

The jointed-veined rock mass characterization approach - benchmarking for caveability, fragmentation, and ground stability decision making

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ABSTRACT

Caveability, fragmentation, and ground stability are important aspects impacting production reliability in a caving mine and can be fatal flaws if they are not properly assessed. In addition, there is evidence from historical and current caving mines that revenue recovery loss has occurred due to production disruption from these aspects. The root cause of the unreliable forecasts is often due to failure of rock mass characterizations to accurately determine the key factors controlling rock mass behaviour. A data collection and analysis approach has been developed using a jointed-veined rock mass matrix (previously reported). The overall methodology has been applied to several cases to identify potential challenges and make decisions about caveability, fragmentation, and excavation stability at early stages of a project or mine design implementation. The nature of most caving ore bodies are such that alteration, vein systems, and faults are the main characteristics of the rock mass. The approach relies on borehole geotechnical and geophysics data, laboratory strength testing, and point load index testing that target both the intact rock and veins. Data analysis includes DFN modelling to classify rock masses according to the intensity of both open structures and potential block forming veins using P32 (a nondirectional volumetric intensity parameter). Block modelling of P32 and rock strength is completed to understand spatial variability of characteristics and define geotechnical domains. In this paper, data from various caving operations and projects, as represented in the jointed-veined matrix, are presented to document examples of rock mass characteristics across different orebody classes.

Keywords: Caveability, Fragmentation, Block Cave, DFN, P32, Rock Mass Characterization.

1 INTRODUCTION

With caving projects increasingly being developed in deeper and massive ground, there is a need to improve the rock mass characterization process to improve the reliability of the forecasted cave performance. A key aspect of porphyry copper gold ore bodies situated at depth is the lack of open structures like fractures or joints, except for the large-scale fault systems that typically intersect them. Instead, these rock masses are characterized by intense vein networks (Figure 1) containing various mineral assemblages that contribute to cohesion and significant tensile strength to the rock mass, resulting in its massive feature and

brittle behavior. Review Nugraha et al. (2020) for instance, where caving stall at a Grasberg mine is one of the latest wrongdoings among several other examples in the industry. It is possible to say without doubt that the lack of understanding of the rock mass character in this ore body ranked top in the list to explain the unreliable caving behavior.

Part of the problem is that traditional means of rock mass description and characterization have focussed on joints or just fractures (Brown, 2007). Vein characterization has been recognized as a key element to assess rock mass strength and quality as suggested early on by Laubscher and Jakubek (2000). However, since

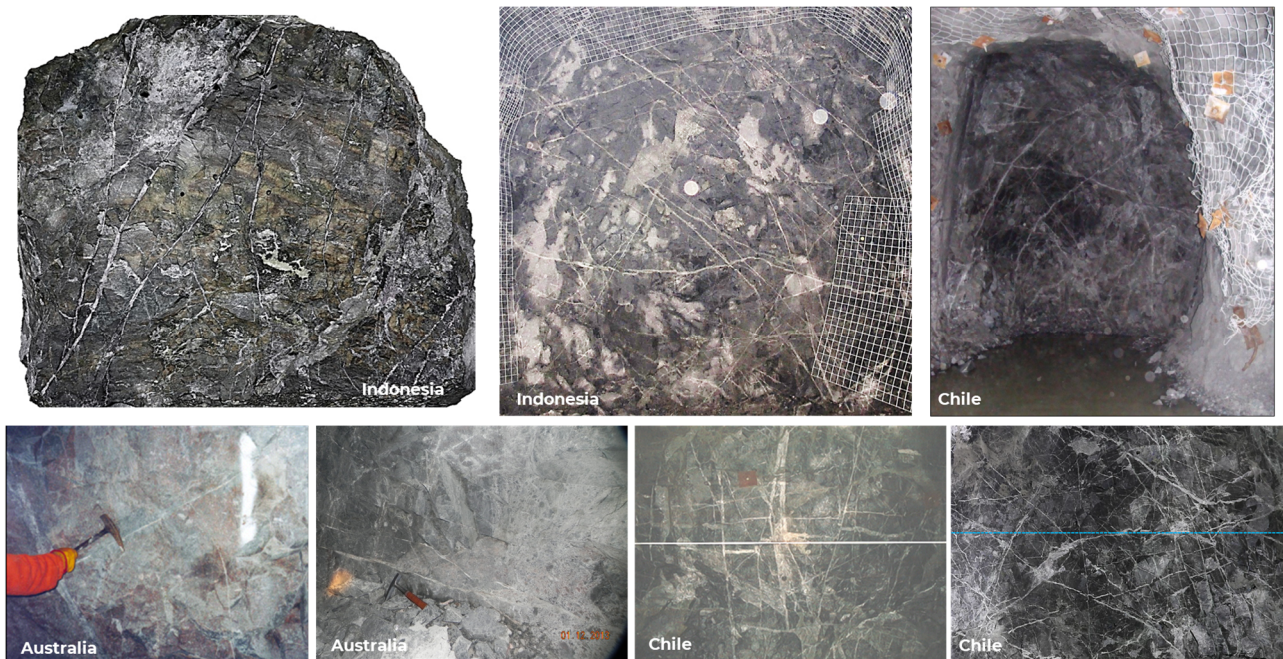


Figure 1 Examples of porphyry copper gold veined rock mass. All photos taken from drive headings.

it has been fully demonstrated that weak veins control fragmentation in these massive and unfractured veined rock masses (Brzovic and Villaescusa 2007) these features have been included in several trial methodologies to be related to rock mass strength (see Day et al., 2019, Russo et al., 2020).

Rock mass characterization for these veined rock masses not only require rock mass strength assessments, but also describing, measuring, and determining how and what controls rock mass strength, fragmentation and caveability and how these geological features are distributed along the orebody that comprise thousands of cubic meters.

In this paper a comprehensive characterization approach is presented, based on recent PFS and FS work undertaken for several caving projects around the world, including some caving operations.

The following two main concepts are relevant to consider when characterizing rock masses for porphyry copper gold ore bodies.

1.1 Jointed versus Veined

The key difference between jointed and veined rock masses can be elucidated by imagining how each of them will behave under loading conditions. A jointed rock mass (Figure 2), defined mostly by removable or kinematic in situ blocks will accommodate strain or movement by rotation and shearing between these blocks, thus GSI (and traditional rock mass classification systems) and Hoek and Brown failure criteria certainly apply.



Figure 2 Jointed Rock Mass.

However, a veined rock mass (Figure 1) is characterized by intense vein networks containing various mineral assemblages that

contribute to cohesion and significant tensile strength, resulting in its massive feature. Shearing and rotation is inhibited in this rock mass due to the lack of open space found within joints or faults. Therefore, a veined rock mass will fail in brittle manner and the failure mode will be determined by confinement conditions, i.e., spalling or shear failure (Kaiser and Kim 2014).

1.2 Key Elements of Veined Characterization

The original concept of assessing rock mass quality and strength with conventional classification schemes by determining the block sizes by open discontinuities and the interlocking strength relationship between them, have not changed for a veined rock mass. The key difference with this approach that needs to be considered and measured is the additional strength component that healed veins pose in the rock mass (cohesion and relevant tensile strength between pseudo blocks). In other words, not only is it required to characterize the special arrangement of veins within the rock mass (pseudo block size distribution they form), but also the strength of the infill mineral contained in the veins with the consideration that not all veins have the same strength characteristics. Therefore, characterization of veins in the rock mass must consider:

- Vein Type – what vein minerals, where are they spatially, and its relation to any alteration type (usually linked).
- Vein Strength – what vein infill minerals are weak and strong.
- Intensity of Structural Features – what are the spatial intensities and geometries of each of the vein types.

Joints and small-scale Faults follow the same approach, i.e., their strength and geometric characteristics need to be assessed. Large faults on the other hand, form part of the large structural model.

2 ROCK MASS CHARACTERIZATION

Typically, during PFS and FS engineering studies there is not underground access to the

orebody, and characterization of the cave volume is done by thousands of meters of geotechnical drill core complemented with geophysics data collection techniques such as ATV/OTV. Intact rock testing campaign (BTS, UCS and TCS) are taken from undisturbed core samples. Recently, the industry has implemented high density collection of PLT in both intact rock and discretely along veins (see Pierce et al., 2022, Bewick et al, 2022) sometimes 1 or 2 meters apart for intact rock and discrete sampling on selected veins. ISRM field testing is part of the characterization suite as well.

Standard geotechnical logging includes discontinuity and defect logging to systematically determine the intensity or frequency, and surface characteristics of geological features such as Faults, Joints, Veins and defects (small veins) as shown the example in Figure 3.



Figure 3 Calcite & Gypsum veins captured during discontinuity and defect logging.

Such intense destructive data collection through systematic PLT and ISRM field tests, coupled with core box handling, results in the final core samples stored in the core shed appearing heavily fractured. This deceptive aspect of the core samples in the core boxes can be confusing to non-expert decision-makers, as shown in Figure 4. Here, an OTV image shows unfractured rock with few continuous veins, contrasting with the same core section at the rig, with few mechanical breaks (marked with a red 'x'), and the core box stored at the core shed. The fractured appearance of this core section in the

core box is attributed to handling and intensive PLT testing (highlighted with red circles in Figure 4), not to the real nature of the rock mass.

Additional data collection techniques are the Dynamic Hardness Testing (DRT) and Hyperspectral Core Imagen (HCI) or Corescan for determining more objective alteration facies.

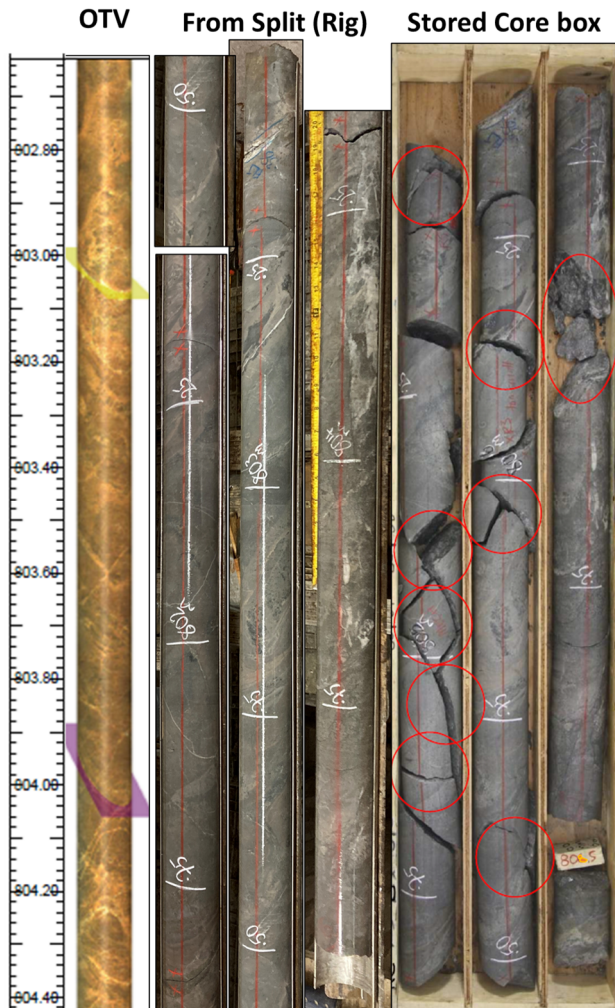


Figure 4 Core samples comparison at rig (split) and at the core shed.

2.1 Characterization Workflow

Through several works for current caving operations, a methodology has been refined to characterize with considerable detail the large volume that comprises porphyry copper gold orebodies. A summary of the different parts of this methodology and their interaction is schematized in Figure 5. The process starts with reviewing and QA/QC the raw data

including lab testing, then discontinuity data is processed to determine intensity along geotechnical holes for Joints, small faults, and veins, which is discussed in section 3.2. Geometric and intensity of all these geological discontinuities are processed through Discrete Fracture Network (DFN) modeling (in section 3.3), which is a key ingredient of this characterization approach. Through DFN analysis in-situ fragmentation are defined which is linked to the volumetric intensity parameter P_{32} (discussed in section 3.3.1) to assess in situ fragmentation of the whole cave volume using block modelling. The large-scale structural model is developed in parallel with the characterization and used to assess its influence on geotechnical domains (in section 3.2.1).

Lab and field-testing data, in particular systematic PLT are used to determine both intact rock mass and vein strength (discussed in section 3.1.2). Intact rock mass strength and discontinuity intensity are the two main components that define the character of the rock mass, therefore these two are the main parameters for block modeling. The PLT index as Is_{50} , would provide spatial variability of the intact rock mass strength through block modeling and the pair of P_{10} - P_{32} would provide spatial variability of discontinuity intensity as well, both discussed in section 3.4.

Geotechnical domains are essentially dependent on the ore body characteristics: what drives strength from the geologic point of view? Lithology and alteration are the first source for domain definition, but block modeling also helps answer this question by spatially quantifying intact rock strength and discontinuity intensity (in section 3.4). After geotechnical domains are defined, rock mass strength assessment is undertaken for jointed and brittle rock masses (in section 4).

Finally, the Jointed-Veined matrix discussion and comparison with caving experience to foresee challenges in term of Fragmentation, Caveability and ground stability (in section 5).

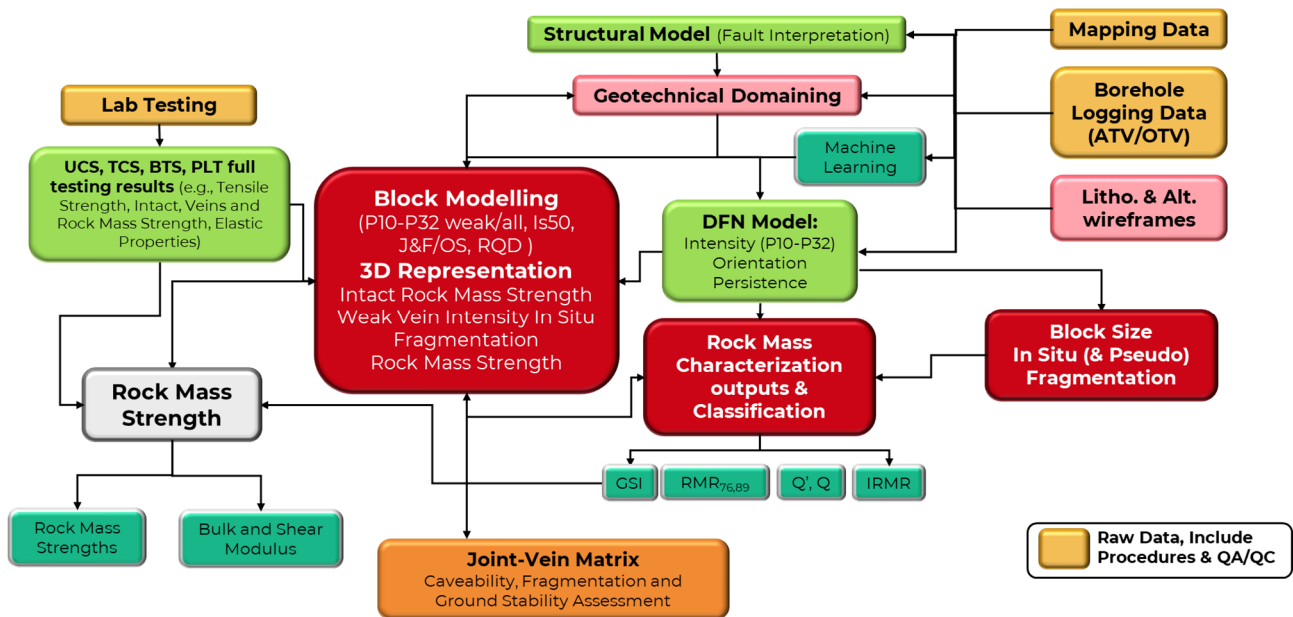


Figure 5 Rock Mass Characterization and Classification Approach (modified from Byrne et al., (2023).

2.1.1 Failures Modes in Testing

One key aspect of the characterization approach presented here is to identify the failure type in all implemented testing techniques. Veined rock masses tend to present continuous veins, hairline veins, and veinlet defects that may influence rock failure during testing (Figure 6).



Figure 6 UCS-TCS test influenced by veins, forming a discrete (left) and combined (right) failure mode.

Failure mode logging has been implemented based on four primary definitions: *Homogeneous*, *Combined*, *Discrete* and *Vein Networks* (Bewick et al., 2021). *Homogeneous* means failure occurs through intact rock, *Discrete* means it happens through a single discontinuity within the sample (usually veins), *Vein Networks* is when failure occurs through multiple veins and *Combined* as mixture of intact and vein network failure modes.

2.1.2 Geotechnical Drill Core Intensity

Geotechnical drillhole density has been assessed and benchmarked against several caving projects (Figure 7). The assessment indicates core density within the resource volume (caveable height of draw), which informs future data collection campaigns of the gaps in geotechnical drilling (Figure 8) within the cave volume that should be targeted.

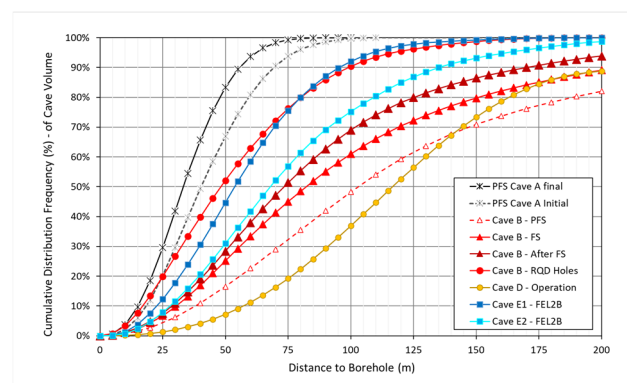


Figure 7 Example of benchmarking of Drillhole Density.

Although not discussed here, the orientation of drilling is part of the gaps analysis to provide guidance to avoid sampling bias.

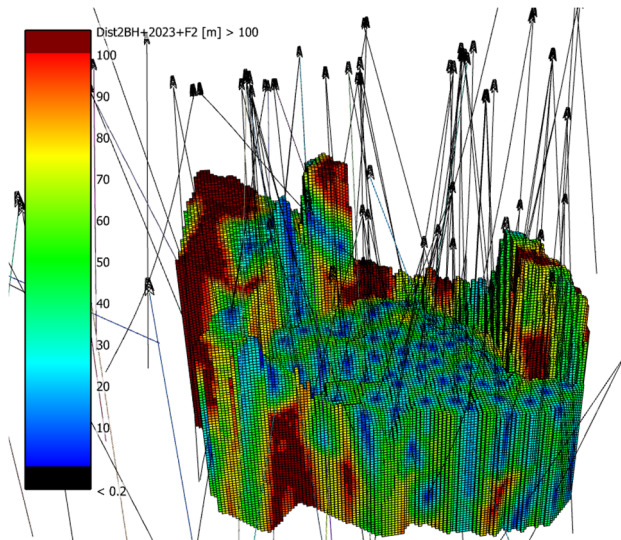


Figure 8 Example of drillhole density within height of draw for a caving project.

3 RESULTS AND DATA ANALYSIS

3.1 Intact Rock Mass Strength

Laboratory rock strength testing data (UCS, TCS, BTS) are used to develop estimates of intact rock strength (e.g., Hoek and Brown 1980; Hoek and Brown 2018) and elastic parameters (Young's Modulus and Poisson's Ratio). Laboratory testing reports and associated photographs are reviewed to assess the failure type of each sample and classify or confirm the failure types as discussed in section 2.1.1.

Curve fitting of intact rock strength is completed using valid triaxial, sample-size-normalized UCS and corrected BTS data points. Current best practice of fitting Hoek-Brown envelopes involves developing separate fits for each of the four failure types (Figure 9). However, sometimes due to the relatively limited set of available data, curve-fitting often needs to consider a combination of failure modes (homogenous and combined). Tensile strengths are estimated using tension cut-offs as per Hoek and Martin (2014), associate readings for detailed procedures are Bewick and Ouellet (2017), Bewick (2021) and Condon et al., (2023).

3.1.1 High Density PLT

Since it is economical and easy to perform at site, the industry has been implementing high

density PLT to assess strength variability of the rock mass (Pierce et al., 2020 and 2022, Bewick et. al, 2022). One current caving project has >37,000 PLT over 100,000 m of drilling to assist with Is₅₀ block modeling and defining domains (examples in Figure 10 and Figure 11). Synthetic PLT estimates can also be created to augment available data sets for block modeling, such as the case presented by Tilley et al., (2022).

Figure 10 is confirming both ideas that geotechnical domaining can be refined using high density of Is₅₀ data and the strength reduction by the influence of veins. Figure 11 is also supporting the idea that Is₅₀ data sets can distinguish geotechnical domains elsewhere as UCS does, but with more abundant data sets based on practical data collection.

3.1.2 Vein Strength

Vein strength assessment is also another key element of the approach discussed here since veins weak enough are also considered block forming discontinuities in the caving environment (Brzovic and Villaescusa 2007). Vein strength assessment can be done using direct tensile or shear tests on veins (Brzovic et al., 2014), but it is more practical to use discrete failure from standard UCS and TCS as discussed by Bewick et al., (2022). Figure 12 presents a real vein strength assessment using standard UCS and TCS of a current caving project, which includes different infill types for discrete failure mode only as is shown in Figure 6 (left photo).

3.1.3 PLT Veins

As with intact rock, PLT conducted directly on veins is more economical, easier to implement on site, and would provide many samples in comparison with using UCS-TCS discrete failure modes from laboratory testing. Determining vein strengths is relevant for fragmentation assessments as is discussed in Section 3.3.2.

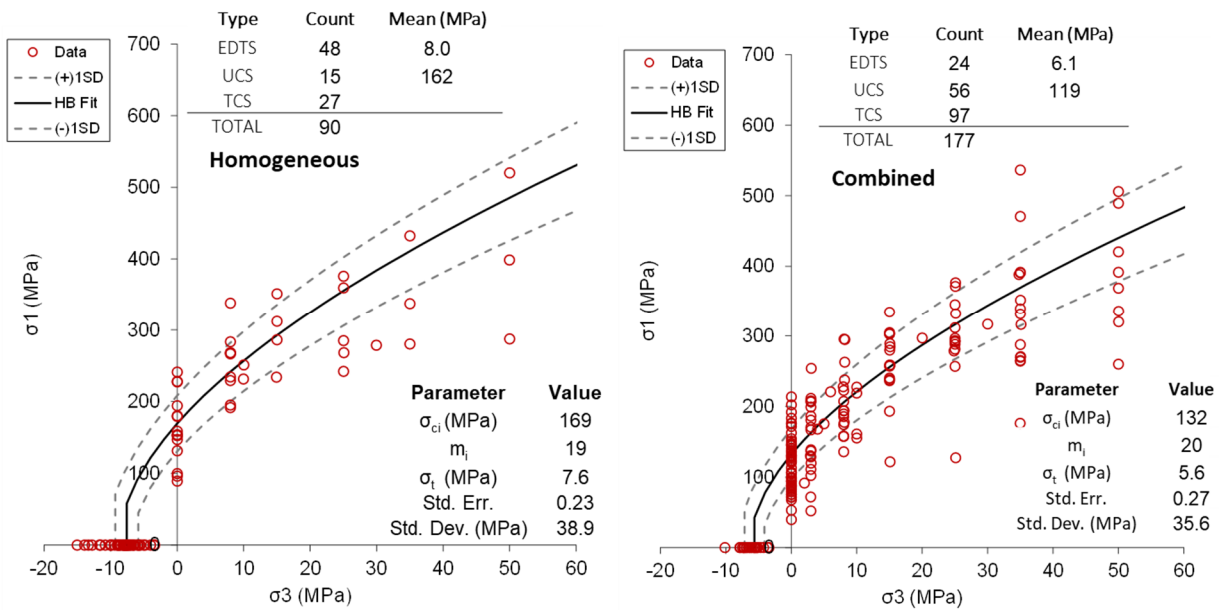


Figure 9 Hoek & Brown fitting considering failure mode for the same unit in a current caving project.

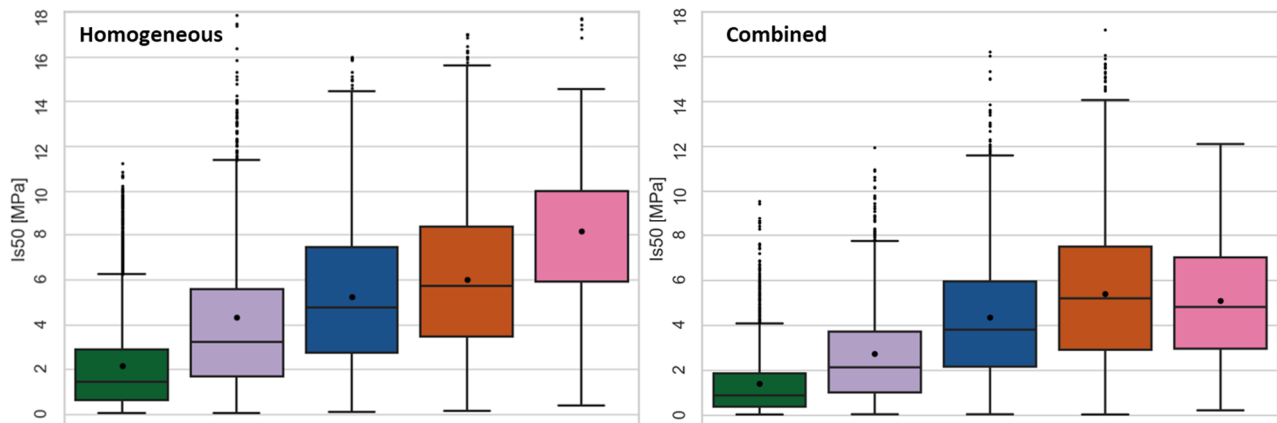


Figure 10 Is50 for different unit types (Domains as different colors) considering failure mode for a current caving project.

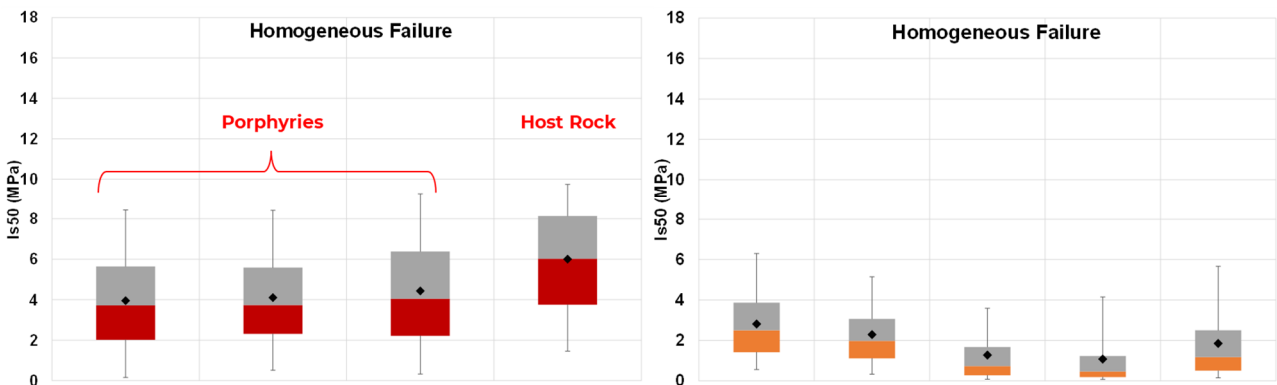


Figure 11 Is50 for different unit types (Domains as different columns) in others two caving projects.

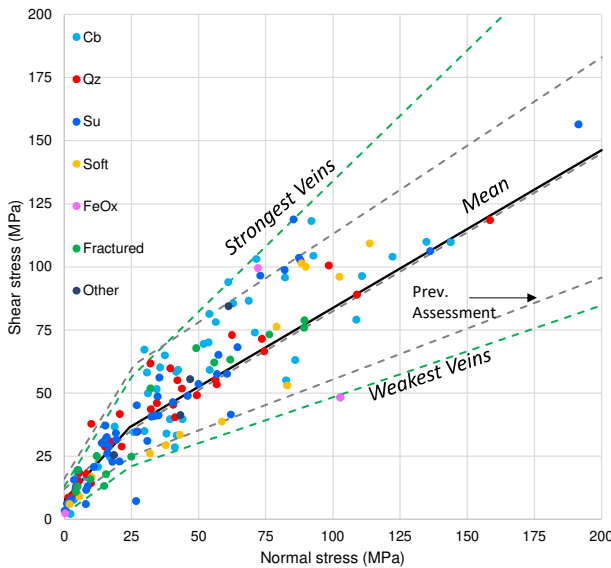


Figure 12 Figure Vein strength assessment for UCS and BTS.

Benchmarking data sets of PLT on veins using only discrete failure mode collected from different caving projects is presented in Figure 13. This figure, with over 4500 data points clearly shows how the mineralogical infill controls vein strength as found by Brzovic (2010). In this figure, similar mineralogical infill type (Py-1 and Py-2 or Ca-1 and Ca-2 for instance) correspond to different caving projects. Comparison between Figure 10 and Figure 13 confirms that veins with weak infill are the weaker path on this massive and unfractured rock masses shown in Figure 1, so characterizing these weak features is a paramount task to understand rock mass strength and disassembly (Fragmentation) under caving conditions. Cave experience has shown that that weak transition to strong veins from that Figure 13 are also vein block forming discontinuities (Brzovic and Villaescusa 2007, Pierce et al., 2020), therefore vein strength assessment would provide insight if such veins would may be consider as weak in the fragmentation assessment.

3.2 Rock Fabric or Rock Struture

Rock mass disassembly is the fundamental mechanism that must occur for a block caving mine to be successful, as it will impact caveability and fragmentation. Rock mass disassembly will occur if there are enough

continuous geological structures that form blocks that can fail by gravity or stress fracturing. In the past, only open structures, such as Faults and Joints were used to assess fragmentation. Today, it is well known that weak veins are also part of the equation, and therefore, must be characterized by describing all their geometric and strength characteristics.

It is important to note that in situ block size or in situ fragmentation refers to rock blocks formed strictly by open structures. Pseudo in situ blocks are defined by a combination of naturally open structures and weak veins, or only by veins considered as weak.

Rock Structures in this approach include:

- Large Structural Model
- OS (Joint and Fault)
- Veins

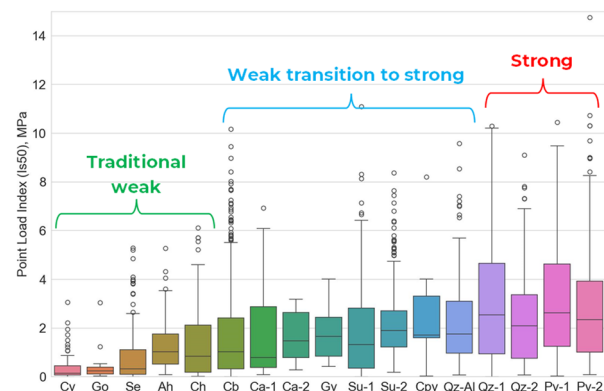


Figure 13 PLT on Veins (modified from Bewick et, al., 2022).

3.2.1 Large Structural Model

Although the large-scale structural model is not an essential part of the discussed characterization approach, it is a basic requirement for a caving project to understand caveability and ground stability at the EL. The large-scale structural model is usually developed in parallel with the rock mass characterization, Figure 14 is shown an example of that work for a current caving project and the methodology to develop such model are found in Byrne et al., (2023) and Stoch et al., (2023). It is necessary to consider if the large-scale structural model may play a role in geotechnical domain selection since small scale structural pattern and intensity

could be associated to such large features as the example shown in Figure 15, which is from one of the caving projects studied.

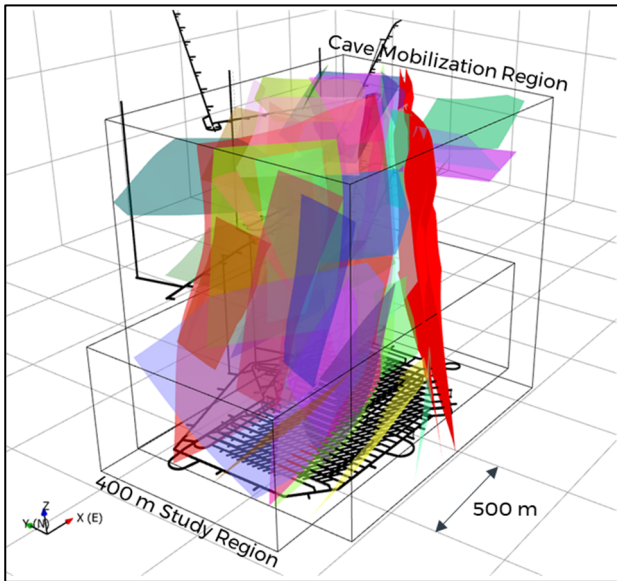


Figure 14 Example large-scale structural model for a Caving project.

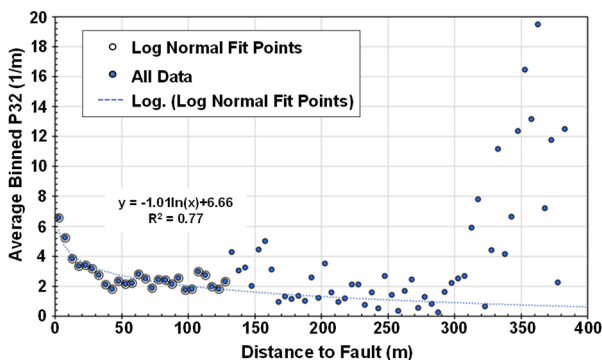


Figure 15 Open structure correlation with large faults in a caving project.

3.2.2 Open Structures

The purpose of open structure characterization is not only to determine in situ block sizes or the degree of fracturing, but also their spatial variability to understand which portion of the rock mass is jointed and where the brittle approach for rock mass strength will be applied (discussed in section 3.4 and 4)

3.2.3 Veins

As it has been discussed previously, vein types and their occurrence within the orebody, their geometric and strength characteristics are all the essential aspects to be collected in porphyry

copper gold deposits suitable for caving. An example of weak vein intensity estimates for current caving project is presented in Figure 16. Vein and weak vein characterization is then used for DFN modelling and block modeling.

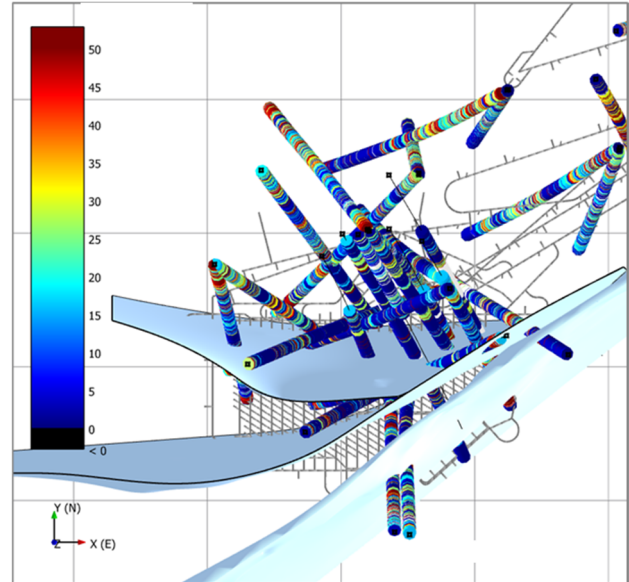


Figure 16 Example of weak vein intensity from geotechnical logging in a current caving project.

3.3 Discrete Fracture Network (DFN) Modelling

DFN modeling is one the best tool to represent and replicate the 3-dimensional nature of the rock structure. A discrete modelling approach captures the heterogeneity of the fracture system by explicitly describing key elements of the system geometry by defining fracture parameters (e.g., fracture size, orientation, and intensity) stochastically and deterministically. This allows to capture the geometry and special variability the geological structures that will aid in the disaggregation of the rock mass during caving. Key parameter for DFN analysis are both discontinuity intensity P_{10} and P_{32} described in following section.

3.3.1 Discontinuity Intensity P_{10} and P_{32}

Fracture frequency (ff) is the number of fractures measured over a unit distance (m) used to characterize the degree of fracturing. Ff is a measurement of the fracture intensity, also named P_{10} . P_{32} , introduce by Dershowitz and Herda (1992), is a 3D measurement that

represent the area of fracturing (m^2) over the volume of the rock mass (m^3). P_{32} represents an isotropic intrinsic measurement, without the bias of conventional measures like spacing and ff and is therefore useful for comparing core measurements and ultimately block modelling of P_{32} intensity as a description of the spatial variation of structural intensity and block size distribution (Rogers et. al, 2014, Bewick et. al, 2022) as is illustrated in Figure 17.

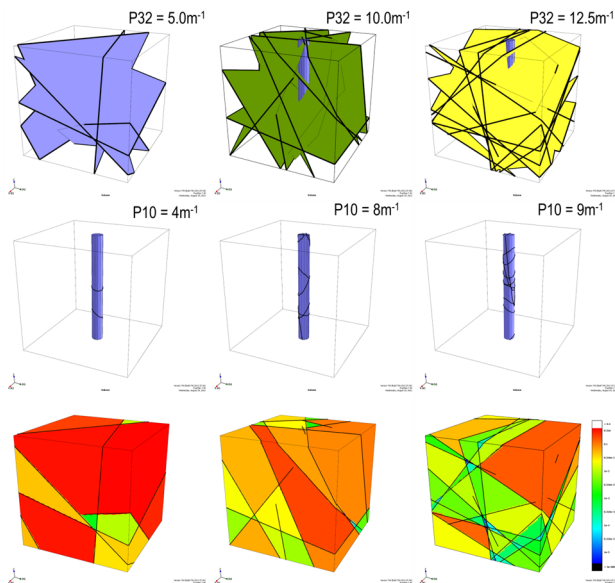


Figure 17 P10, P32 and in situ block volume.

3.3.2 In situ Fragmentation

DFN models are built based on collected data from site (orientation, size and intensity), then in situ or pseudo in situ (by veins) fragmentation or the block size distribution can be defined and linked to a determined P_{32} value. Finally, from core logging measured P_{32} is used in block modeling to determine either discontinuity intensity or block size variability across the ore body. Detailed procedures are described in Rogers et. al, 2014 and Bewick et. al, 2022.

For jointed rock mass a GSI (Marinos & Hoek, 2000) can be estimated from block size using methods outlined by Cai et. al. (2007). Knowing block interlocking (J_c) block size can be converted in GSI and vice versa. Even a GSI equivalent may be used when weak veins are considered. An example of GSI converted from in situ fragmentation (using a J_c of 5.3) is shown in Figure 18, most of the rock mass in this figure,

which is from a caving project studied through this characterization approach, is considered massive ($GSI > 80$).

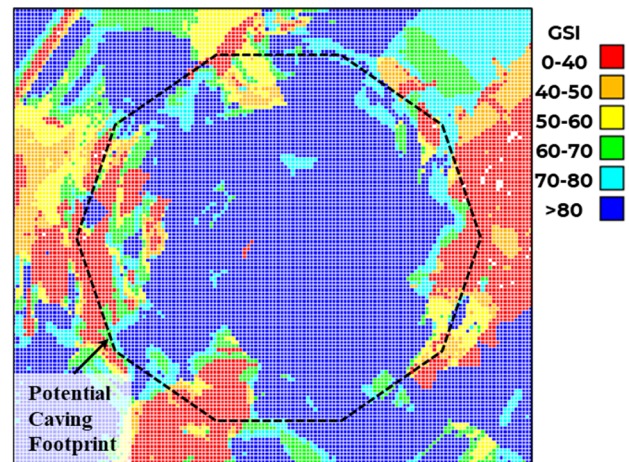


Figure 18 Example of a GSI determined from in situ fragmentation for a current caving project.

3.4 Block Modelling and Geotechnical Domain definition

Block modelling is developed essentially to determine the strength and P_{32} spatial variability across the orebody but could be applied to any desired parameter as the example in Figure 18. Block modeling is also used to assist in geotechnical domaining when a critical parameter such Is_{50} of weak vein intensity may define low or high values within certain volume if a similar rock or alteration type.

Experience in the industry indicate that lithology and alteration are the main driver for geotechnical domain definition, being sometime one more important than the other. Ore body knowledge and data analysis as presented here are the key elements to be developed and achieve a realistic domain definition.

In general, block models are estimated using the Inverse Distance Squared (ID^2) interpolation method, but data availability may control if a more sophisticated interpolation method can be used. A total of three search passes usually is used. The passes serve as a level of confidence in the estimation, with Pass 1 being the highest confidence (search distance up to 100m) and Pass 3 being the lowest confidence (search distance up to 400m). Examples of interpolation confidence levels, intact rock strength (Is_{50}) and

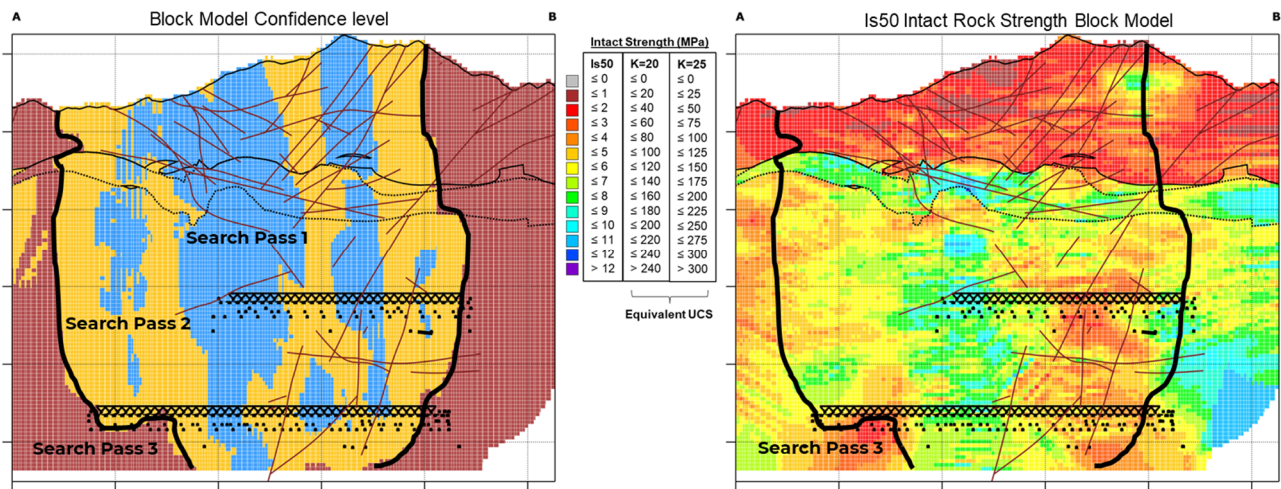


Figure 19 Examples of confidence level applied during block modelling and Intact rock mass strength model for current caving project.

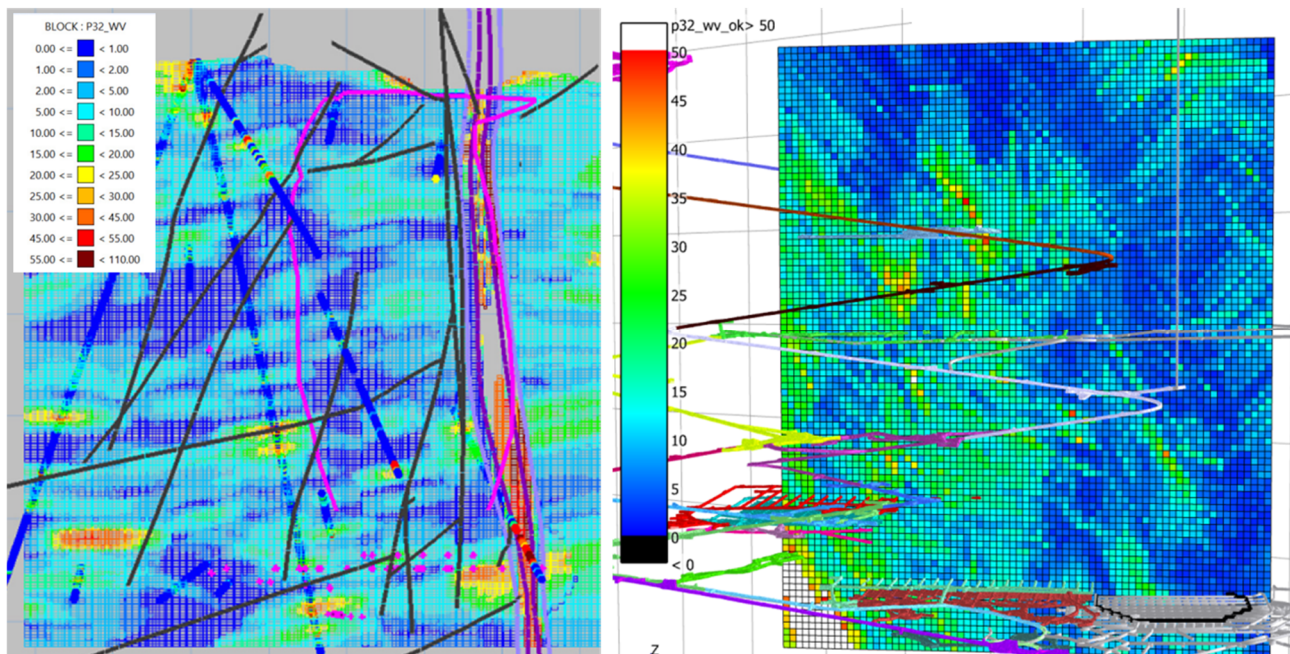


Figure 20 Example of weak vein intensity models developed for a current caving project and caving operation.

weak veins block model are presented in Figure 19 and Figure 20.

4 ROCK MASS STRENGTH

The spatial distribution of the geological discontinuities previously developed define where jointed and massive rock masses are located within the ore body as shown in the example in Figure 18. The Hoek and Brown criteria is applicable for jointed rock masses ($GSI < \sim 65$) and a brittle spalling approach is

used for massive and veined rock masses ($GSI > \sim 65$). Currently the approach suggested by Bewick (2021) is followed.

The spalling limit governs the change from spalling (long cracks) to shear rupture (short cracks) and the change in strength state under low and high confinement conditions. Lower crack initiation (c_i) may be assumed for high intensity of weak structures. The brittle approach generates a tri-linear envelope shape, grey lines

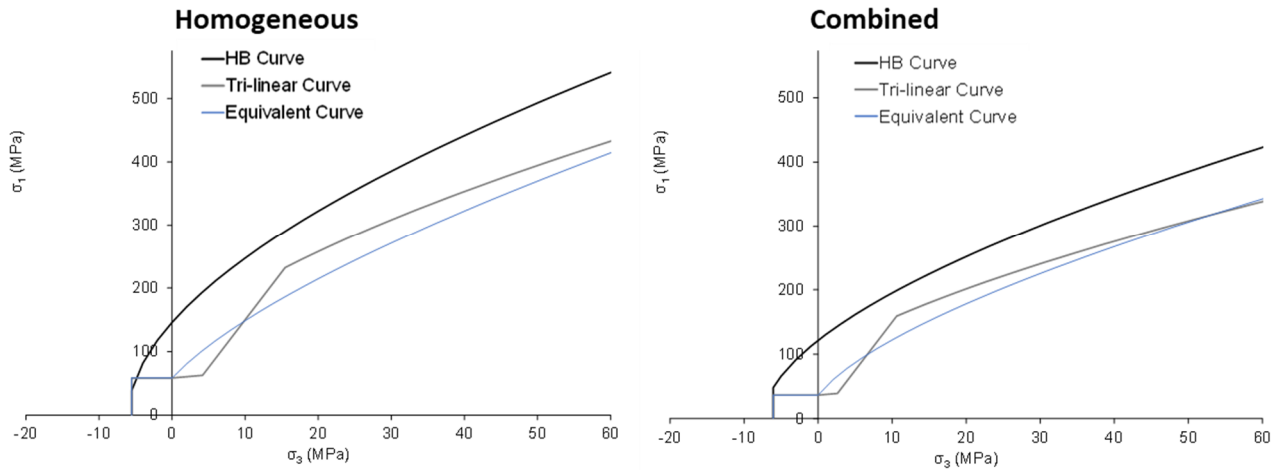


Figure 21 Application of the brittle approach to massive, veined rock masses.

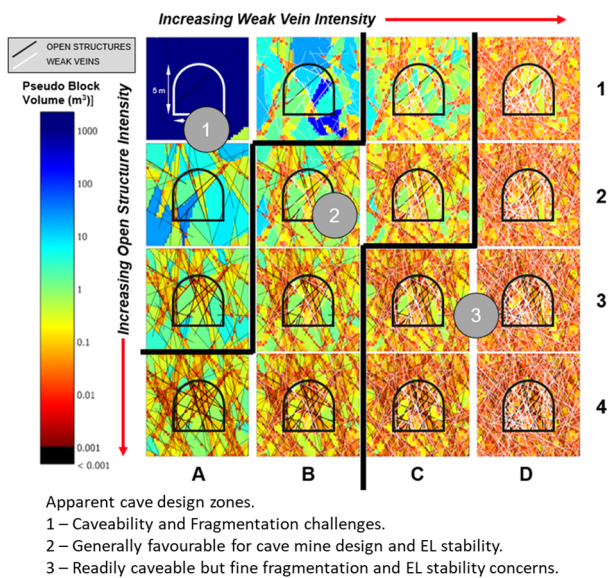


Figure 22 Jointed-Veined Matrix and caving benchmarking experienced.

in Figure 21, but, since the tri-linear envelope cannot be implemented directly into stress models, equivalent HB envelopes (blue in the same Figure 21 are developed). Hoek and Brown intact rock strength estimates in that figure are from the same units presented in Figure 10. These have been tested and proven to forecast depth of failure.

5 DISCUSSION

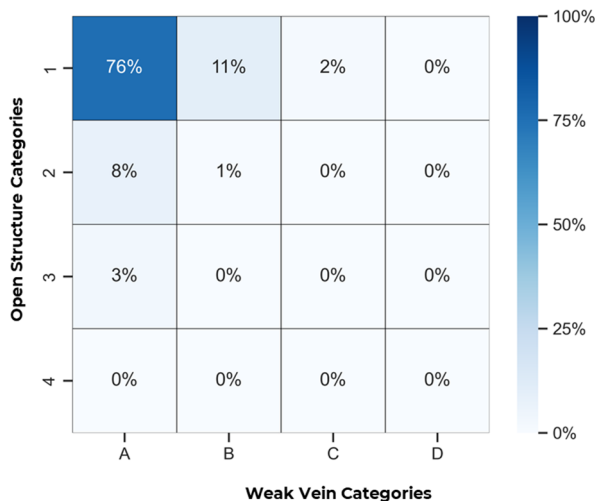
Knowing that main geological features that characterize porphyry copper gold ore bodies are OS and Veins, Bewick et al., (2022) developed a 2x2 matrix in which the input parameters are the intensities of these geological features. In such

and based on benchmarking of caving performance, a caving greenfield project, by simple comparison from the characterization point of view, may foresee the challenges in terms of fragmentation, caveability and stability (Figure 22). In addition, since the input parameters are P_{32} of OS and weak veins, block modelling output can be manipulated to inform what is the spatial distribution of such classes 1, 2 and 3 within the orebody or caving volume. An example of these characterization outputs from a current caving project is presented in Figure 23 that indicates challenging conditions in term of fragmentation and caveability, and maybe seismicity if the proposed caving footprint is located under high stress conditions.

6 CONCLUSIONS

A particular characterization approach for porphyry copper gold ore deposits has been developed and applied to several caving projects at PFS and FS level aiming to support engineering caving front studies.

The characterization approach is based on comprehensive data collection which include a detailed structural characterization and strength determination based on lab and high-density field testing.



Open Structures				Weak Veins			
Model P32	Category	P32 Data Range		Model P32	Category	P32 Data Range	
		Min	Max			Min	Max
0.5	1	0	1.25	0.5	A	0	1.625
2	2	1.25	3.25	2.75	B	1.625	5.125
4.5	3	3.25	6.25	7.5	C	5.125	11.25
8	4	6.25	+	15	D	11.25	+

Figure 23 Example of distribution of joint vein character within the cave volume for a current caving project.

The methodology includes several key aspects and unique developments among standard procedures, some of which are as follows.

- Systematic collection of vein types by their mineralogical infill.
- Intensive intact rock and veins strength determination by PLT and ISRM field tests.
- Discrete Fracture Network modeling, which allows conversion of discontinuity frequency into P32, which is a 3D isotropic measurement of the structural intensity without the bias of conventional measures. P32 is a parameter to be converted in to the in situ and pseudo in situ block size distribution, also known as in situ (and pseudo in situ) fragmentation.
- Block modelling to understand spatial variability of the two main components of the rock mass: intact rock mass strength by Is50 strength parameter and in situ and pseudo in situ block size distribution.
- Rock mass strength assessment using a brittle approach when rock mass is massive and veined ($GSI > \sim 65$).

- Development of a jointed and veined matrix for benchmarking comparison from the characterization point of view of the challenges of caving behavior such as fragmentation, caveability and ground stability.

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REFERENCES

- Bewick, R. P. & Ouellet, A. (2017). Importance of understanding laboratory strength testing data for deep mining. Deep Mining 2017, Perth Australia.
- Bewick, R. P. Brzovic, A., Rogers, S., Griffiths, C. & Otto, S. A. (2022). Benchmarking framework for porphyry copper-gold rock masses for caveability and fragmentation decision-making. in Y Potvin (ed.), Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving, Australian Centre for Geomechanics, Perth, pp.1303-1318.
- Bewick, R. P. (2021). The Strength of Massive to Moderately Jointed Rock and its Application to Cave Mining. *Rock Mechanics and Rock Engineering*. DOI: 10.1007/s00603-021-02466-3. <https://rdcu.be/cj2Gn>.
- Brzovic, A. (2010). Characterisation of primary copper ore for block caving at the El Teniente Mine, Chile. PhD Thesis. Western Australia School of Mines. pp 329.
- Brzovic, A. & Villaescusa, E. (2007), Rock mass characterization and assessment of block-forming geological discontinuities during caving of the primary copper ore at the El Teniente Mine, Chile. *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.*, 44, 565-83.
- Brzovic, A., Schachter, P., de los Santos, C., Vallejos J. A. & Mas Ivars, D. (2014). Characterization and synthetic simulations to determine rock mass behaviour at the El Teniente Mine, Chile. Part 1. In: Caving 2014. Santiago Chile.
- Brown, E. T. (2004). Block Caving Geomechanics. The International Caving Study. JKMR, Queensland, Australia.

- Byrne, C., Zordi, L. & Rogers, S. (2023). Structural data collection as a key input for discrete fracture network analysis. SSIM 2023 – PM Dight (ed.). doi.org/10.36487/ACG_repo/2335_24.
- Cai, M., Kaiser, P. K., Tasaka, Y. & Minami, M. (2007). Determination of Residual Strength Parameters of Jointed Rock Masses Using the GSI System. *International Journal of Rock Mechanics and Mineral Science*. 44, pp. 247-265.
- Condon, K., Martin, J. & Valerio, M. (2023). Considerations for developing intact rock strength parameters for open pit applications. SSIM 2023 – PM Dight (ed.). doi.org/10.36487/ACG_repo/2335_22.
- Day, J. J., Diederichs, M. S. & Hutchinson, D. J. (2019). Composite Geological Strength Index approach with application to hydrothermal vein networks and other intrablock structures in complex rockmasses. *Geotechnical and Geological Engineering*, vol. 37, pp. 5285-5314.
- Dershowitz, W. S. & Herda H. H. (1992). Interpretation of fracture spacing and intensity. In: Proceeding of the 33rd US Rock Mechanics/Geomechanics Symposium, Santa Fe, NM.
- Hoek, E. & Brown, E. T. (1980). Underground excavations in rock. The Institution of Mining and Metallurgy, London.
- Hoek, E. & Martin, D. C. (2014). Fracture initiation and propagation in intact rock—a review. *J Rock Mech Geotech Eng* 6(4):287–300.
- Hoek, E. & Brown, E. T. (2018). The Hoek-Brown failure criterion and GSI – 2018 edition. *J. Rock Mech. Geotech. Eng.* 1, p 445-463.
- Kaiser, P. K. & Kim, B-H. (2014). Characterization of strength of intact brittle rock considering confinement dependent failure processes. *Rock Mech Rock Eng.*; DOI 10.1007/s00603-014-0545-5.
- Laubscher, D. H. & Jakubec, J. (2001). The MRMR Rock Mass Classification for Jointed Rock Masses. In Eds.: Hustrulid, W.A. & Bullock, R.L., *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, SME: Littleton, Colorado, pp. 475-481.
- Marinos, P. & Hoek, E. (2000). GSI: a geologically friendly tool for rock mass strength estimation. Proceedings of GeoEng 2000 at the International Conference on Geotechnical and Geological Engineering (Melbourne, Victoria, Australia). Lancaster, PA: Technomic Publishers, pp. 1422–1446.
- Nugraha, N., Bastiawarman, R. & Edgard, I. (2022). Initial setup of hydraulic fracturing in Deep Mill Level Zone (DMLZ) underground mine, PT Freeport Indonesia, Papua. in R Castro, F Báez & K Suzuki (eds), *MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining*, University of Chile, Santiago, pp. 240-248.
- Pierce, M. E., Campbell, R., Llewelyn, K., Fuenzalida, M., Simanjuntak, K., Kurniawan, A., Hafli, D., Meiriyanto, F. & Rogers, S. (2020). Cave propagation factor for caving rate and drawpoint productivity forecasting at PTFI. in R Castro, F Báez & K Suzuki (eds), *MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining*, University of Chile, Santiago, pp. 519-534.
- Pierce, M. E., Stonestreet, P., Orrego, C., Tennant, D., Garza-Cruz, T. V., Furtney, J. & Thielsen, C. (2022). Development of rock mass strength block models at Cadia East mine. in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 1033-1046.
- Rogers, S., Elmo, D., Webb, G. & Catalan, A. (2014). Volumetric fracture intensity measurement for improved rock mass characterization and fragmentation assessment in block caving operations. *Rock Mech Rock Eng.* DOI 10.1007/s00603-014-0592-y.
- Russo, A., Velo, I. & Hormazabal, E. (2020). Quantification of the intact geological strength index for rock masses in hypogene environment. in R Castro, F Báez & K Suzuki (eds), *MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining*, University of Chile, Santiago, pp. 1188-1201.
- Stoch, B., Darakjian, T., Zordi, L., Luck, S., Luck, D., Moffitt, K., Nicoll, S., Tennant, D. & Pothitos, F. (2023). Development of a fully constrained structural model in a volcano caldera and its influence on open pit slope design. SSIM 2023 – PM Dight (ed.). doi.org/10.36487/ACG_repo/2335_30.
- Tilley, E., Yang, B., Otto, S. A., Sinaga, Y. & Bewick, R. (2022). Objectivity through mineralogy: application of spectrographic data and machine learning for improved geotechnical characterization of porphyries. in Y Potvin (ed.), *Caving 2022: Proceedings of the Fifth International Conference on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp.1293-1302.