Caving 2022 - Y Potvin (ed.)
© 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-3-4
doi:10.36487/ACG_repo/2205_91

Benchmarking framework for porphyry copper-gold rock masses for caveability and fragmentation decision-making

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Abstract

Caveability and fragmentation are two important aspects in a caving project; being very high risks or fatal flaws if they are not properly assessed. There is evidence from historic and current caving mines that there has been significant failure of revenue recovery because the rock mass characterisation process did not properly determine the key elements that control rock mass behaviour.

The main rock mass characteristics of porphyry copper-gold orebodies are the networks of vein systems where most of the ore is located which are super imposed by faults systems. At depths greater than about 500 m, in these massive, competent and multimineral orebodies, joints are typically sparsely occurring or almost non-existent. The main structural features that control strength in these rock masses are faults and the sub-set of veins that are infilled with minerals of weak strength such as gypsum, calcite, chlorite, and, in some cases, chalcopyrite. Traditional caveability and fragmentation assessments use classification schemes and tools that are not designed for a rock mass without joints (except for the in situ rock mass rating system). Rock masses that match these structural characteristics have been shown to range in fragmentation and caving performance from good to not so good.

This paper presents the benchmarking framework that focuses on the key porphyry rock mass characteristics of fault/open structure and weak vein system intensity. A matrix has been developed to allow for consistent benchmarking of rock masses in porphyry deposits so that caveability and fragmentation challenges may be better forecasted in the future and engineering design decision making improved.

Keywords: *block cave, caveability, fragmentation, discrete fracture network, rock mass characterisation, rock mass strength*

1 Introduction

With caving projects increasingly being developed in deeper and massive ground, there is a need to improve the rock mass characterisation process to improve the reliability of the forecasted cave performance. This is because traditional means of rock mass description have a focus on joints (i.e. open structural features). Conversely, a key characteristic of typical copper (Cu) gold (Au) porphyry deposits at depth is strong brittle rock with limited open joints. The main structural features that control strength in these rock masses are faults (and other open structures) and the sub-set of veins that are infilled with minerals of weak strength such as gypsum, calcite, chlorite, and, in some cases, chalcopyrite. The utilisation of traditional rock mass description on deep porphyry deposits compounded by common industry assumptions during data collection (e.g. the logging of mechanical breaks as open structures or joints when in doubt) has resulted in several mis-characterised rock masses and unreliable forecasts of cave performance.

The geomechanical rock mass characterisation is complex because of the spatially variable intensities of vein types through a Cu-Au porphyry orebody and the sizes and strength characteristics of the veins (different veins have different character and need to be separately understood). Veins of importance do vary from deposit to deposit but there are some similarities due to the processes forming porphyry Cu-Au deposits. For example, it has been seen that the main 'block' forming veins (in quotes since these veins are not open in situ) in some caving operations are (from our experience):

- Gypsum and calcite veins at Northparkes, Cadia East and El Salvador.
- Gypsum, calcite and some anhydrite and sulphide veins at Grasberg (Deep Mill Level Zone and Grasberg Block Cave).
- Anhydrite and chalcopyrite veins at the El Teniente.

The complexity also arises because the scale of the problem. For instance, fragmentation is defined at the scale of the drawpoint (within say ~10,000 m^3) and caveability is defined at the scale of the cave back (e.g. 500,000 m^3). Understanding what the controls of caveability and fragmentation are, have thus been challenged.

An obvious question to ask is, are existing rock mass classification or description schemes appropriate for deep caving projects located in sparsely jointed but veined rock masses? Typical rock mass classifications seek to implicitly define metrics on open structures such as joint condition and spacing to define the size of rock blocks and the rock mass strength considering failure processes involving the shearing/rotation of the joint bound rock blocks with low or essentially zero tensile strength arising from the nature of the joints. Within massive and veined rock systems with limited open structures, traditional jointed rock mass description schemes are not reasonable (veins are not of limited tensile strength, are cohesive, and form irregular vein bound 'block' geometries such that block rotation and shearing are inhibited); alternative approaches are needed.

Attempts have been proposed to account for massive but veined rock mass characteristics into some traditional jointed rock mass classification systems (e.g. Day et al. 2019; Russo et al. 2020), however these attempts assume that the rock mass strength scaling equations for jointed rock masses apply to veined rock masses (e.g. Russo et al. 2020). Which is interesting since veins are not joints and have vastly different strength magnitudes, especially the cohesive and tensile aspect of structural feature strength. They also tend to oversimplify the complex nature of a veined rock mass such as the vein type dependent strengths and spatially varying intensity of vein systems.

The in situ rock mass rating (IRMR, Laubscher & Jakubec 2000) which is modified for mining-induced effects to determine the Mining Rock Mass Rating (MRMR) is the only rock mass classification system to directly incorporate veins (and other cohesive defects). The IRMR system incorporates cohesive defects through the estimation of unconfined rock block strength which is a scaled rock strength estimated from laboratory tests on intact specimens exhibiting the homogenous failure type ('intact' rock failure, involving no veins or cohesive defects). From the homogeneous strength, a factor of 0.8 is applied to account for general scaling from the laboratory to the field (after Hoek & Brown 1980). This is followed by a factor ranging from 1 to ~0.6 for the impact of cohesive defect infilling type and intensity (cohesive defects per meter) as represented by the nomogram in Figure 1. This defect scaling nomogram is based on experience and engineering judgement (Laubscher 1975). With the industry at odds with respect to assessing veined rock masses, framing a consistent characterisation approach to capture key rock mass characteristics of these rock masses is of value.

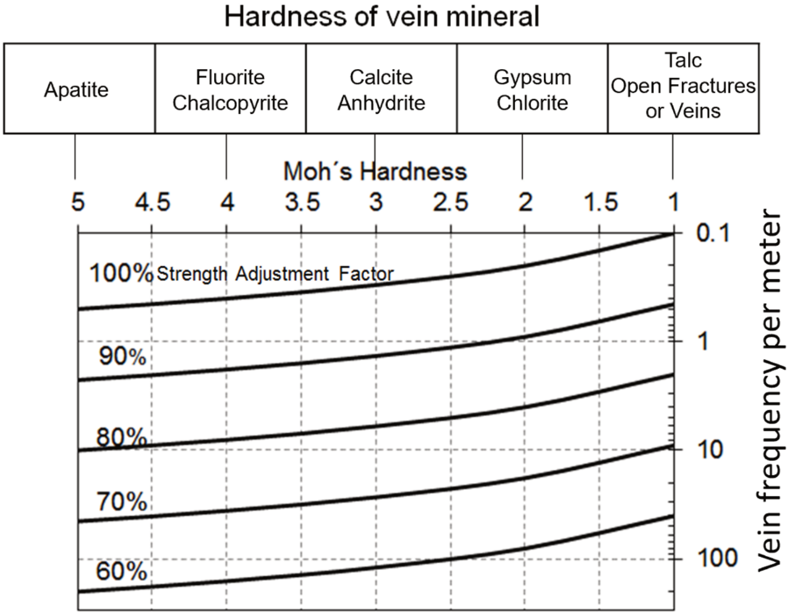


Figure 1 Scaling factors for defects according to the IRMR system (from Bewick et al. 2019a, modified from Laubscher & Jakubec 2000)

This paper presents the benchmarking framework that focuses on the key porphyry rock mass characteristics of fault (and other open structures) and weak vein system intensities. This framework forms a matrix (outlined later in the paper) that will be used in the future to correlate caveability and fragmentation challenges for improved decision making. Some benchmarks are provided from experience while detailed assessments are underway to robustly compare the cases.

2 Veined rock mass characteristics

Porphyry Cu-Au deposits are geologically characterised by multiple porphyry intrusions that generate several phases of hydrothermal fluids and mineralisation that successively develop envelopes of hydrothermal alteration, typically enclosing a core of disseminated ore minerals in often stockwork-forming fractures forming veins (Sillitoe 2010). The geological processes result in several specific rock mass characteristics with large implications for assessments related to defining reliable estimates of caveability and fragmentation. Experience in these Cu-Au porphyry rock masses at depths below approximately 500 m suggest that they are commonly sparsely jointed (but faulted) and veined (Figure 2) with spatially varying vein intensities and infilling compositions.

Veins are healed discontinuities with, generally, <1–100 mm thickness and generally of limited persistence (but can be sheeted and in some cases have a range of persistence), potentially occurring in sets which, when intense enough, intersect to form highly interlocked and cohesively contacted angular rock 'blocks' (Figure 2). The mineralogical infill material creates both cohesion and tensile strength and thus these strength components predominately control a rock mass's strength and behaviour opposed to rock mass quality.

Porphyry deposits typically exhibit well-defined patterns of alteration and distribution of various vein types (Sillitoe 2010) that help characterise specific rock masses within a mining area. In addition, small-scale faults (typically those that appear to resemble joints but are not) exist within the rock masses and tend to be the primary form of open, block forming structures. This means that the following key characteristics are important to reliably define the character of Cu-Au porphyry rock masses:

- Vein type (see Section 2.1) – what are the different vein mineral assemblages present, where are they spatially located, and how do type and spatial distributions relate to dominant alteration types?

- Vein strength (see Section 2.1) – what are the tensile and shear strengths of the different vein types?
- Intensity of structural features (see Section 2.2) – what are the spatial intensities and geometries of the following:
  - Each of the vein types.
  - Small-scale faults.
  - Joints.
- Intact Rock Strength (see Section 2.3) – what is the strength of the non-veined rock and how does both alteration and veining influence intact rock strength?

Additional detail on the approaches for assessment and interpretation of each of these key characteristics are outlined in the following sub-sections.

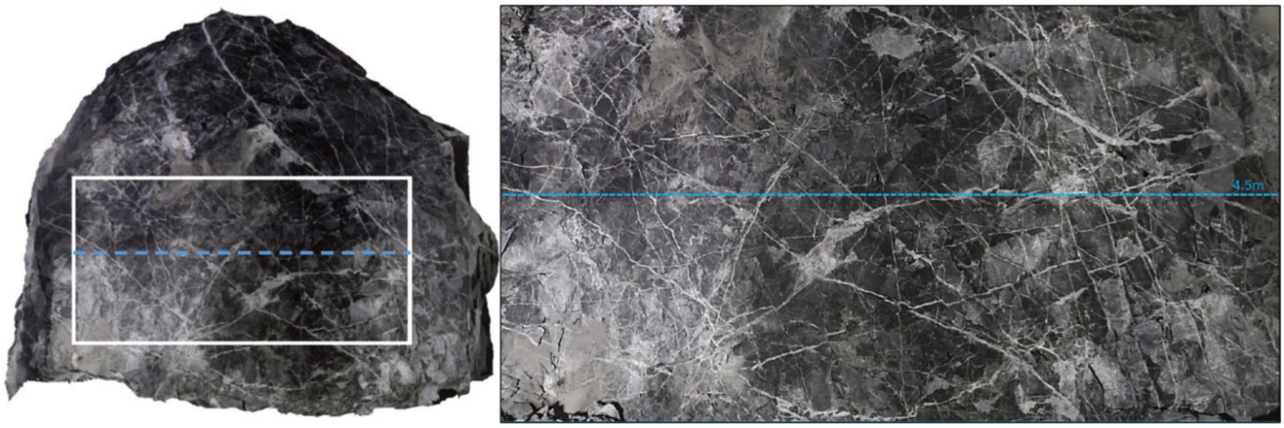


Figure 2 Tunnel face showing typical veinlet system in porphyry Cu-Au rock mass (4.5 m wide window detail). Note how there are no open structures and only cohesive veins are seen in this example

2.1 Vein types and strength

More than 10 vein types may be found in a porphyry ore deposit, some of them may have one or several infill minerals, with or without alteration halos (Figure 3). Their distribution within the rock mass is related to both rock types and alteration. Initial assessment of their strength was the Mohs scale of hardness (Laubscher & Jakubec 2000; Brzovic & Villaescusa 2007), however the recording of failure types has resulted in the strength of veins to be better assessed. For example, discrete failure during triaxial testing and point load index testing (PLT) have provide insight into quantifiable shear and tensile strengths of these cohesive features.

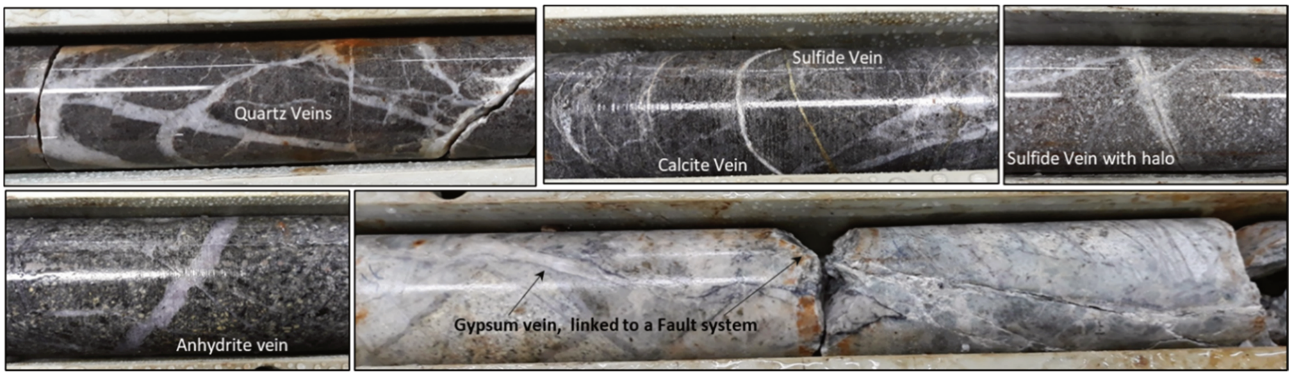


Figure 3 Example typical vein types in Cu-Au porphyry deposits (HQ core for scale)

Using the relationship between direct tensile strength (DTS) and Brazilian tensile strength (BTS) proposed by Perras & Diederichs (2014), the tensile strengths of veins can be assessed through PLT. Some benchmarking PLT results for different vein types can be seen in Figure 4, which tend to confirm the relative strengths from the Mohs hardness scale assessment. Testing measurements coupled with empirical observation highlight the importance of recognising weak veins from the total vein populations, for instance, thick (≥2 mm) and large (≥2 m) weak veins are the ones block forming at the El Teniente mine (Brzovic & Villaescusa 2007; Brzovic & Leon 2017). As is discussed in Section 3, the identification of what vein types should be considered weak may significantly impact the outcome a caving project.

Based on the testing in Figure 4 and work not plotted from other porphyry deposits the following vein categories are generally proposed:

- Weak veins – generally <1 MPa Is50 on average and often are clay (Cy), gouge (Go), sericite (Se), chlorite (Ch), calcite (Ca).
- Transition weak to strong – have a large range that may span the weak to strong categories and often are carbonate (Cb), sulphide (Su), chalcopyrite (Cpy).
- Strong veins – generally >2 MPa Is50 on average and often are quartz (Qz), pyrite (Py) and may include a portion of the Su, Cpy, and Cb veins.

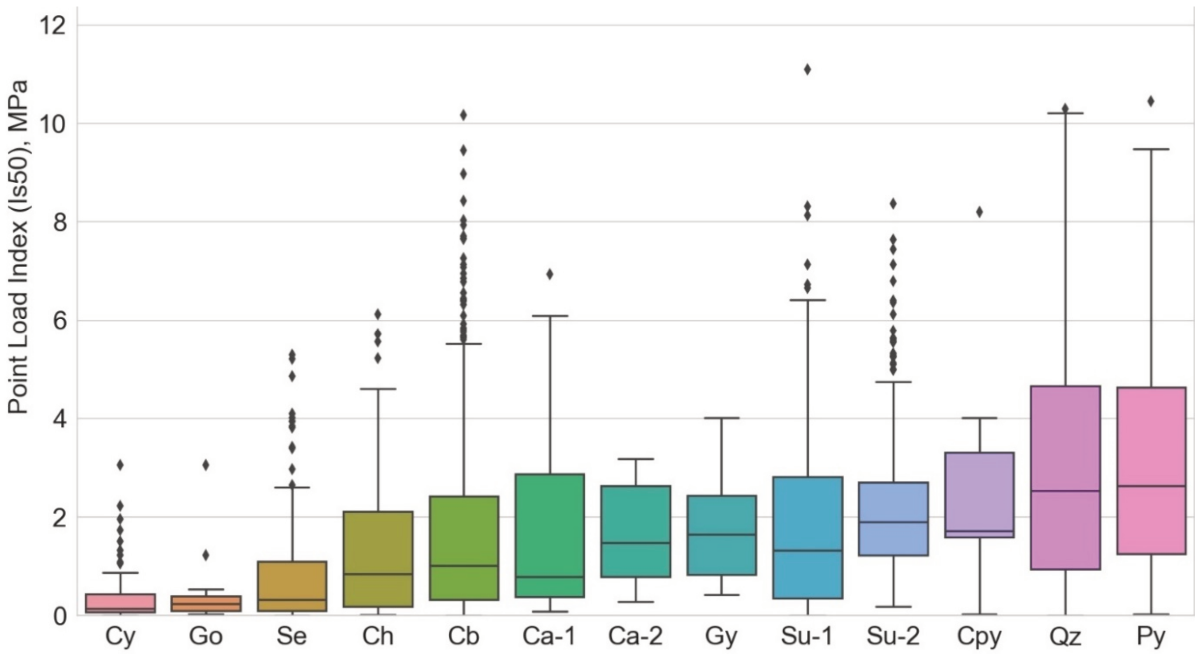
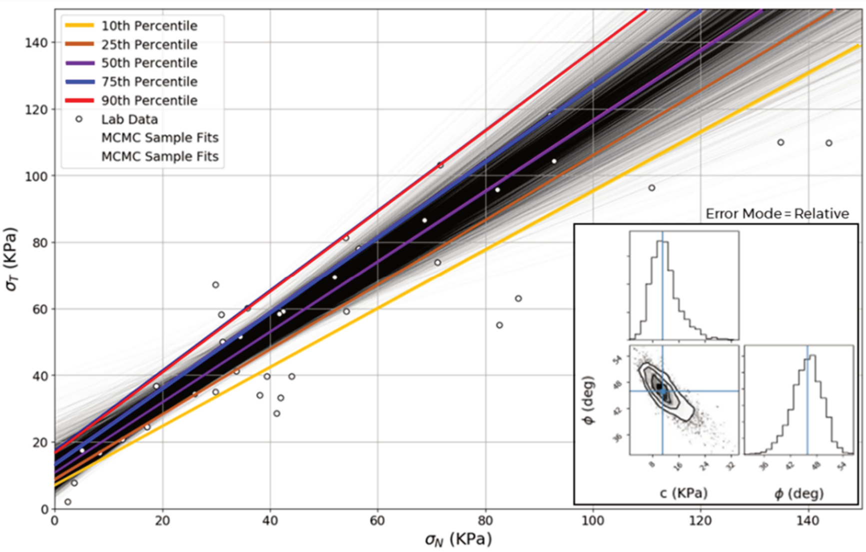


Figure 4 PLT results from >3,000 tests on different vein types. Same letter name with number means results from different porphyry deposits

In addition, the shear strength component of the veins can be assessed by examining discrete failures in uniaxial and triaxial testing, for instance, several triaxial test on Ca/Cb veins describes the strength in terms of friction angle ranging from 39–51° and apparent cohesion from 6–51 MPa (Figure 5). In this figure, the strength variability was assessed using the Markov chain Monte Carlo (MCMC) simulations based on Contreras et al. (2018). Similar tensile and shear strength values using a combination of direct tensile, shear test, and triaxial test were seen in other caving operations (Brzovic et al. 2014).



Percentile	c (MPa)	ϕ (°)
5	5.9	39.6
10	6.8	41.4
15	7.5	42.6
20	8.0	43.6
25	8.4	44.3
30	8.9	44.9
35	9.4	45.4
40	9.8	45.9
45	10.3	46.3
50	10.7	46.7
55	11.2	47.1
60	11.7	47.5
65	12.3	47.8
70	13.0	48.2
75	13.7	48.6
80	14.6	49.1
85	15.7	49.7
90	17.4	50.3
95	19.6	51.3

Standard Deviation: c = 4.4 MPa, ϕ = 3.6°

Figure 5 Example of strength determination for a transition weak to strong vein using Markov chain Monte Carlo simulations

2.2 Intensity and spatial distribution of structural features

The intensity of structures in the rock mass is a critical control on several important caving processes. Intensity needs to be defined for several lower strength structure types, most notably:

- Open structures (typically faults).
- Those veins having weaker mineral fills.
- Joints (if present in meaningful populations).

The intensity of structures typically comes from borehole data (unless there is UG access) as either frequency or spacing data. As a project advances, borehole data is increasingly supplemented by mapping data, either from conventional or photogrammetry means. However, both measurements are directionally biased and sensitive to the orientation of the sampling method (borehole, drift heading orientation, etc.) and the orientation of the intersecting structures. Rogers et al. (2014) has shown that the volumetric fracture intensity property P32 (Dershowitz & Herda 1992) represents a robust and non-directional intrinsic measure of structural intensity that correlates well to rock mass 'block' size. P32 represents the fracture area per unit volume of structures; it cannot be directly measured, but it be calculated from structure frequency measurements using simple analytical solutions (e.g. Chiles et al. 2008).

P32 provides an important component because it represents a robust estimate of anisotropic structural intensity. Converting logged interval measurements of the frequency of open structures as well as different vein types, to downhole P32 measurements, provides an important step in the overall characterisation process.

Having created a dataset of P32 intensity measurements for the different sets of open and cohesive structures of relevance (i.e. faults, joints, and weak vein types), the spatial distribution of these strength controlling structures can be explored. P32 intensity can be meaningfully used as a basis for the domaining of the rock mass. Alternatively block modelling techniques can be used to distribute P32 values through the cave volume using a variety of different approaches (Figure 6). With P32 correlating to potential 'block' size, the local cell based P32 estimates can be converted to average potential 'block' volume and the spatial character of the rock mass displayed, based upon this potential 'block' volume characteristic. This is discussed further in a later section. The term 'potential' 'block' is important. The potential 'blocks' outlined in this approach are not the same as joint bound rock blocks since the 'blocks' are largely formed by weak veins which still have significantly higher strengths than open joints. Therefore, one should not consider jointed rock mass thinking when the term 'block' is used in veined rock masses.

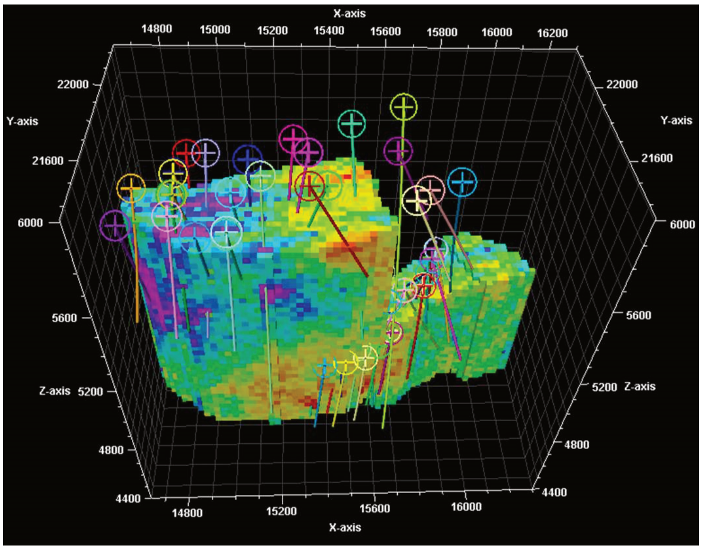


Figure 6 Example of a block model showing P32 intensity for weak veins in a caving operation (Rogers et al. 2014). Hot colours high intensity and cool colours low intensity

2.3 Intact rock strength

In veined or cohesively defected rocks, recording how the specimen failed (Bewick et al. 2015, 2019a; Bewick 2021) is important. The minimum failure types of importance are outlined below:

- Homogeneous failure: failure through the homogeneous rock matrix by extension or shear at low confinement or shear rupture at high confining stress. The term 'homogeneous' is used opposed to 'intact' failure since each of the failure types outlined are for 'intact' rock specimens and thus the term 'intact failure' is not appropriate and confusing.
- Combined failure: failure that includes partial failure on a discrete cohesive feature(s) and extension or shear failure through the otherwise homogeneous rock matrix.
- Weakness or defect network failure: mostly failure along or around multiple veins, clasts, or other cohesive defects.
- Discrete failure: failure along one discrete pre-existing cohesive feature. This failure type cannot be processed in principal stress space and must first be fit in shear-normal stress space and transformed into principal stress space. Guidance for this can be found in Hoek & Brown (1980), Goodman (1989), and Bewick et al. (2019a).

Failure types are more important than recording the mechanism of failure (splitting, shear, multiple shears, spalling) in the quest to understand vein or cohesive defect influence on intact rock strength. Some have argued that since 'failure type' is not included in a laboratory testing standard (e.g. ASTM D 2938-86, ASTM International 1991) or suggested method (e.g. International Society for Rock Mechanics) that 'failure type' does not need to be collected. This is false, because the standards and suggested methods are focused on reducing testing procedure influence on rock strength recording not on the interpretation of testing results.

The failure types outlined represent the influence of vein or cohesive defect intensity on intact rock strength. As more veins are failing in a specimen the strength is reduced. This is reflected in the progression from Homogeneous to Combined to Defect Network to Discrete failures (Figure 7). One aspect to keep in mind is that not 'all' veins or defects impact the homogeneous rock strength. A rock may contain a weak and a strong vein set. While the overall vein intensity in the rock would be the sum of the two vein sets, only the weak vein set may be impacting the rock strength and thus only the weak vein type and intensity should be considered. The summing of vein intensities is only to be done for similar strength vein systems. Recording failure types are critical to properly understand rock strength and vein strength in Cu-Au porphyry rock masses.

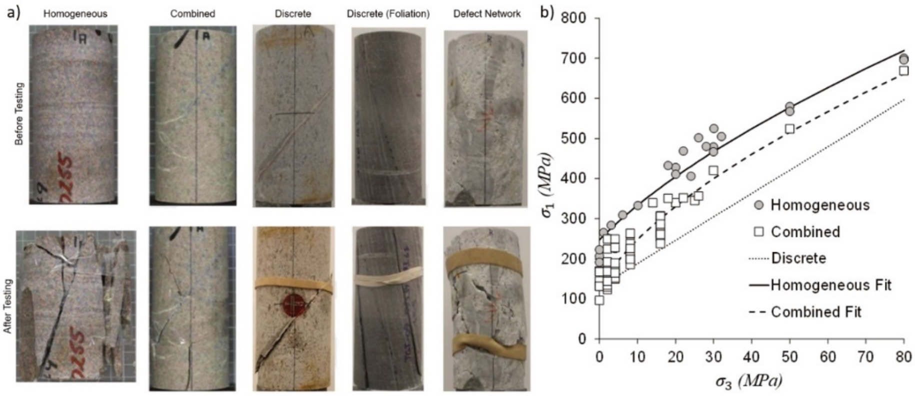


Figure 7 (a) Failure type examples and (b) impact of failure type on intact rock strength showing progressive reduction from homogeneous to discrete (modified from Bewick et al. 2019a). From Bewick (2021)

One question of interest is whether the laboratory test results for the different failure types outlined in the previous section can be used to represent the rock block strength that is estimated in the IRMR system. Figure 8 shows data for defected (veined) rocks tested in the laboratory (corrected by a factor of 0.8 to be consistent with the scaling in the IRMR system) and the corresponding rock block strengths estimated using the IRMR system. As is evident from Figure 8, the laboratory data processed considering the specimen vein intensity results in lower estimates of rock block strength compared to the estimates from the IRMR system. This suggests that the IRMR system is potentially overestimating the rock block strength. Regardless, the data suggests that vein intensity and type influence on intact rock strength can be captured at the laboratory scale when laboratory test results are interpreted using the guidance summarised herein and reasonable but lower rock block strength estimates are found.

In addition, intact strength determination from laboratory specimens considering rock types and alteration have shown an agreement with the vein intensity domains (defined later in Section 3) as shown in Figure 9. In this figure, as more veins are included in the specimens progressing from Cat1 (no veins) to Cat4 (highly veined) strength progressively decreases as evident in the tensile strength and unconfined compressive strength.

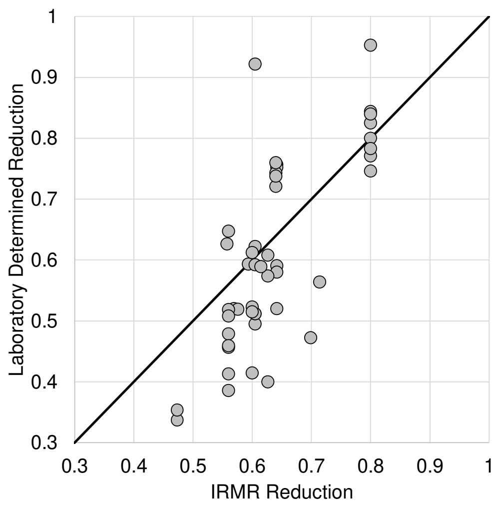


Figure 8 Comparison of rock block strength from IRMR and laboratory determined rock block strengths based on actual vein intensities (1:1 line shown for reference). Modified from Bewick (2021) to include 12 new data points

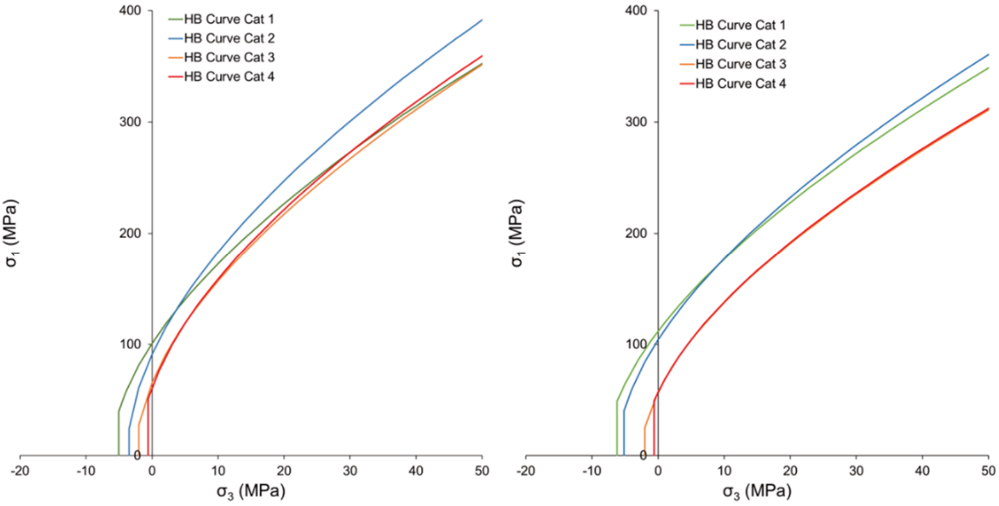


Figure 9 **Example of intact rock mass strength determinations from lab samples considering rock type and alteration features related to weak vein intensity domain. Cat 1 to 4 means increasing vein intensity as discussed in Section 3**

3 Porphyry rock mass benchmarking framework

With the recognition that porphyry Cu-Au rock masses have few open joints and that the weak veins and faults are the primary aid to the disaggregation of the rock mass (e.g. Brzovic & Villaescusa 2007; Bewick et al. 2019b), DFN approaches (Figure 10) are used to capture the geometric and spatial characteristics of the vein and small-scale fault (plus other open structures if relevant) systems within the characterisation process, with the critical goal of reducing the risk of cave performance. This new paradigm of considering the rock mass to be comprised of small-scale faults and some open joints, strong veins (often with strengths greater than the rock mass) and weak veins (e.g. sulphide, gypsum, anhydrite), means that the DFN approach is ideally placed for capturing the geometry and spatial variability of these different structure types. The advantage of a DFN model is that it is better able to describe local scale problems because of its ability to capture the discrete fracture geometry more accurately than larger scale continuum or classification approaches. 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 (where larger features are explicitly known to be present). DFN models can be readily built and, using Monte Carlo techniques, sampled many times to help constrain the likelihood of a particular outcome. Most importantly, they provide a clear and reproducible route, from site investigation data to characterisation to modelling, because real fracture parameters are being preserved throughout the modelling process with limited approximation and judgement. The methodology and issues surrounding DFN model construction and validation can be found elsewhere, e.g. Rogers et al. (2010) and Rogers et al. (2014).

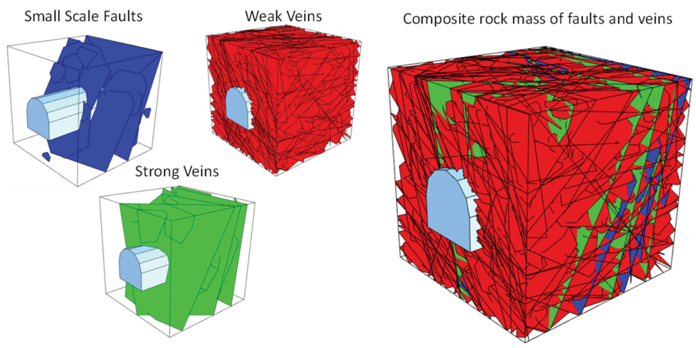


Figure 10 **Example of a composite DFN model, comprising small-scale faults, strong and weak veins. Model size 15 × 15 × 15 m**

Having characterised the geometries of open structures through the derivation of DFN inputs, models can be built to constrain the size of potential or pseudo ‘blocks’ within the rock mass. P32 has been shown to correlate strongly with ‘block’ size metrics. This means that rather than needing to build large cave scale DFN models, we can construct smaller scale models (say 15 × 15 × 15 m) using the constrained size and orientation properties of the domain and then built multiple scenarios of the range of observed P32 values (Figure 11a). Note that the ‘block’ sizes and the concept of ‘blocks’ are not joint bound rock blocks. They are ‘blocks’ defined dominantly by weak veins with some occurrence of open structures. The strengths of the block contacts are significantly stronger (relatively) than joints and thus jointed rock mass thinking should not be considered.

With increasing P32, the average ‘potential’ ‘block’ volume in the DFN models is seen to be reducing (Figure 11a) and shown by the leftward moving fragmentation curves (Figure 11b). These curves can be processed to generate relationships between P32 and critical block volume definitions (e.g. D30, D50, D80 volumes) (Figure 11c).

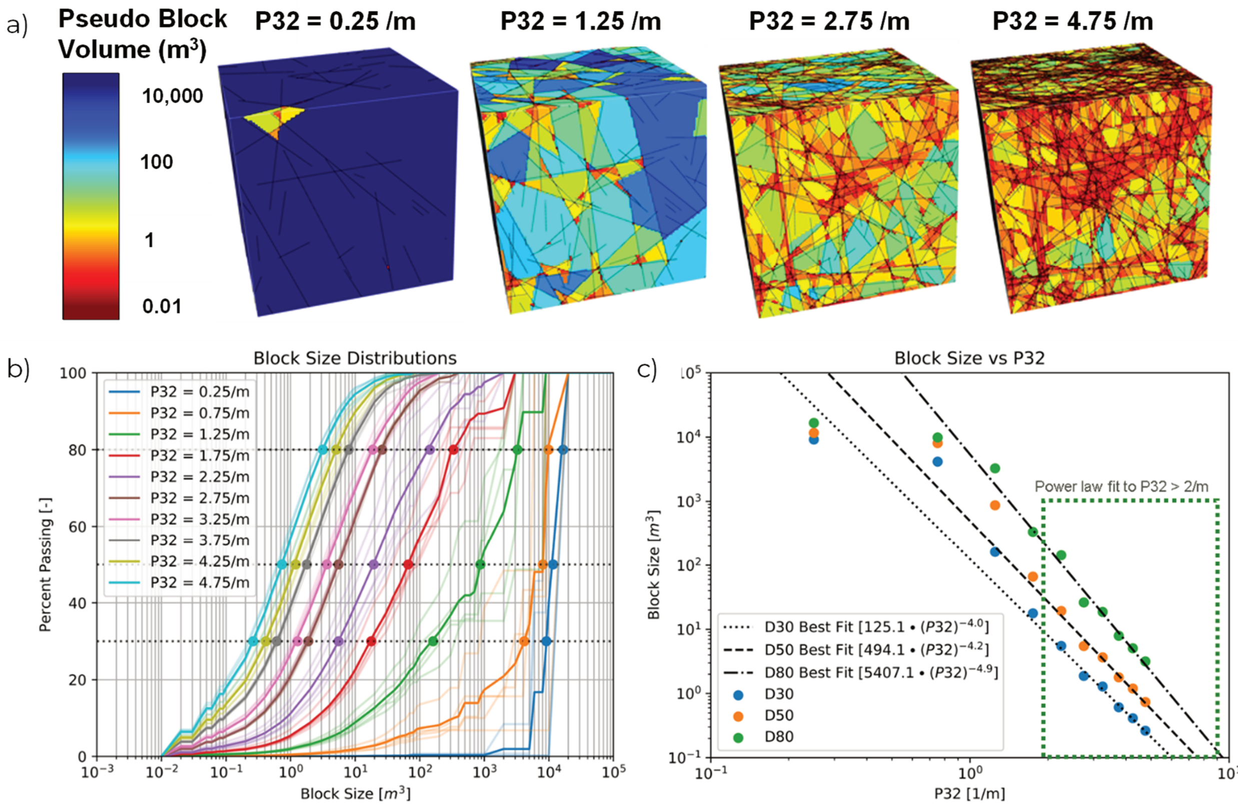
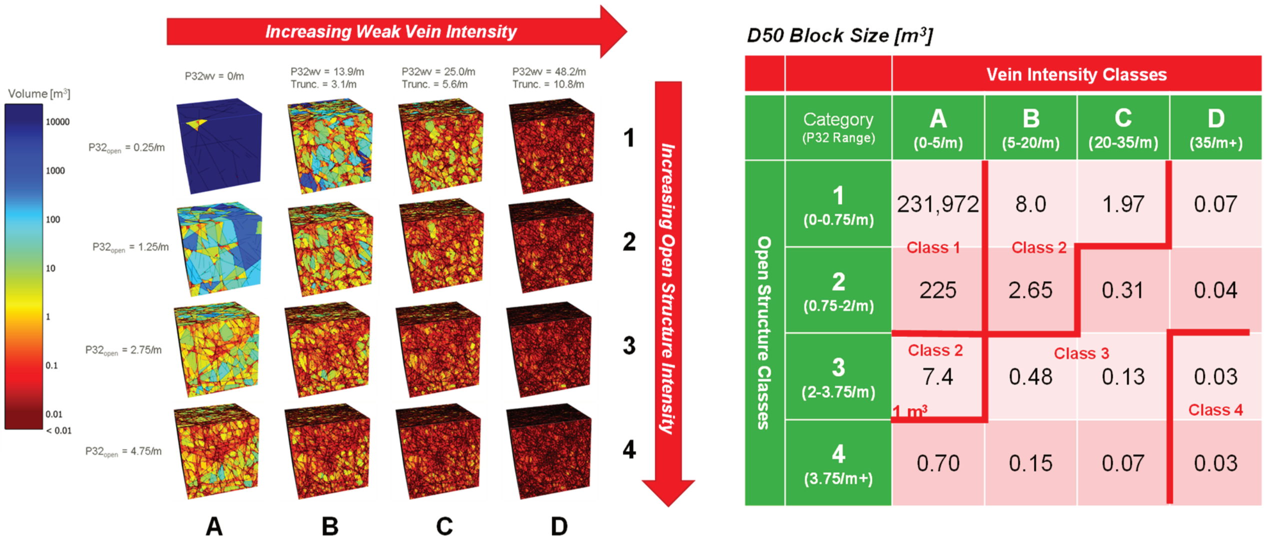


Figure 11 (a) Block size analysis on four different P32 intensities of open structures with blocks coloured by volume; (b) Block size distribution results from DFN model (c) Log-log plot showing 30th, 50th, and 80th percentile block size by input P32 for open structures

As discussed however, there are two kinds of critical structures in these porphyry deposits that need to be considered: open structures and weak veins. This makes determining ‘block’ volumes with two independent P32 variables more problematic. To get around this challenge, an approach called the veined rock mass matrix has been developed where block size estimates are carried out on a 4 x 4 array of P32 values representing the range of open structure intensities and the range of weak vein intensities. The x-axis categories are labelled A through D, while the y-axis categories are labelled 1 through 4 (Figure 12a).



(a) (b)

Figure 12 (a) In situ fragmentation matrix of open structures (increasing in intensity downwards on the y-axis) and weak vein structures (increasing in intensity on the x-axis) and b) Showing D50 potential 'block' size by intensity category. Note that 'block' size is not jointed rock block size and should not be confused with jointed rock mass thinking. Refer to Table Table 1

The D50 (median) 'block' sizes for the 16 categories are also shown in Figure 12b. It should be noted that technically these should be known as pseudo 'block' sizes as the weak veins are not open structures with zero tensile strength. These 16 categories have been assigned to four classes (Cat1 to Cat4) based upon their median 'block' size as shown in Table 1.

Table 1 Rock mass categories used with the vein rock mass matrix

Class	Category	Pseudo/potential 'block' size[1] range
1	No veins or open structures	>27.0 m^3
2	Lightly veined with limited open structures	1.0–27.0 m^3
3	Highly veined with some open structures	2.7×10^{-2}–1 m^3
4	Extremely veined with open structures	1.0×10^{-3} m^3–2.7×10^{-2} m^3

[1]note that the 'block' sizes stated are not joint bound rock blocks. They are 'blocks' defined dominantly by weak veins with some occurrence of open structures. The strengths of the block contacts are significantly stronger (relatively) than joints and thus jointed rock mass thinking should not be considered.

Using the block model of open structures and weak veins, the veined rock mass categories can be flagged spatially within the cave volume by identifying which ranges of structure intensity define each category. An example is shown in Figure 13, illustrating how the open structure and weak vein intensities are combined to flag the location of the rock mass categories at the undercut level of a cave.

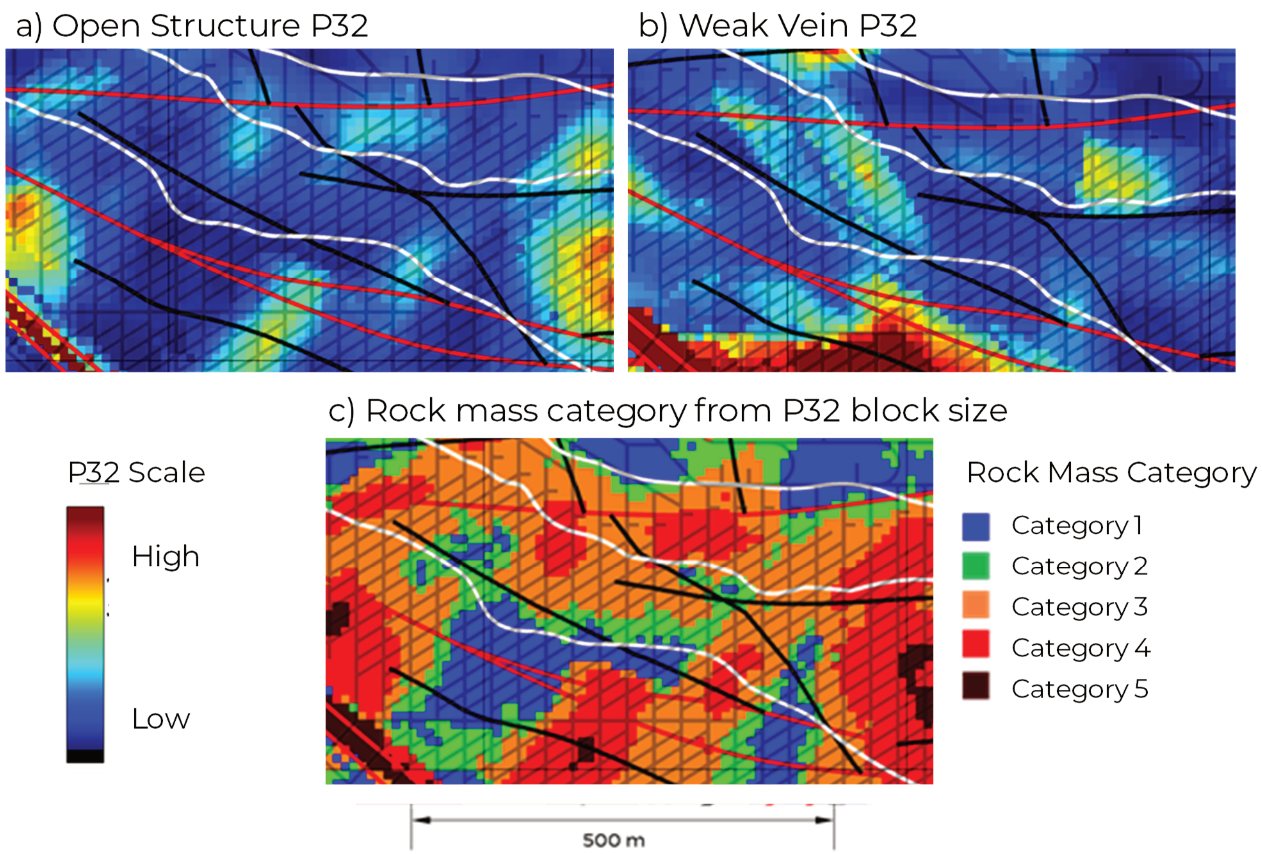


Figure 13 View of a block model showing (a) the open structure; and (b) the weak vein P32 intensities; (c) (a) and (b) are combined to define the rock mass category model as shown in Table 1

3.1 Initial benchmarking through the porphyry rock mass matrix

One the main purpose of the rock vein matrix is to develop a comparable measurement of the rock fabric, so that reliable comparisons may be made between caving experiences, from where caving industry may get some lesson learned to be applied in future caving project. Unfortunately, there are still challenges in the mining industry regarding data collection, which is the starting point from where a proper rock mass characterisation is completed. Understanding the vein character of porphyry Cu-Au rock mass is one of the main problems, and this article outlines a broad methodology to overcome that problem.

Based on this approach an initial benchmarking has been completed for some large caving operation around the world (Figure 14). The cases plotted on the matrix range from caveability challenges to readily caving rock masses. One of the cases (Case 4) also provide evidence for how high intensities of both veins and small-scale faults results in stability issues at the extraction level. Based on the current cases compiled and considering some interpretation (Figure 15), matrix locations A1-3 and B1 are where coarse fragmentation and caveability challenges are likely (Zone 1 in Figure 15). Cases C3-4 and D1-4 are locations where extraction level stability and fine fragmentation may be a concern (Zone 3 in Figure 15). Locations A4, B2-4, and C1-2 appear to be generally favourable for cave mine design (Zone 2 in Figure 15).

Of course, the intensity of weak structures is one consideration. What is currently not addressed in this paper is the rock or rock mass strength to induced stress ratio. This is an important aspect to consider and is currently being assessed as a complementary matrix. The strength to stress ratio is important to consider for rock masses in Zone 1 of Figure 15 for caveability/fragmentation and Zone 3 related to extraction level stability. A combined framework considering both the structural and strength aspects in currently being developed and will be published at a later date.

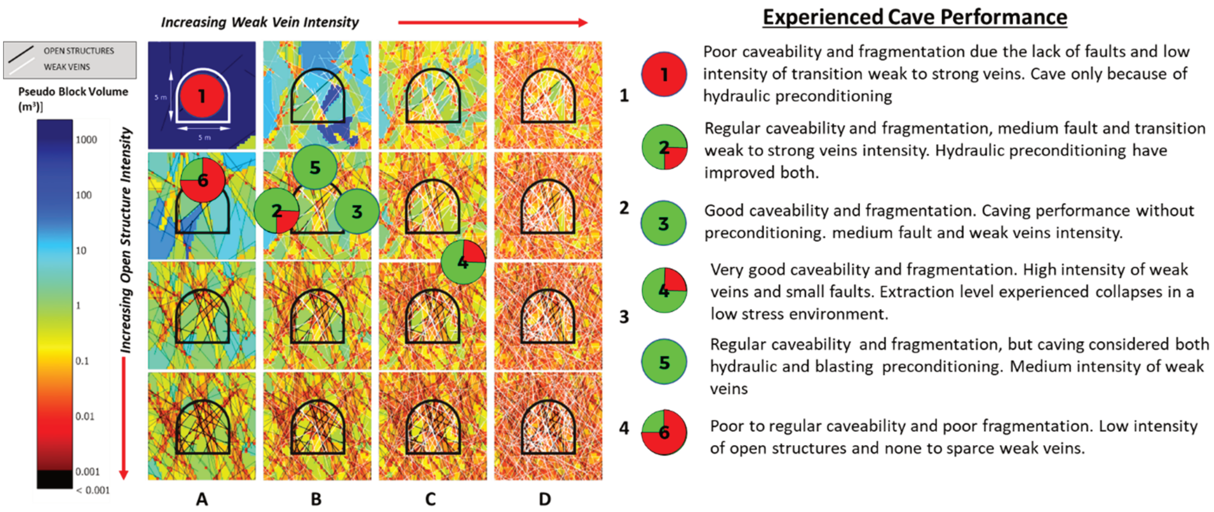


Figure 14 **Porphyry rock mass matrix applied to some large cave operation in the world. Real cases range from caveability challenges to readily caving rock masses**

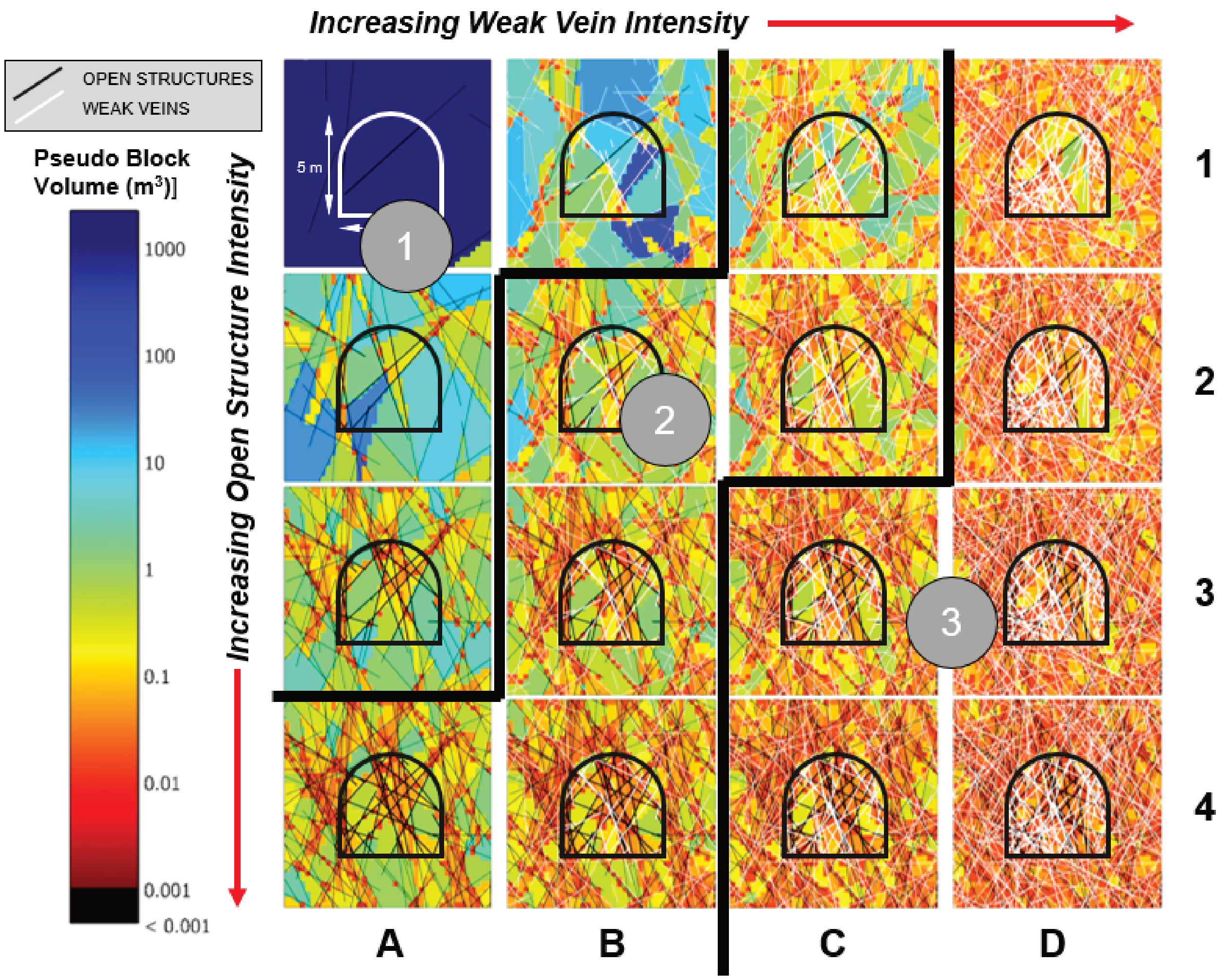


Figure 15 **Apparent cave design zones. 1 – Caveability and fragmentation challenges. 2 – Generally favourable for cave mine design and extraction level stability. 3 – Readily caveable but fine fragmentation and extraction level stability concerns**

4 Conclusion

The components of porphyry rock mass characterisation outlined in this article consider the following:

- Spatial intensity distributions (domains) of weak veins, small-scale faults, and joints. This takes into consideration lithology and alteration influence.
- Intact rock strength components in the different intensity domains considering the structural intensity of veins, lithology, and alteration.
- Vein tensile strengths and shear strengths for the identified vein types in the domains.
- Other aspects such as the larger fault model.

A consistent framework (i.e. the porphyry rock mass matrix outlined in Section 3) is proposed to assess the intensities of open structures and cohesive defects (such as veins) in porphyry rock masses so that consistent benchmarking of, for example, caveability and fragmentation may be completed. Some operating cave mine benchmarks have been plotted on the matrix to show how benchmarking will create a valuable tool that will improve decision making for cave design. The cases currently plotted on the matrix range from caveability challenges to readily caving rock masses and those which have experienced extraction level stability challenges. The matrix already suggests transitions zones that may be used to assess potential caving challenges.

Acknowledgement

The ideas outlined in this paper have progressively evolved over the last few years due to rock mass characterisation work on several Cu-Au porphyry deposits. Several individuals have been involved and should be acknowledged including Marie Costello, Kate Condon, Tina Darakjian, Justin Roy, Danny Towers, Derek Badner, Juliana Martin, Kody Veltin, Ciara Byrne, Roisin Kerr, and Luca Zorzi.

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