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Addressing some of the challenges of cave mining

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Abstract

Cave mining methods have been used in various forms for more than 100 years. Since their introduction, mining engineers and practitioners have strived to improve the method's safety, economics, efficiency, and effectiveness. Over this period, thanks to developments in new technologies for extracting ore, as well as for predicting and monitoring mine performance, we have achieved higher production rates while venturing deeper and into more difficult conditions. However, this journey has not been entirely smooth. In fact, when critically assessing the outcomes of individual operations, most have fallen somewhat short of expectations in one way or another. The author of this paper reflects on the past 40 years and discusses some of the reasons for these shortfalls from the perspective of 'caving rules' and past experiences. It also examines today's diverging thinking and opposing views on mine design and caving processes.

Keywords: *cave mining, caving rules, mine design, caving processes*

1 Introduction

Cave mining is more than 100 years old as a concept, yet only in the last 2 decades has it spread meaningfully beyond a handful of pioneering operations. Today there are 17 individual cave blocks/panels in 13 cave mines in production across 9 countries and 5 continents (Table 1 – current caves), and a growing pipeline of more than 50 projects (some of them with multiple cave footprints and multiple lifts) in various stages of study is moving toward execution (Figure 1).

Table 1 Block and panel caves in production as of 2026

#	Mine	Lift	Country
1	Cadia East	PC1, PC2, PC3	Australia
2	Northparkes	E26 Lift 1 North	Australia
3	New Afton	C-Zone	Canada
4	Andina	Panel III	Chile
5	Chuquicamata UG	S01N, S01S Macroblocks	Chile
6	El Teniente	Multiple caves	Chile
7	Pulang Copper	Lift 1	China
8	Tongkuangyu	Lift 530 m	China
9	Grasberg	Deep mill level zone, Grasberg	Indonesia
10	Donskoy GOK	DNK Mine	Kazakhstan
11	Oyu Tolgoi	Hugo North Panel 0	Mongolia
12	Yauricocha	–	Peru
13	Padcal	760, 798 Levels	Philippines
14	Palabora	Lift 1 & 2	South Africa
15	Premier/Cullinan	C-Cut Phase 1	South Africa
16	Henderson	7210 panels	USA

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This expansion of cave mining is being driven by the depletion of near-surface ore bodies amenable to open pit mining, the high production rates that caving can sustain, and operating costs that are typically lower than any other mass mining underground methods. In several cases, caving is also the only viable continuation of an existing open pit once the stripping ratio can no longer be carried by the head grade. Environmental considerations reinforce the trend that a cave mine generally has a smaller surface footprint than a comparable open pit, since waste rock production is largely limited to development of the underground infrastructure.

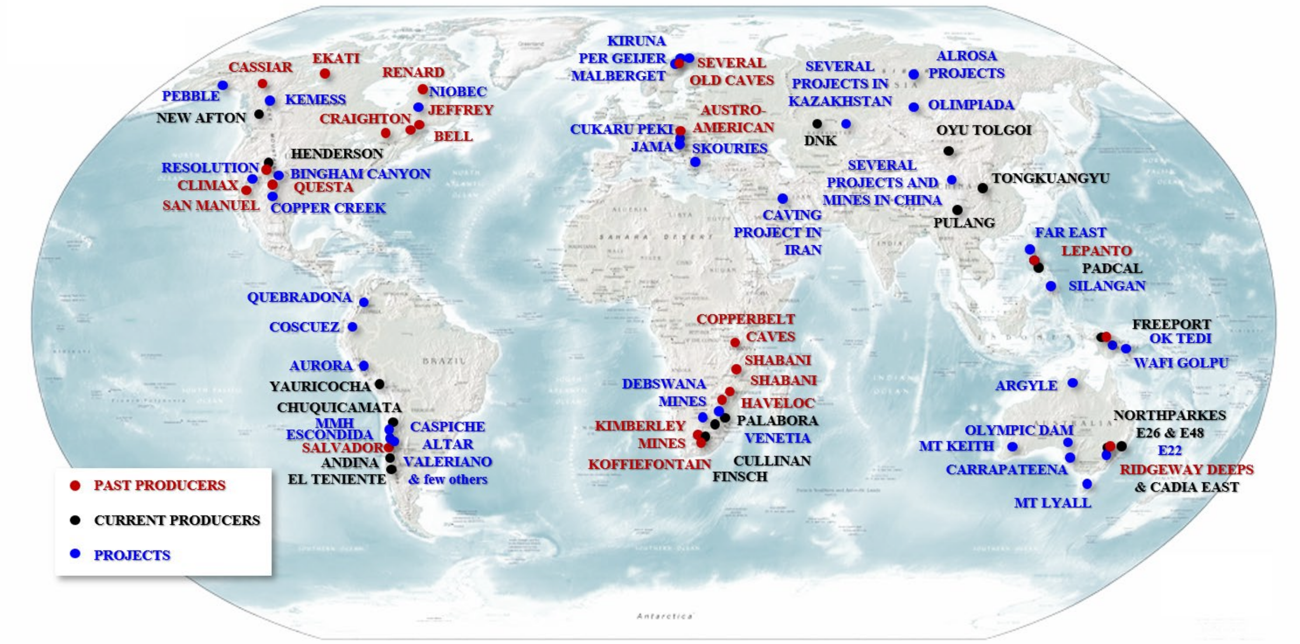


Figure 1 Map of cave mines including past producers and some of the future projects

Because cave mining is a bottom-up method that depends on a large, fixed underground infrastructure being established before any ore is produced, the upfront capital is very high. To make the economics work, that capital must be amortised over correspondingly high production rates and high tonnages per drawpoint. Several modern caves are now producing in excess of 50,000 tpd, and the next generation of 'super caves' (Chuquicamata and the New Mining Level at El Teniente in Chile, Oyu Tolgoi in Mongolia, the Grasberg caving complex in Indonesia, and Resolution Copper in Arizona) is being designed for nameplate capacities of 100,000 tpd or more. However, optimistic predictions about number of super caves to be put into production are falling short of delivery.

The difficulty lies not in operating a cave once it is running, but in getting it there. The lead time from initial studies to first production is typically 7–10 years, and often longer. The cave must be substantially developed before all of its design parameters are known with confidence, which means design decisions have to be robust to a wide range of outcomes and, particularly on greenfield projects, technical success has to take precedence over short-term economic optimisation.

Unfortunately, the performance record of recent cave mines is sobering. Since 1990, out of at least 60 new cave footprints developed and brought into production, the vast majority have encountered some material difficulty, 5 caves closed prematurely and several experienced severe ground control problems rendering large portions of the available footprints inaccessible. Reasons include collapses, coarser-than-expected fragmentation, mining-induced seismicity, mudrushes, ground support underestimation, or departures from basic cave mining principles, particularly in undercutting sequence and draw management. With hindsight, most of these problems could have been anticipated, designed against, or prevented through stricter discipline at the drawpoint.

Looking forward, cave mining is being pushed into new frontiers: stronger rock masses, higher caving columns, greater depths and lower grades (Figure 2).

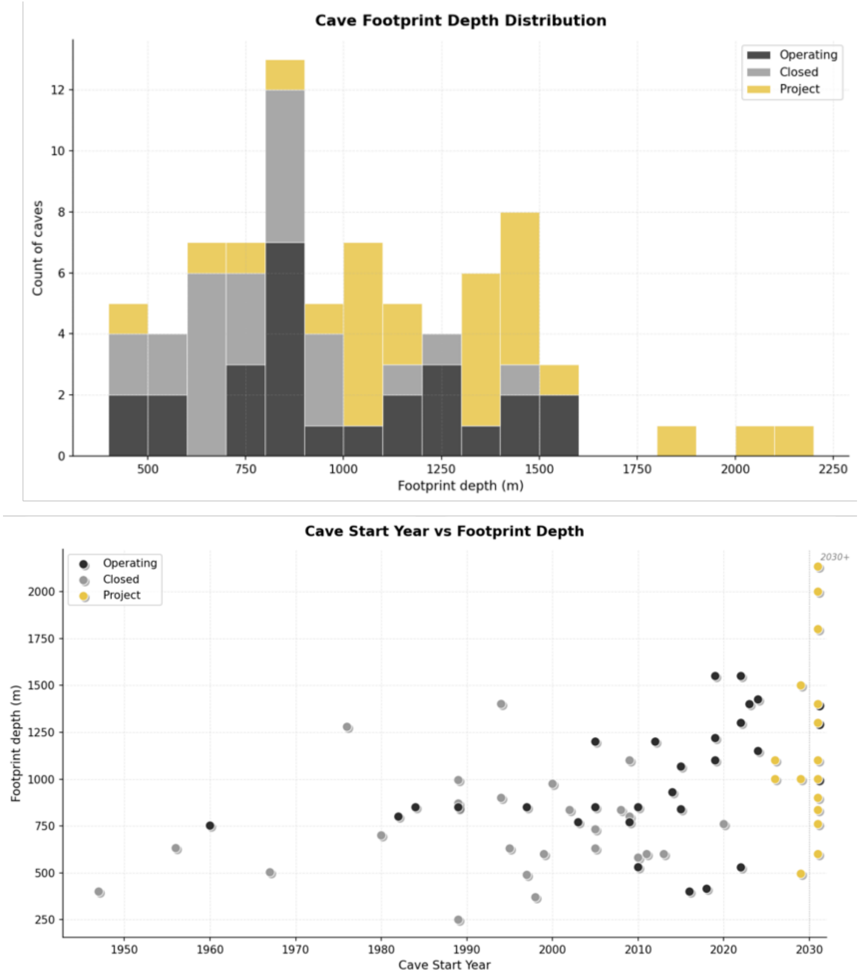


Figure 2 Depth of operating and proposed caves

Resolution, with shafts sunk to 2,100 m to access a deep copper porphyry, sits at the leading edge of that envelope. Highly automated future operations may put fewer than 50 or 60 people underground while producing in excess of 100,000 tpd. Continued advances in drilling accuracy, explosives, ground support, monitoring and instrumentation, and electrified mobile fleets give legitimate cause for optimism. The challenges that will shape the next generation of cave mines are also coming into focus: increased depth and the associated stress, temperature, and seismicity; lower-grade ore bodies with higher dilution; caveability of strong rock masses and the role of preconditioning; rising social and regulatory pressure around surface subsidence; the growing cost of mine closure; and climate-driven hydrological risks such as extreme storms, mine flooding, and mudrushes.

This paper takes a step back from this trajectory and asks why, despite a century of accumulated knowledge and a decade of technological acceleration, the realised performance of modern cave mines so often lags expectations. It revisits the ‘caving rules’ that have historically protected operators against the most damaging failure modes, examines where current practice diverges on questions of mine design and caving process, and offers a view on what the next generation of cave mining engineers should keep, what they should challenge, and where judgement still should lead the modelling.

2 Evolution of cave mining methods

Cave mining developed over past decades from early block caves through grizzly and slusher operations to modern mechanised mass mining. Technology gains have been made in extraction, draw control, prediction, and monitoring.

Cave mining design has diversified into several variations, and several classification schemes can be applied depending on which criterion is considered primary. The principal variations include panel versus block caves, single versus multiple blocks or panels, single versus multiple lifts, horizontal versus inclined layout, gravity versus mechanised extraction (Figure 3), and the degree of intervention applied to initiate or sustain caving, ranging from natural caving through preconditioning to fully assisted caving.

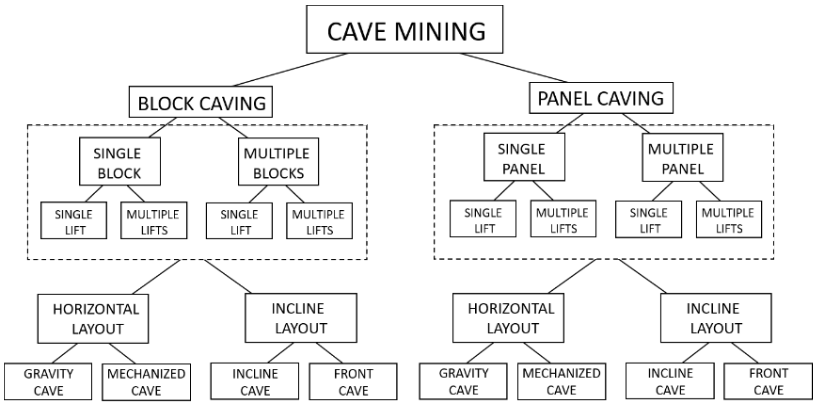


Figure 3 Different cave mining alternatives (Jakubec 2023)

Beyond these classification axes, the rock mass environment exerts a strong influence on method selection. Many of the historical caves (particularly in diamond and asbestos operations) were developed in poor, squeezing rock. More recent caves have been driven into very strong, competent rock masses, such as Cadia East and several Codelco operations developing primary copper porphyries. Shallow caves are typically gravity-driven, whereas deep, strong caves are stress-driven and bring seismicity to the foreground. Deep caves in poor rock masses demand yet another set of design choices. Each orebody has a unique combination of attributes and constraints, and each design is to some degree site specific. Orebody knowledge (geological, structural, and geotechnical) remains the foundation of every credible cave design and evaluation.

Special cases worth flagging include cave extensions (Webster et al. 2020) and the reopening of previously caved operations.

A full description of cave mining variations is beyond the scope of this paper. The discussion that follows focuses on the 3 methods that account for the great majority of modern production: panel caving and block caving with a horizontal extraction layout, and incline caving.

It is worth recalling that, until roughly the 1980s, most caves were developed in poor-quality rock using gravity-based methods: grizzly, scraper, or incline layouts. These operations were labour-intensive and exposed personnel to materially higher risk than modern mechanised caves. The last gravity cave in commercial production was at Kimberley, which closed this year due to a fatal mudrush event.

2.1 Panel caving: horizontal layout

Panel caving is the form of cave mining in which the orebody is undercut and caved progressively in a series of broadly parallel panels. Well-executed examples include the Henderson mine in Colorado and El Teniente in Chile. The common feature of such operations is a comparatively limited panel height, typically less than about 200 m.

Panel caving is best suited to ore bodies with large footprints. The footprint is subdivided into panels in which the panel length is greater than the block height. The undercut is not advanced across the full footprint at the outset; instead, a panel or strip is undercut and allowed to cave, with the undercut progressing continuously along the length of the panel at a rate matched to drawbell construction and commissioning. Production capacity is dictated by footprint width, column height, and undercut advance rate. Draw must be controlled to maintain an inclined ore–waste interface as the cave advances.

As van As & Guest (2020) observe, 'block caving' is now commonly used as a generic term that conflates block and panel caves, but this is an error of terminology that has begun to influence design as well: the 2 are variants of the broader caving family, but their development sequence and production philosophy are fundamentally different.

In very large ore bodies, the footprint elevation is often placed at the base of the high-grade mineralisation, which forces large block heights, typically in excess of 400 m. The temptation to design a single very high column panel cave, rather than multiple stacked caves, is understandable in terms of complexity and infrastructure, but it carries a structural problem: the differential draw between depleted and newly commissioned drawpoints, expressed in production rate curves, becomes very large; the cave front angle becomes very steep; tonnage commitments are high; and the achievable undercutting rate is correspondingly slow.

Some of the main risks of high column panel caves identified by van As & Guest (2020) are sporadic, uncontrolled caving, potential cave stall, irregular cave back geometry and loss of ore in uncaved wedges, and higher incidence of major seismic events and rock bursts.

2.2 Block caving: horizontal layout

Block caving is the method in which the entire cave footprint is undercut, and interactive draw is established across all drawpoints simultaneously. Block height is normally determined by operational considerations (orebody geometry, rock mass strength, comminution behaviour, brow wear, and so on) and is typically greater than the in-plan length of the footprint.

Single footprint examples include Northparkes E26 and E48, Ridgeway Deeps, Palabora, and several diamond mines among them Finsch, the Kimberley mines, and Koffiefontein. Multiple-footprint and multiple-lift configurations include the Cullinan diamond mine, Cadia East with its very high caving lifts, and the recently commissioned Chuquicamata mine which uses a macroblock layout (Flores & Catalan 2019).

Production draws should be kept relatively uniform across the footprint, both to control cave propagation before breakthrough to surface and to promote draw zone interaction, which in turn facilitates mass flow and controls dilution entry. A second advantage of the block layout is that material handling and ventilation infrastructure can be placed outside the footprint, removing it from the highest-stress ground. The differences between panel and block caves are illustrated in Figure 4.

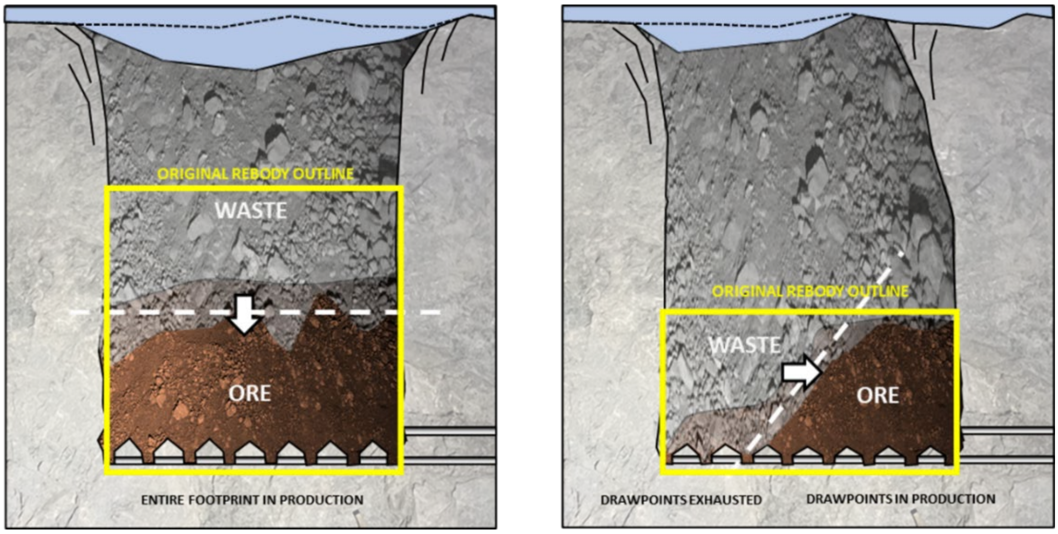


Figure 4 Schematic of block and panel caving principles

2.3 Incline caving

The term 'incline cave layout' denotes a configuration in which rows of drawpoints are offset vertically and aligned on an inclined plane. Within the inclined plane, drawpoint spacing (both within a row and between sublevels) is set to produce full drawzone interaction in essentially the same way as in a horizontal layout.

The interactive draw of an incline cave is fundamentally different from that of sublevel caving (SLC), even though the sublevel geometry can appear superficially similar (Jakubec & Laubscher 2012).

The specific incline configuration depends on the geometry of the orebody and the relevant stability constraints. The layout for a cylindrical vertical kimberlite pipe differs from that for a steeply dipping tabular orebody.

According to Jakubec & Laubscher (2012), compared with a horizontal layout, the main incline layout advantages are (mainly) flexibility in repairs and oversize blasting, structurally stronger layout, more efficient handling of water and wet muck. Some of the disadvantages include higher development capital, more demanding draw control supervision across multiple levels; reduced suitability for electric load–haul–dump (LHD) fleets.

Incline caving was formally patented and described by Janelid (1975). Operating examples existed in Sweden, the United States, Canada, Zimbabwe, and South Africa. Ekati was the last operation to implement the incline method, achieving it successfully in 2020 (Jakubec & Woodward 2020).

2.4 Front caving

Front caving is a compressed-spacing variant of block caving in which the undercut and extraction levels are placed in close vertical proximity (typically separated by only 12–15 m) and the cave advances through a sequence of relatively narrow vertical blocks rather than through a single, full footprint undercut. The upper-level functions as the undercut horizon; the lower level carries the drawpoints and the production fleet.

The compressed geometry simplifies development, shortens the time between undercutting a block and bringing its drawpoints into production, and confines the high-stress zone to a vertically shorter section of the rock mass. In its operating principle, however, front caving remains a block cave (undercut-driven, gravity-fed, and reliant on interactive draw across the extraction level) rather than a sublevel cave, which it can superficially resemble. At Koffiefontein, front caving was adopted specifically to allow extraction of blocks below level 37 while sublevel caving continued on levels above, with the 2 methods operating concurrently and in vertical succession (Hannweg et al. 2004).

Compared with a conventional horizontal block cave, the front caving layout offers a shorter development lead time between undercut completion and drawpoint commissioning; a practical means of extracting a deeper block while keeping a shallower caving method in production above; and better tolerance of narrower or more selective orebody geometries than a full block cave would suit.

The principal disadvantages are demanding draw control discipline; a more constrained development envelope, with reduced flexibility for re-routing services if conditions deviate from design; and limited operational track record outside the diamond industry.

Front caving has been most fully realised at Koffiefontein in South Africa, where it has been used to extract approximately 100 m vertical blocks between successive production levels.

2.5 Raise caving

Raise caving is a recent hybrid cave mining method, developed in collaboration between LKAB and Montanuniversität Leoben, that addresses the principal challenge of caving in strong rock masses at very great depth, managing stress and seismicity in the production infrastructure. It combines elements of conventional caving (gravity-driven extraction of an undercut block) with the active stress-management logic of raise mining. Raise caving has been formally proposed and described in a series of papers by Ladinig et al. (2022a, 2022b), Karlsson et al. (2022), and Gams (2023).

The method proceeds in 2 phases. In the de-stressing phase, large slots are pre-developed from raises with a minimum of supporting infrastructure. The slots are separated by substantial pillars whose purpose is to control stress magnitudes and to prevent uncontrolled propagation of caving into the hanging wall. The slots themselves provide stress shadows that locally de-stress the rock mass. In the production phase, the production infrastructure (drawpoints, drifts, and material handling) is established within those stress shadows, and bulk extraction takes place in the de-stressed ground. As mining progresses, the pillars eventually crush under increasing stress and are extracted in sequence; the hanging wall is then allowed to cave.

The first test mining program is being conducted at the Kiruna iron ore mine in northern Sweden, where orebody geometry, depth, and rock mass behaviour together make conventional sublevel caving increasingly difficult. At the time of writing, no commercial scale raise caving operation has been brought into production. The method should be understood as a developmental concept whose viability is being tested rather than as established practice.

2.6 Vertical-crater-retreat-assisted caving

Vertical-crater-retreat-assisted caving is a variant in which the principles of block caving are combined with the controlled crater blasting techniques of VCR stoping. The method was developed and applied at the De Beers and Bultfontein mines in the Kimberley district in the late 1980s to address 2 persistent problems with conventional block caving in narrow kimberlite pipes: unreliable natural caveability and elevated mudrush risk associated with weak, water-charged kimberlite (Granger 1992).

In a conventional block cave, the cave is initiated by undercutting and propagates upward under gravity once the undercut footprint reaches the hydraulic radius required for self-sustaining caving. In VCR-assisted caving, large-diameter vertical holes are drilled into the orebody above the production level, and crater blasting assists the caving process and directs cave propagation throughout the life of the cave.

The defining characteristic of VCR-assisted caving, compared with both conventional block caving and modern intensive preconditioning, is the role of the blasting in the caving sequence.

VCR-assisted caving was first proposed for the Kimberley mines by Granger (1992) and subsequently applied at the De Beers and Bultfontein operations, where it replaced the sublevel caving method used between 1979 and 1989. The method represents an early diamond industry response to the same problem: caving in difficult rock where natural caveability cannot be relied upon.

2.7 Trough caving

The continuous trough (also called continuous trench, trough cave, or continuous cone trench) is one of the 5 major block cave extraction level layouts identified by Laubscher (2000), alongside herringbone, offset herringbone, the Henderson Z design, and the El Teniente layout. Rather than discrete drawbells with minor-apex pillars between drawpoints, the layout uses a continuous longitudinal trough drift into which drawpoints discharge. In its full form, it requires no separate undercut level, with the trough being developed and ring-blasted from the same level as the production drives. Perceived advantages include reductions in development cost and faster cave establishment program achieved through ring blasting in place of individual slots and elimination of the upper undercut horizon (Weiss 1981; Jude 1990). The principal disadvantage is loss of lateral restraint to the major apex pillars normally provided by the minor apices, which produced extraction level instability at San Manuel (Stevens et al. 1987) and complete collapse in Class 2B–3 A ground at Shabani Block 7AB (Heslop 1981). The earliest documented application was at the Austro-American Magnetite mine, Austria (Weiss 1981).

2.8 Cube caving

Cube caving is a recent design proposal advanced by Geoff Dunstan of Caveman Consulting in Australia (Dunstan 2024). The defining features of cube caving are the use of 90° intersections throughout the production level (eliminating the angled drawpoints characteristic of current designs), the maximisation of pillars between intersections to carry the higher stresses associated with depth, and the segregation of the loading and hauling functions of the extraction fleet. The cube-shaped block geometry that gives the method its name follows from these design choices: a regular grid of right-angle intersections produces blocks of approximately cubic proportions across the production horizon. At the time of writing this method remains a design concept rather than an operating method.

2.9 Caving with subsidence column filling

Caving with subsidence column filling is not a new caving layout in the sense of the methods described above, but rather a variation in how the cave envelope is managed from breakthrough to closure. The methodology has been described in detail by Jakubec et al. (2026a, 2026b) and Monis (2026) and addresses one of the defining external consequences of cave mining: the progressive surface subsidence that develops once the cave breaks through to the original ground surface.

In a conventional cave operation, surface deformation evolves from initial elastic response, through development of tension cracks, to the formation of a subsidence crater that expands both vertically and laterally as ore extraction continues. The footprint of the disturbed surface ultimately reaches its maximum dimension at mine closure. Caving with column filling intervenes in this sequence by depositing fill material into the active subsidence zone (typically beginning before or soon after initial breakthrough and continuing throughout the mine life) to constrain the surrounding ground from moving inward and toppling into the cave.

Compared with conventional caving without subsidence management, caving with column filling is intended to offer a bounded disturbed surface footprint, restricted at the limit to the initial breakthrough area; effective reduction of surface water inflow and reduction of mudrush risk, with consequent reduction in long-term water treatment burden; coverage of reactive overburden and surface materials with fill, reducing exposure to oxygen and water and mitigating acid rock drainage risk; beneficial use of mine tailings that would otherwise require conventional surface storage; and improved closure outcomes through a stabilised, vegetation-capable surface profile.

The principal disadvantages are significant upfront capital and operating cost; uncertainty in cave breakthrough location and shape, which directly affects the design of surface preparation works; potential for fines to migrate through the muckpile, with knock-on effects on dilution and mudrush risk at the extraction level; and non-technical impacts including dust, noise, and traffic on the surface.

Caving with subsidence column filling has been implemented partially or opportunistically at a number of operations (including the Padcal block cave in the Philippines, San Manuel in Arizona, Telfer in Australia, and Kiruna in Sweden) and more systematically at the New Afton mine in Canada, where thickened and cement-amended tailings have been deposited into an inactive subsidence crater (Jakubec et al. 2026b). No operation has yet implemented full column filling from initial breakthrough through to closure; the method should therefore be understood as an emerging operational variation rather than as established practice. Its further development reflects the growing weight of social, regulatory, and closure considerations in modern cave mine design, and the recognition that managing the surface consequences of caving may, in some settings, be as central to a project's viability as the underground design itself.

2.10 Nuclear-assisted block caving

Nuclear-assisted block caving (also referred to as nuclear explosive fracturing) was a proposed variant of block caving developed in the United States during the Plowshare era of the 1960s. The premise was that the energy released by a deeply buried nuclear explosive could fracture a very large volume of hard, otherwise uncaveable rock in a single event, creating a rubble chimney suitable for either modified block cave extraction or in situ leaching. The method was first proposed by Flangas & Shaffer (1960) and developed in technical and economic detail by Hardwick (1970).

A nuclear device, placed at the bottom of a deposit and detonated, was envisaged as creating a vertical column of fragmented rock (the rubble chimney) that would then be extracted from below in a manner geometrically similar to a conventional block cave. For low-grade copper porphyry orebodies, the fragmented rock could alternatively be leached in place, with copper recovered by solution pumping (Russell 1964; Hardwick 1970).

The most fully developed proposal for application to a copper porphyry was Project Sloop, jointly developed in 1967 by Kennecott Copper Corporation and the Atomic Energy Commission for the Safford, Arizona deposit; no nuclear device was ever detonated for that project and the proposal was eventually shelved. The method is therefore best understood as a historical episode in the wider story of cave mining: a serious technical proposal, advanced under specific Cold War conditions, that never reached commercial application.

3 Caving challenges

The preceding section described the principal layout variations of cave mining as they are currently practised and some of the ‘out of the box’ thinking novel caving concepts. This section examines the recurring challenges encountered when those methods are applied at the depths, production rates, caving columns, and social and regulatory pressures characteristic of modern operations. The challenges themselves are not new in kind (most have been recognised since the early decades of cave mining), but they have intensified in scale, urgency, and consequence as cave operations have moved deeper, larger, and into stronger rock.

The principal engineering and rock mechanics challenges of modern cave mining are mining-induced seismicity, wet muck inrushes, caveability of strong rock masses, fragmentation control, cave back instability, surface subsidence, and the depth–stress–temperature envelope that now extends below 1500 m.

The principal operational challenges are draw control discipline, undercutting sequence, the matching of production rate to the rate at which the cave back is actually progressing, wet muck isolation at the drawpoint, the intensity and interpretation of monitoring, and the 7–10 year lead time from initial study to first production.

The principal social, regulatory, and environmental challenges are long-term mine closure and water management, social licence in proximity to host communities, regulatory consequences after fatal incidents, contractor exposure to risk, climate-driven hydrological risk, and the interaction between tailings dams or legacy surface infrastructure and the active cave envelope.

This section addresses 2 challenges with most fatal consequences. It begins with mining-induced seismicity – which is now extensively documented at operating mines – and continues with wet muck ingress risk, commonly called mudrush. Remaining challenges are touched on in the closing synthesis and developed further in subsequent sections of the paper, particularly the discussion of the caving rules and of divergent thinking on design and process.

3.1 Mining-induced seismicity

Mining-induced seismicity has emerged over the past 3 decades as one of the defining engineering challenges of cave mining at modern depths and production rates. The phenomenon is now extensively documented at 5 operations spanning 3 caving methods and 4 countries: panel caving at Cadia East (Australia) and El Teniente (Chile), sublevel caving at LKAB Kiruna and Malmberget (Sweden), and block caving at the Grasberg complex (Indonesia). The records differ in detail but converge on a common conclusion: the engineering response must accept seismicity as routine, not exceptional.

3.1.1 Cadia East

The Cadia East panel caves, among the tallest operating block caves in the world (Cuello & Whiteman 2020), experienced 3 operationally significant seismic events between 2017 and 2026. The first, on 14 April 2017, was a magnitude 4.3 mining-induced earthquake that damaged the crusher chamber and extraction drives at PC1 and accessways at PC2, required approximately 3 months of remediation, and contributed to a 55% fall in gold output for the year (Newcrest Mining Limited 2017). A localised event in PC2 in July 2021 demonstrated that seismicity continued as the caves matured. The most recent event, on 14 April 2026 (exactly nine years to the day after the 2017 event) registered magnitude 4.5, the largest seismic event ever recorded in central New South Wales. All 153 underground personnel returned safely to surface, but full operating capacity is not expected until the third quarter of 2026 (Newmont Corporation 2026a, 2026b). The 9 March 2018 slump of the northern tailings storage facility, sometimes associated with the seismic record, was concluded by the independent technical review board to be a foundation and liquefaction failure of the embankment, unrelated to mining-induced rockbursts (Newcrest Mining Limited 2019).

3.1.2 LKAB Kiruna and Malmberget

LKAB's 2 sublevel cave iron ore mines in northern Sweden provide the sublevel cave parallel to Cadia block cave case. On 18 May 2020, Kiruna mine experienced a local magnitude 3.3/moment magnitude 4.2 event (the largest mining-induced earthquake ever recorded in Scandinavia) with hypocentre at approximately -1,146 m elevation in the footwall, extensive rockburst damage, and infrasound signals detected at up to 286 km from the mine (LKAB 2020; Mawson et al. 2022). El Teniente and the Codelco operations

El Teniente, the world's largest underground copper mine, provides the longest continuous record of mining-induced seismicity in the industry. Systematic rockburst study began at the start of the 1990s, and a digital seismic monitoring system covering the whole mine with 25 seismic stations was installed in 1992. A fatal rockburst killed 6 workers in 1990, the Esmeralda sector experienced collapses in 2010, and a magnitude 3.9 event at the ventilation sublevel of the Andes Norte (New Mine Level) project on 24 July 2023 triggered a rockburst inside the deep new development.

On 31 July 2025, a magnitude 4.2–4.3 mining-induced seismic event triggered a major collapse approximately 2,400 m below surface in active panel caving production zones. Six contract workers were killed and 9 others were injured, with 2 distinct epicentres at the Andesita sector and on sublevel 7 in the northern El Teniente mine. Operations were suspended (Mining Technology 2025; Mining Weekly 2026). The Andes Norte conveyor belt tunnel has since become a published case study in rockburst causal analysis (Rodríguez et al. 2026).

3.1.3 The Grasberg complex (deep ore zone, deep mill level zone, Grasberg block cave)

PT Freeport Indonesia's Grasberg block cave complex in Papua provides a third panel caving and block caving record. The deep ore zone (DOZ), in production from 2000 to its closure in 2021, experienced strainbursts throughout its operating life. Roy et al. (2022) group DOZ with the strainburst records of El Teniente, Northparkes, Cadia, and Telfer as evidence that abutment-loading-driven strainbursts are a general feature of deep block caving. The deep mill level zone (DMLZ), in sustained production from 2019, has been the subject of substantial published seismic monitoring work, including microseismic analysis at the cave abutment and four-dimensional time-lapse tomography to image cave propagation and stress distribution in near real time (Hidayat et al. 2024). Hydraulic-fracture preconditioning and sequence management have reduced but not eliminated production interruption from seismic events.

3.1.4 Mining seismicity conclusions

Across the 5 operations, the cumulative experience is consistent. Mining-induced seismicity in deep cave mines is:

- Method-agnostic: it affects panel caving, sublevel caving, and block caving alike, driven by the geometry of cave abutment loading and the stress redistribution induced by progressive extraction, rather than by mining method or lithology.
- Persistent rather than transient: it does not necessarily subside as caves mature, and individual orebodies can be lost permanently.
- Largely irreducible by changes to layout or sequence alone: the engineering response combines intensive seismic monitoring, hydraulic-fracture preconditioning, adaptive sequencing and ground support upgrades.

Increasingly material to operations and to the social and regulatory licence: recovery from a single large event takes months and is capital-intensive, the human cost can be severe, and regulatory consequences are now routine.

None of these responses necessarily eliminates the hazard. What they do is bring it inside the envelope of what can be measured, predicted within useful limits, and responded to.

3.2 Mudrush risk

Mudrushes (the sudden uncontrolled inflow of wet material into underground workings) are the second of the recurring challenges of cave mining examined in this section. Where seismicity is method-agnostic and largely irreducible by changes to layout or sequence alone, mudrushes are mechanistically more specific: they require the simultaneous presence of fines, water, and an open pathway from a wet source to a drawpoint.

There are cases of injuries and even fatalities from sudden orepass discharges. The collapse and subsequent flow of unconsolidated or poorly consolidated backfill in various underground mining methods operations are inherently susceptible to internal mudrushes because they have the potential to accumulate water (surface and underground), generate fines (the comminution process), and through production activities, provide disturbances as well as a discharge point. Block caving operations are also susceptible to external mudrush flows because the broken muckpile connects the surface with the underground excavations (Butcher et al. 2000; Jakubec et al. 2012). Mudrushes are persistent across the history of cave mining and remain the single most lethal caving consequence at modern mines.

In the past 15 years, several fatal mudrush events at cave mining operations span 5 continents and 6 operations, and at least 18 workers lost their lives. This excludes possible mudrush fatalities in China that are not in the public domain.

In December 2012 at the Padcal block cave in Philippines (Philex Mining), a sudden mud discharge buried a LHD operator at the 782 m level in an area expected to be dry; water accumulation in the ore column above had not been anticipated, and the operator died enroute to hospital (Inquirer News 2012).

In January 2014 at the Mt Lyell copper–gold mine in Tasmania, an underground worker was killed in an area where the safety rating had been elevated from low to medium, yet experienced operators inspecting it minutes before the event judged it lower-risk than the formal rating (Australian Mining 2014). The mine closed afterwards.

In February 2021 at the New Afton block cave in British Columbia, a mudrush beneath the Lift 1 cave killed a contract driller and injured 2 others (Canadian Mining Journal 2021).

In September 2022 at the Yauricocha sublevel cave in Peru, a mudslide killed 3 contractor employees and injured a fourth, demonstrating that mudrush risk is not confined to block caving (Mining Magazine 2022).

The 2 most recent cases from Grasberg and Kimberley are discussed separately in the following sections.

3.2.1 Grasberg block cave 2025

The most recent major mudrush in cave mining occurred at PT Freeport Indonesia’s Grasberg block cave on 8 September 2025, when approximately 800,000 t of wet material from a former pit on the surface entered the active underground mine through a previously unrecognised pathway. The mud entered at the extraction level, travelled down the panel drift and through vent raises, ore passes, and drainage ways, and reached the haulage and service level where 7 miners were working; all seven were killed (Mining 2025). Freeport-McMoRan drew an explicit distinction between this external mudrush (material entering from a previously unrecognised surface source) and the internal wet muck events that the mine had managed safely for decades; the 2025 event was unprecedented at Grasberg in scale and origin. The Big Gossan and DMLZ mines restarted by mid-fourth quarter 2025 and the GBC itself was projected to begin phased restart in the first half of 2026, with full production not expected until 2027 (The Oregon Group 2025).

3.2.2 Kimberley: chronic mudrush risk and the Ekapa Mine 2026 incident

The historic scraper drift block caves at the Kimberley mines of De Beers (Bultfontein, Dutoitspan, Wesselton, De Beers, and the original Kimberley mine) experienced repeated mudrush events through the second half of the 20th Century. Operated as block caves from the 1950s onwards using a slusher drift extraction layout in narrow, mud-prone kimberlite, these mines became the most extensively documented mudrush-affected operations in the industry and Holder et al. (2013) produced what remains the standard reference. A further fatal mudrush occurred on 17 February 2026 at the Ekapa diamond mine in Kimberley, when an inflow of mud and water surged through Tunnel 6 at the Dutoitspan joint shaft approximately 890 m underground and 5 mineworkers were trapped and later declared deceased (African Times 2026; News24 2026; Mining Review Africa 2026; Diamond Fields Advertiser 2026). Ekapa Mining (a joint venture between Petra Diamonds and Ekapa Resources) announced immediate closure of the affected mine and petitioned for liquidation, citing the prolonged diamond-market downturn alongside the tragedy.

3.2.3 Mudrush conclusions

The cave mining mudrush case studies presented above account for 18 worker fatalities at operations on 5 continents since 2011. The events are not declining in frequency over time; the period 2022 to 2026 accounts for 15 of those 18 fatalities, despite 3 decades of published technical work on mudrush risk management. From this cumulative record, four observations emerge:

- Mudrush risk extends across mining methods. The 3 case studies span block caving (Kimberley, Grasberg) and sublevel caving (Yauricocha); the failure mode is not confined to any one extraction layout.
- Mudrush hazards are often invisible until they manifest. Drawpoint instrumentation, mud-mapping practice, and geophysical surveys are improving precursor detection, but lead time before a failure remains short.

The Grasberg 2025 incident has highlighted that mudrush risk at modern cave mines may now extend beyond the cave envelope itself to include legacy material accumulations and structural pathways inherited from earlier mining or surface infrastructure. Cave operators with complex surface histories (former pits, accumulated waste, or tailings above active caves) should expect mudrush risk assessments to expand to include those legacies, not only the active cave column.

4 Revisiting the caving rules

The performance record of cave mines in recent years in terms of extraction level stability and cases of seismicity and mudrushes described in the preceding section invites a question that has been postponed in technical conversation for some time: are the caving rules (the body of empirical guidance that has shaped cave mining for the past half century) still adequate for the operations we are now designing? In recent years a number of advances have been made with respect to cave design. Some past designs have not followed the rules, not always because designers are deliberately pushing boundaries or thinking out of the box, but because they are not familiar with past experience, or because they are under commercial pressure to maximise profit at the expense of robust engineering. The caving rules themselves were developed over the history of caving and are constantly being updated as new experience accumulates.

4.1 Origin and intent of the caving rules

The caving rules as they are commonly understood today derive from a body of empirical work that spans roughly 4 decades. The original rules were developed largely from operating experience at diamond, asbestos, and copper porphyry caves of the 1960s through 1990s: block heights of 100–300 m, depths typically under 1,000 m, and rock masses that were sufficiently jointed to cave reliably under modest hydraulic radius. The foundational text of caving rules was laid out by Dennis Laubscher in *A Practical Manual on Block Caving* (Laubscher et al. 2000), which codified the mining rock mass rating (MRMR)-based caveability chart, drawpoint spacing recommendations, undercut-sequence rules, and draw control principles that became the de facto standard for block and panel cave design through the 1990s and 2000s. *Block Caving Geomechanics* (Brown 2003) consolidated and extended this framework with a more rigorous geomechanical treatment, and *Guidelines on Caving Mining Methods: The Underlying Concepts* (Laubscher et al. 2017) have refined specific elements of the rules in light of operational experience.

4.2 The golden rules of cave mining

Beyond the formal technical guidance, a small set of 'golden rules' has emerged from the operating practice of cave mining, articulated by experienced practitioners as the principles that, when followed, materially reduce the probability of an operation going seriously wrong. They are not a substitute for the formal caving framework; they are a summary of what experience suggests matters most when the formal framework breaks down or is being applied at the margins. The following are particularly load-bearing:

- Prioritise technical success over maximising short-term economics. A cave that has been engineered to succeed will, in the long run, generate substantially more economic value than a cave that has been engineered to maximise the early production rate or the early net present value (NPV). The reverse is not true. This is the most important rule, and it is the one that operations under commercial pressure most often fail to follow.
- Geotechnical constraints should drive equipment selection, not the other way round. Designing an extraction layout around a particular LHD or haulage fleet, and then asking the rock mass to accommodate the choice, is a common failure mode. The rock mass behaviour is fixed; the equipment is not.
- Cave mining works on the principle of interactive draw. Wide drawpoint spacing that produces isolated draw zones is, as practitioners put it, 'economical suicide'. Isolated draw produces poor recovery, irregular cave back geometry, accelerated brow wear, and provides no benefit to pillar stability.
- Until the cave is well established, do not pull hard. Pressure from management or commercial commitments to produce tonnes from a newly initiated cave is the single most common cause of early operational problems. The cave must be allowed to establish, and the early production curve must be subordinated to the geometric and seismic response of the rock mass.
- Do not over-rely on uncalibrated numerical modelling. A well-known aphorism applies: all models are wrong, and some are useful. The usefulness depends on the quality of the calibration data, and in cave mining the calibration data are inherently retrospective. Computers solve equations; people solve problems. Numerical methods have a clear and growing role in cave design, but they are best used in support of engineering judgement, not as a substitute for it. The engineer who understands the rock mass and the operation, and who can recognise when the model output is at odds with what experience tells them, is the indispensable element of every successful cave.
- Operational discipline at the drawpoint is a must; uniform draw, interactive flow, isolation of mud-prone drawbells, controlled secondary breaking remains the standard against which production performance is measured at every modern cave.
- Undercut sequencing remains a critical design decision that materially affects stress at the extraction level.
- The conservative geometric defaults (block height, drawpoint spacing, pillar dimensions) remain the appropriate baseline against which any departure must be justified. The rules do not say a 600 m column is impossible; they say a 600 m column requires a substantially different design conversation from a 200 m column, and several recent operations have not had that conversation in the depth it warranted.

The rules, in short, remain the working framework for any cave mining operation inside the empirical envelope from which they were derived. The next generation question is what set of rules, or supplementary guidance, should apply to the operations that now sit outside that envelope.

4.3 How the rules are bypassed under commercial pressure

Modern cave operations have systematically departed from the conservative defaults of the established rules. The departures are of 2 kinds. Some are driven by the economics of the deposits that are now being mined and by the engineering ambition that recent technology gains have made possible; these are legitimate engineering choices made consciously, with the rules in view, and should be welcomed when the analysis supporting them is rigorous. Others occur because designers are not familiar with the past experience that informed the rules, or because the operation is under commercial pressure to maximise short-term profit at the expense of robust engineering. The first kind of departure can be defended on its merits; the second cannot. The difficulty for the industry is that the operational consequences of the two are often indistinguishable until the cave has failed.

4.4 Toward updated guidance

A full revision of the caving rules is beyond the scope of a single paper, and beyond the scope of any one operator’s experience. The Caving 2026 Conference, of which this paper is a contribution, is one venue in which the wider industry conversation can take that work forward. The following are the elements that an updated rule set will need to address:

- The depth–stress–temperature envelope below 1,000 m where conventional empirical guidance is thin and where seismic hazard, ground support, refrigeration, and dewatering interact in ways not seen at shallower depths
- The interaction between cave geometry and the seismic event-magnitude distribution
- The integration of preconditioning (hydraulic fracturing, confined blasting) into the rule framework, rather than as an ad hoc supplement, with explicit guidance on when preconditioning is required and how its effect should be modelled
- Surface-management requirements (subsidence control, water management, social licence and regulatory tail) that increasingly determine what is operationally feasible
- The role of automation and remote operation, both as a hazard-reduction measure and as a new source of operational complexity.

A revised set of caving rules will be denser, more conditional, and more strongly linked to monitoring data than the rules currently in circulation. It will look more like a structured risk-assessment framework, with caveability prediction as one input among several, with mandatory monitoring intensity tied to geometric departures from the conservative envelope, and with explicit provisions for the operational categories (seismicity, mudrush, fragmentation, subsidence, social licence) that have come to dominate the cave mining safety record. What it will not change, and what the next generation of cave engineers should keep clearly in view, is the small set of golden rules that experience has validated again and again across the diversity of operating caves: prioritise technical success, let geotechnical constraints drive the design, respect interactive draw, do not pull hard on a newly initiated cave, do not over-rely on uncalibrated modelling, and remember that computers solve equations but people solve problems.

5 Divergent and contentious thinking on design and process

Several key questions that could be viewed as contentious or even controversial are discussed below.

5.1 Orebody knowledge: Hands on or machine learning?

Today's technology (laser scanning, photogrammetry-based structural mapping, or machine learning core logging) offers great opportunity but also carries potentially significant pitfalls. The opportunity is real: crews stay out of risky slopes or unsupported ground, datasets become orders of magnitude denser, and a permanent digital record replaces the handwritten notebook. The hidden cost is distance between rocks and geologists and engineers. Geological and geotechnical judgement has historically been built at the rock face or by hand on core, scratching, breaking, and feeling rock fabric. When that contact is replaced by a point cloud or a model output, risks can compound. Black-box output is easily treated as ground truth in downstream resource and geotechnical models, with no audit trail back to a defensible observation. Also, the next generation of caving engineers may never accumulate the pattern-recognition and 'feel for the rocks'.

5.2 Orebody knowledge: rock mass characterisation

All aspects of cave design and performance rely on correct and complete rock mass assessment, domaining and rock mass strength estimates. Rock mass classifications such as geological strength index, rock mass rating or Q are routinely used for this purpose and provide input into commonly used numerical modelling. The appropriate role of classification systems is not as a legacy of the past, as some believe, but to continue to play their role in the industry.

In 1976, Laubscher and Tylor introduced MRMR classification specifically developed for caving operation with associated empirical tools for caveability, rate of caving, draw zones/drawpoint spacings ground support, etc. Most classifications systems incorporate rock quality designation measurements but rock quality designation (RQD) in highly fractured rocks as well is in poorly fractured rocks may not be useful indicators of caveability, fragmentation or stability (Figure 5).

In 1990, Laubscher offered an alternative and replaced RQD with joint spacing or fracture frequency. Furthermore, it was recognised that beside open joint the rock mass behaviour is influenced by internal rock block defects and in 2001 this concept was incorporated in updated IRMR/MRMR system (Laubscher & Jakubec 2001). Although this tool has been available for past 25 years, many rock mass characterisations and numerical modelling inputs are based on classification systems that use RQD values and do not take potentially weakening rock block defects into consideration, resulting in erroneous conclusions.

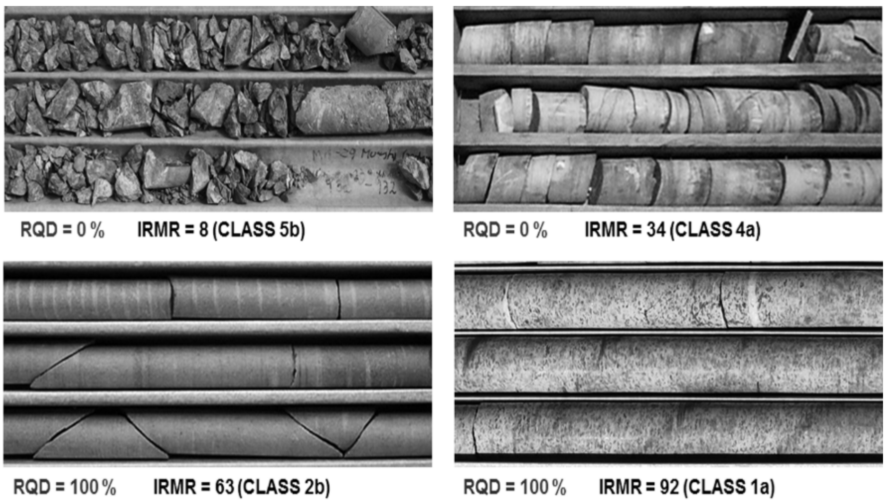


Figure 5 Examples where rock quality designation may not be useful indicator of supportability or caveability and fragmentation

5.3 Natural caving versus preconditioning

Hydraulic fracturing and confined blasting have moved from an experiment at Northparkes in 1997 (van As et al. 2004) to standard practice at most modern hard rock cave operations (El Teniente, Cadia East, Northparkes, Grasberg DMLZ) where they are credited with enabling cave initiation in rock that would not naturally cave, improving fragmentation, regularising the Gutenberg–Richter event distribution, and enabling higher draw rates. The current critical view is that the technique is being relied upon in ways the underlying physics may not warrant. Hydraulic-fracture orientation is dictated by the in situ stress field and cannot be prescribed by the engineer, so the design intent may not be delivered. Verification is technically demanding and is frequently inferred from microseismic response rather than directly measured (Orrego et al. 2024). There are also views that in some cases potential stress reduction could negate benefits of preconditioning. It is clear that preconditioning is in many cases justified and beneficial but should not be treated as universal solution and careful testing and design is essential.

5.4 Experience versus numerical modelling methods

Where the empirical rules no longer cover the case, the design conversation has shifted toward numerical modelling. Cave propagation, stress redistribution, draw flow, and seismic response are now routinely modelled at scales and resolutions that would have been impossible 20 years ago. The technical case for modelling is strong: at depths and column heights outside the empirical envelope, the alternative to a modelled prediction is no prediction at all.

All models are wrong; the question is whether the particular model being used is useful for the question being asked. Models built on a specific orebody's history match its observed behaviour reasonably well; the same models applied to caves substantially outside that history can produce predictions that are precise but not accurate.

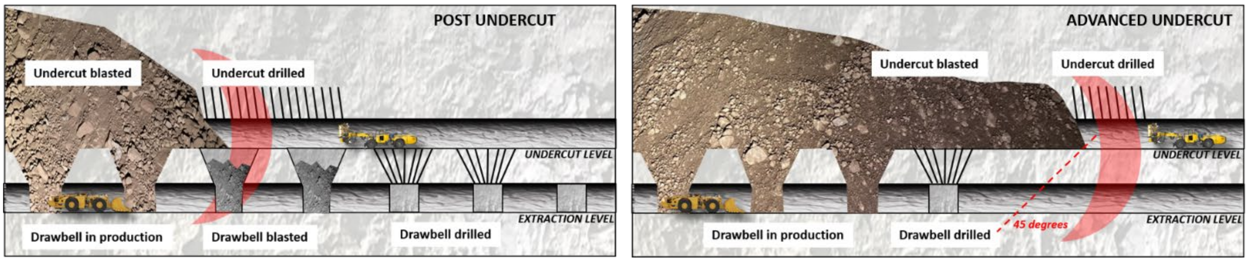
The lesson from the cumulative recent record is not that numerical modelling should be abandoned – it cannot be, at the depths and scales now being designed – but that the confidence the industry places in model output should be proportional to the calibration data that supports it, and that the engineering judgement of experienced practitioners should remain the final filter on what a model is being asked to do. Where the operation lies inside the empirical envelope, the rules and the models will tend to agree. Where the operation lies outside, the rules become unreliable and the models become uncalibrated; in that regime, the engineering response should be additional monitoring, conservative geometric defaults, and a willingness to slow production rather than to extrapolate the model.

5.5 Drawzone and drawpoint spacings

Cave mining is based on interactive draw of the broken rocks between neighbouring drawpoints. If the drawpoints are too far from each other, this interaction will not occur, and drawpoints will not recover material between the drawpoints and isolated draw will occur. However, if drawpoints are too close together, the pillar between the drawpoints may not withstand the caving pressure and instability can occur. This quest for pillar stability and interactive draw is one of the fundamental design questions and Laubscher provided in 1990 guidelines for drawpoint spacing based on the MRMR and fragmentation. This empirical guideline is generally based on poorer rock masses. It is a trend in recent years as caves are getting deeper, to increase drawpoint spacings to increase pillar size and improve stability. However, if the drawpoints are too far apart, resulting in poor interaction and isolated draw, the load on the pillar might increase and benefit of larger pillar may be compromised resulting in poor stability also in addition to poor interaction. The ability of numerical models to reliably model complex system of extraction level geometry, damage during the undercutting and forces during the draw is in question.

5.6 Advanced undercut versus post-undercut

Although there are several types of undercutting strategies, most of the caves recently completed used either post or advanced undercut (Figure 6). There are fundamental advantages and disadvantages between those 2 types of undercutting.



(a) (b)

Figure 6 Schematic section through (a) post-undercut and (b) advanced undercut (Jakubec 2023)

The post-undercut sequence (extraction level drawbells installed before undercutting commences) is the simplest to schedule and the fastest to first ore, because broken undercut material is removed through the already-installed drawbells as soon as undercutting begins. Its disadvantage is fundamental at caves with unfavourable strength-to-stress ratios, especially at deep caves. The drawbells sit directly within the developing abutment-stress envelope, and support alone may not carry the resulting load. Damage initiates at drawpoint bullnoses, brow wear accelerates, and span interrupts (remnant pillars from poor blasting or frozen muck) are difficult to detect until they cause local failure. The early shallow gravity caves or caves with very strong rocks such as Cadia tolerated this regime; modern deep operations with weaker rock mass may not be suitable to this system and the post-undercut repair could be very costly or results in significant section of footprint closed.

The advance undercut strategy keeps the undercut ahead of extraction level development by no less than the inter-level spacing, so drawpoints and drawbells are built behind the abutment-stress front in already de-stressed ground. These better preserve extraction level integrity, and reduce or eliminate the post-undercut repairs. The disadvantages are scheduling complexity: the 2 horizons must be carefully choreographed. The decision between those 2 undercutting strategies should not be based solely on economics.

The selection of post-undercut is often made on economic merits but damage to the rock mass and costly repairs can offset perceived implementation benefits.

5.7 Conservative versus aggressive footprint design

The defining design trend of the past 20 years has been the push from conservative cave geometries (block heights of 100–300 m at moderate depth) toward aggressive designs: column heights above 400 metres, in some cases approaching 600 metres (Figure 7), production rates of 50,000–100,000 tpd from a single footprint, single-campaign extraction of whole orebodies rather than panel sequences, and reliance on preconditioning to deliver caveability the rock mass would not naturally provide. The driver is largely economic. Larger footprints concentrate scale economies, taller columns avoid the cost of multiple lifts, faster ramp-up captures earlier NPV, and dense preconditioning programs are justified against the capital base of the operation as a whole. The risk concentration is correspondingly larger. Predictions made by company executives in 2008 that 5 super caves would be in production within 10 years have not been borne out – barely one is in steady production 15 years later – and the seismic and mudrush record of the operations that did proceed has been more severe than anticipated. The legitimate engineering cases for aggressive design must therefore be defended on their merits cave by cave; the cumulative industry record does not yet justify treating it as the default.

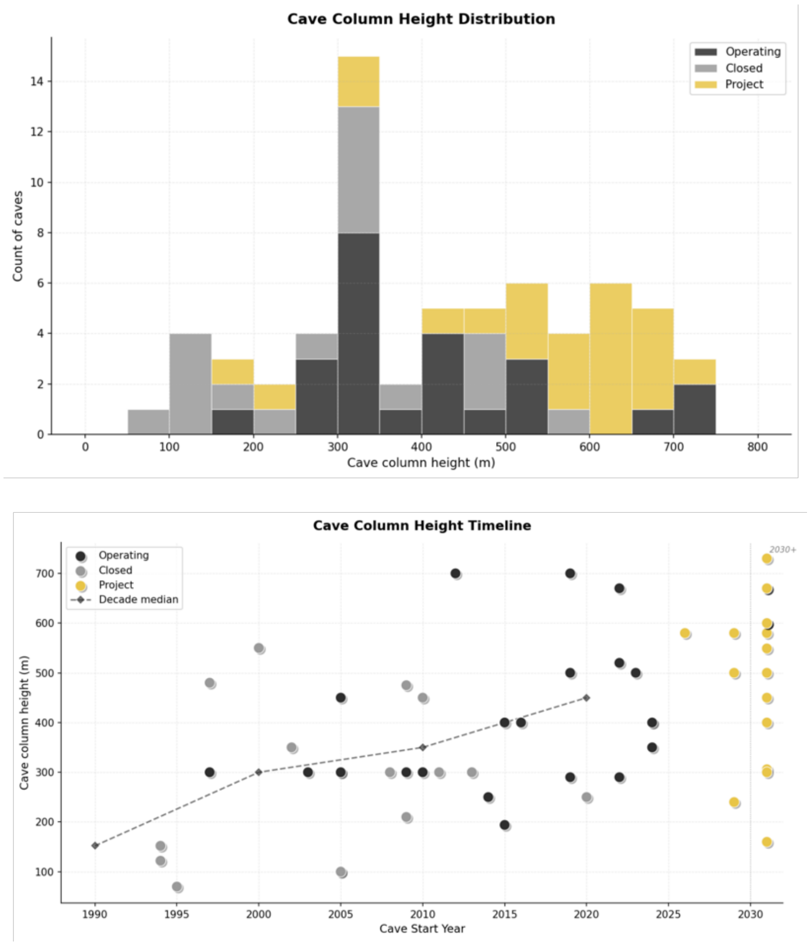


Figure 7 Evolution of cave column height with time

6 Conclusions and path forward

Caving projects unfold over decades and depend on disciplined study and planning, aligned with established best practices (caving rules), and faithful execution from the earliest stages. Cave behaviour is path-dependent: the choices made during study, design, and ramp-up largely determine the performance of the cave through its life. Where that discipline is compromised, the damage does not stay localised; small concessions during establishment compound through the life of the cave, often translating into disproportionate long-term costs and losses in recovery, dilution, and operational flexibility, and yet, that discipline is also what is most vulnerable to commercial pressure.

The recurrence of this pattern points to a governance problem rather than a knowledge problem. Several structural drivers reinforce it: NPV calculations that reward early tonnes but cannot see reserve destroyed years later; a decade-long gap between the people who approve aggressive schedules and the people who later have to operate the cave; competition with shorter-payback alternatives within corporate portfolios; pressure to capture commodity price peaks and meet yearly guidance targets; and a recurring belief that new monitoring or modelling tools will overcome risks they don't actually address. The failure mode is therefore not the state of caving knowledge, but whether an organisation builds the shared understanding and alignment to adhere to recognised best practices and guidelines. That alignment will only become more critical as the industry moves toward larger, deeper, higher-rate, and more complex cave designs.

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