Monitoring and controls for sublevel caving in an anisotropic rock mass

RE Douglas-Brown *BHP, Australia*

Abstract

Nickel West Venus orebody at Leinster, Western Australia is being mined using the sublevel caving (SLC) method. Learnings from the initial caving area, a small footprint SLC project within a high stress environment, are presented in this paper. The Venus orebody is situated within a heterogenous, anisotropic geological setting creating complexities for easy cave creation. Factoring in all geotechnical variables and potential risks, including, but not limited to, seismic response, dilution of ore, airgap creation, mud rush and surface subsidence impacting existing infrastructure. The first section of the Venus orebody SLC was created from three levels and established a means to calibrate the impacts of draw controls in an area with distinct changes in rock mass strength vertical to drawpoints. The draw strategy focused not only on maximising ore extraction but maintaining an adequate crown pillar due to the inferred subsidence zone and potential for interaction with surface infrastructure.
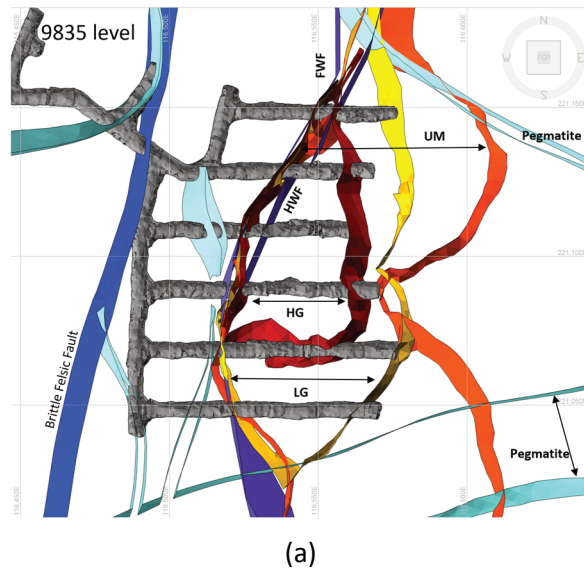
Cave monitoring included seismic analysis, Elexon Smart Markers, fragmentation for bulking factor of blasted and caved material. Displacement of sigma one stress was inferred from seismic analysis, with expected energy release zones established. Cave height was tracked through a combination of all datasets, seismicity, geotechnical instrumentation, and height of draw (HOD).

Keywords: sublevel caving, cave monitoring, draw control, seismicity, height of draw
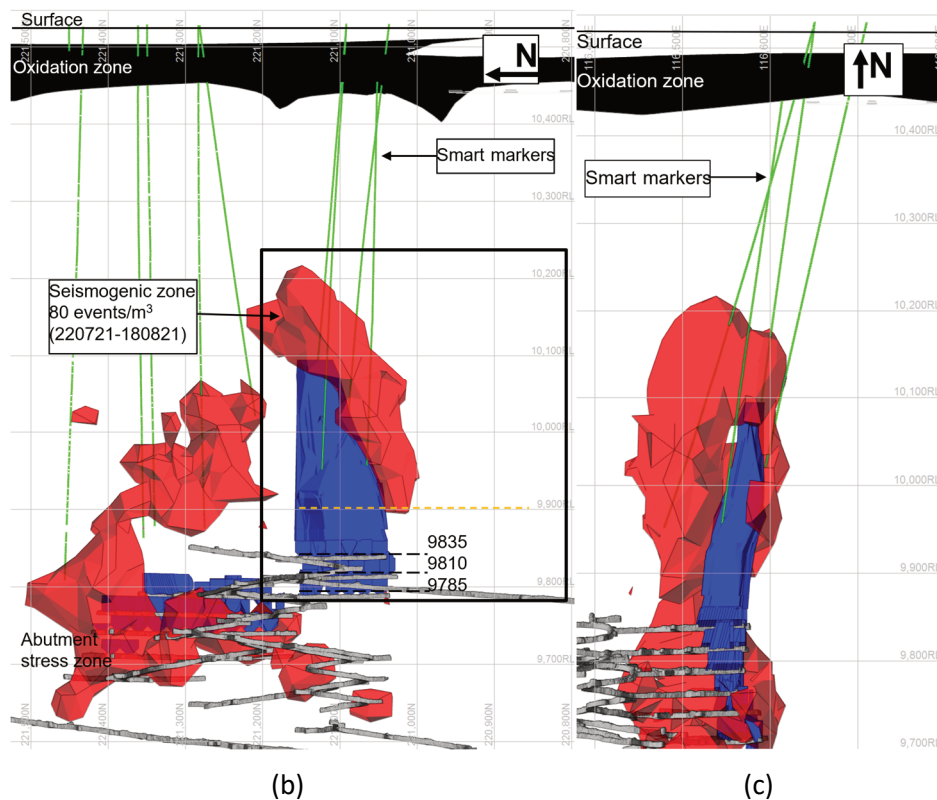
1 Introduction

The Venus orebody at Leinster is a north–south striking, vertical lensing orebody; the result of an originally ductile komatiite type nickel deposit that has been folded and faulted to the current brittle to brittle-ductile system structurally bound within the footwall fault (Dempers & Seymour Pty Ltd 2017; Duuring et al. 2007; Perring 2015). The ore-bearing fault defines the boundary between metasedimentary (Felsic) and ultramafic (UM) rock mass, the distinct difference in strength of these lithology's is compounded by a swarm of pegmatite intrusions that can be classified as two distinct sets, one yielding garnets. The brittle ductile deformation of faulting and folding events in this region created obliquely aligning joint sets with tochilinite compact coatings in the high to low grade disseminated lithology and when subjected to substantial stress changes a low seismic response and high levels of squeezing is documented. This rock domain is classified as the UM and caving of this material equates to irregular, large blocks. The Felsic rock domain is a metasedimentary rock mass of quartzite with some biotite and muscovite foliations running north–south and joint sets running parallel and perpendicular to the main ore-bearing fault, fragments to small, even blocks. The Pegmatite is shown to have high seismic response as the rock stresses reorientate from mining, is low yielding, and fragments to fines. In a homogenous system rock mass rating would be continuous, and a trend in joint set dip and dip direction would enable a means to easily infer the subsidence zone, caved material would be evenly distributed in size and therefore flow and draw strategy estimations would be simplified (Bewick 2021; Kalenchuk et al. 2008; Pierce et al. 2007). The complexities created by the Venus geological setting equates to a unique environment for caving with the primary control being tonnes extracted after mine design. Each SLC crosscut is developed to the east with advance from north to south, a significant pegmatite structure intersects the southern section of the cave running oblique to the surface north of the cave footprint. The domains and structures relevant to the caving zone are depicted as they intersect RL 9835 in Figure 1a, the top mining level of the small caving zone. Cave propagation started in the UM with low

controls for the first two levels due to budget constraints. Figure 1b and 1c depict the final state of propagation of the small south Venus cave with proximity to the surface.

(a)

Figure 1a   9835 Level with dominant structures, the hangingwall, footwall blocks and the brittle felsic fault, the lithology of the rock west of the footwall is the Felsic domain and depicted in the schematic are the ultramafics which encompasses the high grade and low grade disseminated and pegmatite intrusions. This level has the largest width of the UM in the small caving zone

(b)   (c)

Figure 1 b & c   Venus caving area with the south cave boxed, broken rock mass of the Venus south cave and fired development up until August 2021 in blue, seismogenic zone for the five-week period with 80th percentile of seismic events included with all event range in red, Smart Markers pictured in green, oxidation zone and surface level also depicted. Figure 1b is the north facing view of the caved zone depicting the cave propagation as structurally dominated toward the east

2   Monitoring methodology

Core rules have historically been established on site for caving. These include:

- DO ensure slots are to full height and all rings break to a free face.

- DO ensure accurate drill setup.

- DO NOT charge a ring if hole(s) dip short.

- DO NOT continue bogging when drawpoint flow is obstructed.

- DO NOT bog more tonnes than allocated for that day.

- DO maintain brow integrity.

- DO bog across the full draw point width.

In addition to these rules, set percentages of extraction are as follows: 60% of extraction of a fired shape on a level with no above interactions, 80% of extraction with one level above and 100% extraction on subsequent levels. Due to the small size of the cave, with only three levels of interaction, the rules were modified to have 110%+ extraction on the last level of the small cave. A per shift extraction rate of a maximum 800 t/SLC was also applied and as an additional control for seismicity and cave propagation reduced to 500 t/SLC/shift when necessary.

Seismicity and fault activation are expected responses from the rock mass during cavern creation, subsequently astute seismic monitoring is crucial (Cumming-Potvin et al. 2018; Duplancic 2001; Duplancic & Brady 1999; Laubscher 2001). The establishment of seismic zones, identifying faults likely to re-activate assisted in giving a focus for ground support monitoring after seismic events of note. Seismic analysis also determined block movement between regional faults around the caving zone. Bimonthly monitoring included density iso-surface changes within the seismogenic zone and moment tensor analysis to determine composition of seismic events and P- and T-axis trends of events >0.05 M_L. Included in this paper is a longer four-month increment analysis of the evolving seismogenic zone.

Monitoring for caving propagation was completed with weekly inputs from fragmentation, Smart Markers, and tonnes extracted. This enabled a means to reiteratively understand caving mechanisms at play. Dilution was factored in and measured for the ingress of barren material and of felsic material to determine footwall fault competency and understand the paths of propagation of the rock. Additional monitoring of probe holes was used to determine the parameters of the cave for volumetric accuracy.

The breach of brow integrity as a control in zones of rock mass with a low uniaxial tensile strength (UTS) equated to upgrades in ground support standards and communication of these standards to operations. As with only three levels of interaction brow breakback within the 9810 Level equated to ore losses due to no potential for future extraction. The stress re-orienting around levels and level spacing is also considered as a contributing factor to the excess brow breakback and squeezing ground.

Muck pile estimations determined the potential for airgap formation after propagation slowed due to a variation in rock mass strength in each RL above draw points and the geological complexities of the region. Estimations factored in the swell of the rock from caving (10–15% bulk) and bulk of the rock from blasting (30% bulk), due to the variation in rock types present and therefore a variation in bulking of the rock from blasting and caving, a uniform average was applied for monitoring purposes.

Geotechnical rock domains and parameters established for the Venus orebody are listed in Table 1. As the mine developed, new data inputs taken at each development cut enabled a means to understand the rock mass strength further, with face mapping of GSI added to the dataset. Other factors where utilised to determine other geotechnical outputs onsite, such as the Cave Propagation Factor (Sainsbury 2012) which was not useful within this setting considering the variation in rock mass strengths on the 2D plane at each RL within the caving zone.

Table 1   Summary of known rock properties for primary lithological domain

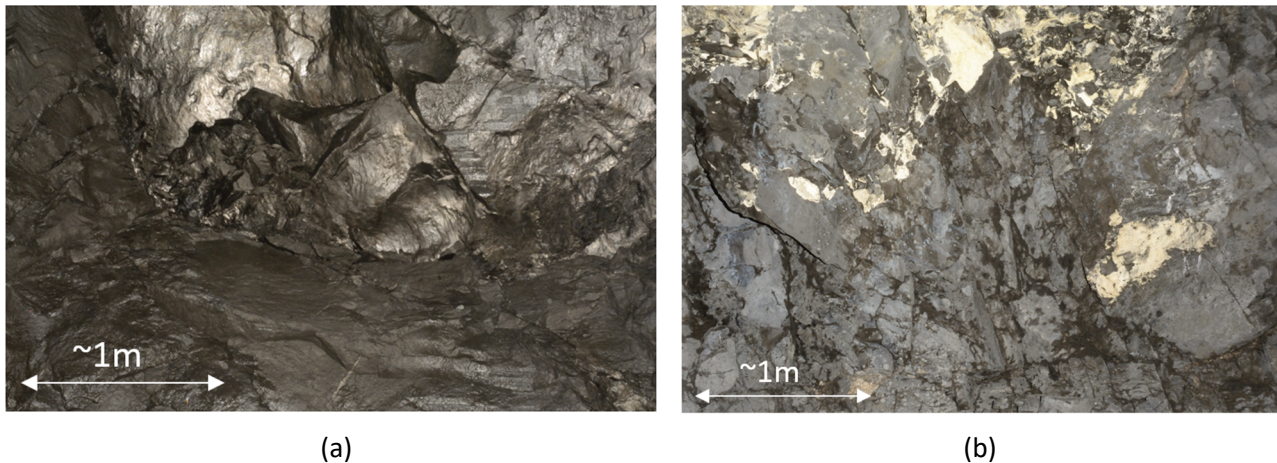|	Felsic	Mafic	Pegmatite	Talc-carbonate (UM)	Ultramafic (UM)	Serpentinised UM
Unit weight (kN/m³)	26	28	26	26	26	27
UCS (MPa)	148	167	72	70	70	90
Poisson's ratio	0.18	0.18	0.13	0.33	0.33	0.33
Young's modulus Intact E (GPa)	38	48	31	37	37	50
UTS (MPa)	14	15	5	5	8	8
m_i value	25	25	20	12	12	12
GSI	60	60	50	25	25	25
Q'	3.7	2.7	4.5	–	1.3	1.3
Q-value (J_w/SRF* = 1/2.5)	9.2	6.6	11.3		3.2	3.2

Adapted from Prado & de Bruyn (2019) and Hogan & Thompson (2019). * Stress Reduction Factor.

3   Discussion

The two main caving mechanisms at play, stress and gravity caving, are impacted by the caving footprint. In this small caving environment the footprint varies on each level. The footprint's relationship with caveability in conjunction with the presence of two distinct rock types, the UM, a low UTS rock mass which is driven by gravity caving and the felsic and pegmatite domains, driven by stress caving. Figure 2a depicts a face cut photo of the UM disseminated high- and low grade material and tochilinite compact coatings on the jointed rock surface. The tochilinite has a Mohs hardness of ~1, this equates to disjointed rock and irregular blocks wanting to unravel. Spiles in conjunction with the typical ground support system of shotcrete and cables are the first line of defence for tunnel development in this environment, a breach in this standard led to significant tunnel deformity and the requirement of a resin injection trial on the 9810 Level as seen in Figure 2b, the middle of the small caving zone. In the UM rock mass within the south Venus setting, the ground unravels easily at each tunnel cut, even at 1.5 m long rounds. The resulting brow breakback, created a poor control on the creation of the SLC and ore extraction. As unravelling occurred at the tunnelling level within this rockmass, it is inferred to continue up within the larger caving system due to the rocks' low tensile strength. It is noted that rock mass with a Q-value of 0.01–1.5 correlates to zones of brow breakback, unravelling and high caveability. A stress reduction factor (SRF) of 2.5 was applied to determine the Q-value used for this analysis and under these conditions a SRF of up to 20 would be more accurate to use the Q-value as correlating factor for caving.
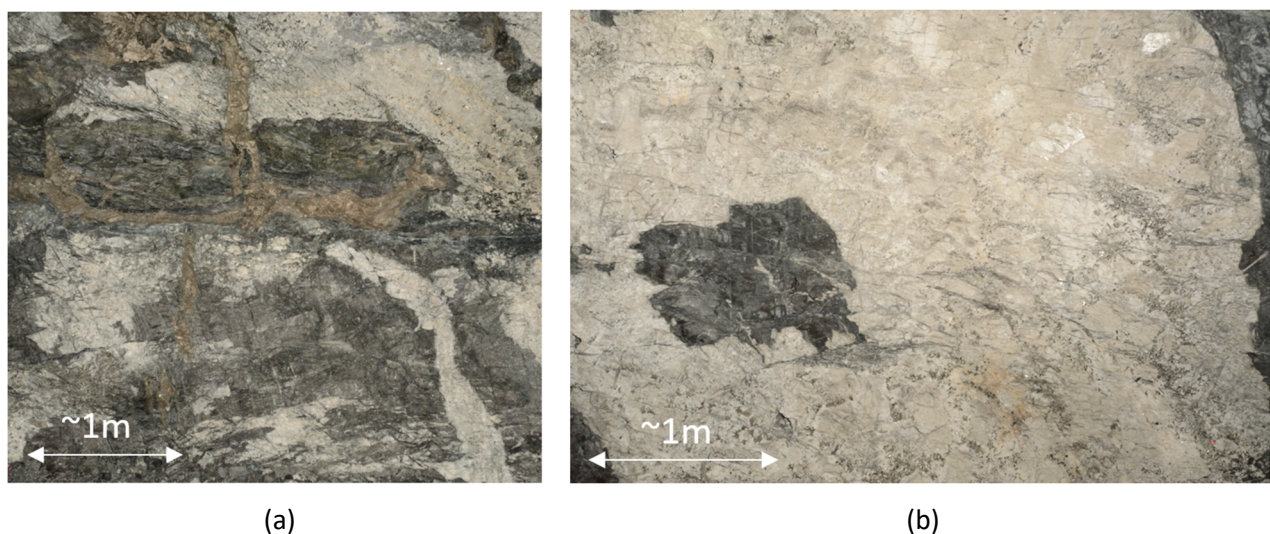
SLC mine design as a contributing factor for caving controls is considered due the potential impact of the pillar between levels on tunnel squeezing and deformity, and brow competency. Varden & Woods (2015) outlined that the pillar between levels in a mine design to mitigate tunnel squeezing and deformity is to be a minimum 15 m. In the Venus south cave the level spacing of 25 m intervals and the high rates of unravelling and squeezing of drives within the UM at the tunnelling level suggest that other factors such as the lead-lag and mining advance direction are controls that might be specific to rock mass strength. In a heterogenous system the rule must be applied for the lowest common denominator of strength capability. In the rock mass with a UTS < 10 or GSI < 50 the blast design of SLC rings can also be reviewed to assist in caving controls in these conditions, such as an increase of the dump of the firing to a standard 20° to assist in reducing brow breakback.
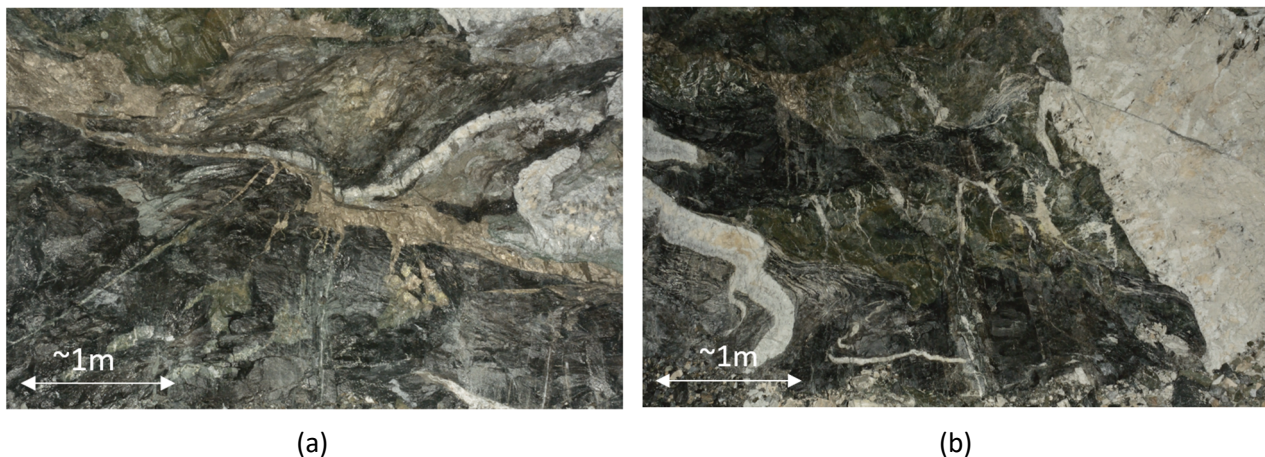
(a)   (b)

Figure 2   **(a) 9835 Level crosscut 10, face photo on 04/11/2019; (b) 9835 Level crosscut 10, face photo on 14/10/2019 with the presence of resin injected into the cut to maintain the drive and prevent brow breakback**

The dominance of the UM in the northern section of the small caving environment contrasts with the remobilised massive sulphide, felsic and pegmatite that intersects the 9835 Level on the southern end of the small caving zone. Figures 3a and 3b depict these complexities along with the pegmatite intrusion that acts as a bounding factor for the UM, inferred to be partially altered by metasomatism and remain competent up along the cave backs to the surface RL.

(a)   (b)

Figure 3   **Southern end of cave. (a) 9835 crosscut 06, development cut photo 12/10/2019. Pegmatite, massive sulphide and felsic, some evidence for metasomatism; (b) 9810 crosscut 05 development cut photo 11/10/2019. Pegmatite with felsic xenolith**

The areas of rock where there is an interplay between the different rock mass domains is pictured in Figures 4a and 4b, depicting the complexities in determining caveability of these transitional zones.
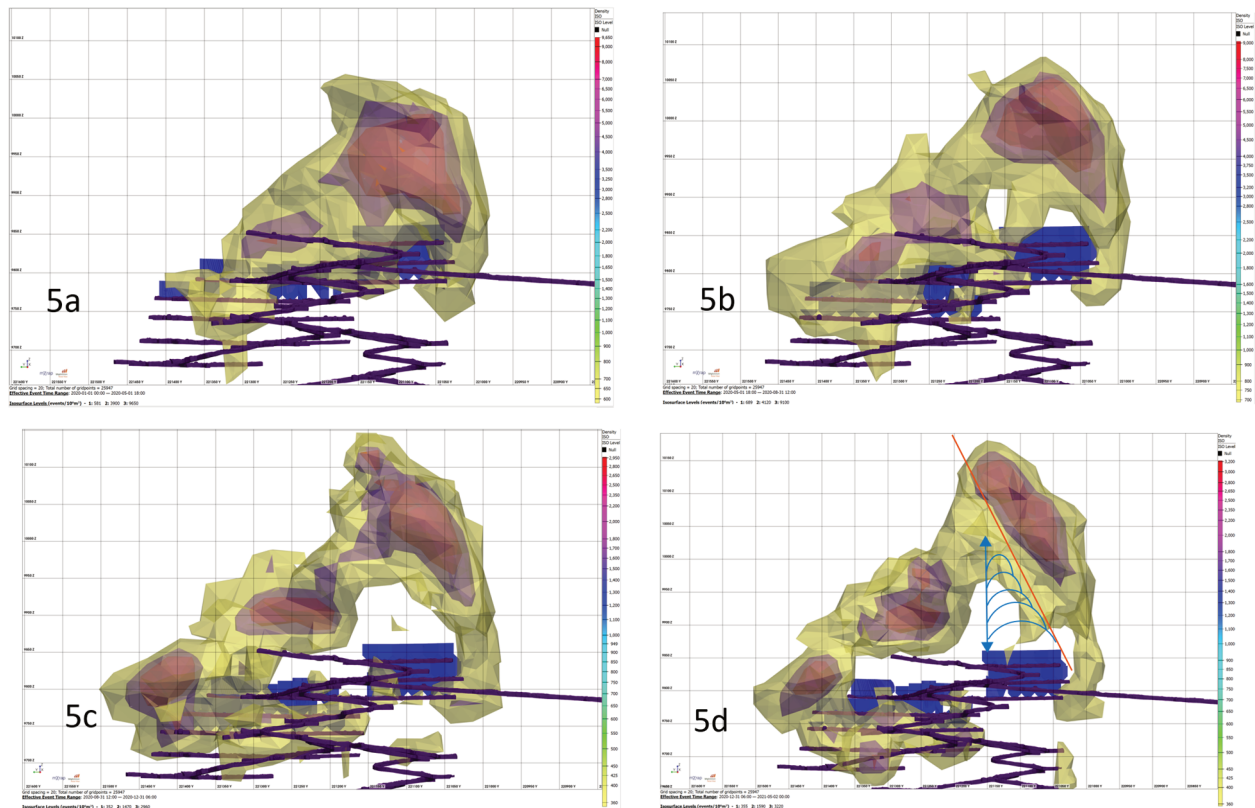
<table>
<tr><td>(a)</td><td>(b)</td></tr>
</table>

Figures 4 **Southern end of the cave. (a) 9785 crosscut 04 development cut photo 16/08/2020, felsic, UM and remobilised massive sulphide, faulting and joint infill; (b) 9785 crosscut 04 development cut photo 07/08/2020. Pegmatite, felsic, UM and remobilised massive sulphide, faulting and joint infill**

As seen in Figures 5a to 5d, the seismogenic zone for the south caving area developed in a typical manner until Figure 5c, which shows a distinct change in cave backs and abutment seismicity. There are several factors to this, the mining of northern Venus occurring in unison with the propagation of the south Venus cave. The shift in rock stress due to the new mining activity along with stress redistributing around the south Venus zone equated to seismic clusters forming in the rock capable of loading the stress being displaced. The seismicity clustered in the pegmatite intrusions, abutment stress zones and the western felsic rock mass, and along the brittle footwall fault within the felsic zone. Seismic monitoring included direct to change shift-by-shift extraction rates as a response to increasing seismicity at locations proximal to the caving zone and close to working areas.

The structures bounding the caving area constrained the cave propagation path and the seismic response. The cave remained structurally bound and chimneyed up the softer rock mass due to the pegmatite creating an arch of the cave backs and main structures driving the path of propagation. The north–south mining approach for the blasting and excavation started in the greatest UM zone vertical to draw points, as such extraction weakening the rock mass up to the 9,950 RL hindering the stress caving of the harder rock mass beyond this level.
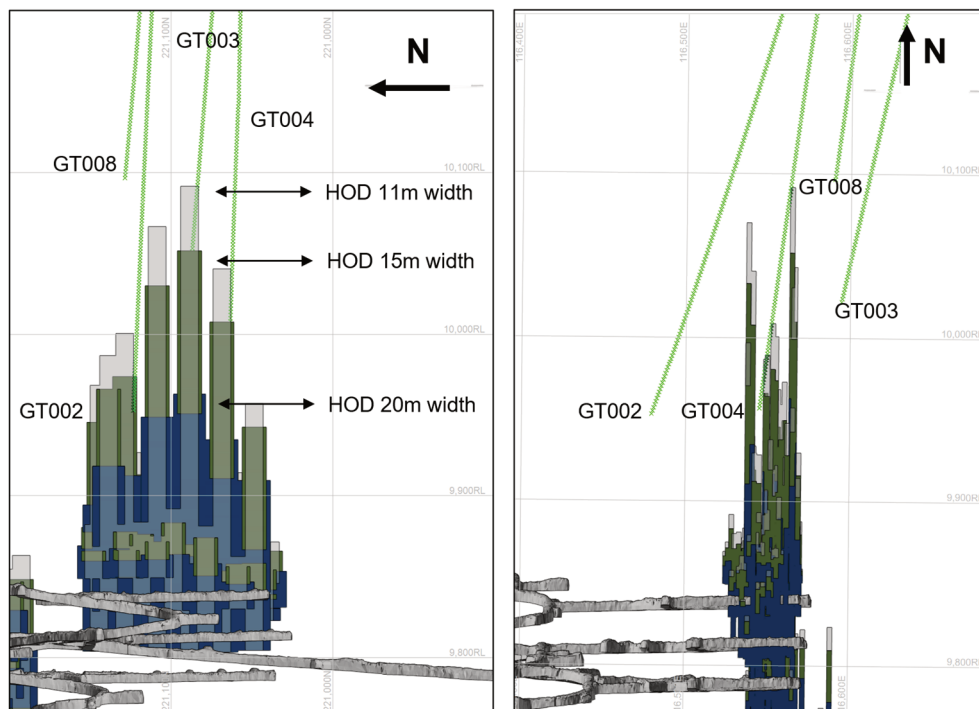
Figure 5 East facing view of the south Venus mining area with the evolving seismogenic zone for the small SLC over four-month periods starting 1/1/2020. Modern development in purple, mined areas in blue with high, medium and low density seismogenic zones pictured in red, purple and yellow evolving as the cave develops. (d) Depicts the south cave propagation path in blue with the pegmatite contact that bounds the small SLC in orange. The seismogenic zone clearly shifts into the pegmatite over the life of the small SLC

Propagation is not inferred as a daily rate in the small caving environment, with increments of yielding rock zones to caved mass tracked as 10–30 m jumps in the rock from a correlation between Smart Marker loss and HOD as depicted in Figure 6. Height of draw acts as a clear indication of where propagation of the rock has seeded to, with marker loss correlating with HOD in caving zones of a GSI of 25–45. Without the pegmatite structure bounding the cave extents, HOD correlates with the height of the yielding zone of rock. The cave's propagation direction was constrained by the dominant ore bearing structures lensing towards the east.

Within the small cave zone the muck pile behaviour is interpreted as a blanket drawdown to determine lowest average of the height of broken rock in the caving zone. This interpretation preceded over an assumption of a cigar drawdown within each height of draw column, due to the inferred high caveability of the UM rock mass.

The felsic, pegmatite and mafic rock masses in Venus all have similar seismic responses to loading with stress and cave propagation, the UM is largely aseismic with the rock inferred to be yielding at a consistent rate due to its behaviour at the tunnelling level. Smart Marker technology allowed a means to calibrate cave extends in the aseismic zone, confirm propagation pathway along the pegmatite contact and define cave parameters in conjunction with surface probe holes.

Surface probe hole interactions and controls around water used for drilling was communicated regarding potential water ingress from drill rigs into the void. Additional probing from levels within development areas also confirmed cave extends. Airgap monitoring of the muck pile was completed weekly with a safety measure of 60 m above the 9835 RL established as the minimum muck pile within the caving zone, and blast walls were installed on the 9835 RL as a precautionary measure.

Figure 6   Height of draw data from the south cave area with different draw widths applied for a rock with density of 2.7 t/m³ and for a bulking factor of 0.2. Also depicted are the Smart Markers up to the last intact marker for each hole above the Venus south cave
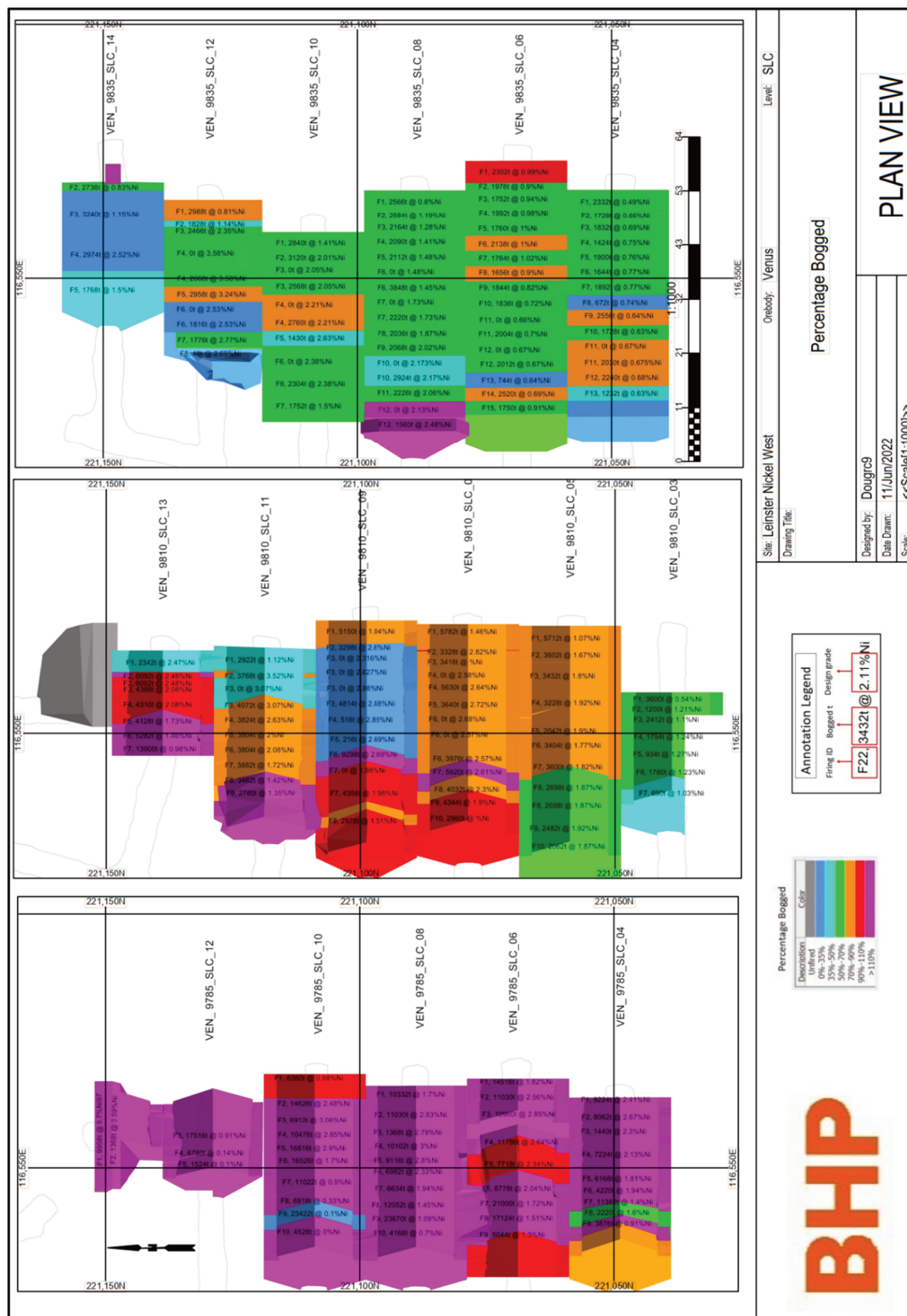
Tracking of nickel grades and caving behaviour was included into a Deswik database for monitoring. This ore extraction asset database provided communications to all relevant stakeholders via plots, depicted in 6a and 6b. The plot outputs depict the different footprint of each level with a plan view of the blasted area, as depicted in the plots each level has a differing footprint geometry which is considered as another variable for the caveability of rock mass with a UTS > 10 or GSI > 50.

The zones of brow breakback, fragmentation, percentages bogged, average nickel and last nickel grades of each firing ring can also be depicted in these plot outputs, establishing a means to monitor and communicate dilution, fragmentation and tonnes extraction to the larger audience of internal and external stakeholders.

As the cave is inferred to have arched from the 9,940 RL to the 10,100 RL along the pegmatite contact, the aim of the small caving project to limit the cave backs at the 10,120 RL for adequate crown pillar coverage to mitigate the potential for surface infrastructure interaction was achieved. If the pegmatite was encompassed into the cave, the contribution to the muck pile would have assisted with airgap risk management, however, this would have had a significant impact on subsidence risk.

4   Future solutions for a similar environment

The concept of maintaining a crown pillar for a SLC is not typical. It categorises the cave as something unique, which requires individual solutions. Underground development can evolve with new technologies, minimising waste outputs and costs while maintaining rock mass strength is possible with in situ bioleaching (Laurent et at. 2019). Biotechnology may be a future means to use in conjunction with caving to maximise ore extraction within environments with unique constraints. The type of ore extracted, and other factors, determine whether this is an appropriate technology to be implemented on site. Through strategic drillholes into the mineralised zone the economic value of the rock can be flushed through or concentrated into a zone more optimum for cave creation (Gumulya et al. 2022; Martens et al. 2021). If there is a requirement to bog through dilution for cave integrity, the implementation of heap bioleaching of high grade waste as an additional step in waste consolidation to maximise ore extraction could be applied on a site-by-site basis (Johnson 2014).

Figure 7a Percentage bogged plots for the three levels of the Venus south cave, all firings with the annotation 0 t are areas of brow breakback
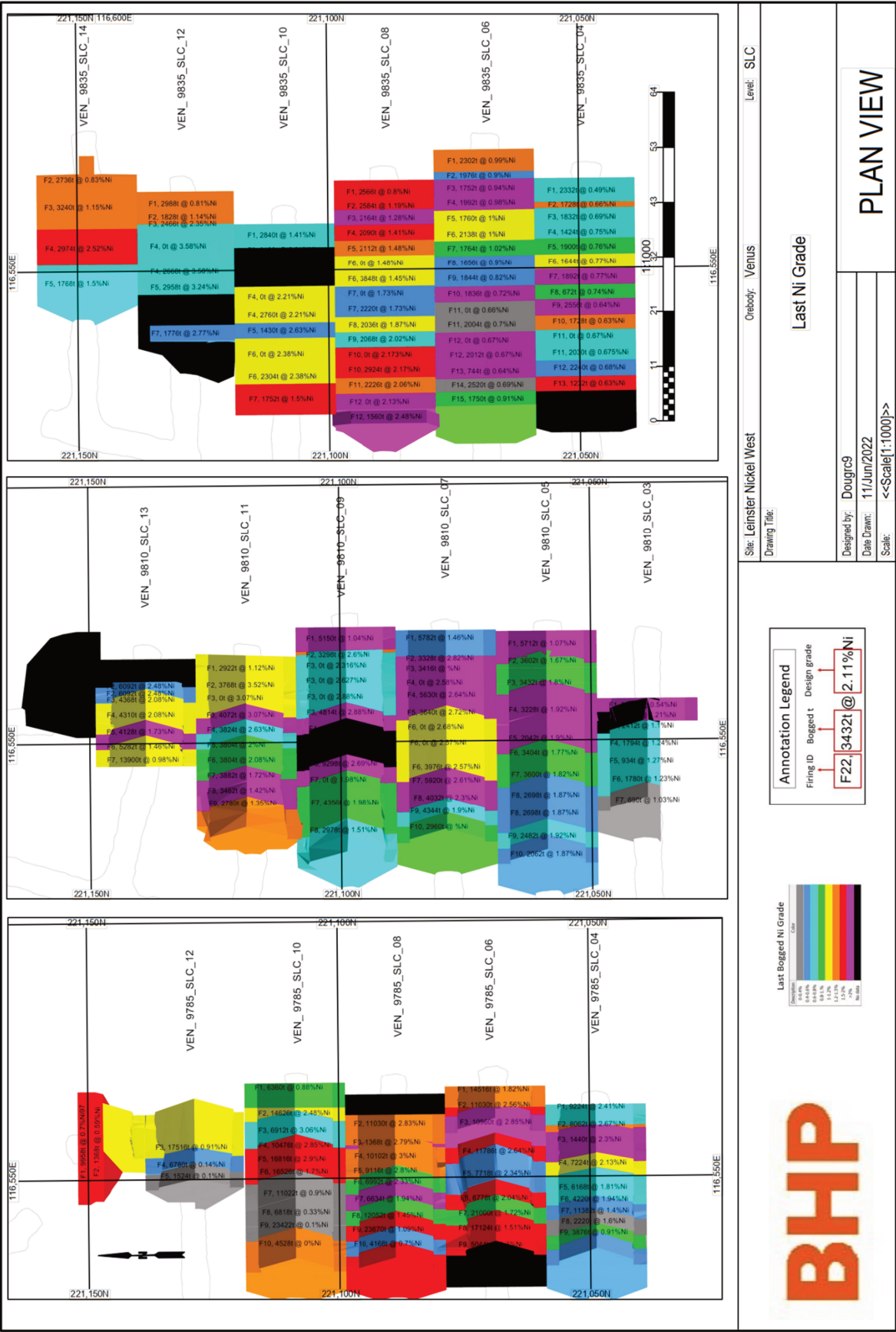
Figure 7b Last captured grade plots for the three levels of the Venus south cave, note that ore has been left within the 9785 Level to maintain the muck pile within the cave

5   Conclusion

The Venus south cave saw unique challenges and learnings, understanding the different caving mechanisms at play within the anisotropic system. Ideally, these learnings will be incorporated and reintegrated holistically into the future planning onsite. Ground support standards as a primary control at the tunnel level proved significant and the observations on the pillar between the levels as a key factor in the stress on tunnels will be monitored with the level pillars expanding 30–35 m as the SLC mining area progresses. Future work could incorporate the impact of varying level-by-level footprints on stress displacement and the ramifications of having the SLC driven by short-term ore capture and not long-term caving.

Dilution fluctuations and the impact of different types of dilution on internal fragmentation and fragmentation zone behaviour was also a factor in calls made around limits to the small SLC. A direct correlation between extraction rates, propagation, and fragmentation is noted with the implementation of shift-by-shift rate of extraction proving effective in cave management. Starting the cave on a level with the highest ore footprint, and largest mass of soft rock was always going to limit the caves propagation to an extent, however HOD proved useful to correlate the height of cave propagation in conjunction with Smart Marker technology and seismic analysis for accurate and safe monitoring. As the seismogenic zone never exceeded 10,200 RL and the height of the high-density clusters never exceeding 10,150 RL this aligned with all other available data inputs to confirm the height of cave. Accuracy in determining the cave parameters created a means to infer the ongoing deduction of the muck pile within the small caving zone. The cave proved an excellent precedent for learnings on site to assist in the future of the project.

Acknowledgement

The Leinster crews for keeping the machine going, technical services for providing data and the entirety of the team for the camaraderie.

References

Bewick, RP 2021, 'The strength of massive to moderately jointed rock and its application to cave mining', *Rock Mechanics and Rock Engineering*, vol. 54, no. 8, pp. 3629–3661. doi:10.1007/s00603-021-02466-3.

Cumming-Potvin, D, Wesseloo, J, Jacobsz, SW & Kearsley, E 2018, 'A re-evaluation of the conceptual model of caving mechanics', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 179–190, https://doi.org/10.36487/ACG_rep/1815_11_Cumming-Potvin

Dempers & Seymour Pty Ltd 2017, *BHP Billiton Nickel West Perseverance MRMM*.

Duplancic, P 2001, *Characterisation of Caving Mechanisms Through Analysis of Stress and Seismicity*, PhD thesis, The University of Western Australia, Perth.

Duplancic, P & Brady, BH 1999, 'Characterisation of caving mechanisms by analysis of seismicity and rock stress', *Proceedings of the 9th ISRM Congress*, International Society for Rock Mechanics, pp. 1049–1053.

Duuring, P, Bleeker, W & Beresford, SW 2007, 'Structural modification of the komatiite-associated Harmony nickel sulfide deposit, Leinster, Western Australia', Economic Geology, vol. 102, no. 2, pp. 277–297.

Gumulya Y, Zea L & Kaksonen AH 2022, 'In situ resource utilisation: The potential for space biomining', *Minerals Engineering*, vol. 176, p. 107288, https://doi.org/10.1016/j.mineng.2021.107288

Hogan, P & Thompson, A 2019, *Report on Intact Rock Properties Testing for Venus Nickel Project*, Western Australian School of Mines, Curtin University.

Johnson, DB 2014, 'Biomining—biotechnologies for extracting and recovering metals from ores and waste materials', *Current Opinion in Biotechnology*, vol. 30, pp. 24–31, ISSN 0958-1669, https://doi.org/10.1016/j.copbio.2014.04.008

Kalenchuk, KS, McKinnon, S & Diederichs, MS 2008, 'Block geometry and rockmass characterization for prediction of dilution potential into sub-level cave mine voids', *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, issue 6, pp. 929–940, https://doi.org/10.1016/j.ijrmms.2007.10.006

Laubscher, DH 2001, 'Cave mining – the state of the art', in WA Hustrulid & RL Bullock (eds), *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, Society for Mining, Metallurgy and Exploration, Englewood, pp. 455–463.

Laurent, G, Izart, C, Lechenard, B, Golfier, F, Marion, P, Collon, P, Truche, L, Royer, JJ & Filippov, L 2019, 'Numerical modelling of column experiments to investigate in-situ bioleaching as an alternative mining technology', *Hydrometallurgy*, vol. 188, pp. 272–290, https://doi.org/10.1016/j.hydromet.2019.07.002

Martens, E, Prommer, H, Sprocati, R, Sun, J, Dai, X, Crane, R, Jamieson, J, Ortega Tong, P, Rolle, M & Fourie, A 2021, 'Toward a more sustainable mining future with electrokinetic in situ leaching', *Science Advances*, vol. 7, no. 18, doi:10.1126/sciadv.abf9971, https://www.science.org/doi/abs/10.1126/sciadv.abf9971

Perring, CS 2015, 'A 3-D geological and structural synthesis of the Leinster area of the Agnew-Wiluna belt, Yilgarn craton, Western Australia, with special reference to the volcanological setting of komatiite-associated nickel sulfide deposits', *Economic Geology*, vol. 110, no. 2, pp. 469–503.

Pierce, M, Cundall, P, Potyondy, D & Mas Ivars, D 2007, 'A synthetic rock mass model for jointed rock', *Proceedings of the 1st Canada-U.S. Rock Mechanics Symposium*, vol. 1, Vancouver, Canada, pp. 341–349.

Prado, D & de Bruyn, I 2019, *Venus Geotechnical Model Update for BHP Nickel West*, SRK Consulting, West Perth.

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

Varden, RP & Woods, MJ 2015, 'Design approach for squeezing ground', in Y Potvin (ed.), *Design Methods 2015: Proceedings of the International Seminar on Design Methods in Underground Mining*, Australian Centre for Geomechanics, Perth, pp. 489–504, https://doi.org/10.36487/ACG_rep/1511_30_Varden