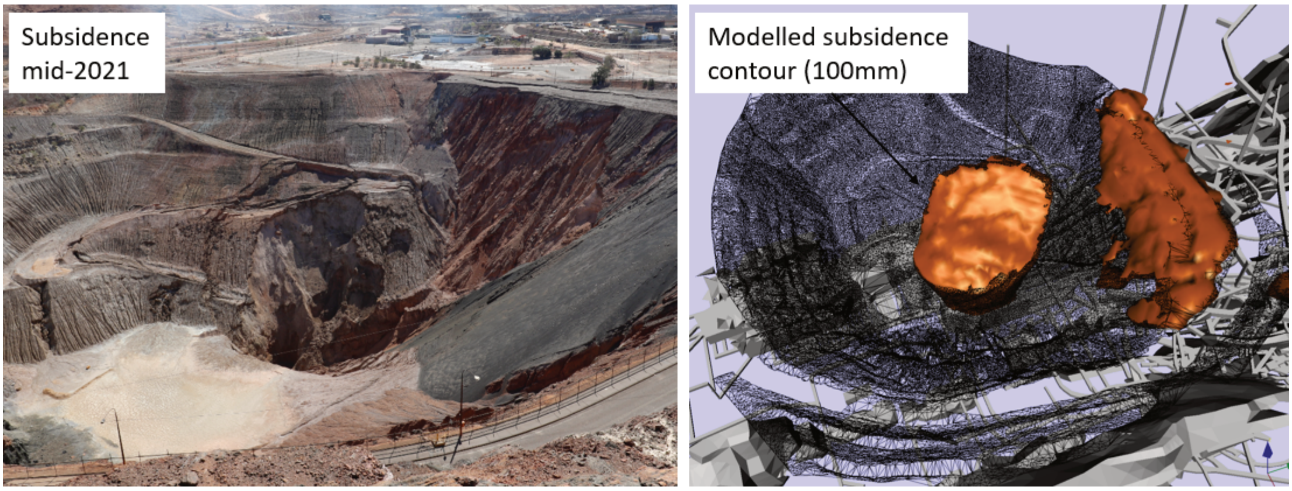
The numerical model was calibrated using subsidence measurements from caving the historic 500 copper orebody in the 1960s to improve the accuracy of the model forecasts, illustrated in Figure 9.



(a) (b)

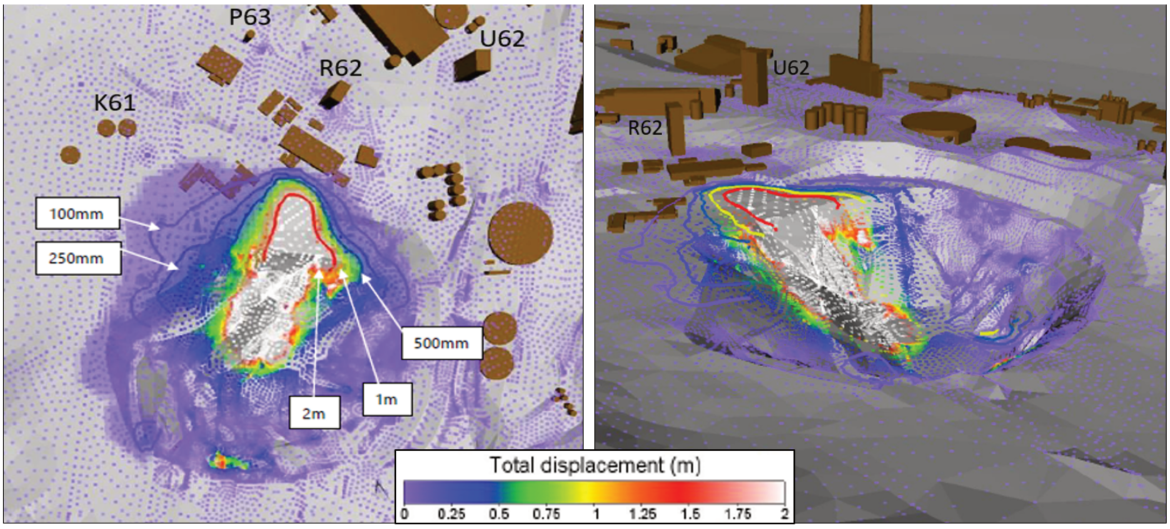
Figure 9 (a) Measured historic subsidence (metres); (b) Model calibration (Beck Engineering 2019)

The initial subsidence model forecasts are a good match to the current subsidence observations, illustrated in Figure 10. The forecast end of mining total displacements for the SLC are illustrated in Figure 11. Displacements of greater than 1 to 2 m are observed in the cave scarp outside the cave zone, with smaller scale displacements of 50 to 100 mm mostly occurring within the vicinity of BROC. A large portion of the observed movement is slumping of the pit fines.



(a) (b)

Figure 10 (a) Actual subsidence in mid-2021; (b) Modelled 100 mm displacement subsidence contour (December 2020 model step)



(a) (b)

Figure 11 Forecast end of mining total displacements, looking (a) plan view and (b) northeast (Beck Engineering 2019)

A number of infrastructure items were required to be demolished for the safe extraction of the Black Rock SLC. This included the mine access road, R62 general mine offices and core shed, the mine sub-station and the R60 headframe.

5.6 Instrumentation and monitoring

A detailed instrumentation system was designed and commissioned for the Black Rock SLC, illustrated in Figure 12. The system includes 15 wireless bi-axial tilt metres, six time domain reflectometers (TDR), two rain gauges, two vibrating wire piezometers, underground seismic sensors, video cameras and blast vibration monitors. Regular large-scale monitoring tools include high resolution fly over photogrammetry and visual inspections.

The surface and internal R62 shaft sensors are all connected to a wireless mesh network, to collect data in near real time and be displayed in the Vista Data Vision (VDV) platform (MDT^{TM} 2022). The VDV is a comprehensive data management system for data collected from geotechnical instruments and stored in data loggers, then loaded into a dedicated database. In addition to the instrumentation and monitoring controls, a fenced exclusion zone was installed around the Black Rock area to manage the risks associated with subsidence.

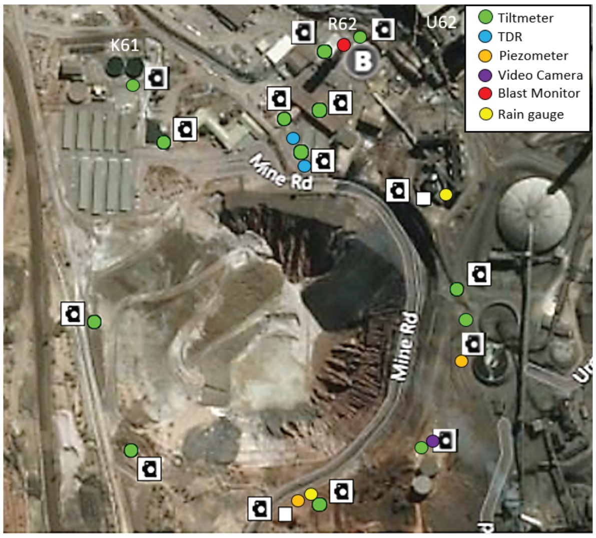


Figure 12 Black Rock surface instrumentation system

6 Experimental trials

6.1 Fragmentation

Particle size distribution (PSD) testing of the orebody and waste domains including the BROC waste fines was conducted to determine inrush potential during operation of the SLC. An additional PSD test was conducted after placing each sample in a cement mixer for approximately 15 minutes to simulate the impact of material flow through the cave (abrasion and gravity stresses) to quantify fragmentation of secondary and tertiary draw (Hocking et al. 2018).

The results of the testing are described in Table 3. It was found that all of the domains were within the 'fine' fragmentation size for both tests. According to industry literature, fragmentation with greater than 70% passing less than a 5 cm sieve gauge is a proxy for inrush potential.

Mount Isa is located within a low rainfall area, the SLC area has also been de-watered due to historic mining. Exclusion zones have been required during periods of heavy rainfall to manage inrush risk. The removal of fines within the overlying BROC was investigated to reduce dilution and inrush hazards; but did not eventuate due to the significant work and costs required.

Table 3 Particle size distribution test results for the Black Rock geotechnical domains

Geotechnical domain	PSD test 1 (% less than 5 cm)	PSD test 2 (% less than 5 cm)
Leached shale (MS/SS)	97.6	97.7
Leached silica dolomite (MSD/SSD)	78.6	82.5
Oxidised shale (OS)	88.5	93.4
BROC waste fines	93.0	99.8

6.2 Cave flow

A scale model of a standard SLC drawpoint was constructed using perspex, aluminium and ply wood at a 1 in 50 scale, illustrated in Figure 13. The construction was observed during a site visit to the Mount Wright Mine, located near Townsville, Queensland in 2019. Two of the geotechnical domains were used in the experiment, at varying moisture content levels with the objective to simulate material flow behaviour.

Part 1 of the experiment involved samples being loaded inside the model above a removable platform and at the drawpoint to choke the brow. The platform was then removed to simulate rapid movement of material above a choked brow. The rill angle and length of run-out from the rill was then measured. This procedure was repeated for each domain at 10, 20 and 30 m hang-ups (Perry 2019a).

The mean rill length and angle after the rapid movement simulation was 28 m and 18 degrees respectively, illustrated in Figure 14a (Perry 2019a).

Part 2 of the experiment involved saturating the material with water to achieve a moisture content of 8.5%. The drawpoint was mined bucket by bucket and flow behaviour monitored. The results indicated narrow draw, rapid chimneying and increased cohesion (sticky), illustrated in Figure 14b.

Potential improvements include adjustments to the construction design by steepening the shoulder angles from 45 to 65 degrees, increasing the drawpoints from one to three, and increasing the depth from one ring to two rings.

Figure 13 Constructed cave and drawpoint scale model (Perry 2019a)

(a) (b)

Figure 14 (a) Flat rill angle observed in the leached shales (2–3% moisture content); (b) Observed chimneying mode in the leached silica dolomite (8.5% moisture content) (Perry 2019a)

6.3 Rock cutter trial

A rock cutter was trialled as a potential means to achieve faster advance rates in poor ground conditions, and to minimise drill and blast induced ground control issues in the weaker geology. The use of a rock cutter also mitigated issues associated with explosives use in hot and reactive ground. The rock cutter was a modified rock break that was onsite (Cat 321D LCR Excavator), illustrated in Figure 15. The modifications included the attachment of a Erkat 1500-1X cutting drum and water spray kit.

The rock cutter was trailed in two domains and results were variable. The rock cutter was found to be efficient in weak rock conditions, but inefficient in moderate to strong rock. A comparison of advance rates with conventional jumbo development is provided in Tables 4 and 5.

(a) (b)

Figure 15 (a) Excavator mobilising to Black Rock; (b) Stripping development at 5L DPT 3 (Perry 2019b)

Table 4 Development performance of the rock cutter trial (primary support cycle)

Geotechnical domain	Total advance (m)	Avg. net cutting rate (BCM/hr)	Avg. advance rate (m/hr)
Leached shale (SS)	10.57	17.0	0.99
Leached silica dolomite (SSD)	0.75	4.9	0.21

Table 5 Comparison of advance rates between mining methods and equipment cutting a 5.0 m (W) × 5.0 m (H) square profile over a 3.7 m advance

Method	Advance rate in leached shale (m/hr)	Difference to jumbo (%)	Advance rate in leached silica dolomite (m/hr)	Difference to jumbo (%)
Jumbo drill and blast (actual)	0.68		0.41	
Erkat 1500-1X cutting head (actual)	0.99	+45 %	0.21	-51 %
Sandvik MT5200 road header (estimated)	1.76	+158 %	0.31	-24 %

7 Conclusion

A significant amount of learnings has been gained from mining in the Black Rock orebody.

The key learnings include:

- Gaining early understanding of the orebody through fragmentation testing and scale model trials to simulate cave flow at varying moisture levels.
- The importance of trial mining during the study phase to validate the basis of design and ground control assumptions, particularly for complex studies.
- Trials with alternate forms of mining equipment to suit the ground conditions and optimise advance rates.
- Existing voids within the orebody can present significant challenges for an SLC mine.
- The combination of hot, reactive, poor, and weak rock mass conditions required considerable effort and research to establish a practical and effective ground support system.

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