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A re-evaluation of the conceptual model of caving mechanics

D Cumming-Potvin *Australian Centre for Geomechanics, The University of Western Australia, Australia*

J Wesseloo *Australian Centre for Geomechanics, The University of Western Australia, Australia*

SW Jacobsz *University of Pretoria, South Africa*

E Kearsley *University of Pretoria, South Africa*

Abstract

The Duplancic conceptual model is the industry accepted model of caving and is the framework within which most results from numerical modelling and cave monitoring are interpreted. The Duplancic conceptual model implies that the damage ahead of the cave back decreases continuously with increasing distance from the cave surface. Evidence from a variety of sources indicates that this may not always be the case and that a discontinuous damage profile may be present.

Cumming-Potvin et al. (2016b) describes a physical modelling program which was undertaken to investigate the fracturing and propagation of the cave. The results of these centrifuge tests showed that caving could occur via a series of fractures oriented parallel to the cave surface and that the cave back progressed vertically via 'jumps' to the next successive parallel fracture. In Cumming-Potvin et al. (2016a), this caving mechanism was termed 'fracture banding'. Multiple examples of a similar mechanism of failure were observed in literature. In addition, the patterns in microseismic event location indicate that fracture banding could be occurring in currently operating caving mines.

This paper examines evidence from a number of sources in the field of caving mechanics and presents an extended conceptual model of caving. The new model is able to account for the mechanism of fracture banding, along with the continuous style of failure from the Duplancic conceptual model. There are still many unknowns about the fracture banding mechanism and propagation of caves. These include the specific conditions under which the caving mechanism changes and whether the mechanisms lie on a continuum, or if there is a sharp, sudden change. Two conceptual models are presented: one which includes only that which is known about the mechanisms of cave propagation and one which speculates upon the factors involved and the underlying origins of the fractures.

Keywords: *fracture banding, cave mining, physical modelling, cave monitoring, seismicity, centrifuge*

1 Introduction

The Duplancic conceptual model of caving is generally accepted as a standard model for interpreting results of monitoring and numerical modelling in caving mines. The Duplancic model implies that the damage ahead of the cave back is continuous, with the damage decreasing with increasing distance from the cave. Based on the results of physical modelling, literature and field observation, Cumming-Potvin et al. (2016a) showed that the damage profile ahead of the cave back can be discontinuous. The damage profile, which consisted of a series of fractures parallel to the cave surface, was termed fracture banding. The presence and importance of the mechanism of fracture banding was previously under-recognised and is not captured by the Duplancic model of caving, creating a need for an extended conceptual model of caving.

The research completed by Cumming-Potvin (2018) forms the basis for this paper. This research involved creating physical models of caving using a geotechnical centrifuge. The tests were essentially two-dimensional. The 'undercut' and 'draw' were created by a series of retracting pistons underneath the sample. Visual observation of the caving behaviour was possible through on-board cameras. Additionally, Cumming-Potvin (2018) examined data from several caving mines. Analysis of microseismicity revealed 'bands' of events which resembled the fracture banding mechanism of caving. Analysis of open hole monitoring data also gave insights into changes in caving mechanism over time. The results of all of this research is united to form an extended conceptual model of caving, presented in this paper.

2 Characteristics of fracture banding

When creating a conceptual model of caving which can account for the fracture banding mechanism, it is important to understand the characteristics of the mechanism. This includes the timing, shape and spacing of the bands, the damage profile and the influence of mine-scale geological features on the bands.

2.1 Discontinuity of damage profile

The presence of a discontinuous damage profile ahead of the cave can be seen in a number of studies utilising a range of approaches. It can be seen in studies using physical modelling (Cumming-Potvin et al. 2016a, b; Nishida et al. 1986; McNearny & Abel 1993), numerical modelling (Vyazmensky et al. 2007; Lisjak et al. 2012; Li et al. 2014) and site observations (Panek 1981; Sharrock et al. 2002; Carlson & Golden 2008; Cumming-Potvin 2018). Additionally, there are a number of studies in which a discontinuous damage profile was found around deep mine tunnels and tabular stopes (Adams & Jager 1980; Shemyakin et al. 1986a, b; Jia et al. 2012). While the mechanism of failure in these cases may not be the same as that of fracture banding, the observations of a discontinuous damage profile lend credence to the idea that the damage profile around excavations can be discontinuous. Examples of discontinuous damage profiles from different sources are given in Figure 1.

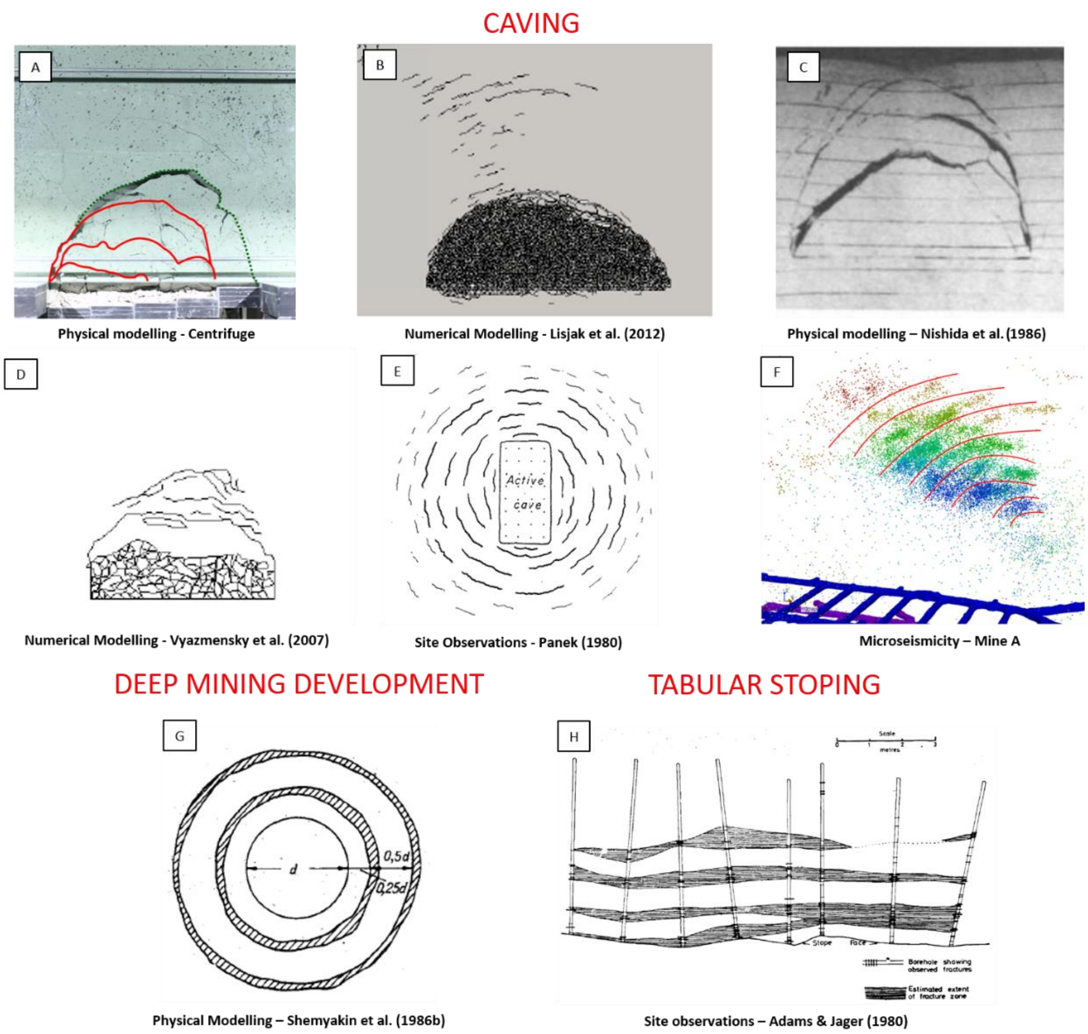


Figure 1 Examples of discontinuous damage profiles

The caving mechanism of fracture banding is a process in which the cave propagates through a series of 'jumps' to successive fractures (or fracture zones) ahead of the cave. This is illustrated in Figure 2. It is important to note that, in these figures, the brown background colour represents the rock mass, which will include a number of in situ joints.

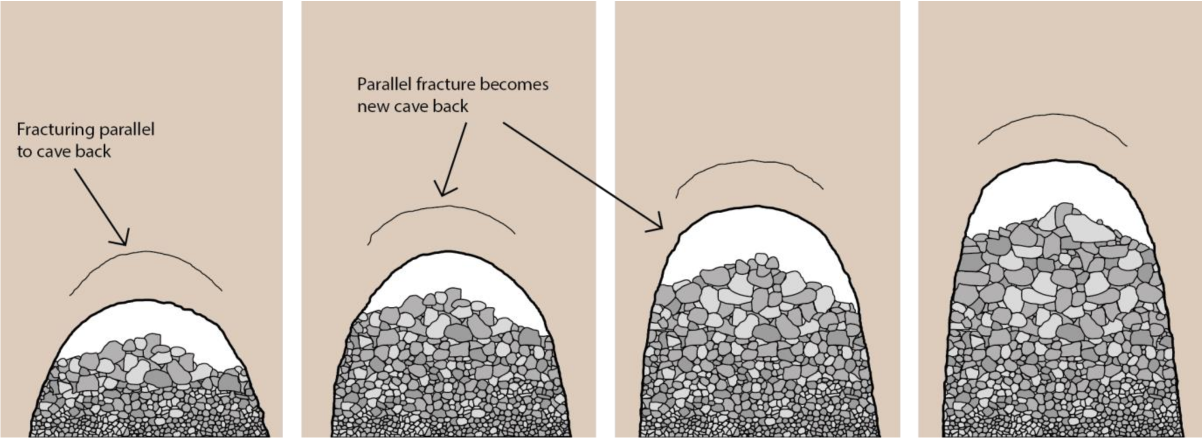


Figure 2 Illustration of cave expanding vertically through fracture banding. Note: the darker background colour in the figures represents the rock mass. Only significant fractures are shown

The damage profile created by fracture banding is discontinuous, with peaks at each of the fractures (or fracture zones), seen in Figure 3. While Duplancic did not explicitly state that there is a continuous damage profile ahead of the cave, it is implied within the model and has been interpreted in this way by the industry (Brown 2007). This contrasts with the continuous damage profile of the Duplancic conceptual model of caving (Figure 4).

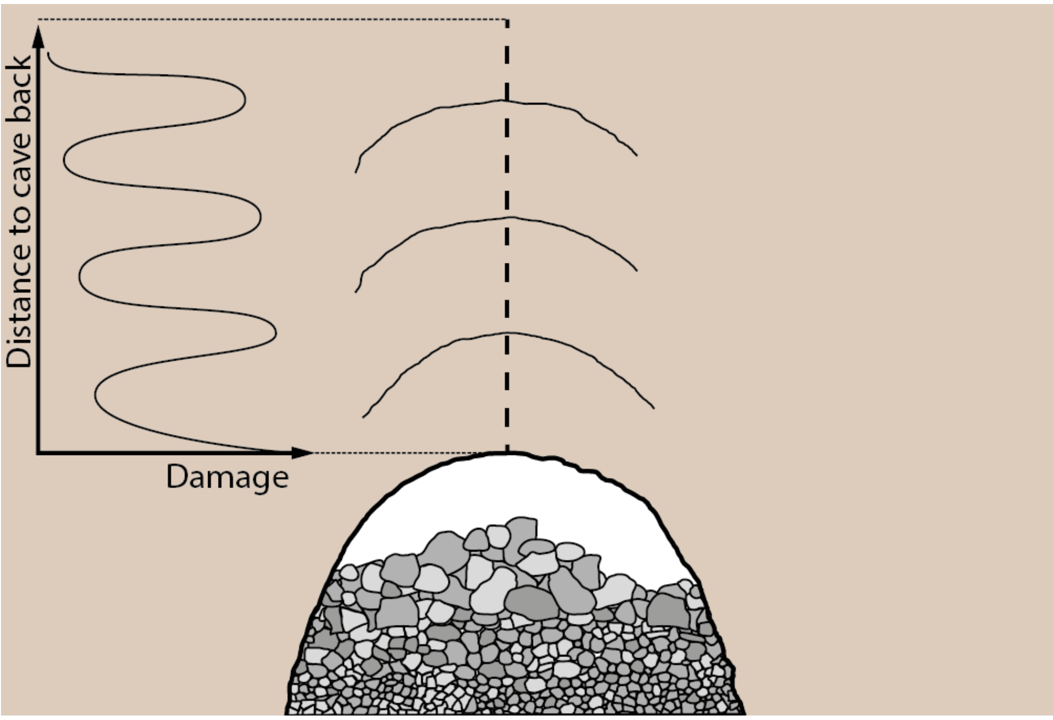


Figure 3 Illustration of discontinuous damage profile associated with fracture banding

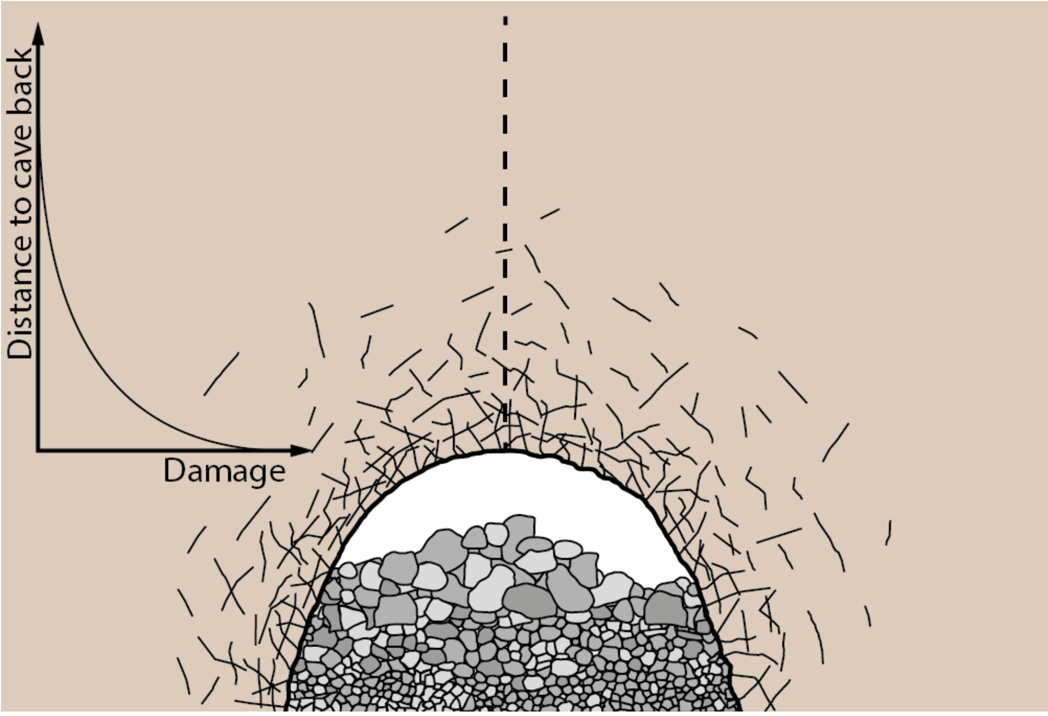


Figure 4 **Illustration of continuous damage profile associated with the Duplancic conceptual model of caving**

2.2 Timing of progression

In the centrifuge models of caving carried out by Cumming-Potvin et al. (2016b), there were multiple examples of new parallel fractures being created between existing fractures. This is shown in Figure 5. Analysis of microseismicity in caving mines by Cumming-Potvin (2018) also indicated that when bands of microseismicity (indicating fracture banding) formed, the activity in each band overlapped. This implies that as one band is still active, another can begin to form. This creates a repeating process where, as fracture bands mature, conditions change and new fracture bands begin to form.

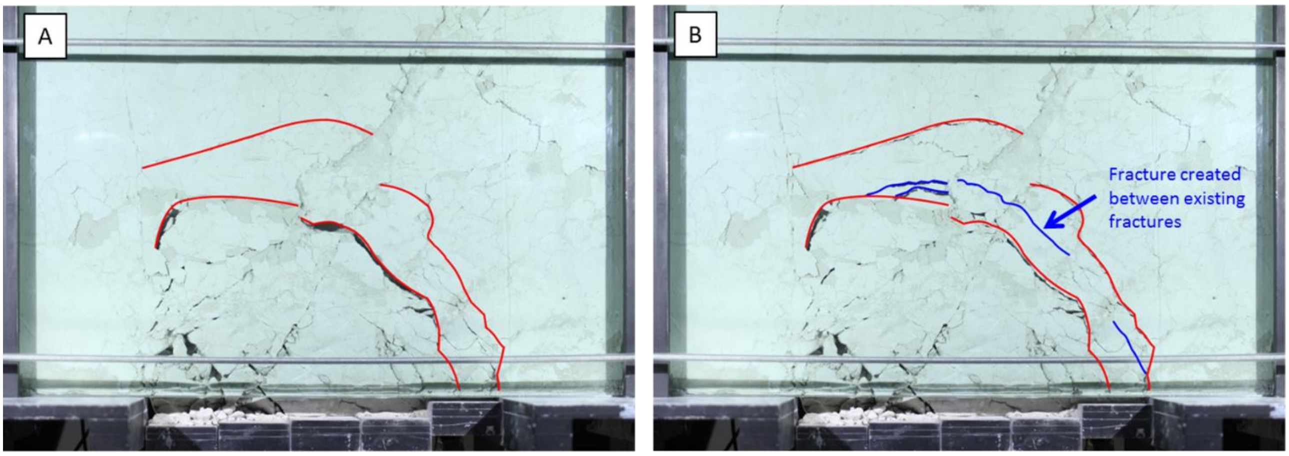


Figure 5 **(a) Fracture forming ahead of cave back; and, (b) Fracture being created between this fracture and the cave back (Test 2)**

It is also possible that, at times, a beam is forming between parallel fractures. This beam may then subsequently fail in a bending mode, with tension cracks forming at the bottom of the beam. An example of this is given in Figure 6.

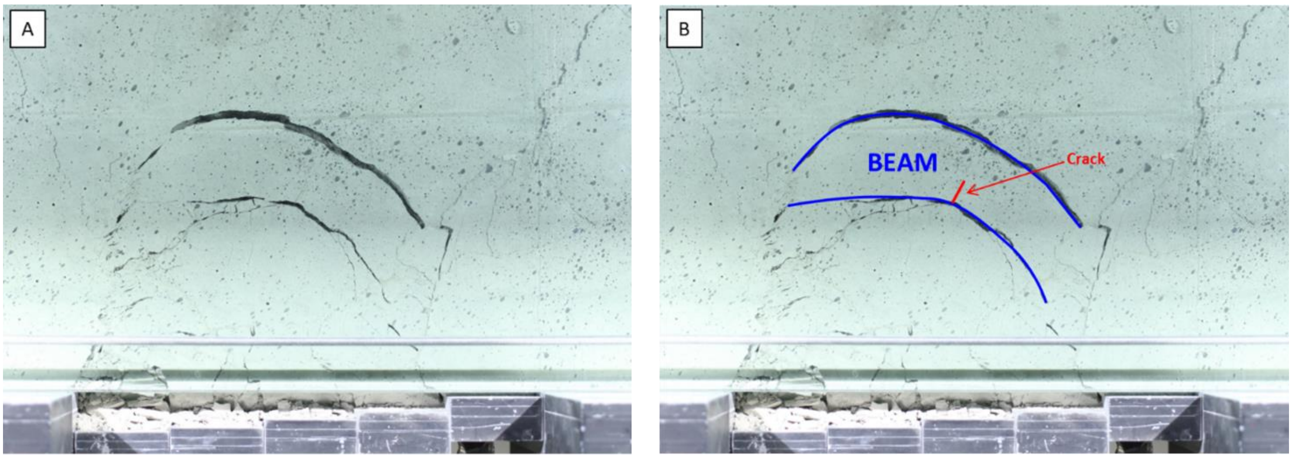
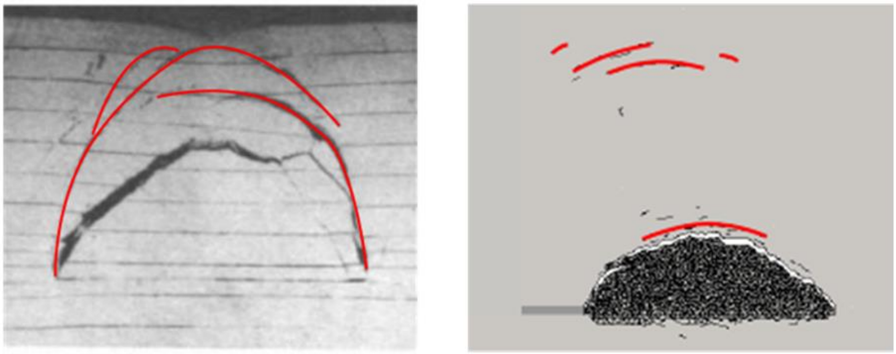


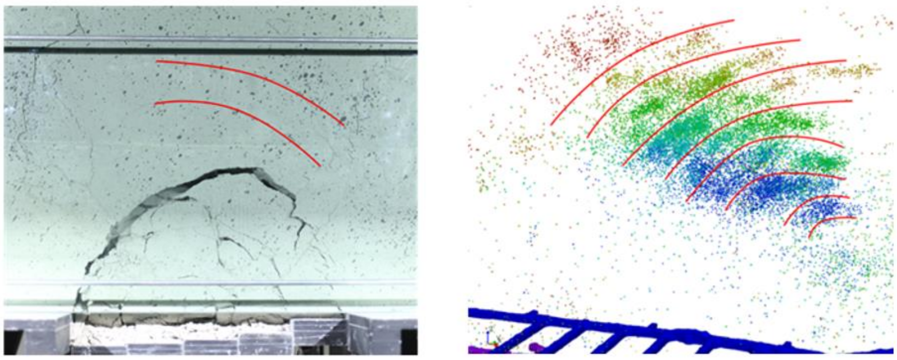
Figure 6 Potential beam forming in centrifuge model

2.3 Shape of fracture bands

A number of studies in literature showed fractures with a shape which matches that of the cave. This parallel alignment means that the fractures are curved to match the cave shape. The same shape was seen in physical modelling and analysis of microseismicity (Cumming-Potvin 2018). Examples of the shape of fractures/fracture zones conforming with the cave shape in the cave crown and periphery are given in Figures 7 and 8 respectively.



Physical modelling - Nishida et al. (1986) **Numerical Modelling - Lisjak et al. (2012)**



Physical modelling – Cumming-Potvin (2018) **Microseismicity – Cumming-Potvin (2018)**

Figure 7 Examples of curved fracture shape in crown of caves. Fractures/fracture zones highlighted in red

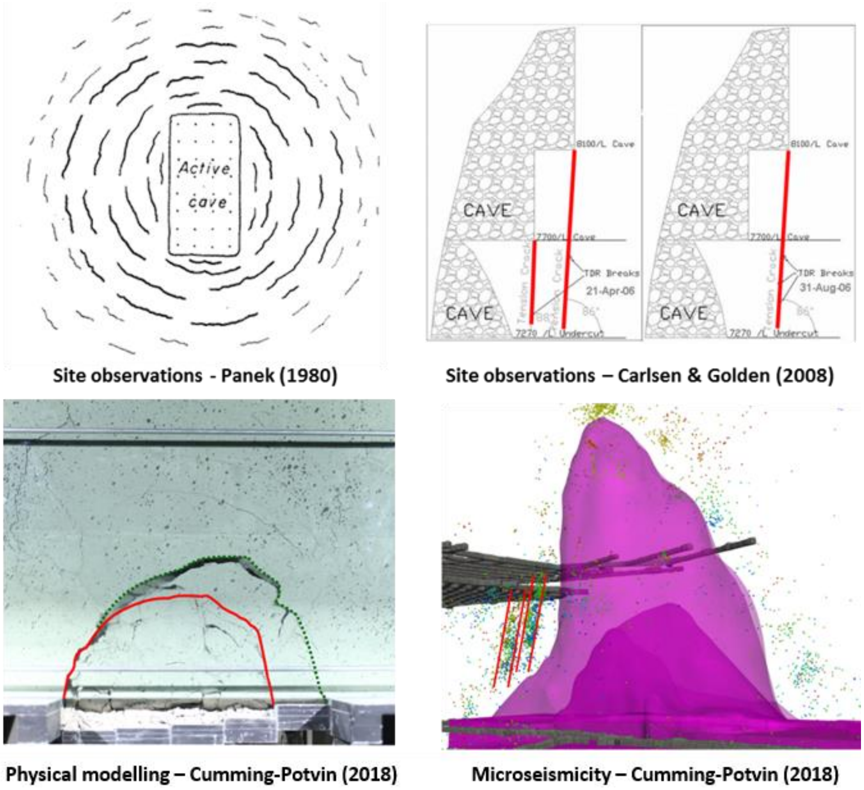


Figure 8 Examples of fractures matching cave shape in periphery. Fractures/fracture zones highlighted in red

2.4 Spacing of fracture bands

Based on evidence from a number of sources, it appears that the spacing between the fractures/fracture zones created as part of fracture banding is relatively consistent. Cumming-Potvin (2018) found that the spacing of fractures seen in the centrifuge modelling was consistent, as shown in Figure 9. Consistent spacing of parallel fractures adjacent to the cave was also found by Panek (1981) through site observations and brick-based physical models of caving (McNearny & Abel 1993). While the spacing was not specifically addressed, the figures given in a number of other studies also indicate a consistent spacing of fractures in physical models (Nishida et al. 1986) and numerical models of caving (Lisjak et al. 2012; Vyazmensky et al. 2007; Li et al. 2014). While the spacing was at times difficult to determine, Cumming-Potvin (2018) found that the spacing of bands of microseismic events was consistent. There is not enough evidence to determine whether there is a characteristic spacing between cases of fracture banding. However, it is clear that the spacing between fractures within one instance of banding is consistent.

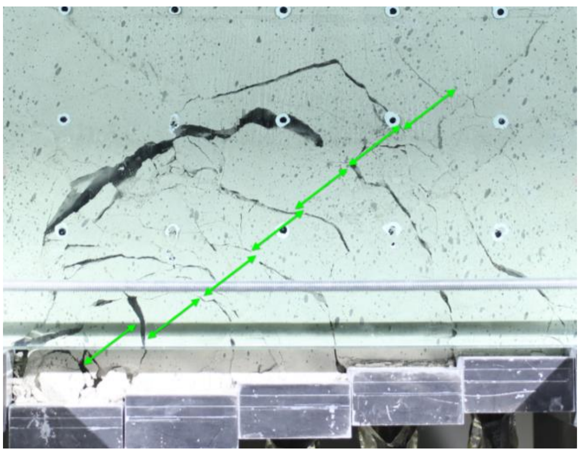


Figure 9 Example of consistent spacing from centrifuge modelling. Spacing indicated by green arrows of equal length (Cumming-Potvin 2018)

2.5 Influence of mine-scale geological features

Mine-scale geological features, such as faults and contacts, can have a significant effect on the propagation of the cave, including propagation through fracture banding. In the centrifuge models of caving, (Cumming-Potvin 2018) found that large pre-existing fractures (analogous to mine-scale geological features) bound the extent of growth of the parallel fractures. This can be seen in Figure 10, where the parallel fractures (shown in red) are bounded by the pre-existing fractures (shown as a dashed blue line). The areas circled in orange are where the fractures did not cross the boundary created by the pre-existing fractures.

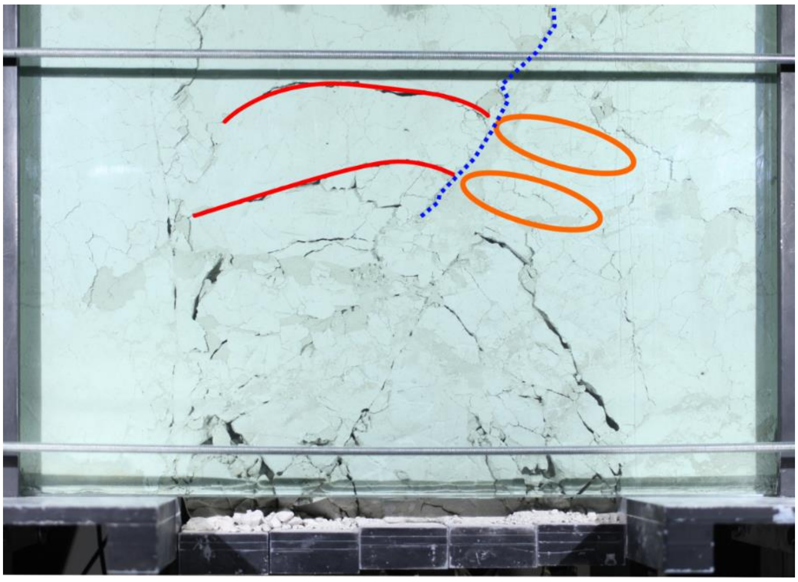


Figure 10 Effect of mine-scale geological features on fracture banding (Cumming-Potvin 2018)

3 Mechanism of fracture generation

Understanding the origin mechanism of the fractures created as part of fracture banding plays a significant role in the understanding of how the cave progresses and under which conditions fracture banding can occur.

Cumming-Potvin (2018) used particle image velocimetry (PIV) in order to observe the direction and magnitude of displacements of centrifuge tests of caving. The results of the PIV indicated that the first direction of movement was perpendicular to the fracture plane, thus suggesting an extensional mechanism (Figure 11). This can also been seen in the raw photographs (Figure 12). The frame rate of photographs taken was too slow (one photograph every four seconds) to determine, with absolute certainty, the mechanism of fracture generation.

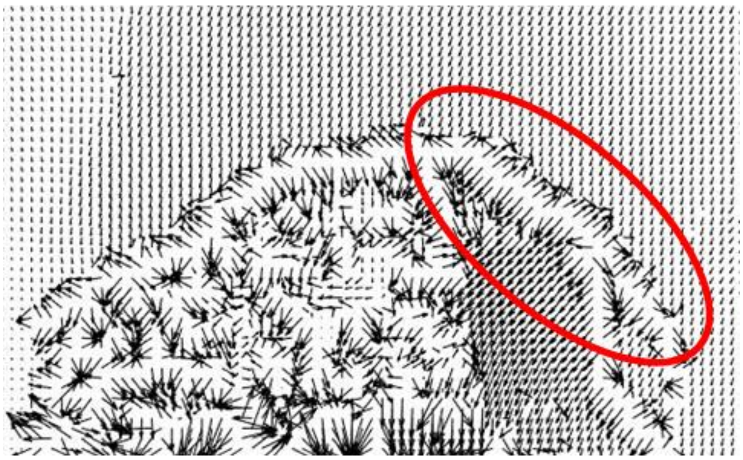


Figure 11 Displacement vectors from PIV results showing displacement perpendicular to fracturing. Arrows not to scale (Cumming-Potvin 2018)

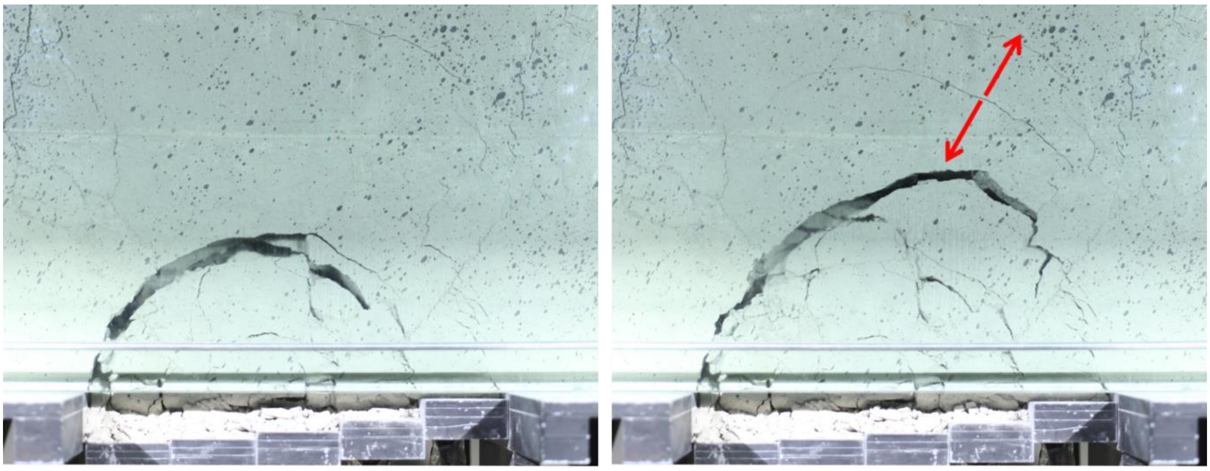


Figure 12 Example of fracture appearing to form in extension

A number of other authors have also made observations of tensile or extensile fracturing ahead of the cave through both site observations (Heslop 1976; Panek 1981; Sharrock et al. 2002; Carlson & Golden 2008) and analysis of microseismicity (Reyes-Montes et al. 2010a; Tibbett et al. 2016). Numerical modelling studies, such as those completed by Garza Cruz and Pierce (2014), also find tensile failure developing subparallel to the cave back.

A number of authors, using primarily microseismic data, have also found evidence of shear failure and slip along pre-existing discontinuities (Duplancic 2001; Glazer & Hepworth 2005; Hudyma et al. 2007a, b; Hudyma & Potvin 2008; Glazer & Townsend 2008; Woodward 2011; Reyes-Montes et al. 2010a, b; Abolfazlzadeh 2013; Tibbett et al. 2015, 2016).

Analysis of open hole monitoring and microseismicity at a block caving mine carried out by Cumming-Potvin (2018) indicated different time periods with distinctly different caving behaviours. One of the periods indicated a shearing mechanism, similar to that described by Duplancic (2001), whereas the other period indicated an extensile, fracture banding mechanism. A 'transition period' between the mechanisms was also noted.

Based on this evidence, it can be concluded that fractures generated during the caving process can originate through both rock mass shearing and extensional fracturing. The specific conditions which give rise to each mechanism are still, however, unknown.

4 Extended conceptual model of caving

From the previously mentioned research, we can determine with a level of certainty some aspects of fracture banding:

- The damage profile evolved from fracture banding is discontinuous.
- Multiple fracture bands can form at the same time, with new fracture bands being formed as the previous fracture bands mature.
- The fracture bands created are parallel to the cave boundary.
- The spacing of the fracture bands is generally consistent.
- The progression of the cave is affected by mine-scale geological features which can either expand, limit or deviate the propagation of the cave depending on the relative orientation and position of the feature and the cave.

There are still a number of unknowns when it comes to fracture banding. The first is whether the bands are formed as single, large fractures as seen in the centrifuge models, or as a zone of smaller fractures in which further failure and coalescence of fractures occurs, similar to the zones seen in analysis of microseismicity (Figure 1). It is also possible that both of these cases are true, and the form the bands take depends on the conditions ahead of the cave. An example of fracture banding shown as zones is given in Figure 13.

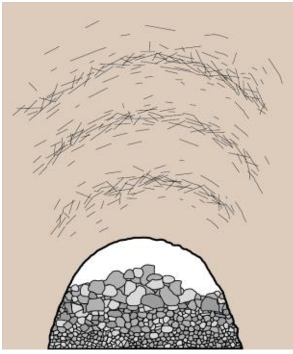


Figure 13 Fracture banding as zones

Another unknown is the specifics behind the evolution of the bands and the way in which they become the subsequent cave back. It is possible that the bands form simultaneously, with the more mature bands closer to the cave back. At some point, the conditions between the lowermost band and the cave back will allow the rapid vertical progression of the cave so that the lowermost band becomes the cave back. This is illustrated in Figure 14.

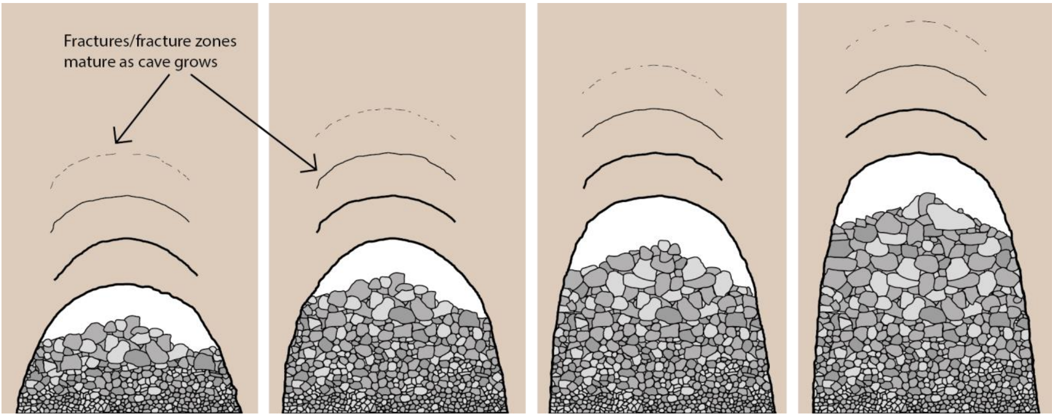


Figure 14 Cave growth through simultaneous formation of fracture bands

It is also possible that beams form between the parallel fractures and the cave back. The beam then fails and the cave expands outwards to the parallel fracture. This is illustrated in Figure 15.

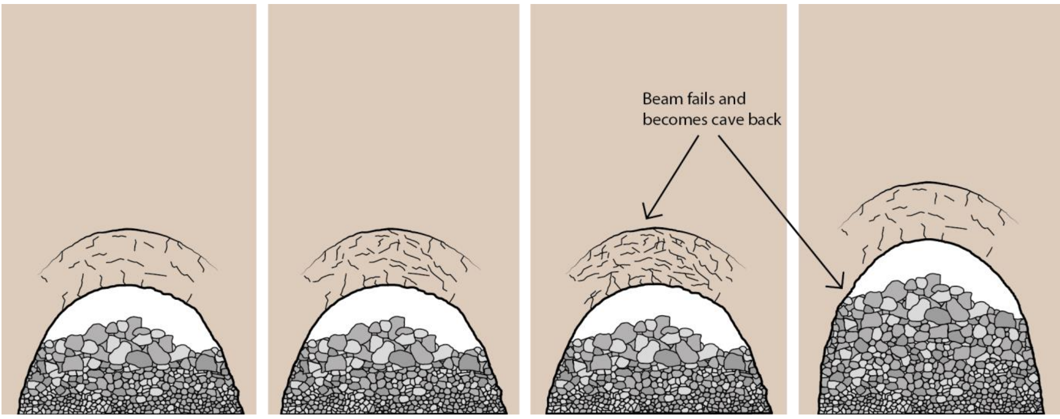


Figure 15 Cave growth through creation and failure of beams

Figure 16 presents an extended conceptual model of caving which captures both fracture banding and the Duplancic mode of caving. As indicated in the figure, caving behaviour can vary between the discontinuous damage profile of fracture banding and the continuous damage profile seen in the Duplancic mode of caving. It is still unknown whether there is a continuum with intermediate states, or whether the transition between the two caving mechanisms is sharply defined (similar to the different modes of borehole breakout observed by Crook et al. 2003). The only evidence observed indicating a continuum is the 'transition period' between caving mechanisms seen in open hole and microseismic monitoring of caving by Cumming-Potvin (2018). The model shown in Figure 16 includes only what is known about the different mechanisms of caving. Figure 17 presents a model that speculates on factors which could influence the caving mechanism realised and the primary origin mechanism of the fracturing evolved.

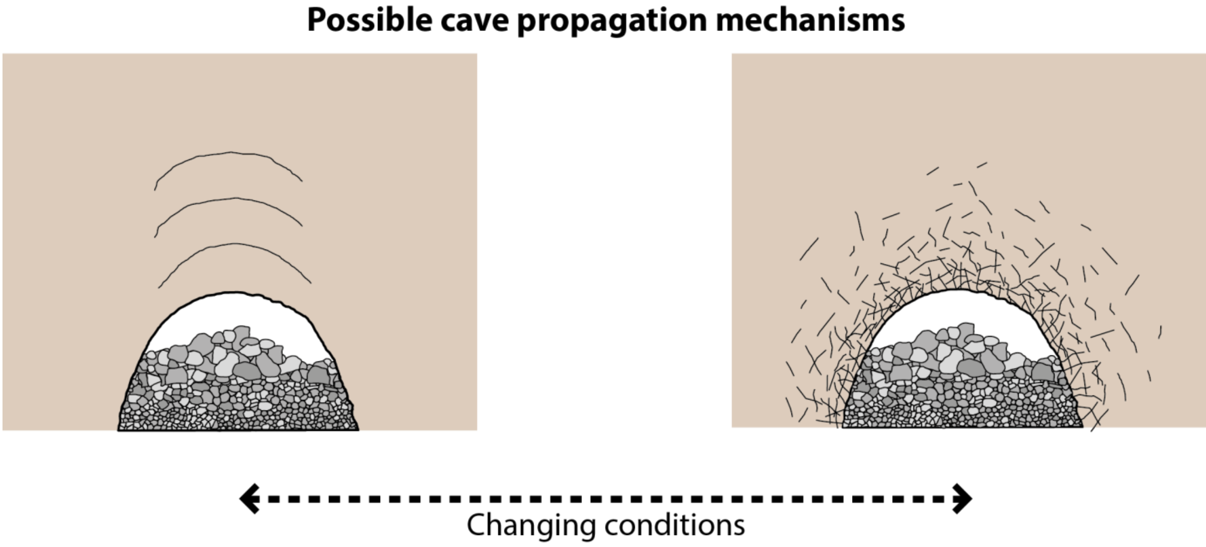


Figure 16 Extended conceptual model of caving, using only knowns

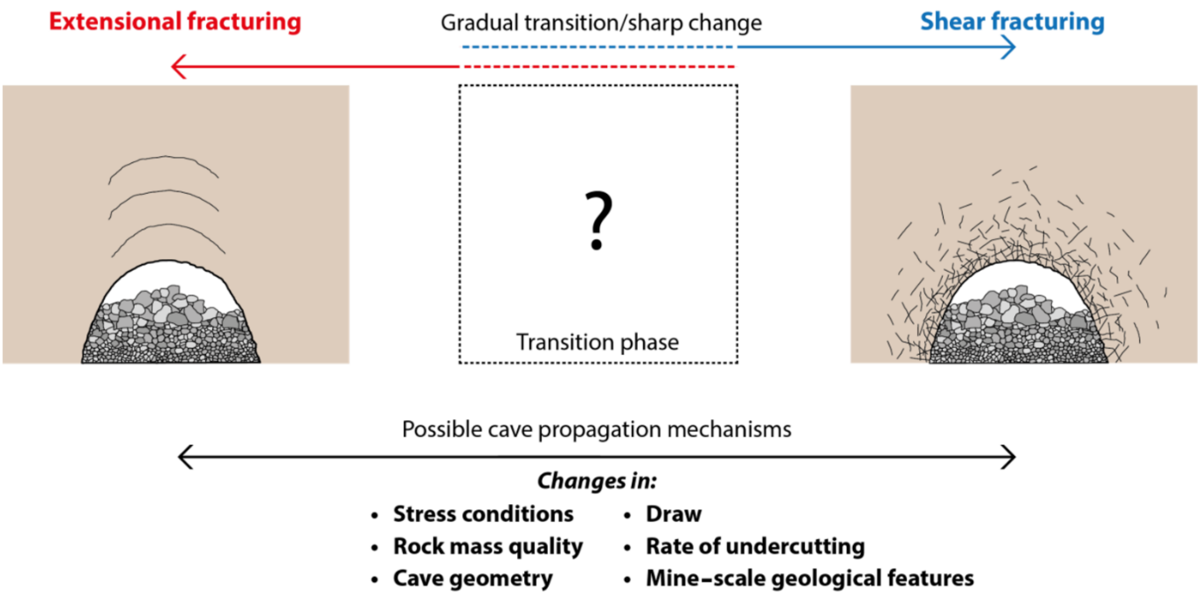


Figure 17 Speculative potential extended conceptual model of caving

5 Conclusion

Based on the evidence presented, a number of characteristics of fracture banding could be determined. These are:

- The damage profile evolved from fracture banding is discontinuous.
- Multiple fracture bands can form at the same time, with new fracture bands being formed as the previous fracture bands mature.
- The fracture bands created are parallel to the cave boundary.
- The spacing of the fracture bands is generally consistent.
- The progression of the cave is affected by mine-scale geological features which can either expand, limit or deviate the propagation of the cave depending on the relative orientation and position of the feature and the cave.

Based on these known characteristics, an extended conceptual caving model was created. This conceptual caving model accounts for the fracture banding mechanism, which was not included in the Duplancic conceptual model of caving. The extended conceptual model indicates that with changing conditions, the mechanism of cave propagation can change from a continuous Duplancic mode to a discontinuous fracture banding behaviour. There are a number of factors which could influence the caving mechanism observed. However, the influence of these factors is not well understood. Future research should focus on assessing the impact that these factors have on caving mechanism.

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