Caving 2026 – A van As, D Cumming-Potvin & J Wesseloo (eds)

doi:10.36487/ACG_repo/2645_90

High columns, high risk: point-load-driven convergence in deep cave mining

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Abstract

The progressive increase in cave column heights in modern cave mining operations has fundamentally changed the dominant damage mechanisms acting on the extraction level, shifting from undercut-induced abutment stress damage to overburden weighting and highly localised point loading as the dominant failure modes. Consequently, the primary geotechnical challenge has moved from cave propagation, ore recovery, and draw performance to preserving the extraction level under extreme loading conditions.

In deep, high-column cave mines, severe convergence is increasingly driven by column loading and the mobilisation of large, partially dislodged rock masses bounded by faults and major structures, which impose concentrated loads on the extraction level, particularly in the vicinity of faults or areas of weaker rock mass. Under these conditions, crushing with the consequent loss of extraction level functionality and productivity has emerged as the dominant life-of-mine risk.

This paper argues that conventional draw control philosophies, historically centred on maximising recovery and minimising dilution, are no longer sufficient, nor primary, in deep, high-column cave environments. The established principles of cave draw control remain valid and are not superseded; however, they do require modification. Draw control must also be reframed as a stress/damage management tool, with the objective of actively managing point loading and convergence through deliberate load shedding. Two structured load shedding strategies are examined: sequenced strip drawing (SSD), a shift-to-shift sequencing discipline for ongoing stress redistribution across the extraction level footprint, and targeted load redistribution draw (TLRD), a spatially focused strategy for reducing significant convergence or point load events by increasing porosity and draw cone interaction in the affected zone. Both recognise that productivity-focused (often automated) draw strategies become secondary considerations once extraction level preservation is at risk.

A critical and related concern is the growing incompatibility between modern cave layouts and effective load shedding. Increasing drawpoint spacings and correspondingly larger pillar dimensions are reducing the likelihood of drawzone interaction, limiting the ability to shed load efficiently, and exacerbating stress concentrations within oversized pillars. This design parameter must be critically re-examined.

The paper concludes that the long-term viability of deep, high-column cave mining will require a paradigm shift in cave mine design philosophy, including reduced block heights and multiple lifts, smaller pillars, and layouts that deliberately promote drawzone interaction, together with new technologies capable of facilitating rapid, reliable load shedding. Current numerical modelling approaches are also identified as insufficiently reliable in capturing the onset and progression of extraction level damage under these conditions, owing to structural uncertainty and the transient, localised nature of point loading.

Keywords: *draw control, load shedding, sequenced strip drawing, targeted load redistribution draw.*

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1 Introduction

Block and panel caving methods for extracting large orebodies have demonstrated exceptional productivity at shallow and moderate depths over several decades. Classical geotechnical design for caving operations has historically focused on three primary concerns: assessing caveability, managing cave propagation to ensure continuous caving, and applying draw control to optimise ore recovery and minimise dilution. At shallow and moderate depths, these priorities have been broadly adequate.

As cave mines progressively extend to greater depths and mining engineers push designs toward taller ore columns, a qualitatively different and more severe set of failure mechanisms has emerged (Guest & van As 2020). The progression to depths exceeding 1,000 m and cave column heights of 500 m or more fundamentally alters the loading environment on the extraction level. Thus, cave mine design requires greater focus on managing sustained overburden loading, structural block mobilisation, and highly concentrated point loading, which are transmitted directly onto the extraction level infrastructure and to the lower mine levels that provide ventilation, dewatering, and haulage services.

The consequences of this shift to taller column heights have been increasingly severe convergence, pillar crushing, drive closure, and drawpoint loss at operating mines worldwide. Critically, these failures are not localised or transient. They are cumulative and progressive, threatening the life-of-mine viability of the extraction level. Productivity losses in these environments are now frequently dictated by infrastructure damage and loss of access rather than by cave propagation behaviour or compliance with feasibility study forecasts (van As 2023).

It is important to emphasise at the outset that the established principles of cave draw control, uniform drawdown, interactive draw, cave maturity constraints, and strict sequence discipline remain technically valid and operationally essential. They are not superseded by the arguments in this paper. What this paper argues is that those principles are insufficient on their own in deep, high-column environments and must be augmented by an explicit stress/damage management draw strategy.

This paper presents a systematic examination of the mechanisms driving the evolution in loading conditions in deep, high-column caves, the adequacy of conventional draw control philosophy as the sole response to those conditions, and the operational and design adaptations that such mines must adopt. The central argument is this: extraction level preservation has become the primary geotechnical constraint in deep, high-column cave mines, and draw control must be refocused as a stress/damage management tool to address it.

2 Evolution of the controlling loading mechanism

2.1 Historical loading environment

Early block cave operations were characterised by moderate cave heights, relatively shallow depths, and rock mass conditions on the extraction level dependent largely on the undercut method employed. The dominant loading mechanism at the extraction level is typically a relatively low magnitude column loading. Extraction level damage was typically limited to those areas developed ahead of the advancing undercut, which, in most cases, was manageable with conventional support and rehabilitation.

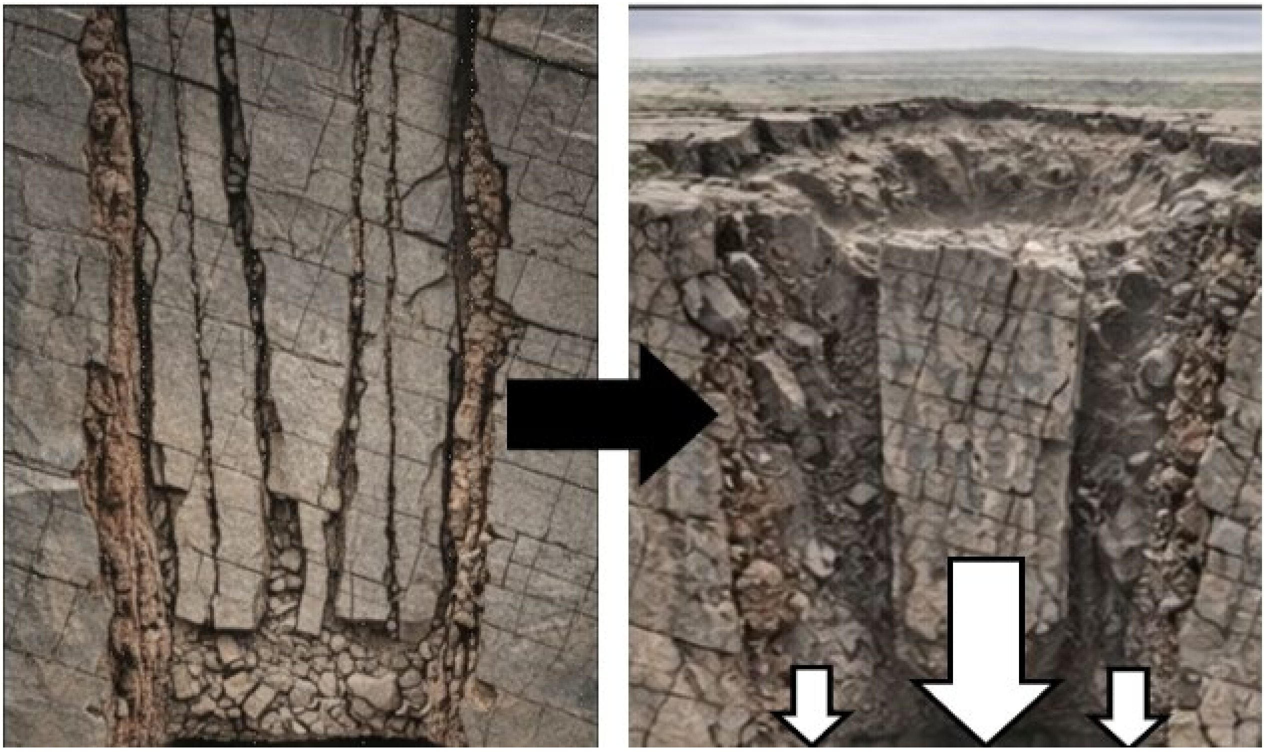
Importantly, once cave propagation was established and the cave-back began to progress upward, overburden stresses tended to relax above the extraction level, transferring load laterally into the cave walls. This progressive destressing of the immediate extraction level was a characteristic feature of cave behaviour at shallow and moderate column heights, generally limiting convergence severity to areas where undercut remnant pillars had formed due to incomplete undercut blasting or in the vicinity of geologically adverse conditions.

2.2 High-column cave loading environment

Modern cave mines are distinguished by fundamentally different geometric and stress conditions. Cave column heights frequently exceed 800–1,200 m, with extraction levels in some single-lift operations located more than 1,000 m below surface.

Two principal mechanisms combine to create a more severe loading regime at the extraction level:

- First, the total mass of the overburden rock generates sustained and substantial overburden pressure (weighting). Unlike the transient abutment stress associated with undercut advance, this loading is essentially permanent and increases progressively as the cave column matures. The ability of the broken rock column to redistribute this load laterally is limited, particularly where draw is not fully interactive and compacted, undrawn zones persist between the more porous draw cones.
- Second, and arguably more damaging, is the progressive mobilisation of large structural rock blocks bounded by faults, shear zones, and major discontinuities (Figure 1). In high-column caves, these structural blocks can partially detach from the surrounding rock mass without fully fragmenting or entering the broken muck column. In this partially dislodged state, they transmit their weight as concentrated, localised loads onto specific and limited areas of the extraction level. This mechanism is similar to that of plug subsidence (Brown 2007) and produces point loading.



(a) (b)

Figure 1 (a) Conceptual illustration of faulted/sheared rock masses that preferentially cave along these weak structures, releasing massive blocks that remain semi-intact; (b) Once these mobilised structural blocks migrate down, their enormous weight causes point loading of the extraction level

Point loading is particularly dangerous because it is spatially variable, temporally unpredictable, and not amenable to management through conventional support measures alone (Butcher 1999). Nevertheless, the locations most prone to point loading damage are not entirely unpredictable; for example, areas where undercutting was incomplete, forming remnant pillars, and the vicinity of large-scale adverse structures, faults, lithological contacts, and weak rock mass domains, all represent the highest-risk zones and should be identified in advance through detailed structural geological characterisation.

2.3 Consequences for the extraction level

A point-loading-dominated environment has severe consequences for the extraction level infrastructure. Convergence is no longer a localised and manageable phenomenon; it becomes cumulative, progressive, and, in advanced cases, irreversible. The sequence of deterioration is characteristic, and typically initiates at a nucleus defined by either an area of poor undercut performance, a major adverse structure, or a lithological boundary creating a mechanical contrast in the rock mass:

- Formation of an initial nucleus of stress induced damage, typically as a consequence of a remnant pillar left on the undercut, or a major fault, or a weak rock mass domain, from which convergence spreads progressively
- Initial drive convergence, manifesting first in pillars and extraction drive sidewalls adjacent to the high-stress nucleus
- Progressive pillar crushing, as oversized drawpoint pillars fail to shed load and instead concentrate stress through overlying muckpile rock compaction
- Drawpoints and drive closures lead to loss of equipment access, progressively removing drawpoints from the active draw schedule
- Drawpoint loss and reserve sterilisation, as sections of the extraction level become inaccessible.

The loss of extraction level functionality is self-reinforcing: as drawpoints are lost to convergence, they are unable to shed load and thus the compaction of material above spreads laterally onto the remaining active drawpoints, increasing localised stress and accelerating further damage. This 'cancerous' mechanism is a defining characteristic of the high-column loading environment and underscores the importance of early intervention.

Several operations have exhibited various stages of this deterioration sequence, with extraction drive closure representing the most extreme consequence where adjusted draw strategies and rehabilitation cannot keep pace with convergence rates. It is important to note that the geotechnical context differs between operations: convergence and drive closure may reflect extreme column loading in competent rock, unfavourable strength-to-stress ratios in weak rock masses, or a combination of both. These distinctions matter for selecting appropriate mitigation strategies.

3 Draw control reconsidered: from recovery optimisation to stress management

3.1 Traditional draw control objectives

Conventional draw control philosophy evolved in the context of shallow to moderate depth cave mines, where the primary risks were dilution, poor recovery, and inadequate cave propagation. The founding framework – principally that of Laubscher (1994), Laubscher (2000), Kvapil (1965), and empirical guidelines based on physical flow experiments and cave mine observations – established draw control as an instrument for achieving uniform cave-back propagation, promoting interactive draw to establish mass flow, controlling the ore–waste interface, and maximising ore recovery while minimising dilution ingress.

These objectives remain technically valid and operationally important. They are, however, predicated on a critical implicit assumption: that extraction level infrastructure will remain functional throughout the life of the cave. At shallow and moderate depths and column heights, this assumption has been broadly justified by field experience, although caves developed in weaker rock masses (such as kimberlites) also use draw control to manage extraction level deformations.

3.2 Limitations of traditional draw control in deep caves

In deep, high-column cave environments, the premise of a fully operational extraction level cannot be taken as given. The extraction level is increasingly the most vulnerable and consequential element of the entire cave system. Damage to it can accumulate faster than rehabilitation can effectively manage, and thus, loss of drawpoint access ultimately translates to reserve loss.

Under these conditions, optimising draw schedules for recovery and dilution management becomes a secondary concern if the infrastructure required to execute those schedules is failing. A draw control strategy that aims to successfully minimise dilution while allowing the extraction level to deteriorate beyond recovery cannot be regarded as successful.

Furthermore, conventional monthly or weekly draw control models and equivalent scheduling tools are typically built on the implicit assumption of interactive draw and fully functioning infrastructure. These tools generally do not incorporate feedback between draw behaviour, load distribution, and extraction level damage in high-column environments. Their outputs can be significantly misleading when applied without explicit consideration of the stress/damage management dimension.

3.3 Draw control as a stress/damage management tool

The conceptual reframing proposed in this paper is straightforward but has profound operational implications. In deep, high-column cave environments, draw control must be understood first and foremost as a mechanism for managing significant column loads through stress redistribution and preserving the integrity of the extraction level. Draw control must be implemented on a shift-by-shift basis, not through monthly or weekly planning cycles alone. Recovery optimisation is a secondary objective, subordinate to infrastructure preservation.

This reframing requires a fundamentally different approach to draw scheduling. Where conventional draw control seeks to achieve uniform cave-back propagation across the footprint, stress-based draw control seeks to actively shed load from stressed and converging zones by increasing porosity and dilation in the muckpile column through disciplined draw sequencing, thereby redistributing overburden weight. The objective is not simply to remove ore in an assumed ‘bin flow’ manner; it is to remove it from the right place, at the right time, in the right sequence, so as to relieve load on the most vulnerable parts of the extraction level. This must operate on a disciplined shift-to-shift basis.

A critical and unifying principle is that all operational draw strategies are implementations of load shedding. Whether applied as uniform draw, height of draw scaling, sequenced strip draw (SSD) (Section 4.2), or targeted load redistribution draw (TLRD) (Section 4.4), the fundamental objective is identical: controlled redistribution of loads within the cave column to maintain drawzone interaction and protect the extraction level. These approaches differ in execution, not in principle.

This philosophy is not entirely new. Load shedding was first recognised as a cave management tool in the De Beers Kimberley operations, where maturity-based draw constraints emerged from observations that cave performance improved as draw was deliberately modulated over time. More recent applications at several large caving operations have demonstrated that sequenced draw is an effective mechanism for managing extraction level loading in a deep, competent rock mass environment. What has changed is the context and urgency: in modern deep, high-column caves, this approach must become the primary draw control objective.

4 Load shedding, sequenced strip drawing, and targeted load redistribution draw

4.1 Physical basis of load shedding

Load shedding, in the context of cave mining, refers to the redistribution of draw such that vertical column loads above the extraction level are progressively redistributed away from highly stressed/converging areas toward adjacent regions better positioned to accommodate the load, in essence, 'mining towards the solid'. The mechanism operates by creating increased porosity in the muckpile column immediately above targeted drawpoints, thereby reducing stress transmission in those zones, as illustrated in Figure 2.

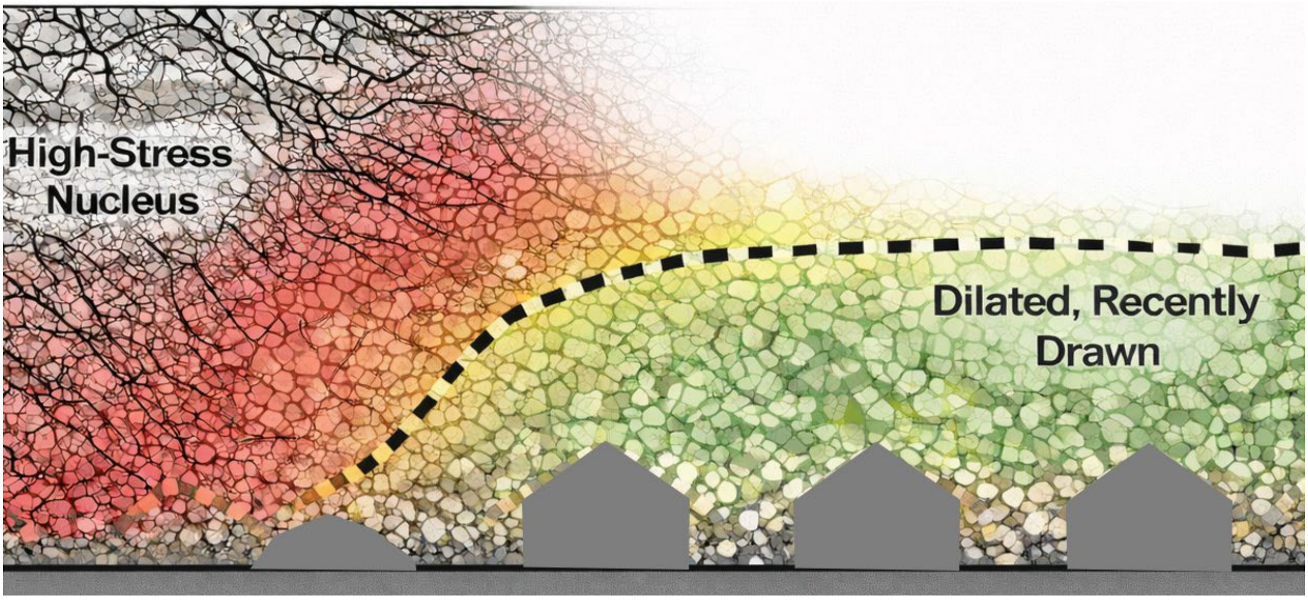


Figure 2 Load shedding in sequenced strip drawing, illustrating the transfer of stress from a compacted high-stress nucleus toward a dilated, high-porosity zone created by systematic strip draw. The progression demonstrates how controlled, uniform draw induces dilation and reduces stress concentration within the cave column

From a cave flow perspective, load shedding operates through several coupled mechanisms:

- increased porosity above drawn drawpoints, reducing the capacity of the column to transmit vertical stress above those drawpoints
- promotion of secondary fragmentation and dilation within the muckpile, disrupting or destroying compacted stress conduits (bridging arches or remnant pillars on the undercut)
- interruption, or destruction of stagnant compacted zones between non-interacting draw zones, which otherwise concentrate and channel stress directly onto pillars and excavations below
- lateral redistribution of stress toward cave margins and abutment zones where competent rock can sustain higher loads without driving convergence.

Where draw is uniform and fully interactive, load shedding occurs as an inherent feature of mass flow. In deep, high-column caves, however, interactive draw conditions are frequently incomplete or transient, and intentional load shedding through disciplined sequencing becomes the mechanism for stress redistribution. Where load shedding must be spatially targeted to address a significant convergence nucleus or structural point load event, this is achieved through targeted load redistribution draw, described in Section 4.4.

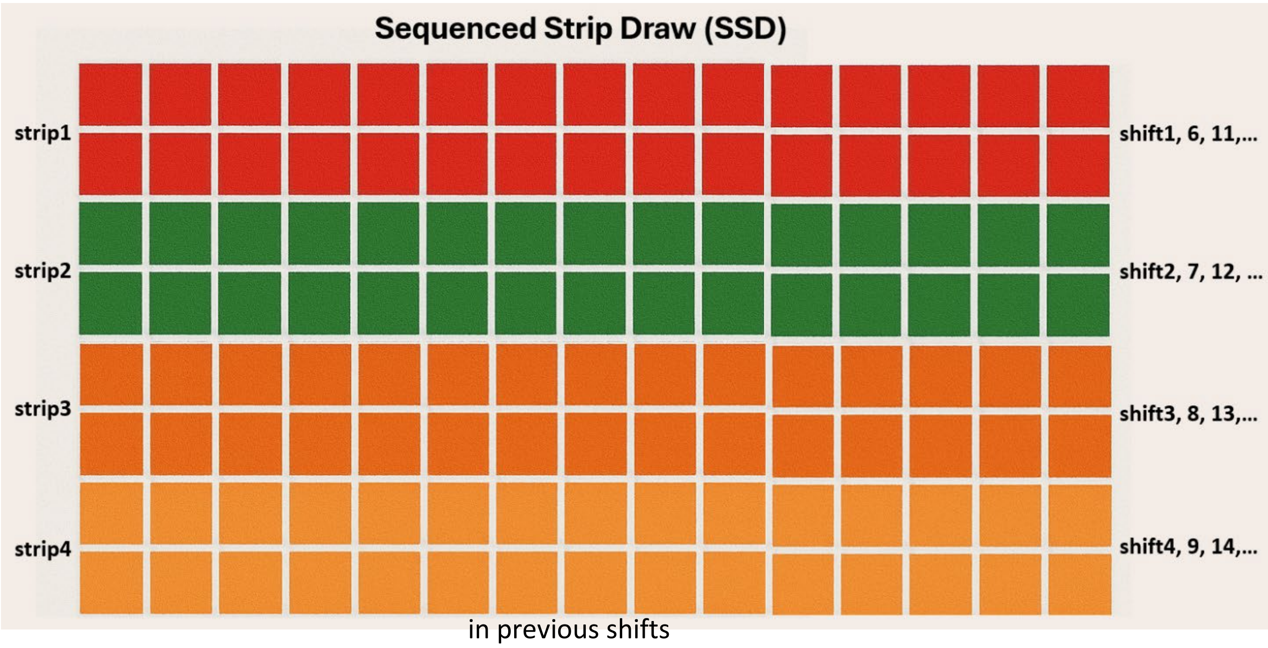
4.2 Sequenced strip drawing

SSD is distinct from, but an implementation of, general load shedding. Where general load shedding describes the broader objective of stress redistribution, SSD describes how that objective is operationally achieved which is by directing concentrated draw along a corridor of drawpoints, a strip that advances progressively from the stressed or initial drawn area toward the cave margin, on a disciplined shift-to-shift basis. In essence, one is reducing the area required to produce the daily 'calls' so that a higher drawpoint call can be achieved from each drawpoint in this smaller area, as opposed to spreading the daily call over the entire cave footprint.

The objective is to create a moving front of stress relief that migrates the load away from the zone of concern, or that uses the load directly in front of the strip to promote interactive draw and secondary fragmentation. Load shedding of hotspots is achieved by applying higher strip calls to drawpoints surrounding a stressed or converging hotspot zone as the strip passes. Key operational requirements include:

- Strict sequence control, such that the drawpoints within the active strip are called first on every shift, without exception.
- Consistent draw waves of similar magnitude and spatial pattern from shift-to-shift, to prevent alternating zones of compaction and dilation that undermine load redistribution continuity
- No 'catch-up' logic in the short-term plan: missed draw from any drawpoint is not planned for in subsequent shifts. Catch-up may only be addressed over a minimum one-month planning horizon, preferably distributed over 3–6 months or the remaining life of mine, as minor incremental adjustments, not as a discernible differential at the drawpoint scale
- Preferential application of increased draw at the boundary of the stressed zone, not within its core, creating an outward-migrating dilation front.
- Explicit compatibility with draw interaction requirements, to avoid inducing ratholing or chimneying within the strip.
- Hangups must be addressed immediately and given priority to production call, the hangup removal and its associated draw are not considered as a 'catch-up' practice.

Figure 3 illustrates the SSD concept schematically, showing the draw wave advancing from the zone of concern toward the cave margin.



in previous shifts

Figure 3 Plan view schematic of a simple sequenced strip drawing showing a full-width active strip advancing across the extraction level in a North to South sequence. The moving high-porosity curtain promotes controlled dilation and outward load shedding while maintaining uniform draw and interaction across the footprint

The daily draw sequence under SSD must be formally agreed jointly by geotechnical, planning, and operations personnel, with geotechnical control explicitly taking precedence during load shedding phases. Automated dispatch systems optimised for short-interval control and fleet efficiency are poorly suited to enforcing SSD sequences, as they typically prioritise drawpoints furthest from their monthly call targets rather than respecting sequence dependency. Manual or semi-manual dispatch is often unavoidable during active SSD phases.

4.3 Observed effectiveness and limitations

SSD and load shedding strategies have been applied at several caving operations where convergence of the extraction level had become a primary concern. The observed effects of well-executed load shedding have been broadly consistent:

- measurable reduction in convergence rates in targeted zones following disciplined strip draw application
- improved extraction level longevity in areas where SSD was implemented early, before irreversible pillar failure
- partial recovery of previously stagnant draw cones following stress redistribution.

However, operational experience also reveals consistent limitations. Load shedding has proven only partially successful in some deep cave operations and, in several cases, has been insufficient to prevent progressive failure of the extraction level. The reasons for this partial effectiveness are examined in Section 5.

Unlike SSD, which represents a structured ongoing draw discipline, broader load shedding interventions are best viewed as transitional measures designed to arrest deterioration and create conditions under which more conventional draw control can resume. Where load shedding has been treated as a background operational adjustment rather than a primary geotechnical control process, results have been consistently poor.

4.4 Targeted load redistribution draw

SSD describes a structured, ongoing draw discipline applied across the extraction level footprint. A related but distinct strategy, TLRD, addresses a more specific operational condition: the concentrated loading of a defined zone arising from a point load event, active convergence nucleus, or sudden structural block mobilisation, often under conditions where normal draw has been disrupted or where the cave is operating in an abnormal loading state such as post-collapse production restart.

TLRD is characterised by 5 defining attributes that distinguish it from both SSD and conventional draw control:

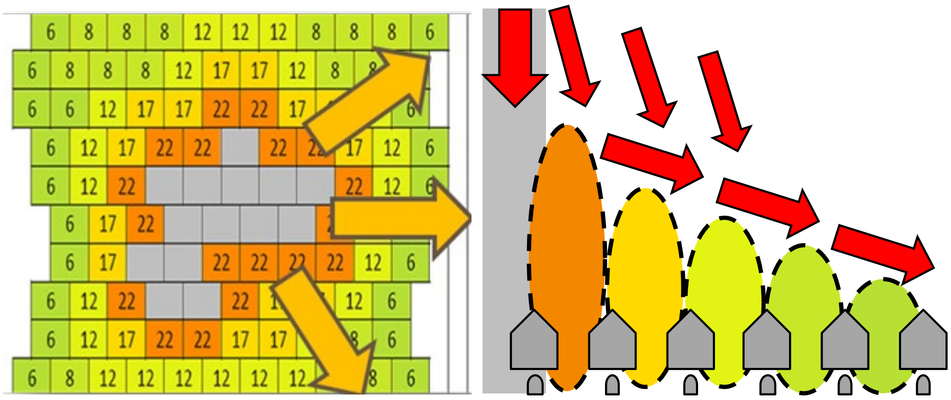
- spatially focused, non-uniform draw, deliberately concentrated in and around the point-loaded or converging zone rather than distributed uniformly across the footprint
- intentional and accelerated porosity development, creating early draw cone interaction specifically in the targeted zone as rapidly as maturity constraints permit, to disrupt compacted stress conduits
- outward redistribution of vertical load toward cave boundaries, using the higher-porosity zone in the target area as a load sink, progressively transferring column load to the cave sidewalls and abutments where competent rock can sustain it
- temporary and deliberate deviation from uniform or grade-based draw, accepted as an explicit geotechnical intervention rather than an operational exception
- strict ban on catch-up tonnes: the draw schedule must be reset daily, and no catch-up tonnage may be applied to lower-call drawpoints, as doing so would equalise porosity across the footprint and undermine the differential effect.

The physical mechanism underpinning TLRD is identical to that of general load shedding: increased porosity above high draw drawpoints reduces the capacity of the column to transmit vertical stress, while interactive draw cones permit lateral stress redistribution. The key operational logic of TLRD is that, given the tonnage constraints of any real operation, attempting to achieve early interaction uniformly across the entire footprint will not deliver the required porosity where it is most urgently needed in sufficient time.

By concentrating draw on the converging zone ('in group'), draw cones develop faster, lateral interaction initiates sooner, and load transfer to the cave boundaries is achieved within a shorter operational time frame.

The first documented application of this strategy was at Northparkes E26 Lift 1, following the catastrophic airblast event of 1999. With the muckpile highly compacted following the cave-back collapse, a ramp-up TLRD was applied, commencing in the centre of the footprint, with high-draw rates in the central zone systematically reducing toward the cave boundaries. The intent was to ensure column load was transferred to the cave sidewalls as rapidly as possible and to prevent point loads from forming on the extraction level infrastructure during restart. The strategy was effective in managing the loading regime during the post-collapse, production ramp-up.

A more direct geotechnical application of TLRD was subsequently employed at Northparkes E48 and Argyle Diamond Mine, where point loading had induced progressive convergence in a defined zone of the extraction level. The same centre-out spatial gradient was adopted, with the highest draw rates applied to drawpoints in and immediately adjacent to the converging nucleus, reducing progressively toward the cave margins. The objective was to create a high-porosity zone capable of redistributing the column load away from the converging area towards the cave boundaries where competent rock and cave walls could carry it (as illustrated in Figure 4).



(a) (b)

Figure 4 (a) Plan view of the targeted load redistribution draw strategy applied at Northparkes E48; (b) Section view illustration of the draw cones decreasing away from the convergence area. The grey area denotes the converging/point-loaded zone; orange drawpoints carry the highest draw call (22 buckets), grading through to green drawpoints with the lowest call (6 buckets)

TLRD is best understood as a transitional intervention: it is applied to arrest or reverse a deteriorating loading condition and restore conditions under which more conventional draw control, including SSD, can be resumed. It is not a permanent draw philosophy and is to be abandoned if no stability improvements after a few weeks. Once convergence has ceased and the muck column appears more fragmented and porous, the draw schedule should transition back to a grade or sequence-based approach. The appropriate transition criterion is best defined by geotechnical monitoring confirming stabilisation of convergence rates, and not simply the passage of time.

A critical distinction between TLRD and SSD is the spatial direction of the load redistribution objective. SSD advances a moving strip front of active drawbells progressively from a (stressed) zone toward the cave margin, distributing load shift/relief across successive strips. TLRD applies maximum draw from the core of the problem outward simultaneously, creating a radial porosity gradient rather than a planar one. In practice, the 2 strategies may be combined: TLRD applied to arrest acute convergence, followed by transition to SSD to maintain load redistribution discipline once the immediate threat is stabilised.

5 Limitations of load shedding in current cave designs

5.1 The drawpoint spacing dilemma

The effectiveness of load shedding as a stress management tool is fundamentally dependent on the ability to create sufficient porosity across an adequate area to interrupt stress transmission, specifically by destroying the compacted bridging arches that form between non-interacting draw cones. This, in turn, depends critically on whether adjacent draw cones interact sufficiently to mobilise material in the zones between drawpoints.

Herein lies a significant and growing incompatibility between the requirements of effective load shedding and the design parameters of modern cave mines. Over the past 3 decades, cave mine designs have progressively increased drawpoint spacing (Flores & Karzulovic 2002), driven by larger load–haul dump buckets and stability requirements for apex pillars under high-stress conditions and the assumption, contested by the authors, that wider drawzone dimensions develop in high-column, high-stress environments or that larger pillars ensure extraction level stability. Furthermore, economic pressure to speed up development and production ramp-up is frequently ‘resolved’ by widening extraction level layouts.

The direct consequence of wider drawpoint spacing for load shedding is that larger drawpoint spacings produce larger minor and major apex pillars. Where stress concentrations occur, particularly in the vicinity of adverse structures or poor undercut zones, these larger pillars may be exposed to substantially higher loads than simple tributary-area loading assumptions would suggest. More critically, larger spacing reduces the probability of drawzone interaction, preserving stagnant compacted zones between draw cones that act as persistent high-stress conduits to the extraction level (van As et al. 2008, 2011; Dudley 2014).

5.2 Reduced capacity for stress redistribution

In a mine layout where drawpoint spacing exceeds the effective drawzone interaction diameter, isolated draw becomes the dominant flow regime, to varying degrees, regardless of draw discipline (as described by Laubscher 1994, 2000). Under these conditions, no draw sequence – however carefully designed and rigorously enforced – can achieve the lateral stress redistribution that effective load shedding requires. The stagnant columns between non-interacting draw cones remain intact (at least for tens of metres above the extraction level), compact under load, and progressively intensify their role as detrimental vertical stress conduits.

There is a prevailing industry view (primarily based on physical modelling) that interactive draw conditions are more likely at greater depths and higher column heights, as higher stresses are assumed to produce wider draw cones and broader zones of fragment interaction. This view underpins arguments for wider drawpoint spacings in deep, high-column cave designs (Castro et al. 2007; Trueman et al. 2008; Paredes 2022). The authors of this paper dispute this view on empirical grounds. Field evidence from several operations demonstrates that drawzone dimensions in high-column environments frequently contract rather than expand over time, as progressive fragmentation, fining and compaction of the muckpile column reduce effective flow widths (Van Hout et al. 2024). Designs based on the assumption of wide-draw interaction may, in fact, operate under isolated draw conditions, significantly limiting the load shedding capacity of any draw control strategy.

The implication is significant. In current high-column cave designs with wide drawpoint spacings, the very layouts intended to address high-stress stability by providing larger pillars are simultaneously reducing the capacity to shed load from those pillars.

5.3 Structural domains and delayed loading events

A further limitation of current load shedding strategies is their limited ability to adequately address loading events arising from the delayed or sudden mobilisation of large structural blocks, leading to plug-type caving. In high-column caves, large volumes of rock bounded by faults and shear zones may remain partially coherent and structurally supported for extended periods before losing support and transmitting their mass load to the extraction level, as illustrated in Figure 1. The timing and location of these events are difficult to predict with confidence, while their loading effect can be intense and rapid.

When such structural loading events coincide with existing convergence in the extraction level, the combined effect can overwhelm the capacity of load shedding to respond. By the time the loading signature is identified in monitoring data and a draw response is initiated, significant additional extraction level damage may have already occurred. This highlights the reactive rather than proactive nature of current load shedding practice.

Effective management of structurally-driven point loading will ultimately require better integration of structural geology interpretation, real-time monitoring of cave-back geometry and deformation, and proactive adjustment of draw schedules before major loading events develop rather than in response to convergence already observed. It is the authors' opinion that the use of hydraulic fracture, rock mass preconditioning to break up these large blocks prior to cave initiation, is a novel application, though a detailed discussion of this topic is outside of the scope of this paper.

6 Draw rate guidelines and cave maturity

Any discussion of load shedding strategy must be contextualised within the broader framework of cave maturity and draw rate management. Poorly executed load shedding, if applied through excessive draw rates that violate maturity constraints, can produce poor outcomes due to isolated draw, such as accelerated and uncontrolled cave propagation, chimneying or plug caving, and rapid dilution ingress.

The authors emphasise that load shedding is a sequencing discipline, not a tonnage problem. The draw rate applied to any individual drawpoint during SSD or TLRD must remain within the maturity-based limits summarised in Table 1. Exceeding these rates to accelerate stress relief is counterproductive and risks triggering the very cave propagation instabilities that load shedding seeks to avoid.

Table 1 Recommended maximum draw rates by cave maturity stage (indicative guidance). All cave pre-breakthrough draw rates may need to be reduced under airblast trigger action response plans. Deviation from guidelines should only be considered on the basis of monitoring data confirming that increased draw rates do not compromise uniform cave growth, fragmentation, or drive stability

Cave maturity stage	Draw rate (mm/day)	Approximate tonnage (t/dp/day)
Initiation/pre-HR_{cr}, ≤3 months	≤50	30–50
Post-HR_{cr}, 3–6 months	75	~70
Post-HR_{cr}, 6–9 months	130	~120
Continuous caving, ≥9 months	150	~140
Post-breakthrough (steady state)	>200	150–200

The maturity rules reflect the physical reality that the rock mass above the cave requires time to degrade uniformly under stress before draw rates can be safely increased. Premature acceleration causes, besides oversized material, preferential propagation through weaker rock domains, preventing stresses from acting on more competent domains, resulting in an irregular cave-back and undesired rilling. All of which increases the risk of losing parts of the resource that will no longer cave, facilitating early dilution entry. In the context of load shedding, this means that the rate of stress relief achievable through draw is constrained by the cave's maturity status and cannot be arbitrarily accelerated to rapidly address the convergence already underway.

This constraint reinforces the importance of implementing SSD proactively, as soon as indicators of draw isolation and early convergence are identified, rather than reactively once significant extraction level damage has accumulated. Where deterioration has already developed to the point of active convergence or structural point loading, TLRD provides the appropriate immediate response but remains equally constrained by maturity-based draw rate limits.

7 Consequences of inadequate draw control in high-column environments

The consequences of failing to implement or maintain effective draw control in high-column caves are well documented across multiple published case studies. The common failure pathway is consistent regardless of mine geometry or operating context: isolated draw develops, compacted stagnant zones form between draw cones, point loading intensifies on pillars and drives, convergence accelerates, and extraction level functionality is progressively lost. The common failure mechanism is not cave height, stress level, or footprint size, but the inability to sustain interactive draw. Once draw becomes isolated, cave behaviour transitions rapidly from controlled mass flow to unstable, localised collapse and premature dilution. One of the most comprehensively documented (internally) case studies of this failure pathway involves a block cave in a high-stress volcanic and porphyry rock mass. At this operation, ramp-up constraints were not adhered to under production pressure, on the basis that fine fragmentation from the highly stressed volcanic domain implied adequate cave maturity. The consequence was rapid, uncontrolled cave propagation through the weaker domain, early breakthrough into previously caved workings, causing rilling of the waste rock from this old cave. Consequently, this prevented the adjacent competent rock mass domain from caving. The resulting inverted, funnel cave geometry dramatically accelerated the ingress of overlying dilution material, and early dilution combined with the persistent uncaved overhang ultimately sterilised a substantial portion of the planned ore reserve, forcing premature closure of the caving operation.

Key quantitative outcomes from this operation illustrate the magnitude of deviation between planned and actual performance:

- actual reserve recovery: approximately 53% of planned recovery
- cave breakthrough: 4.5 months actual against 3.5 years planned
- cave propagation rate: up to 4.0 m/day actual against 0.2 m/day planned
- dilution entry: dilution observed after only 11 months, against the planned late-in-mine-life dilution entry.

Detailed back-analysis confirmed that isolated draw dominated throughout, with back-calculated drawzone diameters of approximately 4.5–7.0 m, significantly smaller than the assumed design value used in the scheduling software. Rilling along the cave-back interface was the dominant mechanism for rapid lateral and vertical material migration, creating flow conduits responsible for more than 400 m of vertical movement within 6 to 10 days. The magnitude of deviation between planned and actual outcomes cannot be explained by geological variability alone; the discrepancy is directly attributable to the failure to follow the production ramp-up rules and not having developed interactive draw during early cave development.

At several other operations, similar patterns have emerged, leading to complete or near-complete closure of extraction drives in areas where isolated draw persisted (similar to that described at Northparkes Mines by Talu et al. 2010) and to point loading exceeding the load-bearing capacity of pillars on the extraction level. It is important to note that the geotechnical context differs between operations: some cases reflect primarily extreme column loading in competent rock, and others reflect a combination of loading and weak rock mass conditions producing a low strength-to-stress ratio. The appropriate emphasis of the mitigation strategy, load shedding through SSD for ongoing stress redistribution and TLRD for acute convergence or point load response, versus rock mass reinforcement and rehabilitation, depends on this distinction. The fundamental principle, however, is consistent: once draw interaction is lost, and stress conduits form, extraction level deterioration is difficult to reverse, regardless of rock mass quality.

8 Implications for future cave mine design

8.1 Cave height as a critical design parameter

The evidence presented in this paper indicates that cave column height is a primary driver of extraction level loading intensity. Above a critical column height threshold, suggested to be in the range of 500 to 800 m under typical deep cave conditions, the loading regime transitions from manageable column loading to the qualitatively more severe regime of overburden weighting and structural block mobilisation described in Sections 2 and 5. The precise threshold is site-specific and depends on rock mass strength, structure, depth, and in situ stress conditions.

This has a direct and important implication for future cave mine design: maximising cave column height to improve reserve recovery from a single-lift cave may be counterproductive if the resulting extraction level loading cannot be managed over the planned life of the lift. Where excessive cave heights lead to premature loss of extraction level functionality due to convergence, the realised recovery and productivity may fall short of what is achievable from multi-lift caves.

In such cases, consideration should be given to configurations involving multiple lifts of more moderate column heights, particularly when they allow for sustained extraction level integrity and more effective management of loading conditions over time. The optimal approach will depend on the economic value of the orebody, grade distribution, and the relative trade-offs between recovery, productivity, and infrastructure preservation.

It may be argued that current numerical modelling approaches aim to address this issue by explicitly evaluating extraction level stability across different cave heights and layouts. However, in practice, these approaches often fall short of reliably capturing the onset and progression of extraction level damage in deep, high-column caves. This limitation arises from several factors. Firstly, the structural and geological framework controlling rock mass behaviour, particularly the presence, persistence, and strength of faults/shears and other major discontinuities, is often insufficiently constrained, yet these features fundamentally govern the development of large, partially mobilised rock blocks and associated point loading. Secondly, constitutive models and input parameters are typically calibrated to intact or moderately fractured rock mass behaviour and may not adequately represent the progressive degradation, bulking evolution, and load transfer mechanisms that occur within a caving rock mass.

In addition, numerical models generally assume adherence to planned mining sequences, draw strategies, and production ramp-up profiles. In practice, operational deviations, such as accelerated ramp-up, uneven draw, delayed development, etc., can significantly alter cave geometry, stress redistribution, and loading conditions on the extraction level, often in ways not captured by models. Furthermore, most modelling approaches struggle to represent the transient and highly localised nature of point loading associated with the delayed mobilisation of structurally bounded rock masses, particularly when these processes are governed by time-dependent damage and episodic failure (van As 2023).

The authors therefore propose that future cave designs explicitly evaluate maximum cave column height as a critical design parameter, defined not solely by orebody geometry or modelled stability, but by the loading threshold beyond which extraction level preservation cannot be reliably maintained under realistic geological uncertainty and operational conditions.

8.2 Pillar size, drawpoint spacing, and load shedding compatibility

As argued in Section 5, current industry trends toward wider drawpoint spacings and larger pillars in deep cave designs are increasingly working against the objective of effective load shedding. While the design tension between pillar stability and draw interaction capacity is real, the balance point in current practice has shifted too far toward wider spacings. Larger pillars in high-column caves do not simply represent more stable structures; they act as large load-bearing stress concentrators. Once these pillars begin to fail under point loading, failure tends to be more catastrophic and far less amenable to recovery through draw intervention. In contrast, smaller and more numerous pillars operating under interactive draw conditions distribute load more uniformly across the extraction level and provide greater opportunity for stress redistribution through sequenced draw and load shedding.

Importantly, the preservation of the extraction level footprint may depend not only on drawpoint spacing but also on excavation geometry. Smaller excavation spans and reduced drive dimensions may prove more effective at maintaining long-term infrastructure stability than simply increasing drawpoint spacing. It is often neglected by design teams that narrower drives reduce exposed span, improve confinement of the surrounding rock mass, and significantly reduce vulnerability of the extraction level to convergence once point loading develops.

Future cave designs should explicitly evaluate drawpoint spacing against the criterion of draw interaction capacity, using conservative and defensible estimates of isolated drawzone dimensions appropriate to the specific rock mass (fragmentation) and cave column height. Designs that cannot achieve interactive draw across the extraction footprint under realistic operating conditions should be reconsidered rather than rationalised through optimistic assumptions regarding drawzone widths in high-column environments.

8.3 Technology requirements for effective load shedding

The operational demands of effective load shedding in high-column caves exceed the capabilities of current standard dispatch and draw control systems that are optimised for productivity. Several technology developments are required to make both SSD and TLRD reliably executable strategies at the speed and precision demanded by active convergence management:

- real-time extraction level convergence monitoring with spatial resolution sufficient to identify the boundary and progression of stressed zones before irreversible damage occurs
- draw control software capable of enforcing strict sequence-based draw orders on a shift-by-shift basis, without override by short-interval productivity optimisation logic
- integration of cave-back geometry monitoring, from seismic, cave tracker, network smart marker or equivalent technologies, with draw scheduling to enable proactive identification of structural loading events before convergence develops
- rapid drawpoint rehabilitation technology capable of maintaining extraction level access in zones of active convergence, so that SSD and TLRD can be sustained through periods of rehabilitation without creating draw gaps that undermine sequence continuity or spatial targeting.

In the longer term, autonomous or semi-autonomous draw execution systems that reliably enforce sequence-based and spatially targeted draw in real-time, without relying on human dispatcher compliance across multiple shifts, would significantly improve the consistency and effectiveness of both SSD and TLRD in high-column environments.

8.4 Multiple lifts as a design response to column height limits

If cave column height must be treated as a critical design parameter subject to an engineering maximum, then orebodies with large vertical extents may need to be mined as multiple sequential caving lifts rather than a single high-column block. This represents a significant departure from the current industry preference for maximising the size and column height of individual cave blocks to reduce development and construction costs.

The economic case for multiple lifts must account not only for additional development costs, but also for the reserve recovery penalty imposed by extraction level deterioration in high-column single-lift designs, the rehabilitation costs associated with managing convergence in deep environments, and the risk premium associated with catastrophic extraction level loss in the event of severe point loading. When these factors are comprehensively incorporated into economic evaluation, the case for multiple lifts of controlled column height may become considerably stronger than a simple comparison of development unit costs would suggest.

9 Conclusions

This paper has examined the progressive evolution of loading mechanisms in deep, high-column cave mines and their implications for extraction level management and cave mine design philosophy. The following principal conclusions are drawn.

The dominant loading mechanism at the extraction level in deep, high-column cave mines is the sustained overburden weighting and highly localised point loading, driven by the partial mobilisation of large structural rock blocks. This becomes particularly severe above cave column heights in excess of 500 to 800 m, and is qualitatively more damaging and less amenable to conventional support-based mitigation. Zones adjacent to major adverse structures and areas of poor undercut performance represent the highest-risk nuclei for convergence initiation.

The established principles of cave draw control, interactive draw, uniform drawdown, cave maturity constraints, and strict sequence discipline remain valid and must be maintained. They are not superseded. However, they are insufficient on their own in deep, high-column environments and must be augmented by stress/damage management draw strategies. All these traditional draw control strategies are implementations of load shedding; they differ in execution, not in principle.

SSD provides the primary structured mechanism for stress redistribution and extraction level convergence management in high-column caves. SSD is a fast-moving, cyclic, shift-to-shift sequencing discipline, distinct from both general load shedding interventions and historical De Beers-style wide strip draw practices, whose effectiveness depends on strict sequence control, consistent draw waves, elimination of short-term catch-up logic, and boundary-focused application of increased draw.

Where acute convergence or point load events require an immediate, spatially focused intervention, TLRD provides a defined strategy distinct from SSD. TLRD concentrates draw on and around the converging zone to develop porosity and interactive draw conditions preferentially in the target area, redistributing column load outward toward the cave boundaries. TLRD is a transitional measure intended to arrest deterioration; once convergence is stabilised, draw discipline transitions to SSD or conventional grade-based scheduling as geotechnical conditions permit. The 2 strategies are complementary: TLRD arrests acute loading events and SSD maintains load redistribution discipline over the life of the extraction level.

Current cave mine designs, characterised by wide drawpoint spacings and large pillars, are increasingly incompatible with effective SSD, TLRD, and load shedding more broadly. The trend toward wider drawpoint spacings reduces draw interaction capacity, increases stress concentration on individual pillars, and limits the spatial effectiveness of draw in redistributing stress. This design parameter requires critical re-examination.

The long-term viability of deep, high-column cave mining will require a paradigm shift in design philosophy: treating cave column height as a controlled parameter with an engineering maximum, evaluating drawpoint spacing against draw interaction criteria, integrating column loading management as a primary design objective, and considering multiple lift configurations where column heights cannot be maintained within manageable limits. Current numerical modelling approaches are insufficient to reliably predict the onset and progression of extraction level damage in deep, high-column caves. Structural uncertainty, limitations in constitutive models calibrated to moderate rock mass conditions, and the inability to represent the transient, localised nature of point loading from delayed structural block mobilisation all constrain confidence in numerical model-based design. Cave height thresholds and pillar sizing decisions must therefore be informed by operational experience and conservative geological assumptions, not solely by modelled stability outputs.

Preserving the extraction level over the life of the mine, rather than maximising short-term draw performance or minimising development costs, is the controlling criterion for successful cave mining at depth.

Acknowledgements

The authors acknowledge the valuable operational experience and insights contributed by colleagues and technical staff at several cave mining operations, which have informed the observations and case evidence presented in this paper. The views expressed are those of the authors and do not necessarily represent those of any operating company or client organisation.

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