Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)
© 2026 Australian Centre for Geomechanics, Perth, ISBN 978-1-7636842-3-2
doi:10.36487/ACG_repo/2645_100

Integrated caving and gravity flow modelling for remnant resource optimisation at Chuquicamata underground Lift 1

Raúl Castro [a], Yonathan Molina [b], Rodrigo Quiroz Alegría [b], Lenin Arancibia [c,*]

[a] *University of Chile, Chile*

[b] *Chuquicamata, Codelco, Chile*

[c] *BCTEC Engineering and Technology, Chile*

Abstract

The Chuquicamata Division (DCH) 2025 Business Plan (PND2025) provides strategies to optimise the transition to deeper mining sectors. A critical component of this optimisation is the accurate characterisation of remnant resources over Lift 1, which are subject to complex cave flow dynamics. To overcome the limitations of traditional vertical mixing models in predicting these dynamics, this study implemented a robust and integrated modelling approach to improve recoverable reserve estimates and validate production forecasts. This methodology coupled FLAC3D with the ITASCA Constitutive Model for Advanced Strain Softening (IMASS) constitutive model to simulate cave propagation and FlowSim BC to model gravity flow and material mixing. The cave propagation model was rigorously calibrated using seismic records and topographic data (LiDAR/RADAR), confirming that propagation is structurally controlled, and the gravity flow model was calibrated using geotechnical parameters. The coupling of these tools significantly improved forecast accuracy compared to a vertical mixing model. Finally, this validated framework provides important information for business planning and a strategic basis for maximising asset value for Lifts 1 and 2.

Keywords: *resource optimisation, gravity flow simulation, cave propagation, model calibration, Chuquicamata*

1 Introduction

The Chuquicamata underground project represents one of the most significant open pit-to-underground transitions in the global copper industry. The Chuquicamata Division (DCH) of Codelco is advancing the development of Lift 1 (Figure 1), a block/panel caving operation that mines the orebody beneath the world's largest open pit copper mine. With ore columns reaching 750 m and average in situ copper grades between 0.93 and 1.10% in the central macroblocks, the project has exceptional economic significance.

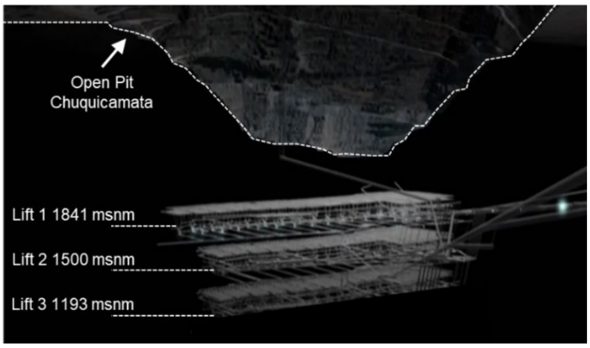

Figure 2 Production levels at Chuquicamata underground

* Corresponding author.

As mining matures and production from the central macroblocks (N1S1, N2N3 and S2S3) progress, the accurate characterisation of remnant resources becomes strategically critical. The current planning framework relies on a vertical mixing model (Laubscher model) as the baseline approach for diluted grade estimation. However, this methodology presents significant limitations: it does not account for lateral material contributions, consistently underestimates column heights in zones where extraction height exceeds the in situ column height, and fails to capture the structural controls governing caving propagation. These shortcomings lead to systematic underestimation of recoverable grades, with copper grade errors of up to 8% observed for macroblock N1S1 and molybdenum grade errors of up to 27% for macroblock N2N3.

The authors implemented an integrated numerical modelling methodology combining FLAC3D – with the ITASCA IMASS constitutive model – for cave propagation simulation, and FlowSim BC v6.4 for gravity flow and material mixing simulation. This coupled approach incorporates caving geometries derived from seismic apparent volumes and topographic surveys (LiDAR/RADAR), geomechanical unit (UGTB) models, historical extraction records from 2019 to 2025, block models including copper and molybdenum grade distributions, and measured dilution from the West Fault.

The study was developed in support of the PND2025 Business Plan (2025–2044), with 3 specific objectives to calibrate and validate the coupled caving–flow model against historical production data; to quantify and categorise the remnant resources remaining at the end of Lift 1 extraction; and to evaluate the potential of a cut-off grade plan to extend mine life and maximise asset value. This paper presents the methodology, key results and strategic implications of the integrated modelling framework for Lift 1 of Chuquicamata underground.

2 Geotechnical context and input data

The characterisation of Lift 1 required the integration of multiple geotechnical and operational data sources. The DCH geotechnical model defines the rock mass in terms of basic UGTBs that combine lithology and alteration degree. The principal UGTBs intersecting the production footprint are the Potassic East Porphyry (PEK), Sericitic East Porphyry (PES), Quartz Greater Sericite (QMS) and Quartz Equal Sericite (QIS). Of these, PEK consistently presents the highest uniaxial compressive strength (UCS) values and the greatest resistance to caving propagation.

Table 1 summarises the geomechanical parameters for macroblock N1S1, which is representative of central sector conditions. Similar parameter sets were defined for N2N3 and S2S3.

Table 1 Geomechanical parameters for macroblock N1S1 (Codelco 2024)

Geomechanical unit	Density (g/cm^3)	Uniaxial compressive strength (MPa)	Ei (GPa)	mi	Geological strength index
PEK	2.61	96.5	37.12	20.77	59–73
PES	2.66	69.9	29.48	16.13	51–73
QIS	2.70	67.2	20.06	17.36	54–70
QMS	2.70	76.6	27.01	23.64	62–71
QMES	2.58	20.3	9.39	22.82	33–54
PEK	2.61	96.5	37.12	20.77	59–73

The in situ stress state was characterised from 14 measurement points covering depths from 187 to 1,083 m. The stress analysis yielded average horizontal-to-vertical stress ratios of Kh1 = 1.6 and Khh = 0.98, with a representative vertical stress gradient of 0.281 MPa/m at a reference depth of 380 m. Table 2 presents the representative stress state used in numerical models.

Table 2 Representative in situ stress state for Lift 1 DCH numerical modelling

Sxx (MPa)	Syy (MPa)	Szz (MPa)	Depth (m)	Vertical stress profile (MPa/m)	Kh1
14.7	16.1	9.73	380	0.281	1.6

Topographic data collected via RADAR surveys from 2019 to 2025 confirmed a surface slide on the western slope, while the eastern, southern and northern slopes remained stable. The in situ column height at the production level averaged 393 m in 2019, with the undercut level located at elevation 1,841 m and the production level at 1,823 m. Historical extraction data for macroblocks N1S1, N2N3 and S2S3 cover the period from May 2019 to April 2025, growing from initial rates of 15,000–25,000 tpd to a peak near 65,000 tpd in 2024. Measured copper grades averaged 1.10% for N1S1, 0.93% for N2N3 and 0.96% for S2S3; molybdenum grades averaged 0.078, 0.063, and 0.071% for N1S1, N2N3 and S2S3, respectively. Cavity geometries were estimated from seismic apparent volumes using Mendecki's (2013) potency–energy formulation, providing calibration targets for the FLAC3D model. Subsidence angles were determined at 75° for the northern, southern and eastern walls, and 55° for the western wall, where the West Fault governs toppling and creep mechanisms.

3 Methodology

The integrated modelling framework was structured in 6 sequential stages:

1. data collection and review
2. FLAC3D caving model development and calibration
3. update of the FlowSim BC gravity flow model incorporating FLAC3D-derived cavities
4. simulation of the PND2025 long-range plan
5. generation and categorisation of the Lift 1 remnant resource model
6. simulation of a cut-off grade production plan.

3.1 Cave propagation model (FLAC3D–IMASS)

Cave propagation was simulated in FLAC3D using the IMASS constitutive model (ITASCA 2020; Ghazvinian et al. 2020). The IMASS model reproduces the progressive failure of the rock mass through 3 Hoek–Brown failure envelopes: a peak envelope, a post-peak envelope representing fractured-but-interlocked rock (zero porosity), and an ultimate envelope representing fully disaggregated material. The caving propagation algorithm (Sainsbury 2012) applies rock mass resistance properties and prescribed extraction rates to simulate the evolution of the cave back, as shown in Figure 2.

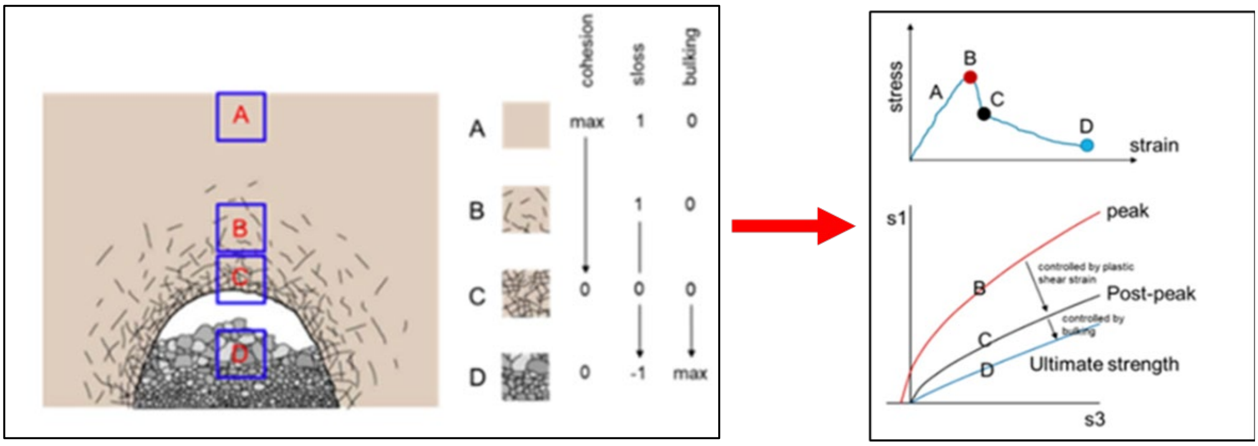

Figure 2 Modelling using ITASCA Constitutive Model for Advanced Strain Softening (Sainsbury 2012)

The model domain measured 3,490 × 2,574 × 1,103 m and incorporated the full UGTB geometry and structural model, as shown in Figure 3.

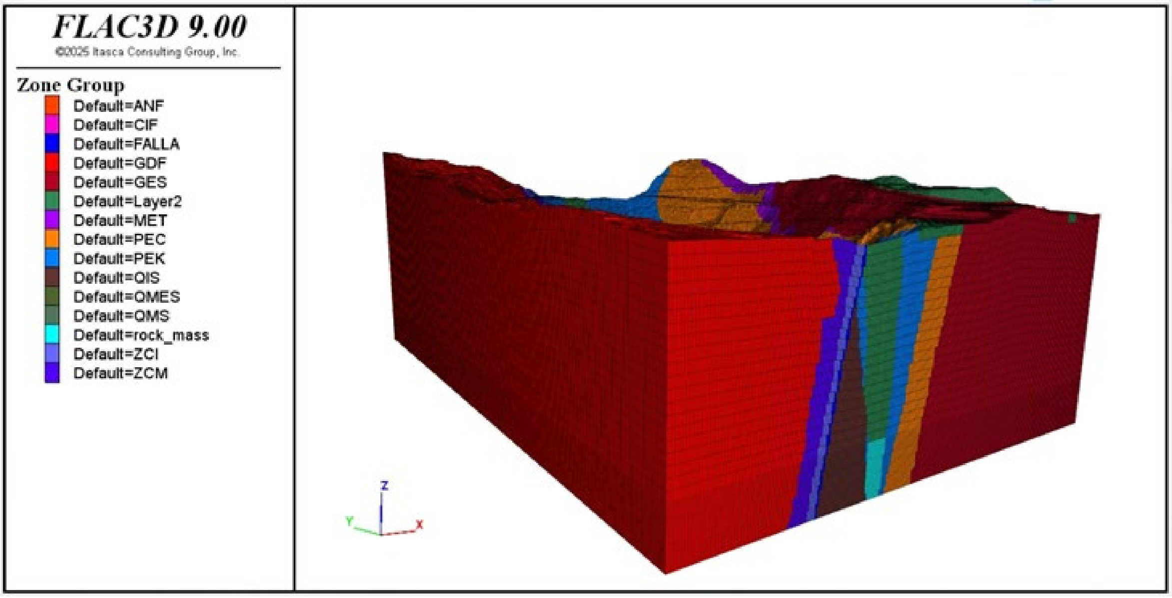

Figure 3 Isometric view of the FLAC3D model

Two calibration parameters were adjusted to match the observed caving evolution: 'multicrit', which controls the brittle-to-ductile transition of the rock mass, calibrated to 1.0 (intermediate behaviour), and 'Sloss', which controls the spatial extent of the damage zone relative to the mobilised zone, calibrated to 0.5. Calibration targets included the year of surface connection for each central macroblock (Table 3) and the S2S3 hang-up event of October 2022, which required de-stressing of the adjacent Calle 0 area and is attributed to the high PEK/PES proportion in the extractable column.

Table 3 Calibration results – observed versus FLAC3D-simulated year of surface connection by macroblock

Macroblocks	Year of surface connections (observed)	Year of surface connection (FLAC3D)
N1S1	2020	2020
N2N3	2022	2022
S2S3	2023	2023

Figure 4 presents a comparison between measured cave back propagation and caving model results, showing differences of less than 30 m.

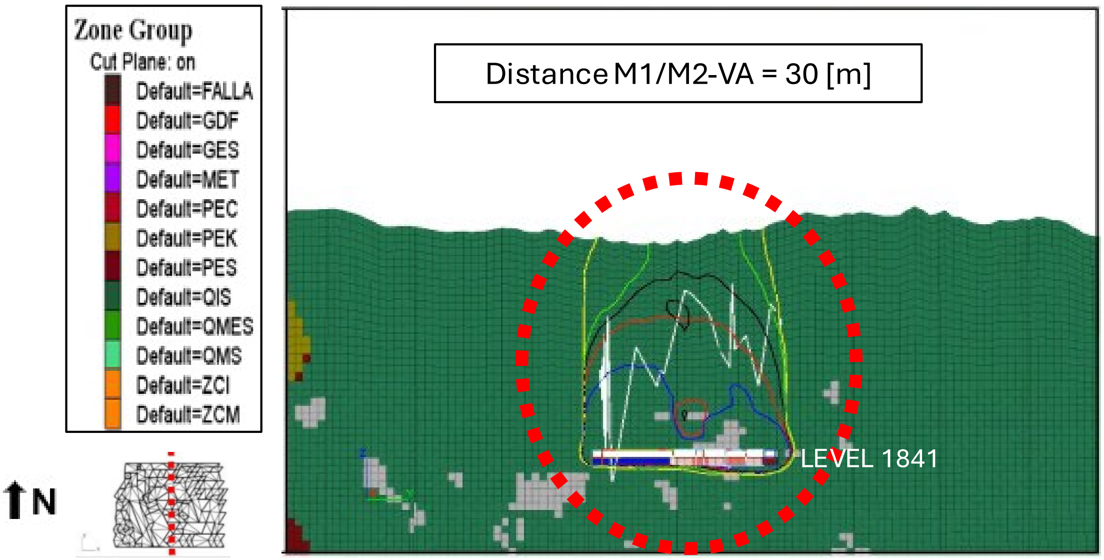

Figure 4 Comparison of cave back measurements and modelling results in N1S1, June 2020

Once calibrated, the model was applied to simulate cave propagation for all Lift 1 macroblocks under the PND2025 extraction schedule through 2044 (see Figure 5). Key outputs include hydraulic radius at caving initiation, propagation rates, connection timing between adjacent macroblocks, and final cavity geometry per macroblock. Propagation rates range from 10–20 cm/day for N42 (dominated by PEK) to 65–75 cm/day for S5 (dominated by QIS-rich columns). The southern sector (S2S3 and adjacent macroblocks) exhibits a preferential westward caving direction due to the presence of the QIS unit, while N42 in the northern sector shows the lowest propagation rate of all Lift 1 macroblocks, partially explained by an in situ pillar between N42 and N41.

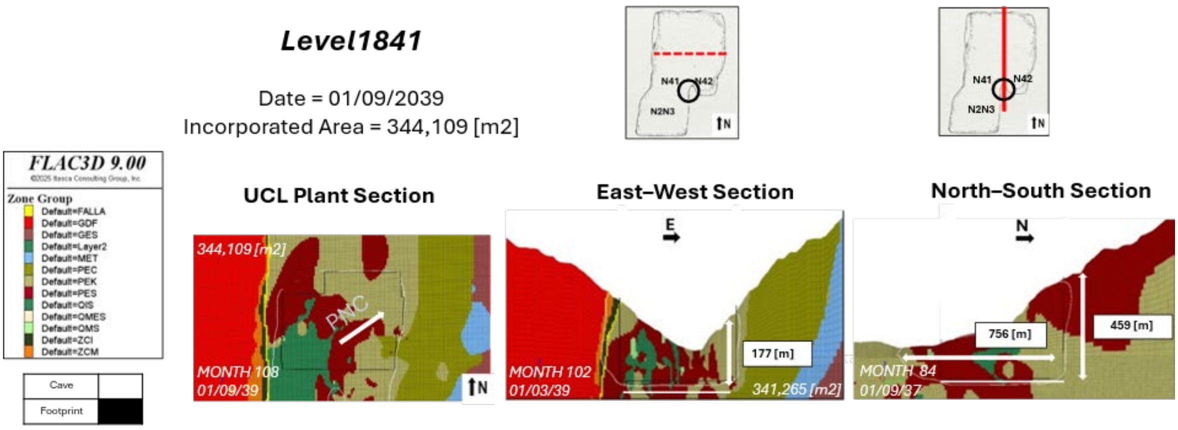

Figure 5 Caving model for Level 1, north sector (N41, N42 and continuous north panel)

The extraction rates applied in FLAC3D per macroblock are summarised in Table 4.

Table 4 Extraction rates by central macroblock used in FLAC3D caving model calibration

Macroblock	Minimum rate (t/(m^2 × day))	Mean rate (t/(m^2 × day))	Maximum rate (t/(m^2 × day))
N1S1	>1 (preconditioning)	>1 (preconditioning)	>1 (preconditioning)
N2N3	0.03	0.10	0.54
S2S3	0.02	0.15	0.60

3.2 Gravity flow model (FlowSim BC)

Gravity flow simulation was performed using FlowSim BC, a particle-based simulator that reproduces material flow at the drawpoint scale. The model incorporates 2 mechanisms of particular relevance to Chuquicamata:

- the evolution of extraction zones as a function of extracted tonnage and rock fragmentation (d80), which controls the isolated extraction zone diameter – ranging from approximately 10 m for fine fragmentation (d80 = 0.1 m) to 34 m for coarse fragmentation (d80 = 1.2 m) (Castro 2007; Le-Feaux et al. 2021)
- fine material migration, modelled through the characteristic particle size (d50) of each block, which governs the rate of fine percolation through coarser material (Arancibia 2021; Castro et al. 2022).

The flow model was initialised using the block model (20 × 20 × 20 m cells) from 2019, which contains copper grade, molybdenum grade, density, rock type (UGTB) and characteristic fragmentation size (d50) per block. The 2024 updated block model was used to validate temporal grade evolution. FLAC3D-derived cavity geometries were incorporated as the caving boundary at each simulation period. Dilution from the West Fault was included for macroblocks N1S1 and N2N3 from 2023 onward. Measured dilution reached 0.85% for N1S1 and 0.40% for N2N3 by early 2025.

The model encompasses 2,909 drawpoints (PEX) across the production and panel levels (elevations 1,823 and 1,803 m), simulating 308 monthly periods from 2025 to 2044 as part of PND2025, in addition to the historical extraction from 2019 to 2025.

4 Model calibration and back-analysis

Model calibration against the historical extraction record (May 2019–April 2025) provides the primary validation of the integrated framework. Table 5 summarises the overall performance of FlowSim BC versus the vertical mixing model (DCH baseline) for the combined production of N1S1, N2N3 and S2S3.

Table 5 Summary of back-analysis results: historical record versus vertical mixing model versus FlowSim BC (2019–2025)

Model	Total tonnage (Mt)	Cu grade (%)	Cu fines (kt)	Mo grade (%)	Mo fines (kt)
Historical	69.95	1.02	710.97	0.072	50.70
Vertical mixing	69.95	0.95 (−6%)	665.89 (−6%)	0.057 (−21%)	40.14 (−21%)
FlowSim BC	69.95	1.01 (−1%)	706.65 (−1%)	0.062 (−15%)	43.05 (−15%)

FlowSim BC achieves a copper grade error of −1% and a molybdenum grade error of −15%, compared with −6 and −21%, respectively, for the vertical mixing model. The improvement in FlowSim BC is primarily attributed to its ability to estimate grades for drawpoints with extraction height exceeding the in situ column height, a condition prevalent in N1S1 where lateral contributions from adjacent material – including broken ore from the West Fault corridor – are significant. For macroblock N1S1 individually, FlowSim BC achieves a copper grade deviation of only +0.5%, versus −8% for the vertical mixing model. In N2N3, FlowSim BC shows −4 versus −8%, and in S2S3, −0.4 versus −0.8%.

The copper grade evolution reproduced by FlowSim BC closely tracks the measured historical values of 0.95–1.10% between 2023 and 2025, while the vertical mixing model consistently underestimates at 0.85–0.94%. For molybdenum, both models underestimate the historical record; however, FlowSim BC maintains a closer fit, particularly in the 2023–2025 period. Simulated dilution from the West Fault follows the observed increasing trend reaching approximately 0.8% for N1S1 and 0.4% for N2N3 by early 2025, confirming adequate representation of the dilution mechanism.

These results confirm that the integrated FLAC3D–FlowSim BC framework provides a substantially more accurate representation of the actual extraction behaviour than the vertical mixing baseline, justifying its application for forward-looking PND2025 simulation and remnant resource estimation.

The integration is based on FLAC3D providing FlowSim with the volumes of rock mass that have been fragmented and are therefore available to flow toward the drawpoints. Based on this information, FlowSim incorporates the key mechanisms governing gravity flow in block caving operations, including:

- evolution of the extraction zone (IEZ growth)
- fine material migration
- preferential flow along major faults and geological structures
- internal and surface rilling
- secondary fragmentation.

These mechanisms allow FlowSim to realistically simulate material movement within the cave, including the effects of changing draw conditions, material mixing, recovery, dilution and operational constraints.

5 PND2025 simulation results

As previously mentioned, PND2025 corresponds to the long-term mine plan. For this study, the analysis focused on the central sector of Level 1 at Chuquicamata underground, between 2026 and 2044.

The full Lift 1 simulation covers all macroblocks from the northern boundary (N63) to the southern boundary (S06), including the panel macroblocks (PC and PS2S3) adjacent to the central sector. Production is scheduled to ramp up from 2025, reaching the design throughput of 140,000 tpd between 2033 and 2038, before declining progressively to 15,000 tpd by 2044. The simulated peak coincides with the simultaneous contribution of northern, central and southern macroblocks.

PND2025 simulation results by sector and macroblock for the period 2025–2044 show the central sector delivers the highest copper grades (1.00% average), driven by the N2N3 (1.15% Cu) and PS2S3 (1.03% Cu) macroblocks. The northern and southern sectors average 0.70% and 0.72% Cu, respectively, yielding a Lift 1 overall grade of 0.74% Cu and 0.046% Mo.

Compared with the DCH vertical mixing model baseline for the same plan (PND2025), FlowSim BC projects 4% higher copper grades and 3% more fine copper tonnage (4,653 kt versus 4,514 kt), along with 5% more fine molybdenum (289.9 kt versus 277.0 kt). The total tonnage is essentially equivalent (628.8 Mt versus 631.3 Mt), confirming that grade differences arise from the improved flow representation rather than volume discrepancies.

The gravity flow evolution confirms that residual high-grade material (>0.9% Cu) remains unmined at the end of the PND2025 period within N1S1 and N2N3, associated with drawpoints that have not been extracted due to design constraints, motivating the remnant resource quantification presented in Section 6.

6 Remnant resource model

Upon completion of the PND2025 extraction, FlowSim BC produces a residual block model (20 × 20 × 20 m resolution) representing the material remaining within and above the Lift 1 footprint, as shown in Figure 6.

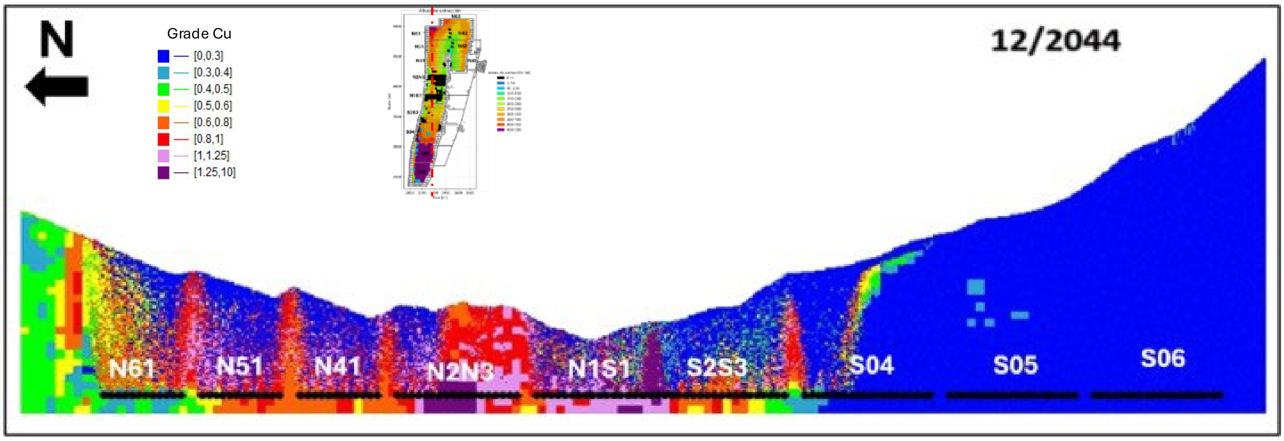

Figure 6 Remnant resource model

The remnant resource was categorised into 4 geometrically and geomechanically distinct sectors based on material state and spatial position relative to the macroblocks. Table 6 presents the quantification of remnant resources at the end of PND2025 for all 4 categories.

Table 6 Lift 1 remnant resources summary at end of PND2025, by sector (FlowSim BC)

Sector	Total tonnage (Mt)	Cu grade (%)	Cu fines (kt)	Mo grade (%)	Mo fines (kt)
In situ pillars	25.7	0.74	190.4	0.044	11.3
Broken ore above in situ pillars	94.4	0.86	808.2	0.045	42.8
West Fault pillar	63.1	0.82	518.9	0.025	16.0
Broken ore above macroblocks	432.4	0.6	2,602.7	0.033	141.3

The total remnant resource amounts to 615.6 Mt at average grades of 0.67% Cu and 0.034% Mo, representing 4,120 kt of fine copper and 212 kt of fine molybdenum. The highest-grade concentrations are found in the broken ore above inter-macroblock pillars (0.86% Cu) and in the West Fault pillar (0.82% Cu). The largest tonnage contributor is broken ore above the macroblocks (432.4 Mt), where the central and northern sectors host the most attractive grades.

These results demonstrate that, even under the PND2025 extraction plan, substantial high-grade resources remain recoverable above and between the macroblocks, providing the basis for future recovery strategies in Lift 2 design and for the cut-off grade plan evaluated in Section 7.

7 Cut-off grade plan

Building on the remnant resource characterisation, an extended production plan (cut-off grade plan) was constructed to evaluate the additional extractable potential of Lift 1 beyond the PND2025 horizon. The methodology extended production at drawpoints with final copper grades ≥0.30% Cu by assigning an additional extraction height of 400 m at a rate of 4,000 tpm per drawpoint. Drawpoints were stopped when 2 consecutive periods fell below the 0.30% Cu threshold or the grade in the final period was below this cut-off.

The resulting plan maintains the same production ramp-up as PND2025, reaching 140,000 tpd in 2033, and extends mine life to 2059 – an additional 15 years beyond PND2025. Table 7 compares the 2 plans.

Table 7 Comparison of PND2025 versus cut-off grade plan (FlowSim BC simulation results)

Plan	Total tonnage (Mt)	Cu grade (%)	Cu fines (kt)	Mo grade (%)	Mo fines (kt)	Below cut-off (Mt)
PND 2025	628.8	0.74	4,653.3	0.044	289.9	11.8
Cut-off grade plan	1,031.3 (+64%)	0.69 (−7%)	7,094.8 (+52%)	0.039 (−11%)	399.7 (+38%)	13.2 (+12%)

The cut-off grade plan increases total extractable tonnage by 64% (from 628.8 to 1,031.3 Mt), the amount of contained copper metal by 52% (from 4,653 to 7,095 kt), and the amount of contained molybdenum metal by 38% (from 289.9 to 399.7 kt). The reduction in average copper grade from 0.74% to 0.69% reflects the progressive incorporation of lower-grade peripheral sectors as the plan extends into post-2044 territory. The copper grade profile stabilises around 0.60% between 2030 and 2058 before declining, while the molybdenum grade stabilises between 0.02% and 0.03% through approximately 2055, as shown in Figure 7.

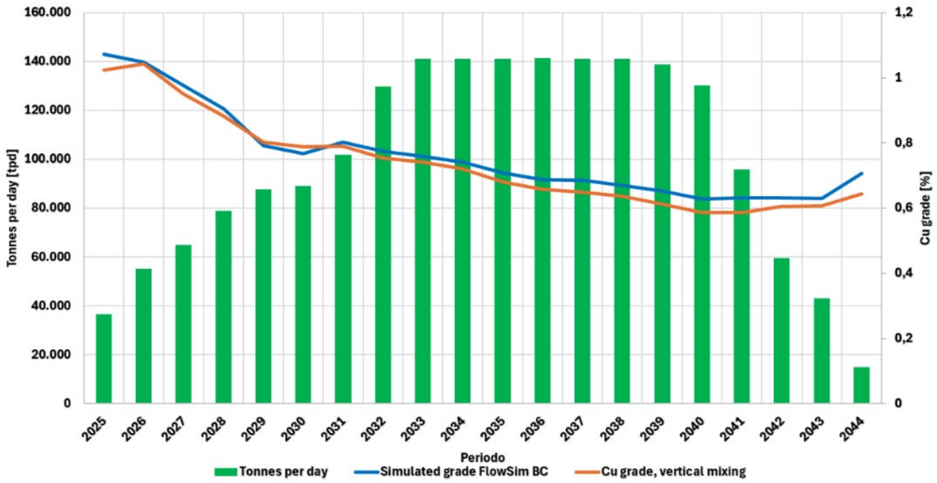

Figure 7 Comparison between FlowSim-simulated copper grades and vertical mixing estimates

It is important to note that this analysis represents an exploratory exercise aimed at identifying the extractable potential ceiling of Lift 1. The cut-off grade plan must undergo rigorous technical and economic validation before integration into the DCH planning cycle, including verification of drawpoint accessibility, infrastructure sustainability at extended heights of draw, and updated dilution modelling. Nevertheless, the results conclusively demonstrate that the extractable potential of Lift 1 is substantially greater than currently estimated under PND2025.

8 Conclusion

The integration of caving modelling (FLAC3D) with gravity flow modelling (FlowSim BC) provides a more robust methodology for caving mine planning, enabling a more comprehensive evaluation of production plans. This integrated approach makes it possible to:

- increase mineable reserves by identifying and recovering material that may not be captured through conventional planning approaches
- improve dilution management through a better understanding of material flow mechanisms and cave evolution
- estimate remnant ore distribution for multi-level mining operations, supporting long-term extraction strategies and future mine development
- evaluate the interaction between cave propagation and gravity flow

- enhance production planning by incorporating both geomechanical and material flow processes into the decision-making framework.

Acknowledgement

The authors would like to acknowledge the valuable contributions of all those involved in this study. In particular, we would like to thank Bryan Castro, Mauricio Valderrama and Sebastian Ortiz from BCTEC Engineering and Technology, as well as Dayham Fuentes and Valeria Paleo from Codelco, for their support, collaboration and contributions throughout the development of this work.

References

Arancibia, L 2021, *Experimental and Empirical Modelling of Dilution in Block Caving*, MSc thesis, Universidad de Chile, Santiago.

Castro, RL 2007, *Study of the Mechanisms of Gravity Flow for Block Caving*, PhD thesis, The University of Queensland, Brisbane.

Castro, R, Gomez, R & Arancibia, L 2022, 'Fine material migration modelled by cellular automata', *Granular Matter*, vol. 24, no. 1.

Codelco 2025, *GMRD-SEG-INF-063-2025*, internal document, Codelco Chuquicamata Division, Calama.

Ghazvinian, E, Garza-Cruz, T, Bouzeran, L, Fuenzalida, M, Cheng, Z, Cancino, C & Pierce, M 2020, 'Theory and implementation of the Itasca constitutive model for advanced strain softening (IMASS)', *Proceedings of MassMin 2020*, University of Chile, Santiago, pp. 451–461.

ITASCA 2020, *FLAC3D Documentation: IMASS Model*, Itasca Consulting Group, Minneapolis.

Le-Feaux, R, Castro, R, Cortez, D, Gómez, R & Silva, D 2021, 'A hybrid extraction level layout for block caving', *Mining Technology*, vol. 131, no. 1, pp. 51–65.

Mendecki, AJ 2013, 'Mine seismology: glossary of selected terms', *Proceedings of Eighth International Symposium on Rockbursts and Seismicity in Mines*, in A Malovichko & D Malovichko (eds), *RaSiM8*, Geophysical survey of Russian Academy of Sciences, Mining Institute of Ural Branch of Russian Academy of Sciences. 2013. p. 527–551.

Sainsbury, BL 2012, *A Model for Cave Propagation and Subsidence Assessment in Jointed Rock Masses*, PhD thesis, University of New South Wales, Sydney.