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Beyond a single conceptual caving model: monitoring evidence for multiple cave propagation mechanisms

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Abstract

Conceptual models of cave propagation, including the Duplancic framework and fracture banding, are commonly applied in practice as if they represent a single, generalised failure process. However, increasingly detailed monitoring data from operating cave mines indicate cave propagation patterns that are not always consistent with the assumptions of any single existing model.

This paper reviews principal cave propagation concepts described in the literature and presents selected tilt monitoring datasets from two operating cave mines that were originally implemented to track cave back location. During analysis, tilt changes were observed well ahead of the interpreted cave back, interpreted as spatially localised zones of elevated rock mass response separated by intervals of comparatively limited disturbance. Cave advance appears to occur in a non-continuous, stepwise manner towards these zones.

While such behaviour may be qualitatively consistent with fracture banding concepts or driven by geological features, the available datasets are incomplete and lack corroborating measurements, preventing definitive identification of the governing failure mechanism. The observations, however, are clearly inconsistent with the assumptions of a specific cave propagation concept, but more likely a combination of concepts. This paper therefore presents an intermediate assessment intended to document these behaviours, define current interpretive limitations, and outline lessons learned to guide future monitoring and investigation, rather than to validate any specific cave propagation model.

Keywords: *conceptual cave model, cave propagation, monitoring, tilt*

1 Introduction

Block and panel caving are among the most productive large-scale underground mining methods in the world and are increasingly applied to low-grade, high-tonnage orebodies that would be uneconomic to mine by alternative methods (Brown 2002). Caving relies on gravity-driven fragmentation of the orebody following undercutting, sustained by continuous draw through production drawpoints. Despite its operational simplicity at scale, a detailed understanding of the geomechanics governing cave propagation remains limited, largely due to the lack of direct visual access to the caving column during mining (Cumming-Potvin & Wesseloo 2014).

Understanding how a cave propagates – including its rate, direction, and failure mechanism – is central to managing key geotechnical risks associated with caving operations. These include cave back hang-ups, uncontrolled large-scale caving events with airblast potential, seismic hazard, and dilution resulting from out-of-orebody caving (Brown 2002). Consequently, significant effort has been invested in developing monitoring systems capable of characterising the evolving state of the rock mass within and above the cave column, as well as conceptual frameworks to support interpretation of the data generated by these systems (Cumming-Potvin & Wesseloo 2014; Kamp et al. 2024).

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Since its introduction, the conceptual model of cave propagation proposed by Duplancic & Brady (1999) has served as the dominant interpretive framework for cave monitoring across the industry. The model describes a set of spatially distinct zones characterised by increasing rock mass damage towards the cave back, advancing progressively upwards as caving propagates. This framework has remained largely unchallenged in operational practice despite growing evidence from physical modelling, numerical simulations, and selected field observations suggesting that alternative or complementary damage development patterns may occur ahead of the cave back that are neither continuous nor gradual (Cumming-Potvin et al. 2016a; Cumming-Potvin et al. 2018; Wesseloo et al. 2020).

In response to these observations, Cumming-Potvin et al. (2018) proposed an extended conceptual model incorporating a fracture-banding mechanism, in which discrete, subparallel fracture zones develop ahead of the cave back and exert a primary control on cave propagation, rather than a continuously advancing damage front. Fracture banding has been demonstrated in geotechnical centrifuge experiments and is qualitatively consistent with selected microseismic interpretations from operating mines.

However, fracture banding remains a theoretical construct derived primarily from physical modelling, numerical simulations, and indirect interpretations of field datasets. While the predicted signatures provide a useful reference framework, identifying fracture banding in operating mines requires targeted, dense, early-installed, and multi-modal monitoring arrays, ideally supported by independent corroborating datasets. Such datasets have not been consistently obtained because most operational monitoring programs are designed to identify cave back locations and manage immediate hazards, rather than to distinguish detailed mechanisms of cave propagation.

While analysing monitoring datasets originally implemented to delineate cave back location, the authors observed deformation patterns occurring well ahead of the interpreted cave back. The key observation was not merely that individual markers tilted, but that tilt response appeared spatially organised into localised intervals, with comparatively stable intervals between them. In several examples, these intervals developed ahead of, and were later approached by, the interpreted cave back.

This behaviour is not readily explained by a simple continuous damage front alone. It may reflect fracture banding, activation of geological structures, lithological contrasts, rock mass stresses, cave shape driven by draw, or a combination of these mechanisms. The available datasets are incomplete and lack sufficient independent corroboration to confidently identify the governing mechanism.

Nevertheless, the observed behaviour is sufficiently significant to warrant documenting because it indicates that dense deformation monitoring may detect early rock mass damage ahead of the cave back.

Accordingly, this paper presents these observations as an intermediate assessment rather than a conclusive validation of any specific cave propagation mechanism. The intent is to document current observations, highlight the limitations of the available datasets, and outline lessons learned to inform future monitoring design and investigation.

Specifically, this paper aims to:

- revisit the Duplancic framework and the fracture banding model, highlighting their key characteristics, assumptions and expected monitoring signatures
- present selected Geo4Sight tilt monitoring datasets from two operating cave mines and document observed spatial-temporal deformation patterns.

2 Conceptual models of cave propagation

2.1 The Duplancic framework

The Duplancic conceptual model (Duplancic & Brady 1999) remains the industry standard for interpreting cave behaviour and monitoring data. It describes the cave column in terms of five spatially distinct zones, each characterised by a specific state of rock mass damage (Figure 1):

- Pseudo-continuous Domain (Elastic Zone): the intact rock mass surrounding and overlying the caving column. The rock mass in this region remains largely undamaged, with stresses redistributed elastically from the undercut.
- Seismogenic Zone: the region of rock mass adjacent to the yielded zone in which stress changes induced by cave progression cause seismicity through slip on joints and brittle fracturing. This zone is the primary target of microseismic monitoring systems.
- Yielded Zone (Zone of Loosening): the region between the seismogenic zone and the cave back in which the rock mass has been fractured and has lost cohesive strength. Rock mass in this zone provides minimal support to the overlying material. Time-domain reflectometer (TDR) cable breaks, signal loss in open holes, and extensometer displacement are expected in this zone.
- Airgap: the void that may exist between the cave back and the top of the muckpile.
- Mobilised (Caved) Zone: the granular mass of broken rock that has fallen from the cave back onto the muckpile.

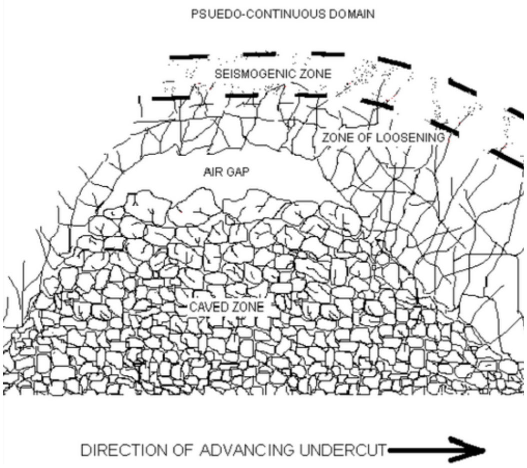

Figure 1 Conceptual caving model extracted from Duplancic & Brady (1999)

A key implication of the Duplancic model is that the transition from intact to fully caved rock is spatially continuous and gradual: the degree of damage decreases monotonically with increasing distance from the cave back. From an instrumentation perspective, this implies that sensors should be progressively disturbed as the cave advances towards them, with deformation increasing incrementally over time. Boundaries between zones are described as diffuse rather than sharp (Brown 2002). In practice, however, geology, stress state, cave geometry and draw control may modify this idealised response.

This framework has been applied to interpret monitoring data from most major block and panel cave operations worldwide, providing a vocabulary for communicating cave state and a structure for integrating monitoring datasets (Kamp et al. 2024). However, the model was originally inferred from indirect observations and has seldom been rigorously field-validated against direct, spatially dense monitoring data.

2.2 Fracture banding

Building on geotechnical centrifuge experimental work (Cumming-Potvin et al. 2016a, 2016b), Cumming-Potvin et al. (2018) proposed a fracture-banding mechanism of cave propagation that presents a fundamentally different view of damage progression.

In fracture banding, cave propagation does not proceed via a continuously advancing damage front. Instead, discrete fractures (or fracture zones) form ahead of the cave back, parallel to the cave surface. The cave back then progresses via ‘jumps’, advancing to each successive fracture band as the rock mass between the cave and that band collapses. The resulting damage profile is discontinuous, with peaks at each fracture band and comparatively undamaged rock in between (Figure 2).

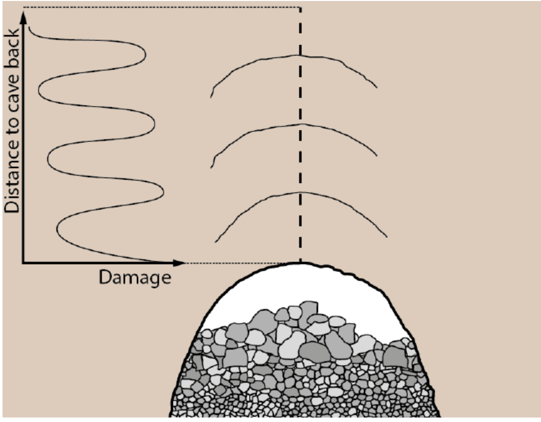

Figure 2 Illustration of discontinuous damage profile associated with fracture banding extracted from Cumming-Potvin et al. (2016a)

The key characteristics of fracture banding identified by Cumming-Potvin et al. (2018) and Wesseloo et al. (2020) are:

- Discontinuous damage profile ahead of the cave back. This discontinuity is not predicted by the Duplancic model.
- Parallel fracture orientation. Fractures form parallel to the cave surface and share the curved geometry of the cave back. This has been observed in centrifuge experiments and numerical models.
- Consistent spacing. The spacing between successive fracture bands within a single banding episode is relatively consistent. The characteristic spacing may vary between mines depending on rock mass strength and in situ stress.
- Temporal overlap. New fracture bands can begin to form before existing bands have fully collapsed. Multiple bands may be simultaneously active, creating a spatially distributed but organised pattern of microseismic activity.
- Influence of geological structures. Mine-scale discontinuities such as faults and contacts can bound the lateral extent of fracture bands, creating discontinuities in the banding pattern across structural domains.
- Extensional fracture mechanism. Particle image velocimetry (PIV) analysis of centrifuge tests indicated that the initial movement associated with fracture formation is perpendicular to the fracture plane, consistent with an extensional (tensile) mechanism. Secondary shear fractures predominantly occurred on the sides of the cave, closer to the abutment.

This mechanism has also been supported by the physical modelling work published in Wesseloo et al. (2020). Their work confirmed that cave propagation in the centrifuge is dominated by extension fracturing initiating at the cave crown, with secondary shear fracturing near the abutment.

The microseismic signature of fracture banding is distinct from that expected from continuous damage accumulation: rather than a diffuse, approximately spatially uniform distribution of events within the seismogenic zone, fracture banding produces spatially concentrated bands of microseismic activity that are roughly parallel to the cave surface (Cumming-Potvin 2018). Analysis of microseismic data from multiple operating caving mines identified patterns consistent with fracture banding (Cumming-Potvin 2018).

An important distinction must be made between the fracture-band mechanism and remote fracturing. Remote fracturing refers to isolated fracturing that may occur well beyond the primary yielded zone, often driven by stress interactions with adjacent mining, geological heterogeneity, or structural effects. Remote fracturing is a localised phenomenon (Kamp et al. 2024), whereas fracture banding is a systematic, cave-scale propagation mechanism.

2.3 Comparative summary

Table 1 summarises the principal distinguishing characteristics of the Duplancic continuous model and the fracture-banding model. These are not mutually exclusive: both mechanisms may operate together and at different spatial scales, at different elevations, in different structural domains, or at different stages of cave development within a single mine. This observation is central to the interpretive framework proposed in this paper.

Table 1 Comparison of principal cave propagation mechanisms

Characteristic	Duplancic (continuous)	Fracture banding
Damage profile	Continuous, decreasing with distance from cave	Discontinuous; peaks at fracture bands
Zone boundaries	Diffuse	Relatively discrete
Propagation style	Gradual, continuous advancement	Episodic 'jumps' to successive bands
Fracture orientation	Broadly parallel to cave back	Strongly parallel to cave back
Microseismic signature	Continuous, diffuse seismogenic volume	Banded, parallel to cave concentration
Monitoring signature	Progressive, gradual sensor response	Episodic step changes in sensor response

2.4 Panel caving

Panel caving is a variant of the cave mining method characterised by orebodies with large footprints that cannot be economically undercut in a single block within an acceptable timeframe. Rather than completing the undercut across the entire footprint before commencing production draw – as in block caving – panel caving progressively advances the undercut along the length of the footprint, with drawbell construction and commissioning approximately in equilibrium with drawbell closure rates for the given production target (Brown 2002; van As & Guest 2020). Although the terms 'block cave' and 'panel cave' are used interchangeably in much of the industry reporting, the two methods are operationally and geomechanically distinct (van As & Guest 2020).

The defining geometric distinction between block and panel caving is the relationship between footprint dimensions and caving column height. In block caving, the footprint is approximately equidimensional and the column height typically exceeds the footprint width, producing a broadly symmetric caving geometry in which uniform draw across the entire footprint aims to maintain a near-horizontal cave back and promote mass flow above the height of interaction zone. In panel caving, the footprint length substantially exceeds the column height (van As & Guest 2020) and production is sustained by the continuous advance of the undercut face. The resulting cave geometry is inherently asymmetric: the drawn-down leading end maintains a more advanced, lower muckpile, while the lagging end receives fresh undercut material as the panel progresses. The draw philosophy for a panel cave must actively develop and maintain an inclined ore–waste interface, typically at approximately 45° to horizontal, to ensure controlled dilution entry and maximum ore recovery (Laubscher 1994; van As & Guest 2020).

The Duplancic zone framework and the fracture-banding mechanism were originally developed and validated from block cave observations and centrifuge experiments with symmetric cave geometries (Duplancic & Brady 1999; Cumming-Potvin et al. 2016a; Schoeman et al. 2022). The Duplancic zone vocabulary remains applicable, but the geometry of zone boundaries must conform to the inclined cave profile of a panel cave rather than the near-horizontal boundaries assumed in many block cave implementations. Similarly, fracture banding – where operative in a panel cave – would produce tilt activation fronts inclined in sympathy with the cave geometry rather than the horizontal bands characteristic of block cave observations. The case studies presented in this paper include both a panel cave and a block cave, providing an opportunity to compare monitoring signatures across cave types.

3 Cave monitoring methods

3.1 Overview

The limited access to the caving column means that cave monitoring is, by necessity, indirect. A range of monitoring technologies is employed, each suited to characterising different aspects of the cave state within the Duplancic zone framework (Cumming-Potvin & Wesseloo 2014; Kamp et al. 2024):

- Open hole surveying provides direct point measurements of the cave back or muckpile level by lowering a camera or probe into a borehole from above. It is reliable, but episodic, and logistically challenging.
- TDR cables are grouted into boreholes and register cable breaks as the caving front advances past sensor depth.
- Microseismic monitoring is the primary volumetric technique, capturing seismic events within the seismogenic zone as distributed across a network of geophones installed in and around the mine. It is sensitive to the degree of rock mass damage but requires significant expertise to interpret in terms of zone boundaries.
- Extensometers provide point displacement measurements over a defined gauge length. They are useful for detecting the onset and magnitude of displacement but lose sensitivity once the rock mass has fully yielded.
- Geo4Sight, also known as Networked Smart Markers (NSMs), are wireless markers grouted into boreholes at known elevations and deployed as a networked monitoring array.

The advantage of multi-technology monitoring programs that combine several of the above methods has been shown to provide more robust characterisation of cave state than any single method alone.

3.2 Geo4Sight markers

The monitoring instrumentation used in this study was provided by Elexon (https://elexonmining.com), a specialist supplier of geotechnical monitoring systems for underground mining environments. Elexon borehole monitoring systems provide high-density, multi-parameter measurements, enabling spatial and temporal resolution beneficial for characterising cave propagation mechanisms. Geo4Sight communicates data wirelessly through rock and was specifically developed to withstand the rugged environment of caves and to continue measuring and communicating even as the rock mass deteriorates. This system provides unique insights that cabled instrumentation cannot provide due to the need to maintain cabled connections.

3.2.1 Tilt monitoring

Geo4Sight tilt markers employ accelerometer and magnetometers to capture tilt data, which are converted into dip and direction. Dip is the angle to the horizontal plane and the direction relative to north.

When deployed in dense arrays within a caving mine, tilt sensors provide a spatial profile of deformation that is highly complementary to the point measurements from other monitoring systems and can track deformation well before the rock mass reaches complete failure (Kamp et al. 2024).

A limitation of tilt monitoring is that it only captures differential lateral movement relative to the borehole orientation. If the movement does not cause tilt changes relative to the borehole orientation, for example, pure translation movement, the tilt markers will not capture the movement. If a change in tilt is reported, rock movement is confirmed; however, the absence of a change in tilt does not necessarily confirm no rock movement.

In the context of conceptual model discrimination, it is assumed that rock mass damage will cause differential lateral movement relative to the monitoring borehole orientation and the tilt magnitude is relative to the extent of rock mass damage. It should be noted that both the Duplancic model and fracture banding may be impacted by geological structures and rock mass variability; however, the following general tilt behaviour is expected::

- Under the Duplancic continuous model, tilt sensors should show a progressive, smooth increase in measured tilt change as the cave front approaches from below. The closest sensor to the cave back would show the highest tilt, with tilt decreasing monotonically with increasing distance from the cave.
- Under fracture banding, tilt sensors within and near a forming fracture band should show a relatively abrupt onset of tilt change – consistent with the sudden formation of a discrete fracture rather than gradual accumulation. Sensors just above the fracture band would show little deformation until the cave 'jumps' to the next band. This creates a spatial pattern of tilt enhancement that is concentrated at discrete elevation horizons rather than distributed across a smooth gradient.

The ability to distinguish between these patterns requires a sufficiently dense sensor array with near-continuous temporal resolution – characteristics that were partially met by the monitoring datasets described in this paper.

3.2.2 Radio signal strength indicator monitoring

Geo4Sight markers measure the strength of the radio signal when communicating between each other. The radio signal strength is normalised to obtain a radio signal strength indicator (RSSI). While RSSI cannot be used to measure distance between markers, a change in RSSI allows us to infer a change between markers, with a change in distance being the most likely. Markers typically lose communication at a distance of about 5–6 m, which allows us to infer displacement between markers.

4 Case studies

Tilt data from two anonymous hard rock mines – a panel cave and a block cave – are discussed in this paper.

4.1 Site A – panel cave

At Site A, the chosen example monitoring boreholes were drilled from close collar locations and dip at angles ranging from 25° to 35° and in a similar direction. Geo4Sight tilt markers were installed at 2 m intervals. The panel cave approached the boreholes laterally rather than from directly below. Figure 3 shows a schematic layout of the boreholes.

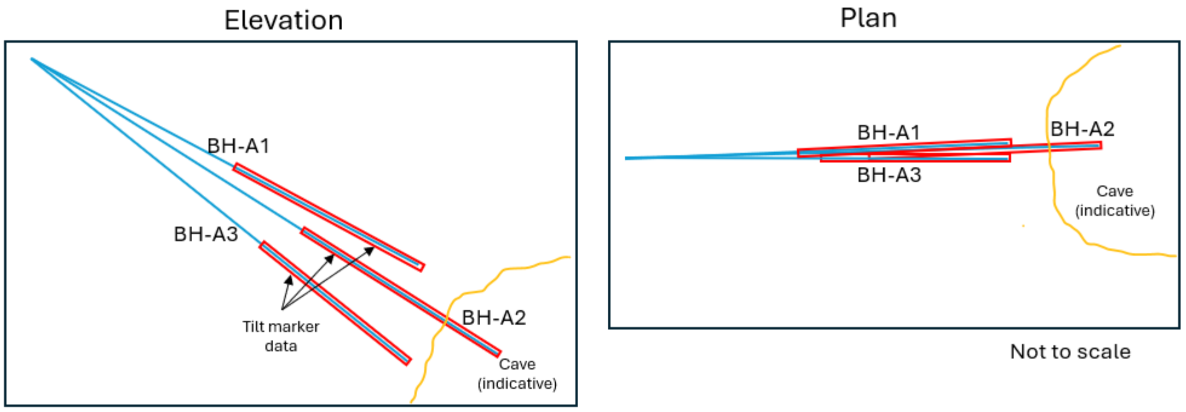

Figure 3 Schematic borehole layout – Site A

Figures 4 to 6 show the change in dip for Site A, boreholes BH-A1 to BH-A3. The change in dip is measured relative to the first dip measurement and presented as an absolute value. The vertical axis in the graphs represents the marker depth as measured from the collar, and the horizontal axis represents time.

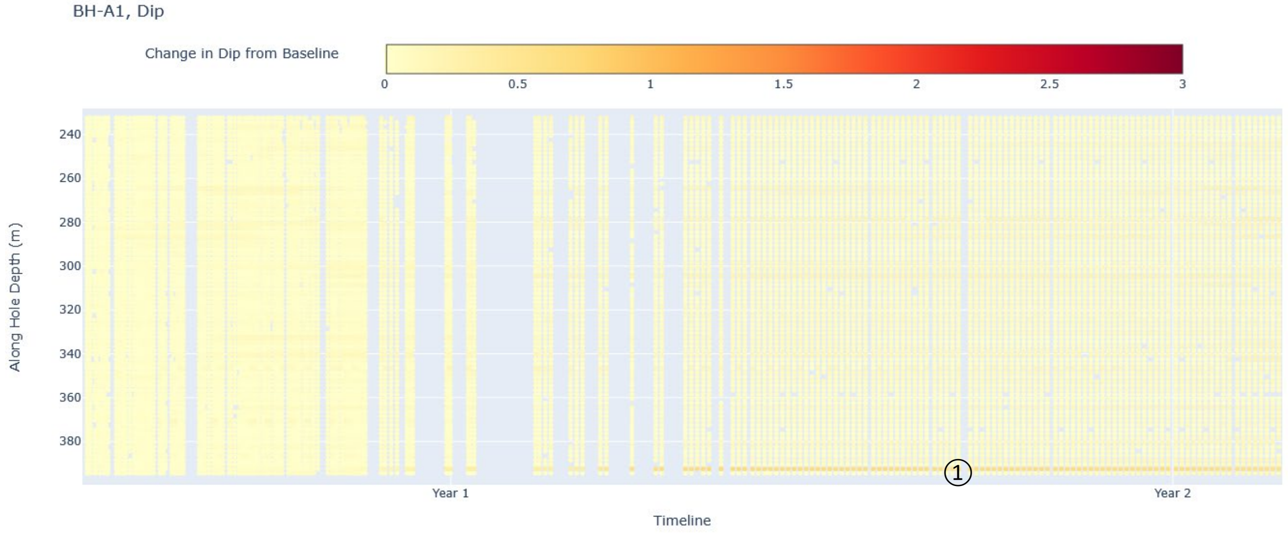

Figure 4 Change in dip – BH-A1

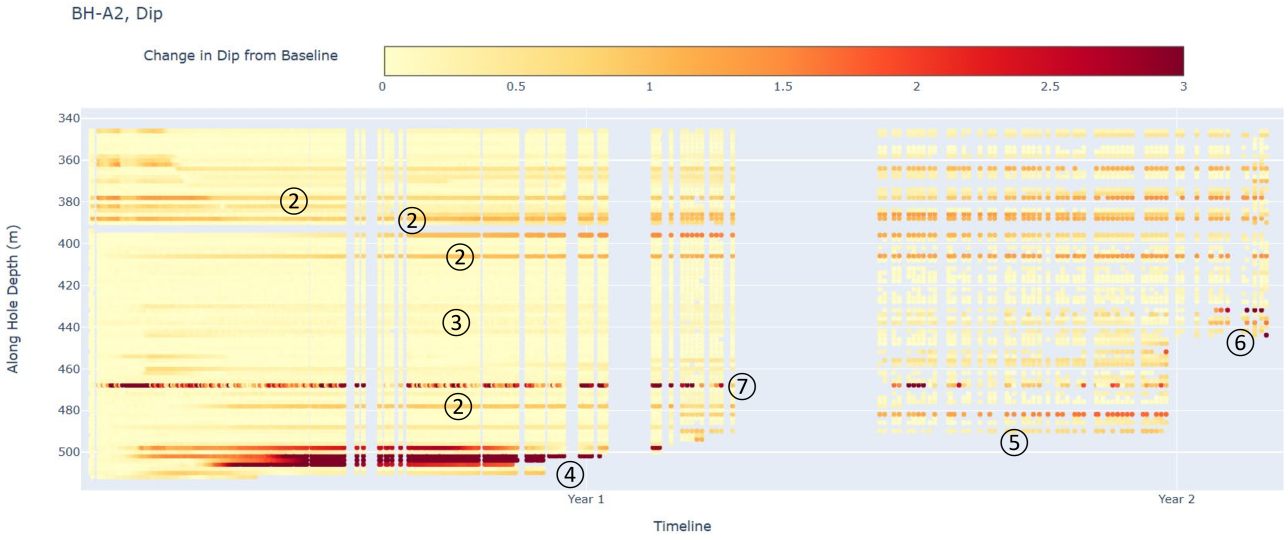

Figure 5 Change in dip – BH-A2

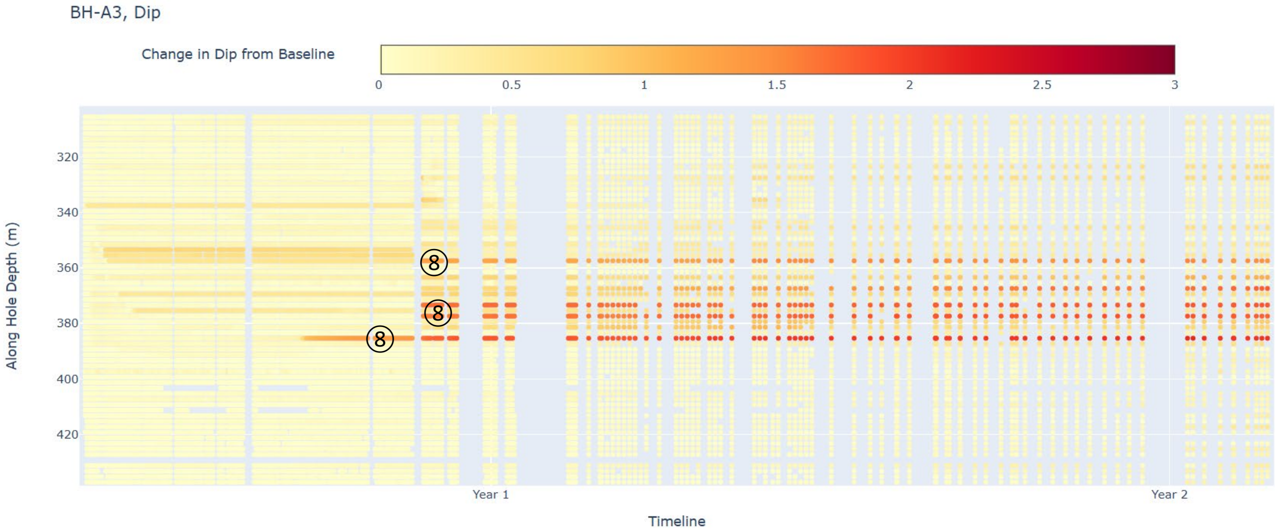

Figure 6 Change in dip – BH-A3

Where available, the interpretation should be considered against the local geological model, structural domains, undercut position, draw history, cave front orientation, and interpreted cave back position. Without these datasets, discrete dip change horizons cannot be uniquely attributed to fracture banding rather than structure-controlled deformation.

4.1.1 BH-A1

Borehole BH-A1 is the upper and the shortest borehole, i.e. the toe of the borehole is the furthest from the interpreted cave. The following is observed from Figure 4 for borehole BH-A1:

- The bottom marker shows a change in dip of about 0.6° (indicated as ①), with no significant dip change higher up in the borehole.
- The remainder of the measured section of the borehole shows no significant change in dip and is assumed to be stable, with no cave back penetration or significant deformation.

4.1.2 BH-A2

Borehole BH-A2 is the central borehole and extends the furthest towards the cave. The following was observed in Figure 5 for borehole BH-A2:

- The tilt markers installed in the borehole measured significant (typically more than 1°) changes in dip in distinct locations (indicated as ②), while the markers in between did not measure significant dip changes. The typical spacing between markers with significant changes in dip range from 8 to 12 m, except for a 60 m zone that exists with no significant dip changes (indicated as ③). This 60 m zone might indicate that the dip changes above are due to geological features rather than classic fracture banding.
- The lower approximately 20 m of markers gradually went offline (indicated as ④). This response is consistent with the interpreted cave location, as the markers going offline are interpreted as markers falling into the airgap and out of communication range of the markers above. The preceding elevated dip changes developed at this lower section may be interpreted as a continuous damage zone around the cave (in line with the Duplancic model). After the initial cave progress, the interpreted cave back did not progress for about 9 months (indicated as ⑤).
- While several dip change bands developed above the interpreted cave back (about 490 m depth and indicated as ⑤), the rock mass did not break back along these bands, but the cave rapidly progressed to a less prominent dip change zone about 65 m from the bottom of the hole (at about 450 m depth,

indicated as ⑥). This zone developed at a similar time to the lower zones, but exhibited dip changes of approximately 1°, which were smaller than those observed in lower tilt markers.

- Across the borehole, the repeated pattern consists of distinct markers or marker intervals that show progressive dip change, while intervening markers remain comparatively stable. Some markers show an increase in dip followed by a decrease in dip (for example, indicated in ⑦), which may reflect episodic deformation or stress redistribution.

4.1.3 BH-A3

The following is observed from Figure 6 for borehole BH-A3:

- No lower markers went offline. This may be interpreted as the cave had not yet reached the bottom of the hole. The data from the lower part of hole BH-A2 (the hole above) indicate possible cave back reaching the hole; it should be noted that hole BH-A2 extends further into the orebody.
- Several markers show progressive development of dip change exceeding 1° (indicated as ⑧). Early in the monitoring period, these markers showing dip change are spaced out. These markers may be interpreted as discrete deformation horizons and stable sections in between. A broader zone of response, approximately 30 m thick, appears to develop before Year 1, suggesting a more distributed deformation episode superimposed on earlier localised response.

4.1.4 Combined Site A interpretation

Across BH-A2 and BH-A3, repeated localised dip change horizons with intervals interpreted as comparatively stable based on their low measured dip change were observed along the length of the monitored holes, from an early moment of the cave's development. The dip changes increase late in the monitoring period, which may be interpreted as rock mass damage causing additional dip change.

4.2 Site B – block cave

At Site B, the monitoring boreholes are close to vertical, drilled from the surface, and the cave progresses upward. Figure 7 shows a schematic layout of the boreholes.

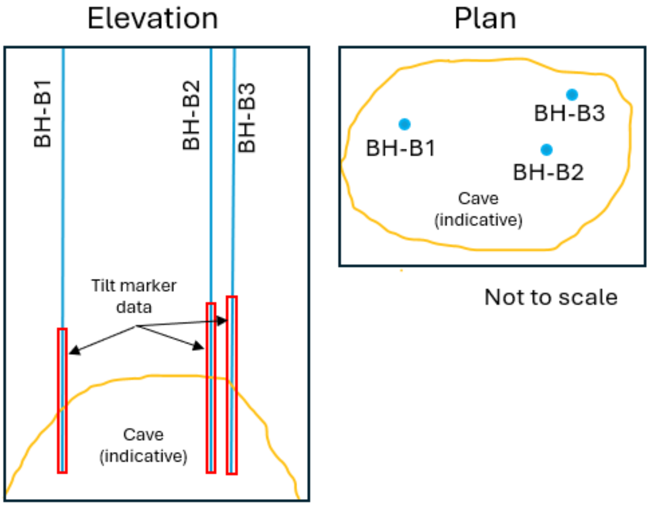

Figure 7 Schematic borehole layout – Site B

The tilt data from the boreholes were captured by Geo4Sight tilt markers. The markers in BH-B1 and BH-B2 were spaced at 4 m intervals and in BH-B3 at 2 m intervals during installation.

Figures 8 to 10 show the change in dip for Site B, boreholes BH-B1 to BH-B3. The change in dip is measured relative to the first dip measurement and presented as an absolute value. The vertical axis in the graphs represents marker depth, and the horizontal axis represents time.

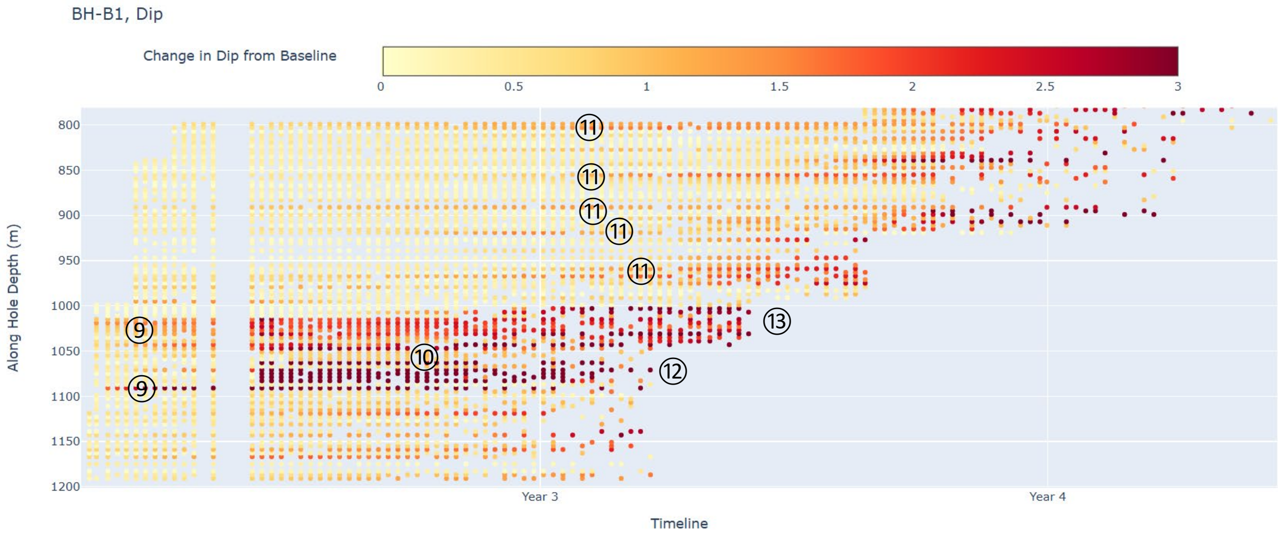

Figure 8 Change in dip – BH-B1

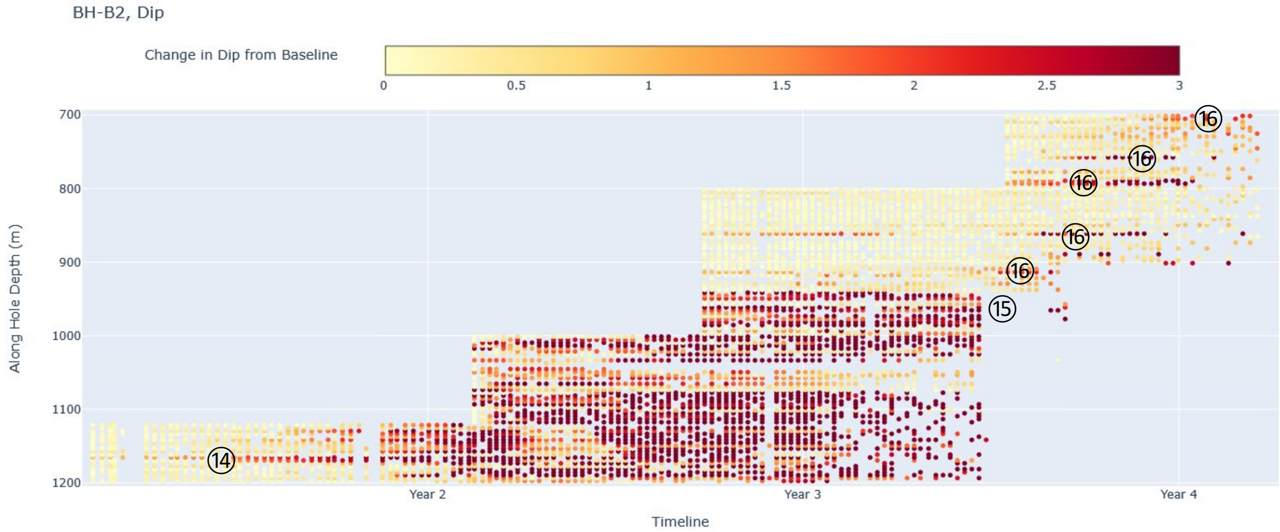

Figure 9 Change in dip – BH-B2

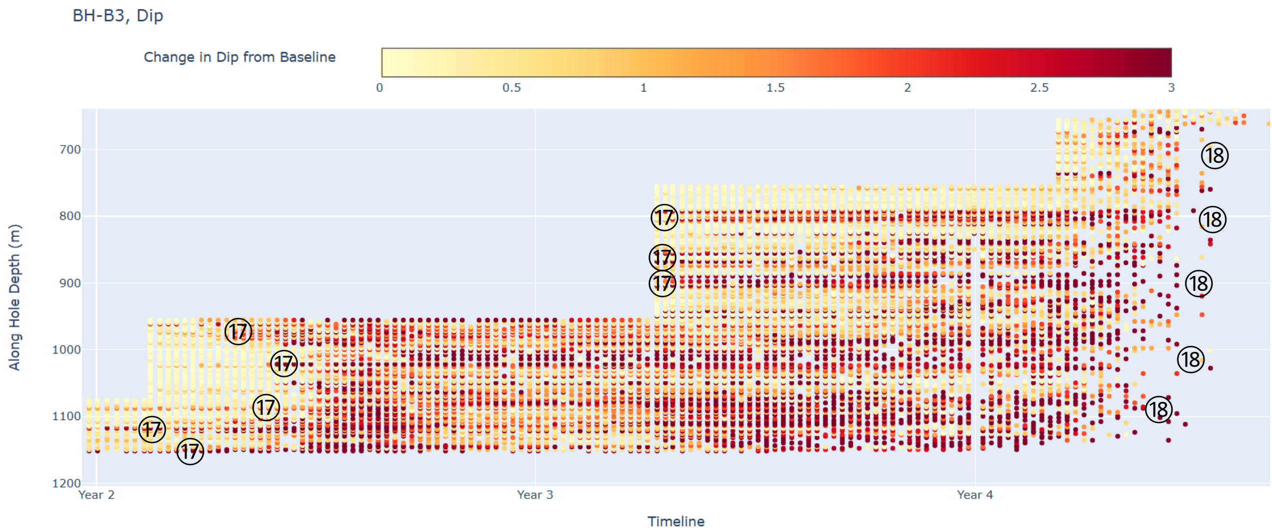

Figure 10 Change in dip – BH-B3

4.2.1 BH-B1

The following is observed from Figure 8 for borehole BH-B1:

- Multiple significant dip change horizons develop in the lower 200 m of the hole. Two significant dip change horizons (indicated as ⑨) expand their vertical extent (interpreted as expanding damage zones), with only a small band of low dip change measurements (interpreted as a stable zone) between them (indicated as ⑩).
- Multiple further significant dip change zones (indicated as ⑪) develop with deemed stable zones separating them.
- The cave appears to have progressed vertically to the first major significant dip change zone (indicated as ⑫) and then to continue to the second dip change zone (indicated as ⑬).
- The cave then continues stepwise, from significant dip change zone to significant dip change zone.

4.2.2 BH-B2

The following is observed from Figure 9 for borehole BH-B2:

- A single significant dip change horizon developed at an early stage (indicated as ⑭), interpreted as a damaged zone. Further significant dip change zones in the lower 250 m appear to have joined to a single massive damage zone that failed (based on markers going offline) in a single step (within 1 week, indicated as ⑮).
- Above this zone, narrower significant dip change zones are established (indicated as ⑯), with deemed stable sections separating them.

4.2.3 BH-B3

The following is observed from Figure 10 for borehole BH-B3:

- In the lower approximate 400 m of the hole, a multitude of significant dip change zones developed at an early stage (indicated as ⑰). These zones appear to have joined into a single massive damage zone that did not fail in a single step (within 1 week), but rather through a gradual, bottom-up failure, in which the entire damage zone degraded to the point that marker communication was interrupted (indicated as ⑱). This could indicate a very tight airgap that did not cause a break in marker communication and possible continuation of tilt monitoring into the muckpile.

4.2.4 Combined Site B interpretation

In boreholes BH-B2 and BH-B3, large, immobile, well-developed damage zones (interpreted) developed in the lower sections (Figures 9 and 10). In borehole BH-B1 (Figure 8), the lower 100 m shows fewer signs of a well-developed damage zone; however, the next 100 m above shows a well-developed damage zone (interpreted).

Once these well-developed damage zones were mobilised and consumed by the cave, the rock mass exhibited similar patterns in all three boreholes, with narrow damage horizons developing well above the interpreted cave location (indicated as ⑪, ⑯ and upper ⑰ on the figures) and stable rock masses in between. The interpreted cave tended to progress in steps, following these damaged zones.

5 Limitations

Significant dip change appears to be developing at an unexpectedly early stage in the monitoring program and at a depth well above the undercutting level. The monitoring programs were not intended to capture these phenomena but to focus on identifying the cave back location, not on changes in the rock mass ahead of the cave. As a result, only data from markers close to the assumed cave back locations were collected.

Therefore, critical data were not collected at early stages and all along the boreholes in which the early onset of fracturing was not observed.

Tilt changes capture only differential lateral movement perpendicular to the hole direction, and adding translational movement (either monitored or inferred) may improve the interpretation of rock mass damage. The results presented show that significant differential lateral movement does occur and highlight the value of tilt measurements as part of the larger monitoring program.

6 Implications and future directions

While knowledge of the cave back's location is critical for identifying geotechnical hazards, it is retrospective. The later such conditions are identified, the less ability there is to influence the outcomes. Measuring and identifying the onset and conditions of caving mechanisms supports more proactive management of cave behaviour.

This paper illustrates the development of dip changes, interpreted as rock mass damage well in advance of the interpreted cave back. Measuring the full extent of the borehole, rather than focusing only on a limited area near the interpreted cave back, provides valuable insight into the early onset of rock mass damage.

Equipped with the knowledge described in this paper, future cave monitoring programs will be expanded and enhanced to ensure that critical monitoring data are collected to enable the data to be analysed in conjunction with complementary datasets such as geological and geotechnical models of the mine, numerical modelling, production data and alternative monitoring methods for the purpose of gaining more comprehensive insights into caving mechanisms and factors that influence it.

7 Conclusion

The following conclusions are made based on the literature review, data and discussion presented in this paper:

- The literature review presented the Duplancic model and the fracture banding model and their key characteristics.
- Selected tilt monitoring datasets from two operating cave mines, one panel cave and one block cave, are presented and explored for alignments with conceptual cave models.
- The monitoring data for the panel and the block caves show bands of significant dip changes. This may indicate rock mass damage due to a weaker geological structure or the development of fracture bands (although the spacing is inconsistent). The mechanisms appear complex and may involve a mixture of caving mechanisms.
- Duplancic or fracture banding mechanisms are not obviously distinguishable, which is not helped by a lack of early monitoring data for Site B.
- The data presented show activity well in advance of the interpreted cave back and highlight the value of monitoring the full borehole rather than focusing only on a limited area near the interpreted cave back, as it may provide valuable insight into the early onset of rock mass damage.
- Both datasets showed the interpreted cave back progressing in a mostly stepwise fashion.

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