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Structural data collection as a key input for discrete fracture network analysis

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Abstract

Accurate characterisation of the geometry and continuity of structural systems (joint, fault and vein systems) within porphyry deposits is essential during all stages of mine life. Structural systems associated with porphyry deposits are generally complex, with highly segmented fault systems, interdependencies between faults and dykes, and spatially varying vein mineralogies and intensities. These intricacies are a function of the deformational, rheological and hydrothermal history of the geological system.

The generation of a comprehensive 3D geological interpretation tailored to geotechnical and hydrogeological designs and assessments requires a workflow that includes the development of a conceptual model, data collection and storage, quality control and interpretation of data. During the lifetime of an operational mine, the structural model should ideally be evolving into a comprehensive database that contains not only large-scale faults (i.e. regional and mine scale) but also an insight into small-scale fabrics, represented by discrete fracture networks (DFN), that may be present in the rock mass. A significant quantity of structural information must be available to allow for the generation of DFN models for numerous fabrics in the rock mass, including open structures, mafic dykes and vein structures. The correlation between large-scale and small-scale structures is a novel modelling approach that has provided great insight into strategies for data collection and interpretation. This approach also gives a heightened level of clarity to the genetic and evolutionary relationship that can exist between structural systems and deposits themselves.

This paper will present the methodology used to identify and delineate key structures, describe characterisation methodologies that have been applied, and present examples of how identification and characterisation of structural systems can successfully inform decision-making for mining operations.

Keywords: *discrete fracture network, optimisation, workflow, data collection, stability, structural geology*

1 Introduction

Structural systems associated with porphyry deposits are generally complex, with fault systems defined by a highly variable degree of segmentation, interdependencies between faults and dykes, and spatially varying vein mineralogies and intensities. These intricacies are a function of the deformational, rheological and hydrothermal history of the geological units. Accurate characterisation of the geometry and continuity of structural systems (joint, faults, vein, bedding and foliation) within porphyry deposits is essential during all stages of mine life.

Structural interpretation surrounding an ore deposit must consider geology, deformational history (e.g. fault kinematics and timing relationship), fracture mechanics, and interaction between structural systems and fluid flow (e.g. hydrothermal fluids and groundwater flows). The role of the structural model in rock mass characterisation is shown in Figure 1. This figure also shows how closely linked the structural model and discrete fracture network (DFN) model are, sharing similar inputs and outputs. Deformation is generally scale invariant (Bonnet et al. 2001), implying that any observations made at a large-scale (i.e. regional and mine scale) should also be applicable to the small scale (i.e. DFN). During the evolution of an open pit mine there are ample opportunities for data collection. Ideally, the structural model for the area surrounding the deposit will advance (throughout the life of the mine) into a 3D interpretation that incorporates regional and local changes in geology, alteration and structural environment. Smaller structures are generally not modelled as discrete planes, given their frequency and distribution. For this reason, a hybrid approach has been developed. This hybrid approach considers the structural evolution of the area and allows for the development of correlations between primary systems (i.e. fault and dyke wireframes) and secondary systems comprised of small-scale networks (i.e. DFNs) of faults, veins and dykes.

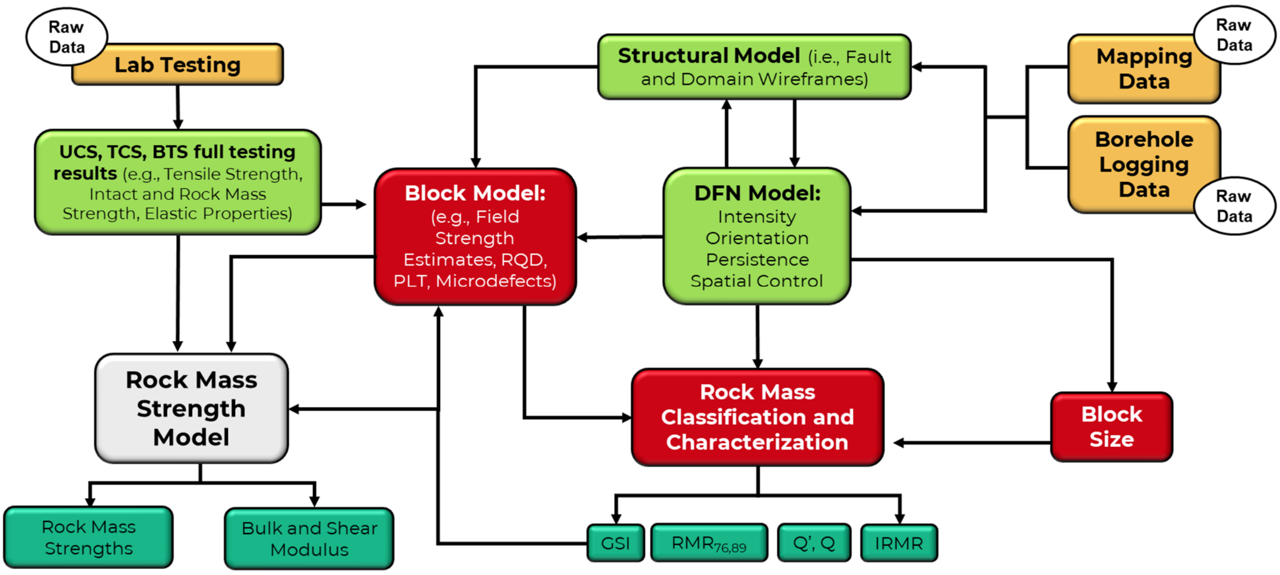


Figure 1 **Schematic of rock mass characterisation workflow**

2 Data collection and assumptions

Although all deposits are unique, there are trends in deformational behaviour that can be geospatially correlated. A fault-controlled mineral deposit is unlikely to be solitary, with other ore shoots expected to be nearby. If the deformational and geological history is widely understood there may be an indication of the deposit geometry and continuity that should be expected. Hence it is fundamental that a geological and deformational model is defined prior to developing a 3D structural model. It is important that the conceptual interpretation represents a data-driven hypothesis of the geological conditions of a deposit. To reduce the uncertainties that accompany the hypothesis, geological analogues should be considered and compared against the interpretation. Structural modelling is an iterative process, shown in Figure 2, that must be revisited and updated whenever new data become available.

One of the cornerstones of structural modelling is having a variety of data sources with clearly outlined assumptions and uncertainties. Although observations of regional structures are generally made at the surface, subsurface interpretation is required to confirm structure presence and persistence at depth (as seen in Figure 2). For that reason, structural mapping and oriented geotechnical core logging (and/or borehole geophysical data) are the two key inputs for developing a structural model. Other sources of information that may be useful include assay data and hydrogeological data (e.g. packer testing results and monitoring data from piezometers). Assay data may give an insight into the historic movement of fluids in the subsurface while hydrogeological data is helpful for indicating which areas of the subsurface currently have active/passive conduits.

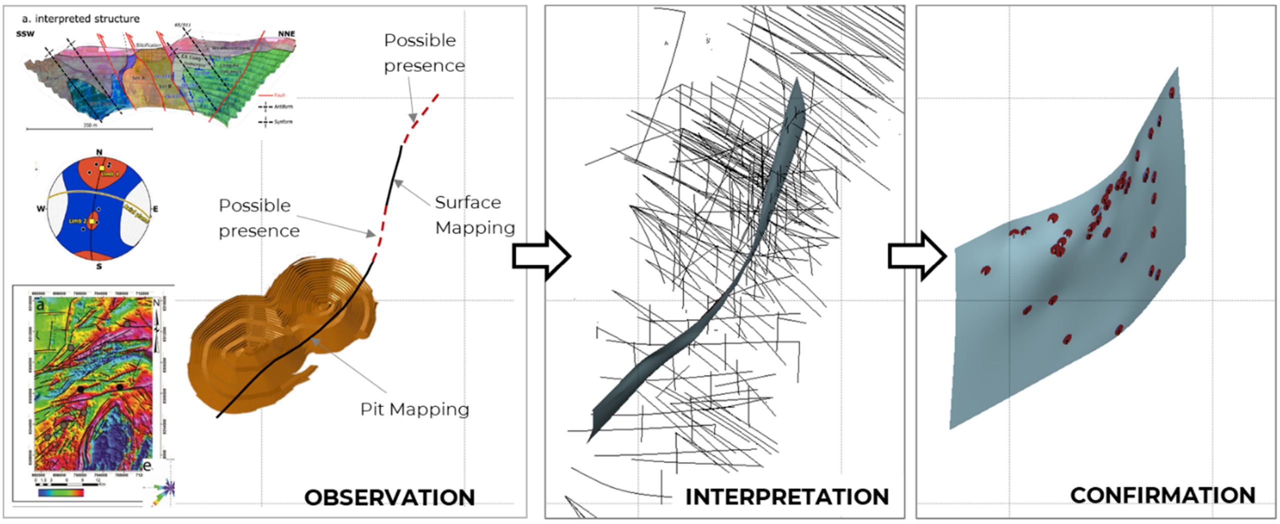


Figure 2 **An example of structural model development**

Structural mapping can be carried out in multiple different settings including open pit bench faces, underground drift headings, aerial/satellite photography and drone-based 3D photogrammetry models. Field mapping, when possible and safe, aims to collect information primarily on key structural parameters such as orientation, persistence, kinematics, timing relationships and alteration. When dealing with a deposit that persists across numerous rock mass conditions it is important to have a robust and comprehensive dataset. Data from a single source cannot be relied upon to capture the entire structural variability of a deposit. Common issues with using mapping data are problems with georeferencing or incomplete information on the mapped area.

Oriented core logging for geotechnical purposes is expected to include a host of information about both open and closed structures, as summarised in Table 1. Although closed structures are less likely to cause an issue in open pit or underground operations (i.e. not block forming), they do tell an important part of the structural history of the area. Availability of core photographs and geophysical data, such as acoustic televeiwer (ATV) logging, are useful for consideration with oriented core logging.

Table 1 **Summary of information collected during core logging**

Logging type	Details collected
Interval logging	Rock unit, lithology, degree/type of alteration, degree of weathering, rock quality designation (RQD), International Society for Rock Mechanics rock strength estimate[1]
Open structure logging: joint, fault, vein, bedding	Structure type, orientation (alpha/beta/gamma), reliability, count, mineralogy, joint condition rating (JCR)
Closed structure logging: fault, vein, bedding, brecciation, foliation	Structure type, intensity, orientation, reliability, mineralogy (for veining)

[1] International Society for Rock Mechanics (ISRM) rock strength estimate is a standard terminology for uniaxial compressive strength that is approximated during core logging

Common issues with using oriented borehole data are incorrect drilling surveys, duplicated or overlapping intervals in drilling data, problems with recording the orientation line downhole and inconsistent logging information. The importance of correcting errors or assumptions immediately in the field should not be overlooked. One of the common systems used during geotechnical design is the rock mass rating (RMR) system (Bieniawski 1989). The inputs for the RMR estimation include joint or discontinuity spacing, RQD and joint orientation. These properties are calculated on core logging intervals using the logged structures within the interval. Although core logging is often considered to be the most straightforward part of the assessment, the accurate and consistent identification of structures will affect confidence in the structural interpretation.

3 3D structural model construction

The methodology that has been used to identify and delineate key structures is outlined in Figure 3. In this example the workflow is being used to develop a primary fault system comprised of 3D wireframes. It is important to note that a 3D wireframe is a digital sketch of the interpreted understanding of the geological and structural setting given the available dataset at any given time. The workflow for generating a new fault wireframe begins at Step 1 (in Figure 3), where multiple data sources are considered in order to identify a local or regional trend. After the generation of a wireframe, photo logging (which is discussed later in this section) is carried out at potential borehole-fault intersections. Photo logging uses a buffer zone that can be up to 20 m on either side of the potential intersection. The final step in the workflow is the generation of a structural catalogue. The catalogue is a database that records the key attributes and properties for each of the wireframes interpreted in the structural model. This is updated as each wireframe is generated and issued with the model to provide a comprehensive description of the interpreted information. The structural catalogue is highly useful in identifying which parts of the model will need to be considered in analysis and design by other disciplines (e.g. geomechanical analysis or hydrogeological modelling).

The workflow for reviewing an existing fault wireframe begins at Step 2 (in Figure 3) and is carried out when new data becomes available. The structural catalogue is updated when wireframes are reviewed and is reissued when any changes have been made.

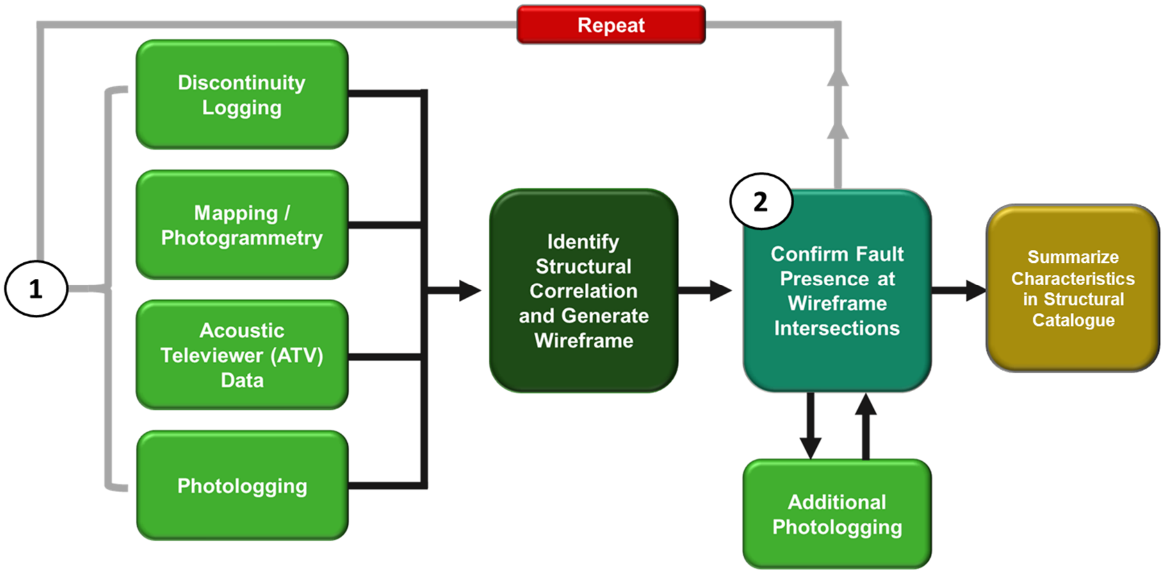


Figure 3 Approach for the generation of a structural model

Photo logging is a useful approach for utilising historic photographs of core logging intervals to both quality check (QC) existing data and to collect additional information on key characteristics within structurally relevant intervals (faults, veins, fracture zones). Borehole intervals are described based on the presence of fractures, rubble, gouge and oxidation. Based on the observations made, each photo-logged interval can be assigned a fault category. Fault categories, generally ranging from A (i.e. fault with gouge and/or cataclasite) to E (i.e. weathering/alteration of unknown origin), are useful during post-processing of data to provide increased efficiency for investigating the spatial variability of key parameters such as, but not limited to, presence/absence of gouge, feature type, thickness and infill type. An example of fault categories from photo logging can be seen in Figure 4. This example shows how photo logging can be used to enhance structural knowledge around a target area. Photo logging to QC data sources against each other is carried out during the initial stages of wireframe development. Figure 5 shows an example where an ATV survey and historic core logging do not reconcile. The success of borehole geophysics (i.e. ATV) hinges on the condition of the borehole wall as well as the expertise of the data analyst. Zones with very poor rock quality pose a risk to the ATV equipment and are therefore unlikely to be surveyed. Core photographs of the interval (shown in Figure 5) capture the true state of the core when it was drilled and provide great insight into what the in situ rock mass condition is.

The continuity along strike of the interpreted wireframe is controlled by the timing relationships that are interpreted between structures in the system. This interpretation is based on the distribution of mapping and borehole data as well as the understanding of deformational history. Wireframes are terminated if their presence has low confidence or cannot be confirmed, as shown in Figure 6.

Once a structural model has been created with high confidence it can be used for a range of applications including resource mapping, and the development of geotechnical domains and small-scale DFN models.

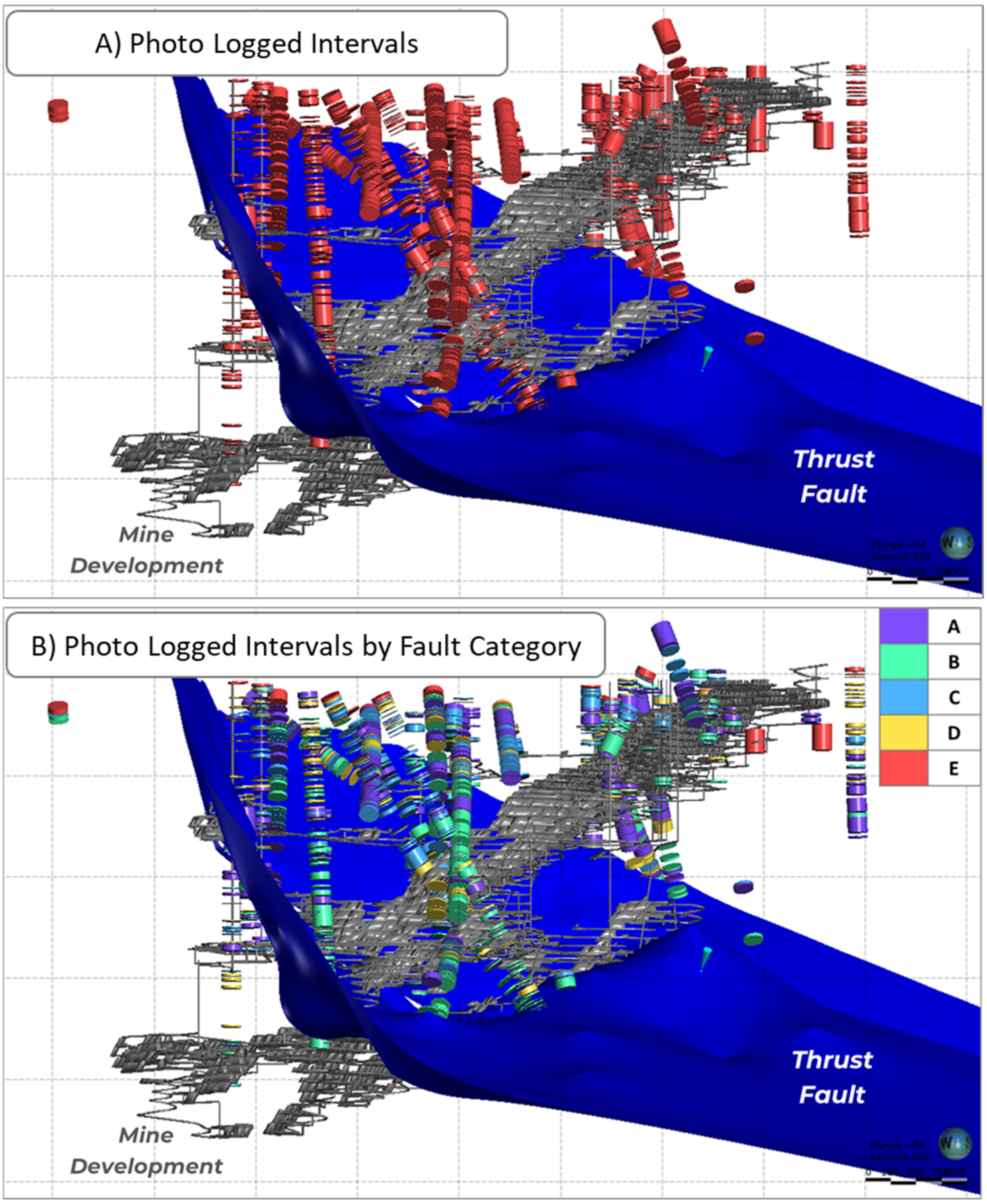


Figure 4 Example of photo logging distribution for structural modelling. (a) Undifferentiated photo-logged intervals; (b) Photo-logged intervals differentiated by fault category

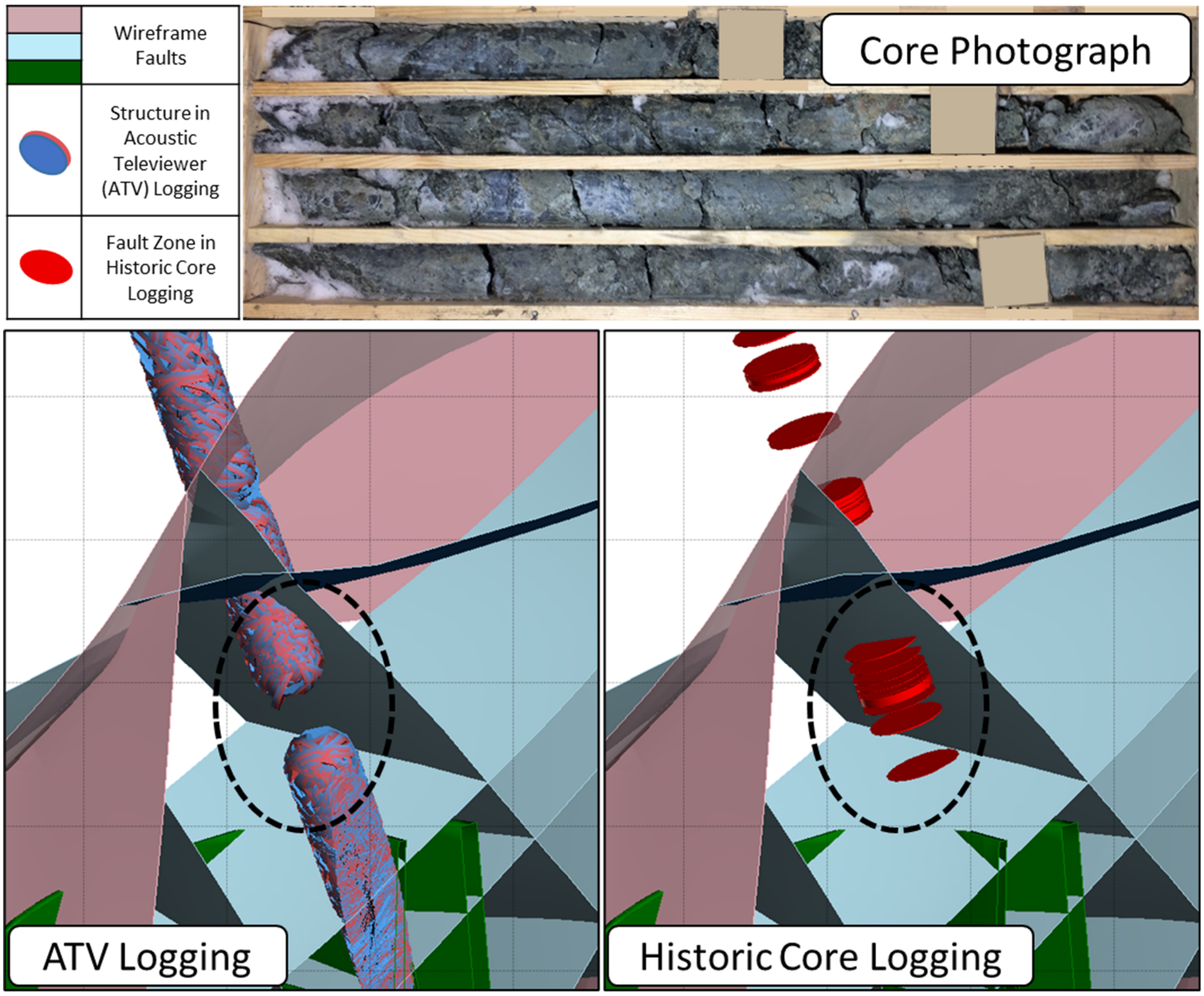


Figure 5 Interval comparison from three data sources: ATV logging, historic core logging and core photographs

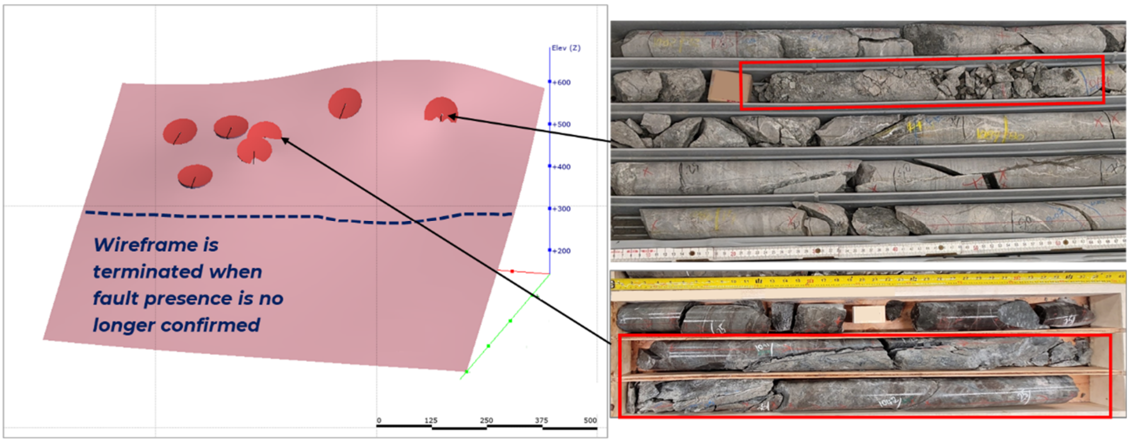


Figure 6 Example of an interpretation for wireframe termination

4 Discrete fracture network model construction

The objective of using a DFN model is to explicitly represent relevant fabric in 3D space, whether that be joints, faults, bedding or dykes. Geological and geotechnical data are used to estimate quantitative parameters that describe the fracture network and its variability, similar to the large-scale structural modelling but for the smaller-scale structural fabric (referred to herein as 'fractures'). Using field data in this way can replace the inherent conservatism of implicit or simplified approaches with actual realism. In general, the widest and most persistent faults are developed into wireframe structures in a 3D structural model. The advantage of generating a 3D structural model and DFN model in parallel is the comprehensive understanding of the rock mass fabric at all scales that can then be used for different applications. Although the regional- and mine-scale structures are important for understanding the mechanics that may be impacting deposit geometry and continuity, the effective excavation of the mine design is heavily influenced by the smaller-scale structures (i.e. DFN) that control inter-ramp and bench-scale stability. The key inputs for generating either of these DFN models are intensity, orientation, size and any existing spatial correlations (shown in Figure 7).

Intensity values for the fracture network are generally derived from oriented borehole logging and ATV logging but can also be derived from local photogrammetry data for smaller areas with more specific analysis. Fracture intensity measures are classified based upon the dimension of the measurement region and the dimension of the fracture, as shown in Figure 8 (Dershowitz & Herda 1992). Note that fracture intensity measurements from borehole intersections are expressed as P10 (fracture count/unit length) and from mapping as P21 (fracture length/unit area). Both P10 and P21 are generally converted into a 3D intensity measurement, P32 (fracture area/unit volume), for modelling purposes.

Observations from core logging and photogrammetry mapping should always be considered with respect to the structural model. The relationship between large-scale and small-scale structures has been discussed with respect to scale (i.e. that deformation is scale invariant), but should be contemplated with regards to frequency of occurrence (i.e. intensity). Increased fracture frequency in intervals that immediately precede and follow a fault zone can indicate a possible association between faults (large-scale) and fractures (small-scale). Once there has been an indication of a possible correlation, the relationship between wireframe fault structures and fracture intensity can be established by determining the minimum distance from each drilling interval to the nearest wireframe fault. The average intensity for each interval can then be plotted against the distance from a wireframe fault, and the trend of the correlation will represent the relationship between wireframe faults and the widespread structural population. Using this method ensures that fracture intensity is accurately modelled.

Fracture length distributions for DFN models are sourced primarily from open pit photogrammetry mapping, bench mapping and surface mapping, and from the structural model. Structures have been observed to follow a power law trend when plotted together in many instances. Power law analysis (Rogers et al. 2016) reflects the common observation that many geological structures show scale invariant properties over large-scale ranges (Bonnet et al. 2001). The size distribution can be expressed as a single number: the power law slope trend.

Structural orientation data for fractures is primarily sourced from geotechnical logging (i.e. oriented core logging) and ATV logging, however, it can also be acquired from open pit photogrammetry mapping and bench mapping. The observed terminations of large-scale faults are an important consideration during the development of structural domains and should be reflected in any related DFN models.

In addition to faults, veins and dykes can represent a relatively high frequency of discrete bodies within the rock mass surrounding a porphyry deposit. The presence of these structures can be incorporated into block modelling to assist with structural correlations and domain identification. Although the intensity of vein and dyke structures can be approximated using methods similar to small-scale faults, their orientation can be more difficult to characterise and may need to be considered alongside aperture. Vein systems are highly variable and can improve or degrade the rock mass, depending on the infilling mineralogy. Dykes comprise strong material that could potentially impact geotechnical considerations in the mine area. Comparably to vein modelling, the approach for modelling dykes considers aperture. Deterministic dyke wireframes can be developed for large and persistent dyke structures while a stochastic dyke intensity can be developed for smaller dykes.

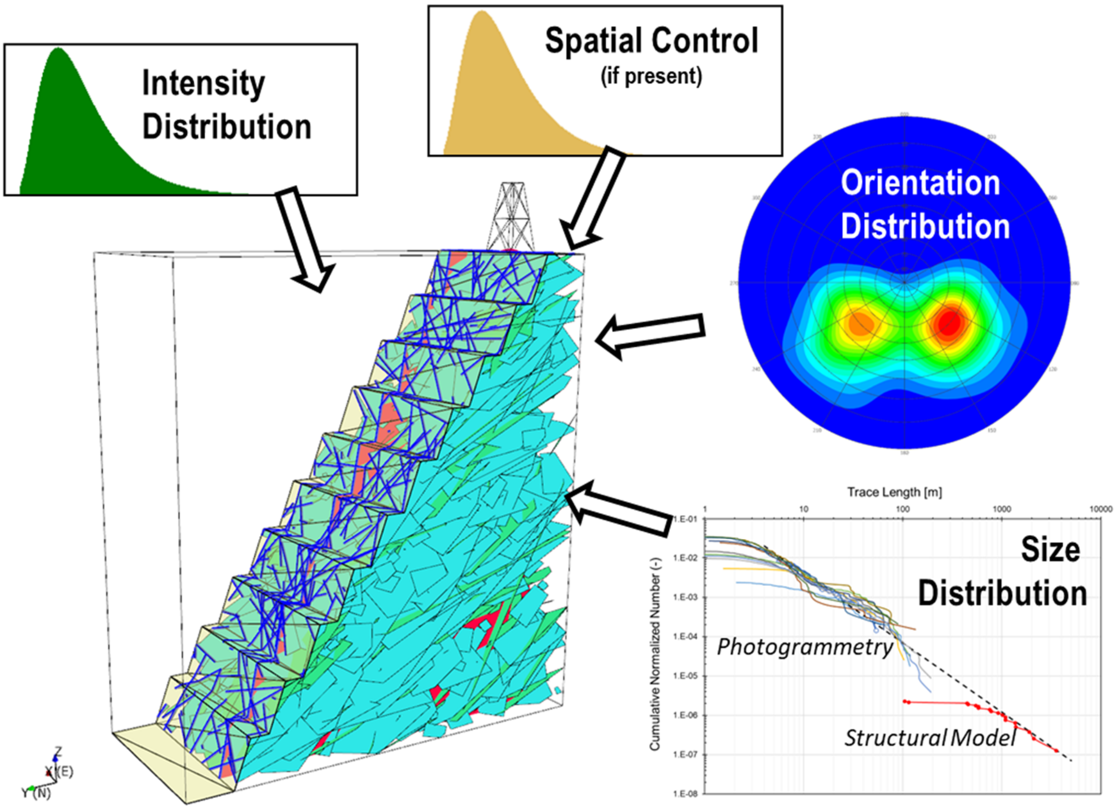
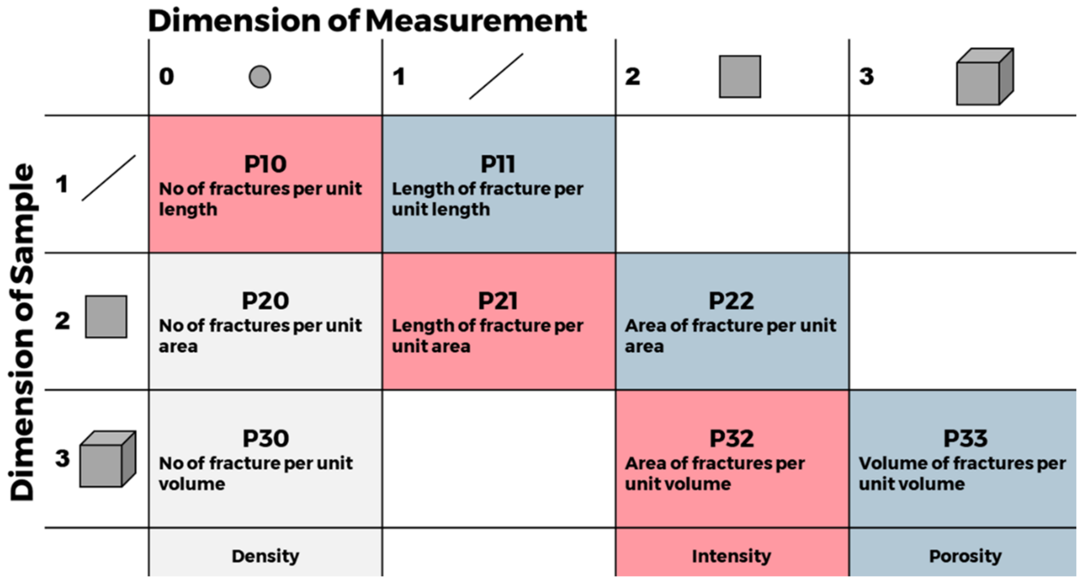


Figure 7 Schematic of discrete fracture network inputs



Dimension of Sample	Dimension of Measurement: 0	1	2	3
1	**P10** No of fractures per unit length	**P11** Length of fracture per unit length		
2	**P20** No of fractures per unit area	**P21** Length of fracture per unit area	**P22** Area of fracture per unit area	
3	**P30** No of fracture per unit volume		**P32** Area of fractures per unit volume	**P33** Volume of fractures per unit volume
	Density		Intensity	Porosity

Figure 8 Intensity measurements from mapping are expressed as P21 (fracture length/unit area) and converted into a 3D intensity measurement, P32 (fracture area/unit volume)

5 Conclusion

The correlation between large-scale and small-scale structures is a novel modelling approach that has provided great insight into strategies for data collection and interpretation. This approach also gives a heightened level of clarity to the genetic and evolutionary relationship that can exist between structural systems and deposits themselves.

References

Bieniawski, ZT 1989, *Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering*, John Willey & Sons, New York.

Bonnet, E, Bour, O, Odling, NE, Davy, P, Main, I, Cowie, P & Berkowitz, B 2001, 'Scaling of fracture systems in geological media', *Reviews of Geophysics*, vol. 39, no. 3, pp. 349–383.

Dershowitz, WS & Herda, HH 1992, 'Interpretation of fracture spacing and intensity', *Proceedings of the 33rd US Rock Mechanics Symposium*.

Rogers, S, Elmo, D, Webb, G & Guajardo, C 2016, 'DFN modelling of major structural instabilities in a large open pit for end-of-life planning purpose', *Proceedings of the 50th US Rock Mechanics Symposium*.