Guidelines for Structural and Geological Models

Prepared for

University of Queensland - LOP 3 Project

Prepared by

SRK Consulting (Canada) Inc.
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Cover Photograph

Interference folding of S_2 foliation at Venetia Mine, showing localized impact on bench stability.

1 Introduction

1.1 Objective

The objective of this white paper is to provide structural geologists and geotechnical engineers working in open pit mines guidance on the creation and critical evaluation of 3-D structural geology models. 3-D structural geology models often guide the input parameters or provide direct input as contact lines or wireframes into slope design analytical software used by engineers. The creation of 3-D lithological and alteration models are also addressed, particularly in context of the most reliable model being the product of an integrated structural, lithological and alteration model. This paper is intended to supplement the Guidelines for Open Pit Slope Design (Read and Stacey, 2009), with specific reference to their Slope Design Process.

Geology requires a strong interpretative component, involving the evaluation of geological observational data. This subjectivity influences all downstream analytical and interpretive processes. However, the geologists creating the models seldom understand how the models influence geotechnical design decisions and the engineers seldom appreciate the complexity of the geology and the simplifications, assumptions, and errors in the 3-D models. There needs to be greater emphasis on formal and comprehensive communication between technical disciplines, and this white paper explores and recommends communication tools that have proved effective on many open pit mining projects around the world.

The white paper starts with the fundamentals of geological data collection. The systematic workflow is explained that is required, step by step, to build the basic data-based foundation for a 3-D structural geological model. The requirements of mapping and logging derived data as input into geological models are explained. The objectives, challenges, and solutions for building appropriate 3-D geological models from data are discussed in detail, including factors which are important to geotechnical engineers.

One of the big challenges for this paper is to introduce the concept of reliability of a geological model into practical open pit engineering. The concepts of uncertainty are explored with specific reference to all the parameters and factors that are included in a geological interpretation, with the aim of highlighting the key factors that should be more closely reviewed and measured, if possible. A method to create a Reliability Index appropriate for open pits is also explored.

1.2 Model Development Workflow

The workflow steps and quality controls for developing the geological model should be clearly defined prior to initiating the development of a model. Each step in the model development is dependent on the quality of previous steps (Figure 1-1), starting from initial data collection, to the data management and verification, to 3-D geological model construction and peer review, and to final communication of the product to the end-user. Such a process should always be circular on developing or mature mining projects, such that each iteration of a model improves as data and knowledge increases.

Model construction starts with:

- Understanding the Objective(s): To create a successful geological model, all persons involved need to understand the objectives and purpose of the model to ensure that the data and interpretations are of appropriate resolution and content, and based on acceptable assumptions. This requires clear inter-disciplinary communication and discussion around potential misunderstandings, such as what type and scale of structures are relevant during mapping. Although the model may primarily reside with the resource geology team, for the purpose of this guideline document we emphasize the importance of starting with a discussion on the model requirements with the relevant Geotechnical Engineer. Resource domains may be different to geotechnical domains. A creation of a high-resolution master geological model may be the initial objective, but from which appropriate domains can be created overlapping the same volume that are specific to the objectives of each client, such as the geotechnical engineers.

- Data Collection: The geologist undertaking the data collection through mapping or logging must be adequately competent. Geological data collection is not just data gathering, but also a process of interpreting, testing and understanding the data and the likely geological patterns the data represents. Nevertheless, observation data must be distinguishable from interpretation.

- Data Storage: Captured data must be carefully managed and protected and stored in a reliable manner to prevent loss or corruption over time. The storage format must also be adequate to retain all inherent properties of the original data and be useful for further interpretation. This includes all metadata, including declination, coordinate system, mine grid, and core measurement conventions.

- Data Verification: Captured data must be reviewed to check for errors, and if transferred into a database, must be reviewed for data-entry errors. There should also be a documented process to validate or review the quality and internal consistency of the original data measurements in the field, such as by peer review, if appropriate.

- Data Integration and Conceptual Model development: In the early stages of geological interpretation, the data (if available) should drive the geologist’s formulation of an overall conceptual model understanding of the geological system. Existing subregional geological knowledge is an important “data” source but techniques should be employed to keep the conceptual interpretation unbiased. This conceptual model will help keep the more detailed interpretation coherent and realistic.

- Detailed Interpretation and Analysis: The detailed 3-D model interpretation should be done by the person who collected the data, or by a geological modelling specialist with the field geologists’ close oversight. The interpretation process should include identifying and confirming geological patterns through the use of data analysis tools and 3-D spatial visualization.

- 3-D Model Construction: The construction of the wireframe model must be done with the appropriate software and the user must be adequately trained or guided to use the full required functionality of the software and achieve the objective.

- Peer Review and Test Biases: All interpretation along the workflow to the final model should be reviewed by a competent person. It is preferable if biases are tested and alternative interpretations compared.

- Publishing: The model represents the best understanding of the geology based on available data at a specific time. It should be "published" and safely stored and made available to the appropriate persons.

- Communication of Reliability: All assumptions and simplifications used in the model should be communicated appropriately to the persons using the model for guiding further interpretation or engineering decisions. The possible variations in interpretation deviating from the model should be communicated as clearly as possible.

This entire data collection and interpretative modelling process is then verified and reconciled to new observations, and started again (Figure 1-1) building on the previous interpretation.

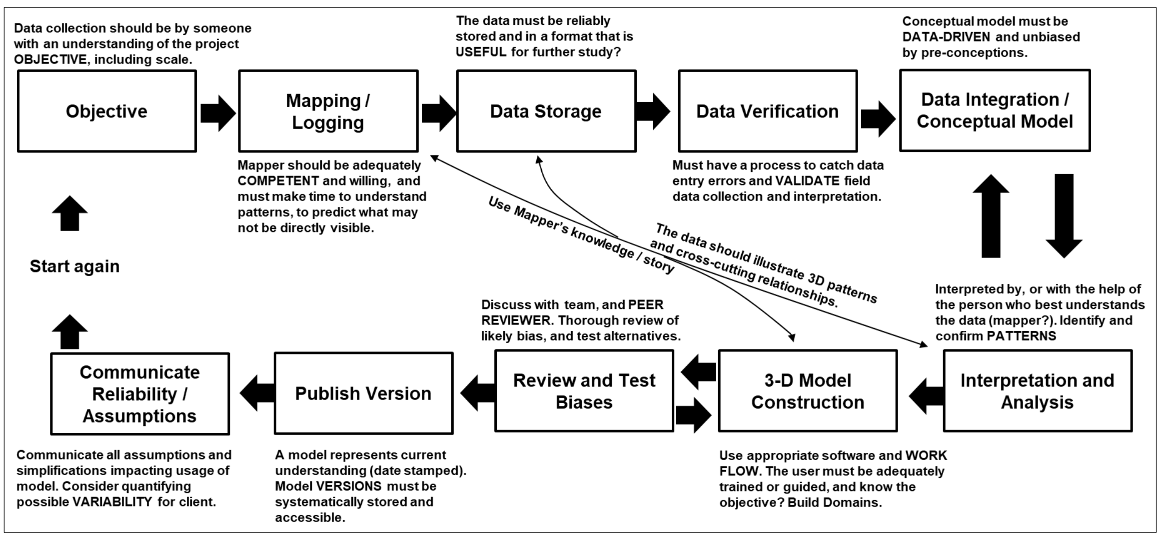


Figure 1-1: Summary diagram of the model development workflow

2 Geological Data for 3-D Modelling

2.1 Overview

The reliability of a geological model is clearly based on the distribution and quality of input data, and the quality of the model is important to the end user. There is a significant range in types of data and a growing number of technological ways to capture data. In this section we focus on the fundamental data inputs required for a geological model.

2.2 3-D Modelling Starts at the Rock Face

The 3-D geological modelling should be guided by data and a geologist familiar with the geology of the area in question. This maximises the ability to integrate first-hand factual and derived conceptual knowledge of the geology of the area into the 3-D model. In many cases, this means that the on-site project geologists should conduct the major phases of integration, 3-D interpretation and validation. The result of this is a valid geological interpretation, constrained by known geological data and compatible with geological constraints (ages, cross-cutting relationships), and structural style.

In addition, a geologist can gain great insight and 3-D visualization while examining rock exposures and interpreting the geology during mapping of a pit bench or drill core. The framework of the possible structural interpretations is set during the mapping and logging process, and subsequently refined using 3-D modelling tools.

The geologist’s objective is to develop an understanding of the 3-D geology within the context of the overall project objectives (Figure 1-1), and then collect the data necessary for the project, at an appropriate scale. This requires the geologist to be very familiar with the project goals, before initiating the mapping process. In the case of open pit geotechnical studies, the geologist would likely focus on geological features and domains discussed in this document and would include additional features specified by the engineer in charge of the project.

2.3 Mapping Patterns for 3-D Modelling

Data and interpretations recorded on paper or electronic tablets are the first stage of 3-D modelling. Data types include rock type and textural variations, alteration type and intensity, structural features and patterns, and specific mineral types of interest. Most important in geological mapping is the observation and interpretation of spatial and temporal relationships between each mapped feature.

Structural geology relies upon the recognition and understanding of patterns. Patterns help understand every aspect of deformation process, including fault and fold systems, intrusion-related deformation, radial, concentric and orthogonal fracture systems and zones of brecciation, and are therefore a fundamental part of the mapping process. If the deformation patterns can be determined, then both the kinematics of the structural system and cross-cutting relationships with other structural systems can be more easily understood.

A fault system typically consists of faults of different scale, all working together to accommodate displacement through a volume of rock. Larger or more continuous fault surfaces are interconnected by smaller faults, defining a pattern. Components of a fault pattern are commonly described in terms fault order. First-order faults can be described as those faults that define the overall fault system continuity, accommodate most of the displacement, and commonly have thicker core zones. Second-order faults connect and typically terminate on the first-order faults, and more likely have less displacement and thinner core zones. Third-order, smaller faults then similarly connect the second-order faults, etc. The understanding of the structural geometry can then also be extended to include lower-order structures in a manner that can be predictive, even without direct observation where data may be obscured or limited.

The ultimate objective of structural mapping is to define what structural features are clearly observed, and also to highlight structural features that were not observed but are considered likely to exist, given the understanding of structural patterns observed. Mapping should also include interpretations that extend into the non-visible rock mass. These unconfirmed, interpreted structures must be accounted for in the geotechnical analysis.

Structural pattern mapping is rarely done in mining operations. Pattern mapping differs from simply recording orientations with a compass or electronic device. In order to map a pattern, the geologist must draw and interpret either on paper (e.g. Anaconda method of Einaudi, 1997; Groshong, 2006; McClay, 2013) or electronic tablet, and then store in a format that allows importing that pattern into the 3-D interpretation software. Patterns are increasingly captured through photogrammetry, laser scanners or drones, which is useful for large-scale coverage of inaccessible areas, but may lack detail to fully understand the structural system and their physical properties without complementary detailed observations. The current trends in safety regulations are increasingly prohibitive to pit mapping, but can be partially supplemented by remote sensing technologies.

See Appendix A, Section 1.1 for further explanation of the mapping data that should be captured as input into 3-D models.

See Appendix A, Section 2.2 for more detailed explanation of data types required to be measured to constrain and define the geometry of fold systems necessary as input into 3-D models.

2.4 Core Logging for 3-D Modelling

For most mine development projects in the world, drill core is the most abundant source of data for building the 3-D interpretation. Lithological, alteration and structural “mapping” of drill core, like field mapping, is a process of identifying and understanding patterns, including those of fault and fold systems. The logger should record descriptive observations on patterns and kinematics, and on fault zone textures. These observations and measurements must be captured in data format in order to be available for querying during the structural model construction.

It is possible to significantly increase the reliability of a model by optimizing oriented drilling technologies and core logging data capture methodologies. Kramer Bernhard, et al. (2020) provides a detailed review of the techniques required to obtain appropriate quality controlled structural data from drill core logging, in order to build a model. In general, oriented core data are less reliable than pit bench mapping, unless the highest quality core orientation and quality control protocols are employed and the hole orientations representatively sample the structural orientations and types. The inclusion of acoustic and optical televiewer data capture commonly provides a significant improvement in the quality of orientation data from drill holes and provides greater overall data reliability if combined with oriented core observations (Kramer Bernhard et al., 2020).

Information on structural continuity is insignificant until an organized interpretation is completed. It is more difficult to determine the size (strike length/depth extent) or significance of a fault observed in drill core, as compared to pit bench or rock outcrop. The relevance of an observation may also be questioned during the 3-D modelling process, for whether the logged feature is truly a fault, or another category of broken core logged by someone lacking training.

Certain fault textures are more indicative of the core of a fault zone, whereas other textures are more representative of the extremities (near the tip-line) of a fault zone, or of the damage zone that may bracket the fault. Heavily fractured core is not necessarily related to a fault. A model's reliability can be improved by including information about the fault textures if organized and available to the modeller. Good categorized observations of the fault zones in core can greatly improve the reliability of the model. Kramer Bernhard et al. (2020) propose five structural observational categories (classes) that should be distinguished during structural logging. See Appendix A, Section 1.2 for a description and explanation of the categories.

2.4.1 Data Capture, Organization and Verification

Field, pit bench, and drill core geological measurements, descriptions, interpreted patterns and spatial relationships can be collectively called "geological data". Geological data forms the foundation of a geological model interpretation, which in turn is the basis for decisions of financial expenditure related to mine development. Geological data uncertainty impacts the reliability of the geological model. Geological data must be systematically organized, verified and securely stored (Figure 1-1; Caumon et al., 2009).

Unreliable data (erroneous or uncertain) can be found on development projects and mines, including those that have database management protocols. The type of storage technology chosen is important but is less important than having adequately trained accountable people with the ability to preserve data integrity and migrate the data onto more modern storage technologies when required. Data collection processes can include data measurement errors, and data management processes are affected by data entry errors. A robust geological data verification process is therefore required (Figure 1-1). The database management protocols should include a technical specialist who can verify (and train) data collection at the rock face and in drill core. The protocols should also include a data management specialist who implements data entry quality control processes, implementation of metadata and longer-term data protection.

Retaining and transmitting 3-D understanding of pattern and timing relationships from the mapping geologist to the 3-D computer interpretation process constitutes a challenge in many mines. Mines that have invested in training generations of geologists in good pattern mapping practices may have all their data on paper stored in cabinets and requiring laborious digitization and verification work in order to be used in a 3-D modelling process. Although many mine geologists now capture all mapping data digitally, they commonly favour data point measurements and neglect to capture observations and sketches of patterns.

Spatial GIS databases are more appropriate for storage of mine mapping data, which can include point and pattern data. GIS mapping approaches allow modernization of pattern mapping through the use of electronic tablets and augmented reality data capture tools (Onsel et al., 2019; Onsel et al., 2020.), thereby overcoming challenges of paper-stored data inaccessibility. Patterns and field interpretations can be effectively captured (Figure 2-1), stored in spatial databases and imported into 3-D modelling software.

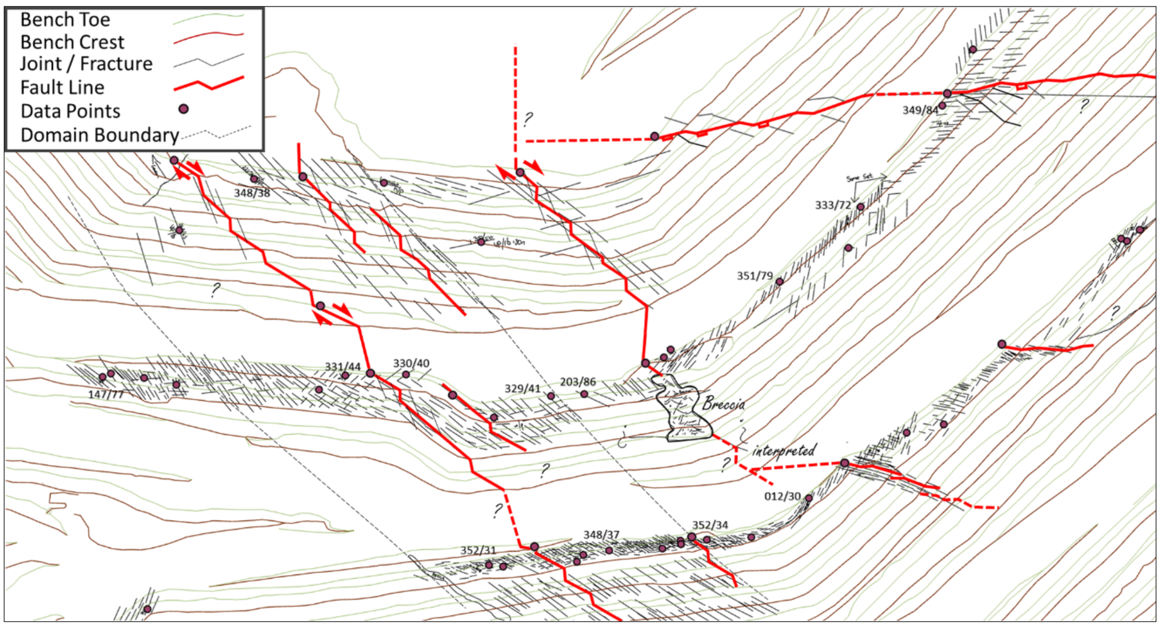


Figure 2-1: Example of structural bench mapping which includes structural measurements, annotation, observed and interpreted structural features that will help the 3-D modeller make decisions. Mapping includes the bigger picture spatial relationships between faults and clustered fracture systems to define domains.

3 3-D Structural Model Development

3.1 Overview

This chapter explains how to translate the structural observations and field conceptual model into a realistic 3-D wireframe structural model. Key challenges for realistic structural model construction will be discussed, including solutions that can be considered for constraining pattern, continuity, and age/crosscutting relationships.

3.2 3-D Structural Modelling

The ultimate purpose of the 3-D structural model must be well defined in order to develop the most efficient workflow strategy to develop an appropriate model (Ringrose and Bentley, 2015; Stenhouse et al., 2020).

The 3-D interpretation includes data integration, visualization and exploration for trends and patterns, before constructing the final model to serve as input to geotechnical analyses. Regardless of the ‘life of mine’ cycle stage, the steps outlined below for building the model remain the same.

A conceptual model needs to be developed from existing knowledge and enhanced though 3-D visualization and data exploration. The geologist can start to build wireframe interpretations of the structures only after developing a high degree of familiarization with the input data. A series of technologies and techniques can be used to assist in the visualization and refinement of a wireframe, particularly where mapping data and oriented core logging is absent or provides limited guidance (e.g. Cowen, 2020).

Several types of challenges may arise depending on the geological complexity intrinsic to the pit, and on input data quality, quantity, and distribution. A key phase of work is to ensure that the various aspects of the model, its inherent assumptions and reliability assessment are adequately conveyed to the end users.

3.2.1 Modelling Step 1: Building a Conceptual Structural Model Through Data Visualization and Pattern Exploration

The modelling geologist’s priority is to develop a conceptual understanding (or conceptual model; Figure 1-1) of the geology. The modelling tools available in 3-D modelling software seldom provide an immediate and unequivocal visual understanding of the structure being modelled or of how to proceed with development of the model. The development of a geological model should therefore be both data-driven and geo-model driven.

The geo-model driven approach considers primary data as observations providing input to geological knowledge, which drives the development of a conceptual model (Wellman and Caumon, 2018). The conceptual lithological and structural model informs decisions on how to best interpret between the data points during 3-D modelling.

The conceptual model is essentially an intrepreted understanding of the tectonic model or geological events and timing relationships that lead to the large-scale structural patterns and geological formations in the area of interest. For example, are the deformation patterns primarily compressional, extensional or strike-slip, or a combination and with what cross-cutting relationships? As a first step, this can be derived from existing regional geological maps, or conceptualized by researching locally relevant publications, reviewing satellite or airborne photography, or undertaking subregional mapping, or even by local mapping of good outcrop focused on resolving superimposed deformation patterns and timing relationships (perhaps using a recognized expert geologist).

The data-driven approach relies on matching the interpretation closely to data constraints such as georeferenced structural measurements or geophysical survey images. Data-driven interpretation may enhance a conceptual model understanding, but is typically influenced by the conceptual model.

The conceptual geo-model approach is important in exploration projects in which data are limited or equivocal. Mine geologists sometimes down-play the technical skill of geo-model interpretation and focus on data-based interpretation that result in unrealistic interpretations that honour data points. A conceptual geo-model interpretation is also required in mining to better interpret patterns away from data. The conceptual model may initially be a high-level understanding and may be partly inherited from previous exploration phases of the project. The conceptual understanding should include a sense of the regional structural/tectonic framework. If the geological conceptual model is not already available from previous mapping or interpretational work, its development must be given top priority as the initial stage of modelling.

In order to further develop the structural conceptual model at a mine scale, all pertinent data must be imported into the modelling software 3-D environment. Data may include mapping, drill core logging tables, downhole probe and core scans, as well images and interpretations from remote sensing methods. For example, photogrammetry and LiDAR images can provide excellent coverage and control on the pattern and continuity of structures in open pits. The geological data needs to be visualized and explored in 3-D geometry to understand the limitations and benefits of each data source, and to determine potential contradictory relationships that need to be resolved

In the early phases of open pit mine development, the structural model is strongly dependant on drill hole data, even where outcrop volume is high. Once the pit is in operation, mapping data should become the primary means of confirming geological features and domains that impact wall stability and ore continuity. Confirmatory mapping of structural patterns is critical for further developing the overall conceptual understanding. The mapper should be involved through the various stages of model development to help integrate pit observations and the geological concept and to guide decisions on the most realistic interpretations.

Once all the data are imported and understood, the modelling software tools can be used to advance the interpretation. Additional software tools or workflows may be required to further analyze data (e.g. stereonets, paleo-stress analyses) and test interpretation possibilities. It may be necessary to iteratively question then update the overall conceptual model until all key geological information is included in the model (Figure 1-1). During the visualization and data exploration step, the interpreter uses all pertinent data to identify and build wireframes that represent discrete structures or structural domains that are relevant to the model's end users.

Modelling Challenge 1: Finding Structural Patterns

The interpreter should start by using the highest confidence data (e.g. good mapping data) to constrain patterns. Then expand the 3-D visual exploration, searching for similar patterns that fit the conceptual model. This pattern search process is one of the most important steps in the model development. It can lead to a new understanding and discovery of opportunities and risks through the identification and incorporation of previously unrecognized patterns. This modelling step can therefore produce significant improvements in the overall structural or geological interpretation and reliability. The modeller should also recognize that interpreted patterns may be strongly biased.

Finding a pattern in the data involves looking for and noting various trends that might represent geological surfaces or intersections that need to be considered while developing the model. A pattern may be a fault zone that can be traced through multiple drill holes, or more subtle structural features such as fold interference patterns, and fault and fold cross-cutting relationships. Note that the trends do not have to be linear. Faults are commonly curved, and folded contacts or intrusive bodies may be much more complex depending on the deformation history.

As described above, a fault system commonly develops as a network of faults of different scale, all working together to accommodate displacement through a volume of rock. The modeller should try identify the likely first-order faults and other lower-order faults and associated pattern. The modeller should be aware that fault patterns are commonly repeated at different scales, and should understand Riedel fault patterns (Price and Cosgrove, 1990).

From the start of the model development, the cognitive process must overcome the following important limiting factors:

1. Excessive data noise. Many projects have very large databases and the amount of noise creates a challenge for the 3-D data exploration process (Figure 3-1). It takes experience to be able to visualize and interpret large amounts of data on the computer screen at one time. Contemporary software provides tools to reduce, decluster and manage the size or width of the viewing window so that smaller volumes of data can be interpreted at one time. It is paramount to make use of such tools from the start of the interpretational process. Rotating the data on the screen slowly, rather than rapidly, also helps 3-D perception (a concept recognized pre-personal computers by Shepard and Metzler, 1971).
2. Multiple models: Where there are large amounts of data, it is common for multiple possible interpretations to exist. Instead of simply choosing the first possibility, it is recommended that interpretational polylines be snapped directly onto the drill hole traces or point data in order to capture the different interpretations (Figure 3-2). These draft interpretational lines can be retained until a preferred interpretation is chosen.

3. Overestimating continuity: Cognitive biases are significant during interpretation, leading to visualization of connections between random points and finding justification for interpretations, even where patterns are coincidental. A very common bias consists of assigning excessive continuity to structural trends by allowing the model to be influenced by data points that are slightly off the structural trend.

4. Drill hole fan bias: Based on the authors' experience, geologists preferentially interpret trends that are perpendicular to each drill hole trace. This can highlight localized, co-incidental trends and over-estimates their strength and continuity. There is also a related mathematically quantifiable direction bias defined by Terzaghi (1965) that similarly can influence interpretive model decisions, since structures oriented closer to being parallel to drill holes are less likely to be intersected by the drill holes and therefore less likely to be modelled. In order to mitigate this bias, it is necessary to explore all possibilities and make use of the structural patterns known in the area.

   Interpretational biases are inherent to the human brain and every geologist has bias based on their training and experiences. Note the example discussion at http://www.orefind.com/blog/orefind_blog/2017/10/23/the-fundamental-reason-why-your-geological-models-may-be-completely-wrong, and Bond et al. (2008). It is recommended to include geologists who have different biases as peer-reviewers of the interpretations (Section 5.2.1).

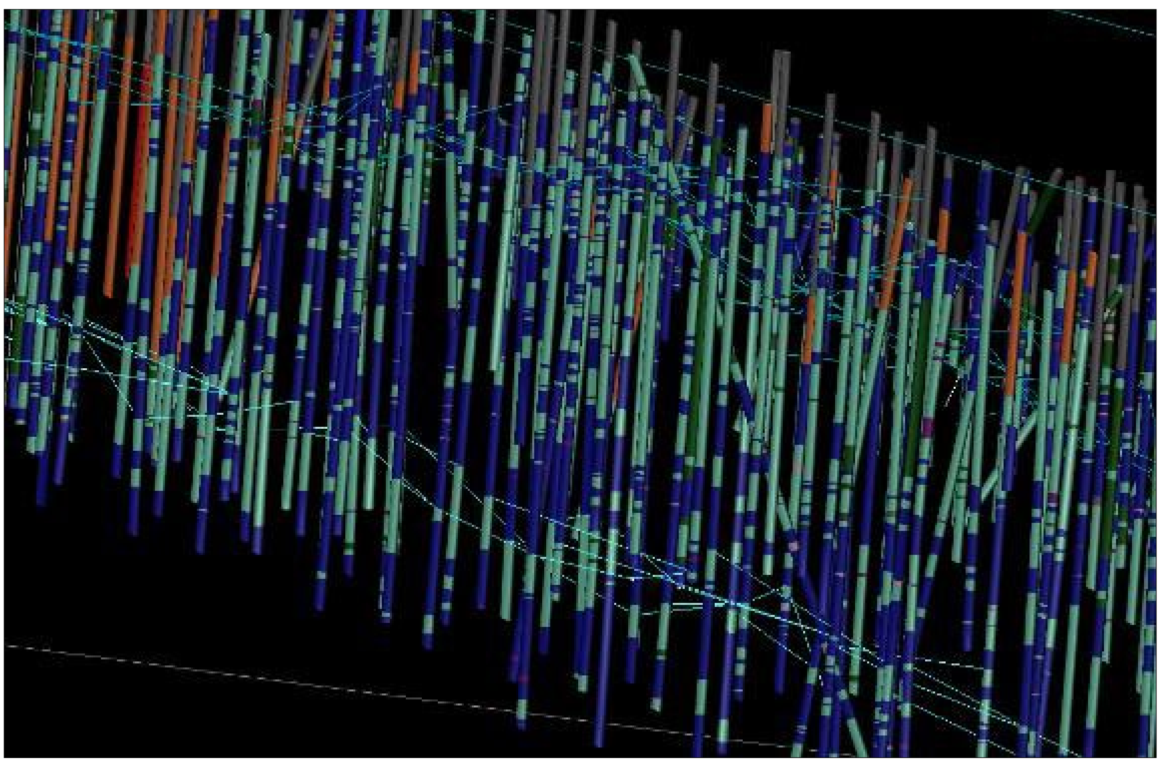


Figure 3-1: Dense data sets can be difficult to visualize and may require multiple interpretations. Use of an interpretational polyline to trace identified trends allows the modeler to track possible interpretations, until a final interpretation can be made

Modelling Challenge 2: Faults Are Not Straight Lines…

Although planar trends are the best way to identify faults in 3-D data, faults are seldom perfectly planar. Faults develop through a process of segmentation and linkage, and therefore may undulate or form dilatational or compressional relay jogs with displacements stepping from one plane to another (Figure 3-2). Smaller lower-order faults may have not developed as much and might have limited continuity and greater segmentation with intact rock bridges between faults (Figure 3-3).

Representative modelling of the shape and continuity of faults is an important challenge for structural geologists. Finding field evidence to support the interpreted continuity will greatly improve the reliability of the model (Figure 3-3).

Figure 3-2: Illustration of the complexity and lack of continuity of many partially developed faults. Fault segmentation and linkage is clear. How the geologist models faults such as this in 3-D depends on the project objective(s) and scale requirements

In some cases, the geologist uses thickness of the fault intersections to distinguish groups of faults of different maturity levels and possibly different continuity. For example, in a certain domain, 1 to 10 cm thick fault breccia and gouge may be indicative of second-order faults, whereas faults with greater than 20 cm thick breccia and gouge may represent the first-order fault system. In other domains the thicknesses may be different by an order of magnitude. In general, thicker faults are more likely to have greater continuity (De Joussineau and Aydin, 2007), with well-formed relays between segments. However, fault thickness can change along short strike and dip distances, and a drill hole intersection may exaggerate an apparent width, and therefore interpretations that rely heavily on fault core thickness characteristics measured from drill core should be assigned low confidence.

First-order fault zones may have well developed fracture zones and associated second-order faults forming the first-order damage zone. Damage zones of sub-regional to regional fault zones may be tens to hundreds of meters wide.

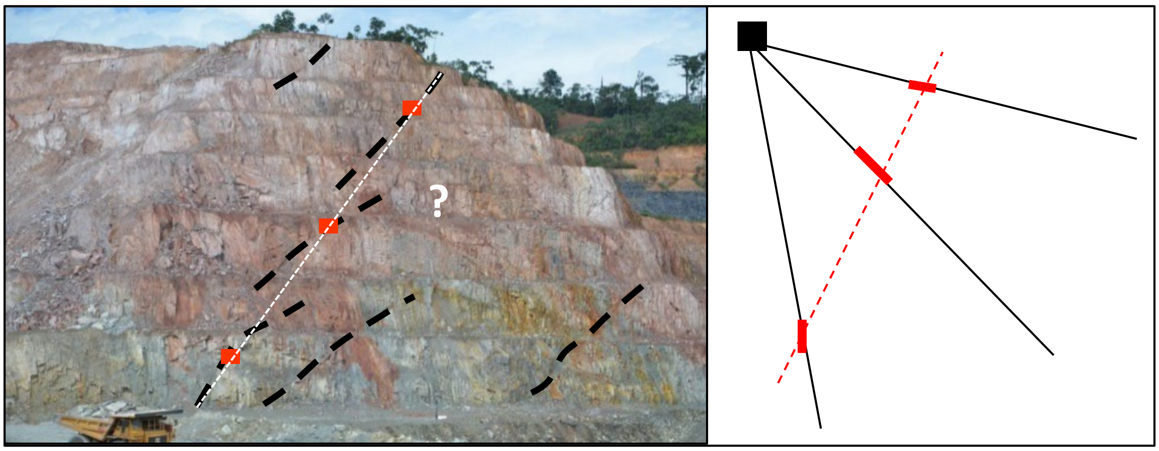


Figure 3-3: The challenge of defining fault continuity from drill hole intersections alone (right), when reality can look different (left)

The relative timing and cross-cutting relationships between structures of different generations and orientations can impact the structural continuity. Where relative timing relationships are recorded on maps, the different fault sets must be distinguished, and the continuity of the older structures must be reduced by clipping older faults against each younger fault.

The common practice of allowing faults to cross-cut mutually is not a realistic interpretation and generally inappropriate for geotechnical studies.

Modelling Challenge 3: Projects Apparently Lacking Structural Data

In cases where pit exposures and oriented core are not available or accessible, the geologists may be challenged to produce a structural model. Consider the following data sources:

- A structural model should always be integrated with the lithology model as part of the interpretation process, if possible. Even if a lithological model is not a specified deliverable, a careful review of the local stratigraphy and its variations in thickness and elevation may reveal structural patterns that had not been previously recognized, particularly where structural data are lacking. The geologist should search for stratigraphic displacements and, depending on density of drill hole data, interpret those displacements as resulting from faulting, folding or both. Stratigraphy may be offset progressively by syn-sedimentary faults such as basin growth faults or by syn-volcanic faults that control volcaniclastic and volcanic deposition. Syn-depositional fault locations may be inferred from stratigraphic changes in thickness, facies, presence or absencefrom one side ot the fault to the other.

- Regional geological maps and publications may help determine the likely patterns and cross-cutting relationships in the open pit. If of an appropriate scale, drape the maps onto the model to allow direct visual guidance. Ensure that the model and maps have the same coordinate system.
- Regional scale satellite imagery can have great value in determining pattern, continuity and timing relationships. In steep topography, the images can provide an excellent 3-D pattern if they are draped over a topographic surface. Geologists who have the right tools and experience for interpreting high quality geophysical survey data can similarly interpret the structural patterns and in some cases the dip direction of structures. Beware of assuming all lineaments are structures that may impact rock mass stability.
- In-pit LiDAR and high-resolution drone-borne photogrammetry images are collected routinely in many pits to capture the exposed rock faces. These data or images can be interpreted independently, or if suitable, imported as 3-D images and draped onto pit topography for further interpretation.
- Other data that can help interpret faults in 3-D include geotechnical rock mass classification data (RQD and FF), blast hole assays, oxidation profiles and alteration patterns.
- Acoustic and optical televiewer measurements of faults and fractures can help define patterns. Such images can also define brecciation textures and damage zone extents, if at adequate image resolution. Televiewer data plotted on stereonets can highlight dominant structural trends.
- Seismic profiles, electro-magnetic surveys and other geophysical data can be used successfully to image faults, contacts and layers.

3.2.2 Modelling Step 2: Model Construction Process

The specific workflows used for constructing the model will depend on the software used, as well as interpreted geological spatial relationships. Optimization of the workflow requires consideration of (Caumon et al., 2009):

- Model and mesh resolution impact processing and image rendering speed, and the quality and accuracy at which the model honours the data.
- Understanding and interpreting the timing and cross-cutting relationships between structural sets, and with respect to lithology and alteration domains.

When interpreting a fault surface in 3-D, start at the data point that has highest confidence. That point may be a mapping panel or drill hole intersection and may consist of structural measurements or a fault segment mapped on a bench. If logging protocols include clear textural and confidence classifications for fault intersections (Kramer Bernhard et al., 2020), those drill hole intersections logged as high confidence can also be good starting points for interpretation, particularly if the drill hole is oriented.

The interpreter can use software tools like points, disks, or polylines to expand the interpretation along strike and dip in order to include additional high confidence data points (Figure 3-4). It is recommended to rotate the viewing window to search for trends in drill hole intersections that align along a plane, which may be a fault. Typically, the more closely data intersections fit to a single fault plane, the higher the confidence of the interpretation. Significant kinks in the fault plane may hint at fault segmentation. If such kinks line up with kinks in other faults or lithology wireframes, they may indicate a cross-cutting fault.

An interpreted fault can be further expanded by including lower confidence fault data, geotechnical rock quality data (low RQD or high fracture frequency), unusual lithology contacts, or fault-controlled alteration zones. It helps to colour code types of fault intersections by confidence. Additional challenges may arise where faults are curviplanar or segmented rather than planar. In certain cases, additional data may be required in order to interpret a fault with moderate to high confidence. See discussion in Section 3.2.1 – sub-heading Modelling Challenge 2.

Where drill core is not oriented and where structural orientation is not available to guide the model construction, certain structural patterns can be determined from alpha angle measurements to logged faults. If alpha angles were not logged from the original core, fault intersection alpha angles can be estimated from core photographs. It is not necessary to be precise. Because of the natural undulations of fault plane geometries, it is practical and valid to categorize the alpha angle into low (0 to 30 degrees), intermediate (31 to 60 degrees), and high (61 to 90 degrees). Increments of 15 degrees might also work. These alpha angle categories should be displayed in the modelling software in different colours (Figure 3-4).

Fault interpretations based on alpha angles alone can be an arduous process that requires iterative attempts to find optimal solutions. Below is an optimal workflow for interpreting faults from alpha angles:

- Start with polylines to connect logged fault intercepts in adjacent drill holes.
- Next, visually test if the interpreted line satisfies the intersection alpha angle category (low, intermediate, or high) on both drill holes.
- If the intersection angle category is honoured, continue the interpretation along a plausible fault plane until an intersection angle category is not honoured, at which point the interpretation should stop. A decision will then need to be made whether (i) the interpreted fault trace should remain as a fault of limited continuity, or (ii) alternative intersection points should be explored to find a more continuous fault orientation (and therefore possibly a higher confidence fault).
- If fault intersections in the adjacent holes do not match the alpha angle category, it is possible that the fault is not continuous enough to intersect other holes, or that it has a different orientation.

Where possible, use known structural patterns from local or regional studies as a modelling guide, and visually refer to other data sources. Once each fault trace through the data is identified, the fault wireframe construction can be undertaken using different tools, depending on the software used. The fault wireframes must be clipped to correctly illustrate the interpreted cross-cutting (timing) relationship.

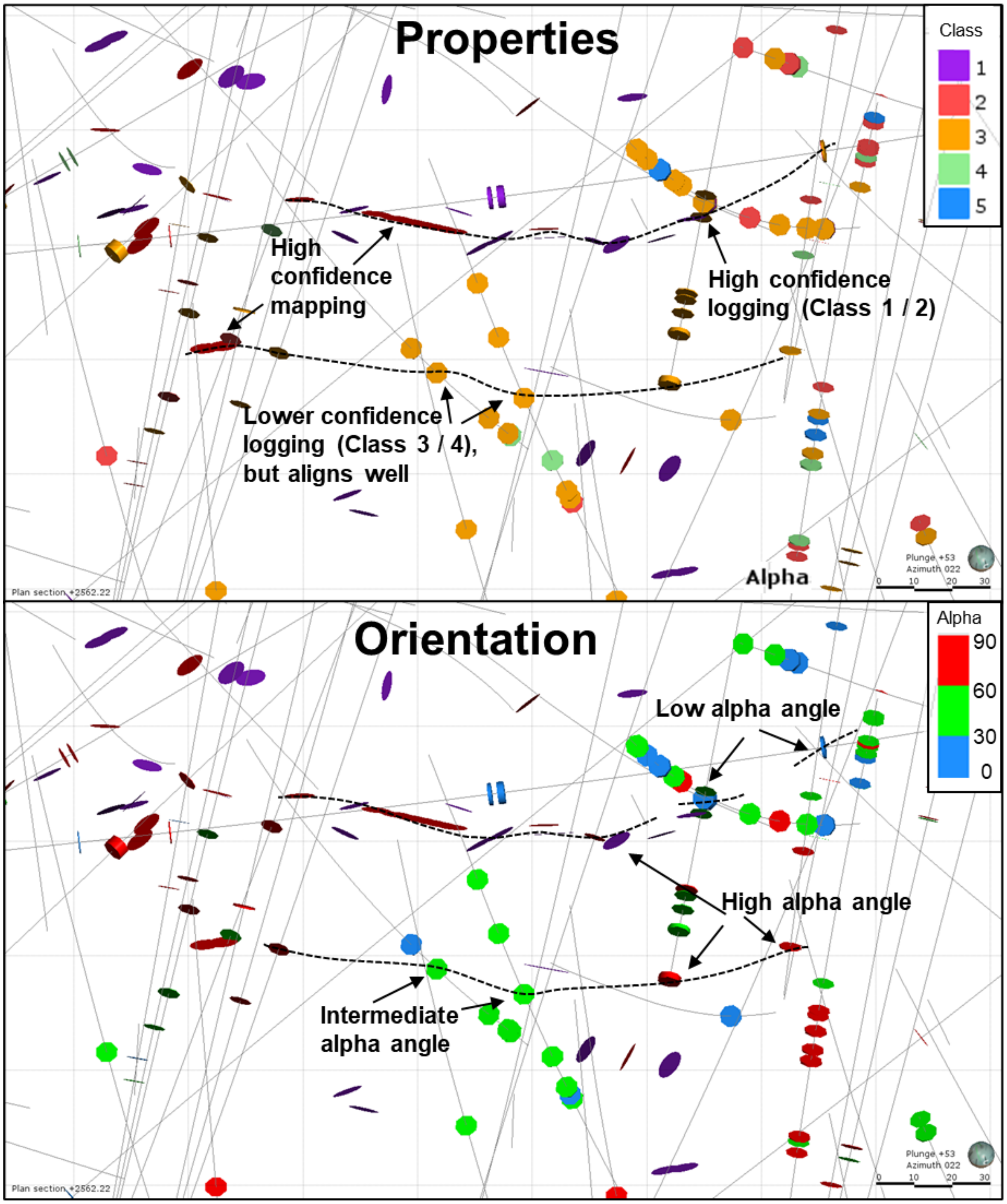


Figure 3-4: Examples of drillhole data driven fault interpretation. Top: Interpretation starts at highest confidence mapping and drilling (Class 1 = highest confidence; Class 5 = lowest confidence) and expands to lower confidence data. Bottom: The interpretation also needs to fit to the alpha angle categories for each fault intersection

3.2.3 Modelling Step 3: Fault Characterization

In order to use the modelled faults in geotechnical studies, fault strengths have to be assigned to the models. This is a very significant challenge because the properties of a fault change along strike and dip, from fault tip-line to centre, and to areas of segmentation and relay zones, and different rock types. It is virtually impossible to describe every part of a fault surface. However, it is possible to determine what features are most representative of the fault zone as a whole, and what components are the weakest or strongest. The geotechnical engineer must be included in the selection of properties that should inform the model.

There are four basic ways to qualify a fault's strength:

- Observe the fault rock textures in rock face or in drill core and record observations of cataclastic rock textures (including clast, matrix, and cement mineralogy, clast size and clay/gouge % content), and of planarity of the fault surface at relevant scale. The engineering classification of cataclastic rocks by Riedmüller et al. (2001) describes cohesionless and cohesive faults.
- Wide fault zones can be described using rock mass classification tools (Fasching and Vanek, 2013). Conversions of rock mass properties to rock mass strength value with shear strength parameters are contentious. Carter and Marinos (2020) suggest the use of the observational and quantitative GSI charts to characterize fault zones.
- Obtain direct shear or triaxial tests of drill core fault intersections or of a cored sample from the rock face. These tests may provide data on frictional and cohesive properties. Representative sampling and very stringent protective packaging are required to ensure that the samples arrive undisturbed at the laboratory.
- Back analysis of fault controlled instability. If excavations through the faults exist, then an appropriate 3-D numerical strain model of the area of interest can be built to include the faults and all rock mass lithologies with characterization. Systematic variation of the fault model input properties can be undertaken until the actual observed rock mass response is approximated, which may give insight on the true fault properties. Failed fault surfaces contribute evidence towards a maximum shear strength value. If there is no actual rock mass response, then that answer also provides a range of possible properties. The results depend on how well the overall model represents reality, which is difficult to quantify.

All properties determined for the fault can be communicated in descriptive text or tables or converted to numeric categories that can interpolated into block models or "painted" on wireframe fault surfaces or volumes. The usefulness of this depends on the complexity of the fault systems and density of data.

3.2.4 Modelling Step 4: Model Handover

The final modelling step consists of ensuring seamless transferability to the end user(s) (see also Section 5.4). No model represents reality precisely. There are assumptions and simplifications based on data and interpreter limitations, model resolution, software limitations and the modelling objective. Unless the interpreter provides adequate communication of the model and its reliability, the model is likely to be mis-used and/or under-utilized. Communication should include data sources, data versus interpretative assumptions/decisions, necessary simplifications from reality, and what the model is specifically meant to represent (Campbell et al., 2014).

Each modelled fault should be supported by a control point database (Table 3-1), which indicates the number of control points used to interpret the fault which gives a quantitative indication of interpretation confidence (Campbell et al., 2014). There are automated ways to create control point summary tables with modern software tools.

Table 3-1: Example control point database for fictional NW6 Fault (from Campbell et al., 2014)

NW6 Fault	Feature Type	Source Type	Source ID	Dip	Dip Dir	Start (m)	End (m)	Thickness
Control Points	Gouge	DDH	BH15-03	43	105	233.54	237.47	3.93
	Gouge	DDH	BH15-08	48	098	288.03	290.05	2.02
	Gouge	DDH	BH15-11	55	090	207.66	208.22	0.56
	Gouge	DDH	BH15-13			310.11	313.76	3.65
	Gouge	DDH	BH15-13			315.32	315.87	0.55
	Shear	DDH	BH15-14	34	101	155.46	158.98	3.52
	Shear	DDH	BH15-14	44	088	160.09	160.55	0.46
	Gouge	DDH	BH15-16	49	096	103.22	105.78	2.56
	Shear	Mapping	STN#3	45	114	12.23	12.98	0.75
	Gouge	Mapping	STN#3	47	108	14.88	15.32	0.44

An enhancement of this approach is to include confidence points (Savage et al., 2013) in the model, which are dropped on the wireframes to represent the subjective model accuracy at the point location (Table 3-2). This approach is applied for faults and any other geological contact. Confidence points can be used for communication by visually colouring confidence across a model.

Table 3-2: Example of a confidence point rating scale (Savage et al., 2013)

Rating	Level of Confidence	Position Accuracy	Example
1	Very High Confidence	2 m	Geological surface point location based on accurate face mapping data with proximal structural measurement and/or drill hole with reliable gamma trace.
2	High Confidence	2 - 5 m	Geological surface location based on strand/feature intersection in surveyed drill hole with televiewer data.
3	Moderate Confidence	5 - 10 m	Geological surface location based on drill hole strand data but no supporting gamma OR from proximal drill holes and/or mapping data.
4	Low Confidence	10 - 20 m	Geological surface location based on interpretation and extrapolation from distal drill hole and/or distal mapping data.
5	Very Low Confidence	20+ m	Geological surface location point based on interpretation only. Low confidence in accuracy of geological surface location due to lack of drill hole and/or surface data.

It is recommended that throughout the model development the interpreter builds and maintains a summary fault list table that conveys the characteristics (orientation, cross-cutting relationships, representative fill and damage zone characteristics), supporting data sources, and Reliability evidence (such as number of intersections from the control point database) for each modelled fault (Campbell et al., 2014, see Structural Matrix Workflow in Figure 3-5). This fault table/matrix is an important component of the model peer review and handover process and allows the end user to prioritize higher confidence faults or request additional data to raise the confidence in low confidence faults. Repeated phases of model development can also be tracked on the matrix to demonstrate increasing model confidence with data collection through advancing project phases, leading to risk profile reduction.

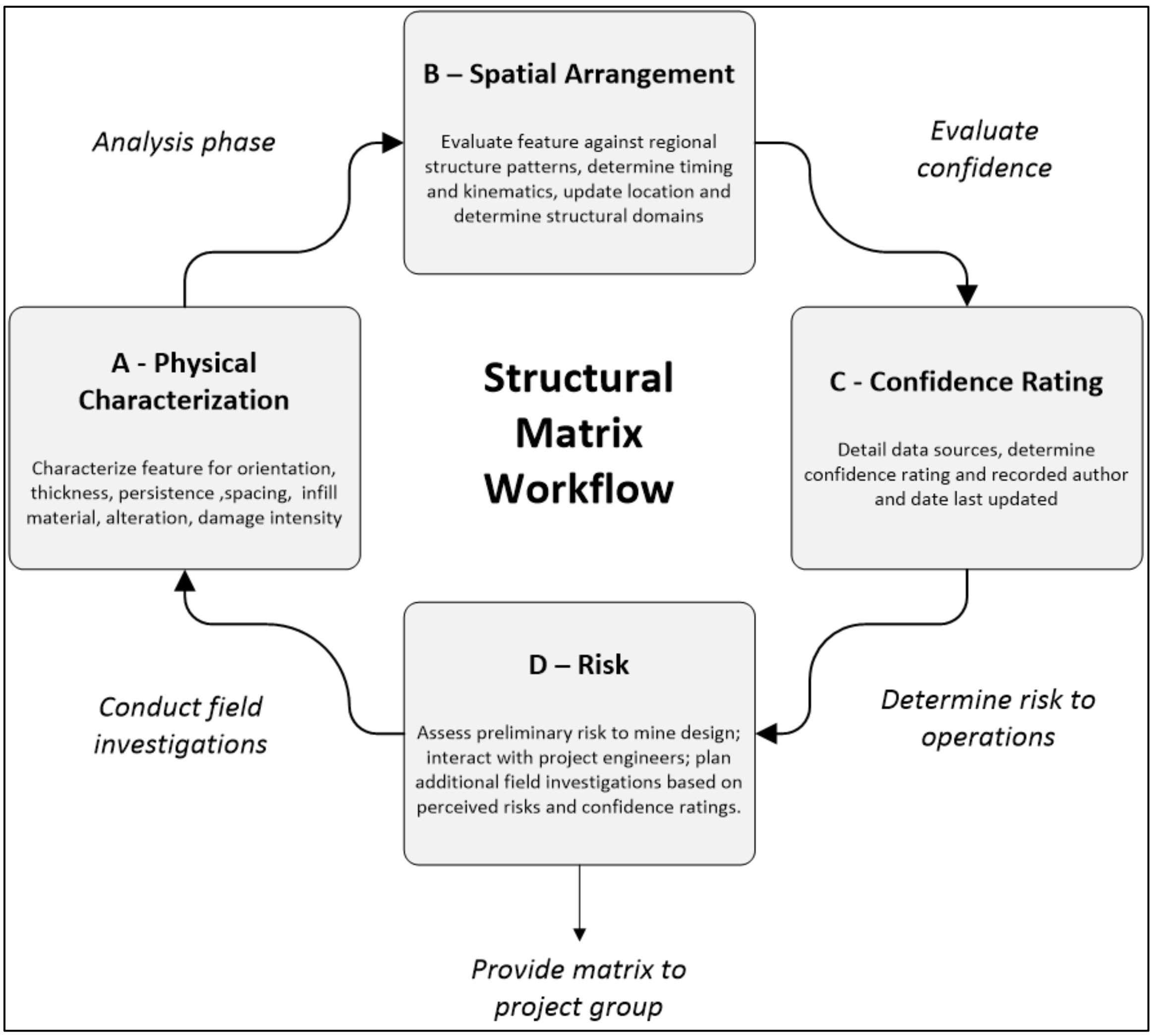


Figure 3-5. Illustration of the Structural Matrix Workflow, used to document structural interpretation, characteristics, data support and overall confidence in the model; and then to communicate with engineers. From Campbell et al. (2014).

3.3 Relevant Structures to Model in Open-Pit Mining Operations

This section provides final context and justification to the types of structures that should be modelled (see also Read and Stacey, 2009; Carter and Marinos, 2020). Geotechnical studies of open-pit mines aim at determining critical structural orientations and the rock mass strength characteristics so that decisions can be made on the geometry of main components of open pit slopes. These components include benches and berms, stacks, and overall slopes. Increasing the slope angle typically has financial benefits to the overall mining project. The geometries of the structures influence the stability of rock mass in the slopes, depending on the orientation, continuity and strength properties of the structures (Figure 3-6; Stead and Wolter, 2015).

Fault “order” (as defined in Section 2.3) may be considered when evaluating the size and relevance of the faults in one specific fault system, in context of the pit stability:

- Pit-scale faults have similar continuity to the height of the pit and are associated with overall pit stability risks (e.g. Severin, 2018). Such faults may be first-order faults in a subregional fault system.

- Stack-scale faults are typically of continuity that can influence stack or inter-ramp stability. These may be the second-order faults in a subregional fault system.

- Bench-scale faults may impact the stability of benches typically 10 to 20 metres in height. These faults may be the third-order faults in a subregional fault system.

Pit- and stack-scale faults typically control pit design and can introduce significant mining risk. It is therefore imperative to understand the nature of each observed fault system, and the order and scale of the faults in each fault system.

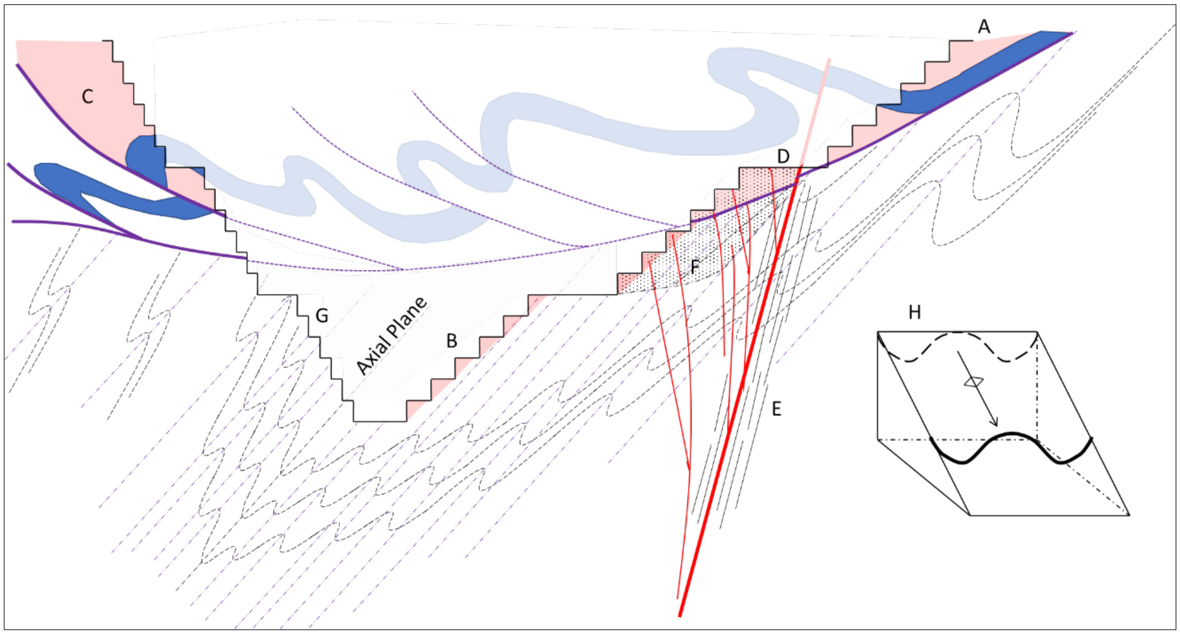


Figure 3-6: Schematic illustration of typical structural geology influences on open pit stability in an orogenic deformed rock mass. From Murphy and Barnett (2018). Red shading indicates possible sliding or wedge failure. Local rock failure may be influenced by, (A) weak or sheared lithological contact, (B) low strength foliation, (C) failure on basal fault surface, (D) failure on basal surface with fault tensile release plane, (E) damage zone around a fault, (F) toppling failure associated with steeply dipping fault system (in red), (G) stable slope with favourable oriented folds and foliation, (H) 3-D perspective of a fold with unfavorable fold plunge if the slope is dipping the same direction.

Large fault zones also tend to have damage zones around them in which the occurrence of second-order faults and fracture frequency is increased (Figure 3-7; Caine et al., 1996; Munier et al., 2003). These damage zones form important geotechnical domains and should also be modelled as wireframe volumes ("solids") with appropriate thickness. The fault cores may also have a significant thickness of breccia and gouge (and classified after Riedmüller et al., 2001), and therefore may also need to be modelled as volumes with appropriate thickness. Decisions on whether to model wireframe volumes or surfaces should be discussed with the geotechnical engineer who is the end user of the model. Structurally complex zones, or domains, may have reduced rock mass quality, which in turn can be detrimental to excavation stability.

The thickness of second order structures might be too small to be represented as wireframe volumes, and if that is the case, the use of surface wireframes may suffice. Decisions around continuity of faults is important, as fault segmentation influences fault continuity and rock bridge size and frequency, which significantly impacts stability analyses (Elmo and Stead, 2020).

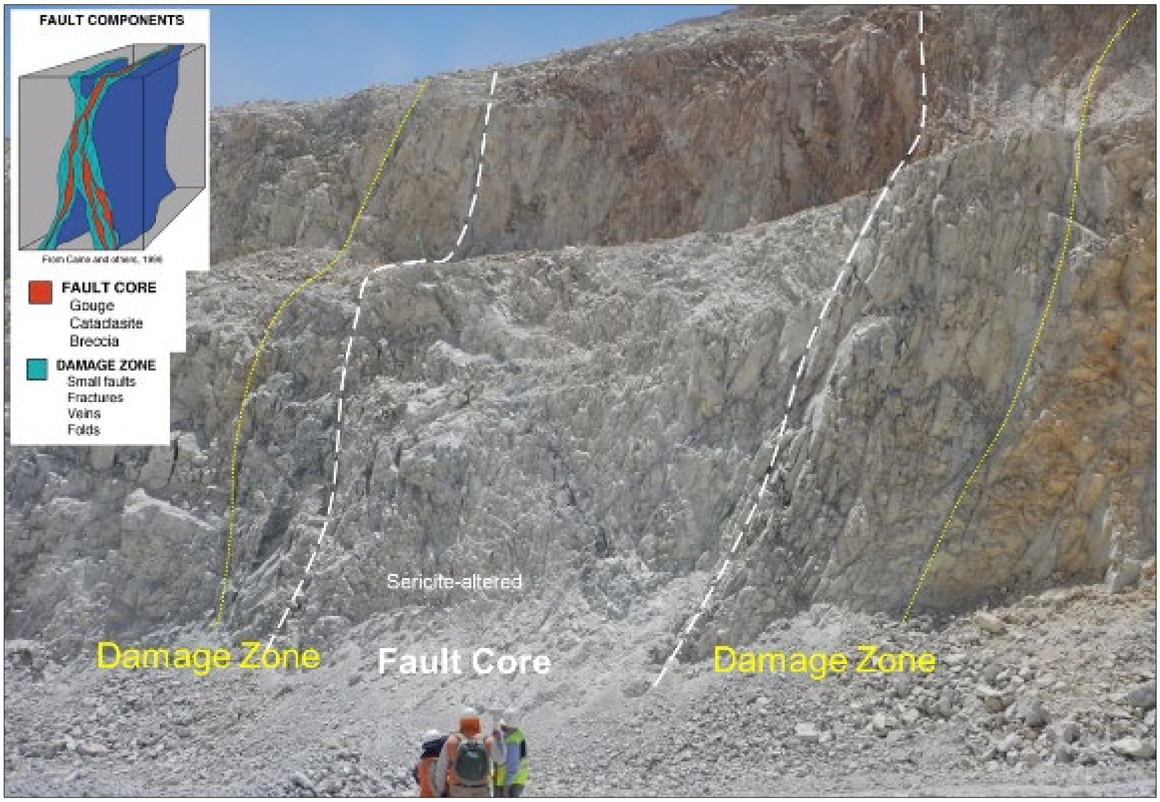


Figure 3-7: Characteristics and components of a typical large pit-scale fault zone, with clearly defined fault core and damage zone margins that may be transitional with the adjacent jointed country rock mass. Modified from Barnett and Carter (2020) and including inserted illustration from Caine et al. (1996).

Modelling third-order structures using the manual digitizing techniques is most often unlikely to produce useful products for mine-scale analyses, as it is time consuming and typically not possible to have enough data to represent realistically the density of these faults. Numerical modelling tools (e.g. discrete fracture networks and finite element models) can do this task more efficiently and effectively, if the patterns and continuities are known. In some cases, it may be necessary to model specific third-order structures for focussed studies on certain benches.

Figure 3-2 illustrates a practical problem for open pit mines. When modelling the stability of a single bench, a detailed model of Figure 3-2 structures may be appropriate. But what if that fault zone continues over hundreds of metres with repeated segmentation? It is very time-consuming (and likely impractical) to model in the detail of the figure. However, the fault zone can be simplified to a single surface or alternatively a solid domain (of appropriate width) that continues along the length of the structural system. This decision should be made with input from the engineer who will be the end user of the model. Choosing to model a single surface may require the slope design engineer to assign increased frictional and cohesive properties to structure, because it is partly intact (rock bridges). This would be challenging or impossible to do accurately. If the segmentation and associated fracturing is wide enough, then representing the fault zone as a domain may be more practical, and rock mass characterization could be used to define the properties (Barnett and Carter, 2020; Carter and Marinos, 2020).

Figure 3-6 also illustrates the relevance of modelling folds and foliation (more commonly called cleavage in fold systems). Depending on scale and geometry, folds can provide complexity and roughness to geological layering that supports slope stability, or alternatively changes in orientation that are unfavourable to stability. Foliation, which is often axial planar to folds, is an anisotropic rock fabric that can reduce the strength of the rock mass along the plane of the foliation. Foliation or multiple sets of foliation can have significant impact on rock mass stability in a pit, such as on bench and slope stability (Saunders et al., 2020). This concept is discussed further in Section 3.4.

Another practical reason for 3-D modelling faults is to define the network of structures that may be controlling groundwater flow. Groundwater pressures are important contributors to slope stability (Beale, 2018; Read and Stacey, 2009). Caine et al. (1996) illustrates how the properties of a fault can influence groundwater flow. Faults with low clay-gouge content form conduits for water, which may be broad zones including the damage zones. Faults with high clay-gouge content form barriers to groundwater flow but may enable fault-parallel flow if an associated damage zone exists.

The challenge for modelling structural geology as a practical input into geotechnical studies is in finding the balance between how much detailed realism is possible, if this benefits the engineer's studies, or rather simplifying the model so that the engineer can more easily use the interpretation in their model. This should be a two-way conversation and decision. Geotechnical model back analyses may help define the main mechanisms of instability and this understanding can be used to focus future data collection and subsequent modelling efforts.

3.4 Rock Fabric Models

A rock fabric represents a penetrative or spaced system of locally sub-planar and sub-parallel geological features that define a directional plane of weakness in the rock mass in comparison to the intact rock. The rock fabric may not be perfectly planar but may undulate in orientation over the scale of a bench or larger, such that the fabric variably impacts rock mass stability. There are three types of geological features that may be considered rock fabric in geotechnical analyses.

- Lithological layering or bedding may be defined by compositional and texture changes or fissile surfaces, such as siltstone or greywacke successions. Compositional layers with weak mineralogy that preferentially break or shear in pit slopes represent a rock fabric.
- A foliation is formed as a product of deformation (Figure 3-6), particularly in micaceous rocks within which the minerals realign perpendicular to the principal direction of compression. A foliation may be penetrative throughout the rock or it may be concentrated in spaced bands or in shear zones (Figure 3-10). Foliation may also be irregular or planar in geometry, and continuity may be variable. Foliation strength is dependant on the rock type and foliation mineralogy and is commonly opened by adjacent blasting activity.
- Pervasive and similarly orientated structural features, such as a set of joints or minor faults/shears, may also be considered to define a rock mass fabric or "structural fabric". This would be the case if there is a consistent and persistent orientation of one set of such

structures that dominates the character of a rock volume or domain, and is the dominant influence on the rock mass behavior of the entire domain.

Rock fabric-parallel instabilities are often expressed at the multi-bench or inter-ramp scale due to the high persistence of the fabric (Saunders et al., 2020). Pit slope designs need to account for the variability in rock fabric character with consideration to the mining geometries being developed. The stability of the rock mass may be influenced by fabric spacing, mineralogy, continuity, roughness, dip and dip direction, and waviness (Saunders et al., 2020).

Modern 3-D geological modeling software (e.g. Gocad™, Leapfrog Geo™) are increasingly being used to model rock fabric as numerical models (Creus et al., 2019) and as direct wireframe input into geotechnical slope designs (Saunders et al., 2020). To create a rock fabric model in 3-D, input data is required to control the construction of rock fabric surfaces. Form lines representing the fabric can be digitized on photogrammetry images and/or based on structural measurements. If the structural data density is high enough, the fabric interpretation can be created directly from the mapping and/or drillhole data (e.g. oriented core or televiewer) using mathematical wireframe interpolants (Figure 3-8; Creus et al., 2019; Saunders et al., 2020), or otherwise interpreted from any available data combined with structural knowledge. Interpretation of variations in rock fabric geometry may need to consider complex structural patterns, based on data defining fold geometry, vergence and interference, and stratigraphic younging direction.

There are important challenges and limitations with modelling rock fabric, mostly related to data distribution and resolution (Saunders et al., 2020). Figure 3-8A illustrates form surfaces representing a rock fabric across an open pit design. Figure 3-8B illustrates how the interpolant is controlled by data. It is important to validate such models since errors in the data, and spatial biases can significantly impact the product and invalidate the geotechnical analyses. Interpolant models based on drill hole data and limited mapping should only be used for initial slope design studies. For implementation, these models should be validated with early pit wall exposures and should be continuously updated with subsequent mapping of benches or use of televiewer data and/or remote sensing.

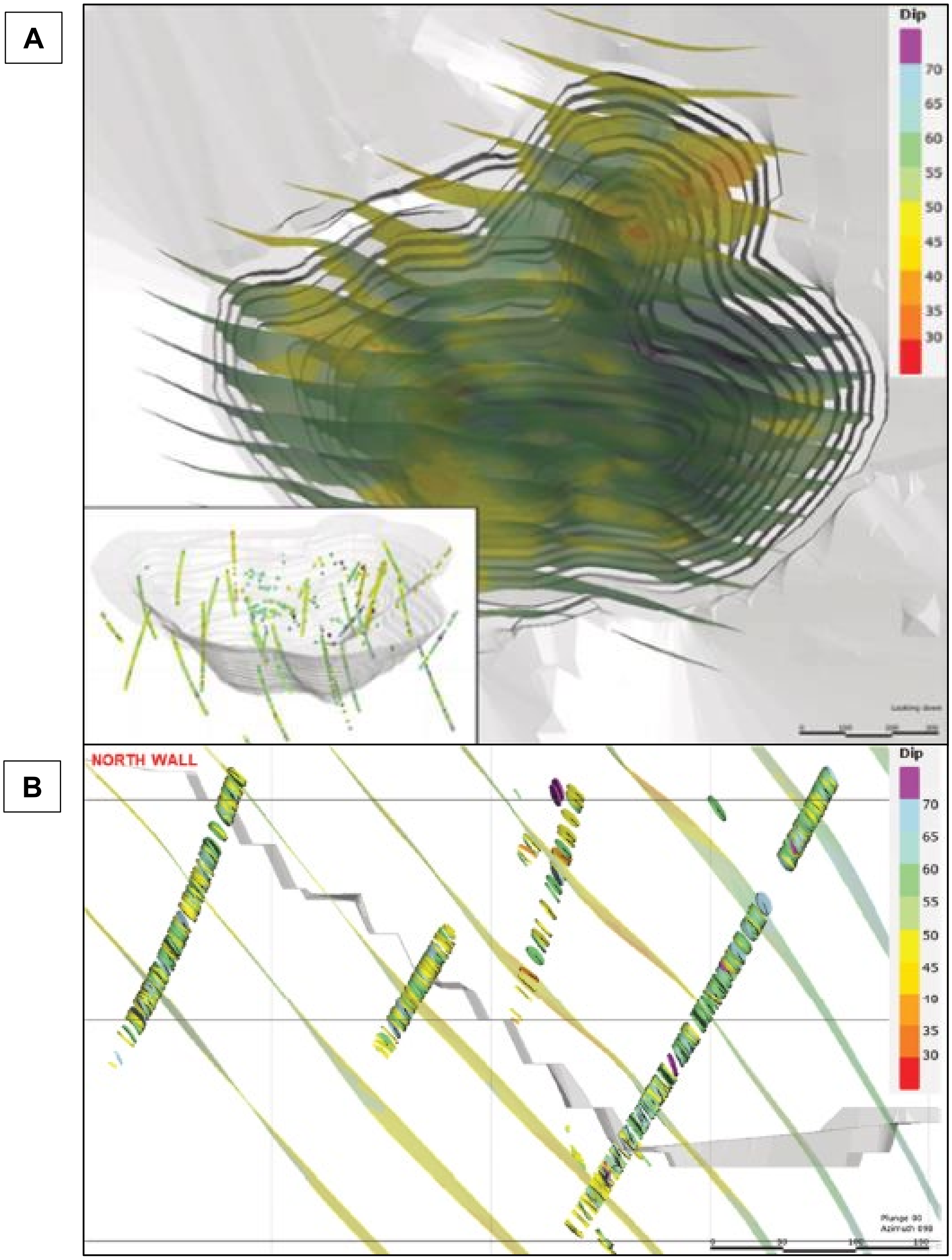


Figure 3-8: 3-D foliation model for Rainy River Mine. A: 3-D view of form surfaces versus input data (inset). B: 3D foliation model compared to the planned north wall and the foliation-parallel joint measurements. Source: Saunders et al. (2020)

3.5 Structural Domains

3.5.1 Why Domains

The geological model objective is to represent an estimate of the physical properties of the subsurface since there is no way to measure the true detail exhaustively (Wellmon and Caumon, 2018). The spatial distribution of properties is not random, however, so geologists can create models that capture the essential aspects of the geological evolution and current spatial configurations in manner appropriate for a specific purpose (Ringrose and Bentley, 2015). Similarly, geotechnical analytical results are not sufficient to represent the true spatial variability of rock mass conditions that needs to be factored in engineering calculations. Therefore, simplifications of actual rock mass and boundary conditions to define domains are always necessary. The scale of domains required are dependant on the granularity of detail needed for the analysis. These simplified domain models must be accurate enough to allow for test assumptions and assessing the representativeness of design parameters, and a range of possible scales should be agreed with the geotechnical engineer requiring the domain model (Barnett and Carter, 2020).

A domain is therefore a volume of rock mass that has similar overall characteristics, bounded by domains of different rock mass characteristics (Figure 3-9; Martin and Tannant, 2004, Carter and Barnett, 2021). Those characteristics may be related to the lithology (and alteration), the structures, and/or the rock mass properties (e.g. GSI, RMR, Q; Barnett and Carter, 2020; Carter and Marinos; 2020). The domain could be characterized by one important property that overrules other properties in its relevance (e.g. a dominant rock fabric, or alteration). The geologist undertaking the mapping or logging should be aware of the geotechnical engineers' ultimate objectives and should be thinking about appropriate geological domains while mapping, such as the clustering of joints or faults of similar orientation (Figure 2-1).

Key aspects of geotechnical and geological domaining requirements are highlighted by Stegman (2001) and Read and Stacey (2009). Domains should be defined by a geologist's understanding of the geology and structure, not just drawn based on computer modelling (Carter and Barnett, 2021). The definition of a domain must consider correct structural fabric and structural boundary controls. The boundaries should represent locations of realistic change, but not too broad to create too much averaging of parameters, and not too tight to ignore natural localized variability. A domain should also be of appropriate scale relative to the overall project scale and relative to the resolution appropriate for the required engineering design, such as pit overall slope, or stack or bench.

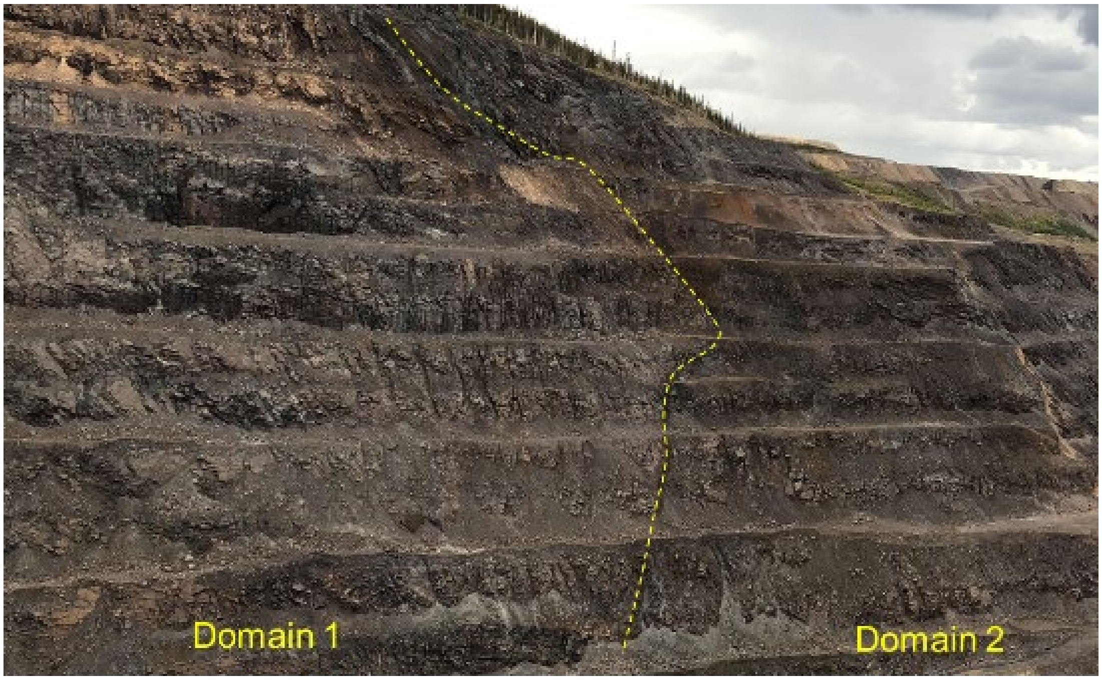


Figure 3-9: Example of a sharp domain boundary, likely caused by a boundary fault to a fault zone characterized by low rock mass quality in Domain 2. The annotated domains show clearly different rock mass conditions that impacts the slope behaviour.

3.5.2 Types of Controls on Structural Domains

Sharp Domain Bounding Structures

Sharp bounding features such as a fault or fault zone can be defined easily (Figure 3-9). Bounding faults often displace the rock units, such that the rock type and rock mass properties may be completely different across the domain boundary (Barnett and Carter, 2020). Faults can also cause rotation of inter-fault blocks relative to the adjacent rock mass, and in such cases the pre-fault rock mass fabric is typically also rotated creating two blocks (or domains) with different oriented fabric.

Fault zones may consist of different internal domains. If a fault is surrounded by a pronounced zone of distributed rock strain, distinctly less fractured than the centre of the fault and more fractured than the surrounding rock (Figure 3-7), then a fault damage zone can be defined (Caine et al., 1996). The damage zone is different from the fault core zone itself since the strain or rock deformation is distinctly reduced, and by virtue of the core containing fault breccia and gouge.

Bounding ductile shear zones can similarly define sharp changes in rock mass fabric across domains. Major shears, such as that in Figure 3-10 are ductile fault zones exhibiting a strain gradient from one side of the shear zone to the other. Displacements across a shear zone can be significant and therefore first-order shear zones commonly define domain boundaries. Shear zones also contain foliation patterns that can be a strong anisotropic rock fabric (Figure 3-10). Shear zones should therefore also be considered as domains if sufficiently wide enough relative to the study area and the understood domain scale requirements.

Figure 3-10: Foliated ductile shear zone (image is approximately 10 m high) oriented subparallel to the pit wall. From Barnett and Carter (2020).

Lithological contacts and unconformities can also define sharp domain boundaries if there is sufficient contrast in characteristics across the contact. In such cases, the structural fabric, joints, foliation and rock mass properties may also vary enough to define a new domain.

A rockmass may be strongly foliated because of regional or more localized deformation. Changes in foliation intensity, mineralogy or orientation are often important domain changes in open pits (Figure 3-6). Techniques for 3D modelling foliation are discussed in Section 3.4 (after Saunders et al., 2020). Techniques for analysis of rock fabric such as foliation are increasingly used for design of open design sectors and analysis of risk (Bester et al., 2019).

The fold axial surface is another important domain boundary in folded terranes (Figure 3-6; Nicholas and Sims, 2001). The rock mass fabric, including pre-folding structures and foliation, is rotated about the axial plane hinge line. In theory, the amount of relative rotation of features from one limb to the opposite could vary from 0 of 180 degrees. The amplitude and wavelength of folds will influence how domains are defined. One pit scale fold may create two domains, one for each fold limb. Folds with multi-bench to stack-scale wavelengths may produce multiple domains. Small wavelength folds may influence bench-scale stability (Figure 3-7) and might be grouped within one domain, or multiple domains depending on plunge and amplitude. There may also be parasitic folds on the limbs of the larger folds. The geologist should describe their amplitude and wavelength relative to the pit (Figure 3-7).

Folded geological terranes can include multiple folds of the same age and variable scales (including parasitic folds), as well as folds of different generations and scale, the combination of which may create interference patterns. Fold interference patterns create a unique complexity for defining domains (Thiessen and Means, 1980). The interference patterns need to be recognized in order to be predictable. A domain must represent the structural geology of an area of the pit. Therefore, the amplitude and frequency of the interference pattern is required to define domains.

Domains Zones of Consistent Internal Structure

A second, gradational type of domain boundary structure tends to be harder to define (Barnett and Carter, 2020). Broad zones of strain change within a rock mass may be important enough to constitute a domain boundary. The boundaries may not be clear but on the large scale a clear difference in rock mass conditions can be observed on either side of the diffuse boundary zone. Gradational boundaries need to be drawn at locations of maximum strain change, such as in a location where a fault might have developed if further strain accumulation had occurred (Barnett and Carter, 2020). Strain may be distributed over a wider volume of rock and changes the rock mass properties by developing micro-fractures, joints and/or systems of segmented minor faults with limited displacements.

Transitional boundary zones must be examined carefully. Gradational distributions of strain and associated micro- and macro-structures often results in rock mass properties that are sufficiently different from the adjacent margins to define a domain in its own right (Barnett and Carter, 2020). Regional fault zones can have damage zones that extend over 100 m in width and are commonly represented by diffuse boundary zones as strain and associated fracturing diminishes with distance from the fault core (Faulkner et al., 2010).

Significant alteration zones can be recognized in many large open pits. In many cases alteration zones and zones of fault-controlled alteration may need to be defined as separate domains. Visible alteration varies greatly in intensity and it can be challenging to alteration boundaries. The effects of weathering and alteration related degradation tends to diminish with increasing depth along faults, and contacts may be gradational. Weathering is typically a near-surface feature and can significantly affect rock mass characteristics within a given structural domain.

3.5.3 Domains Aid Extrapolation

Domain delineation also serves the important function of allowing the projection of structural patterns from a location that is characterized on the basis of a robust data set, to a rock volume that has limited or no informing data (Barnett and Carter, 2020). Domain extrapolation is illustrated in the shaded domains of Figure 3-11.

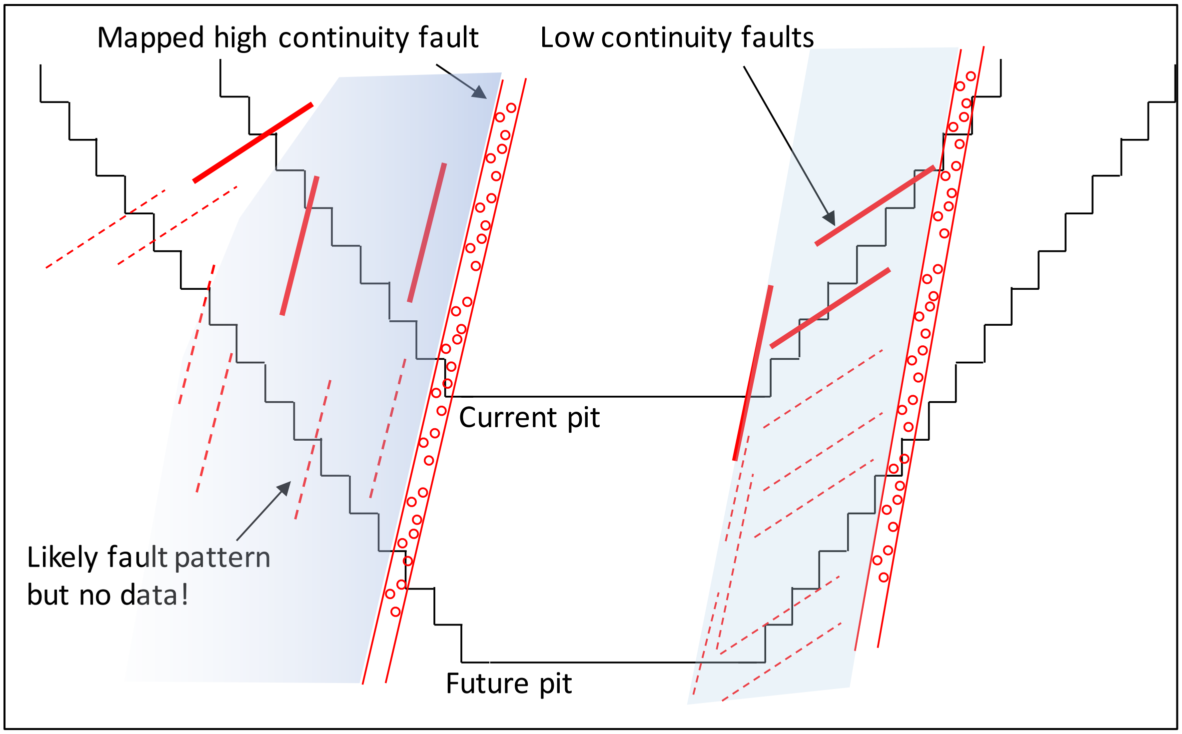


Figure 3-11: Schematic illustration of structural domaining in an open pit. From Barnett and Carter (2020). The largest 1st order structures can be interpreted to have continuity to the depths with greater confidence than smaller structures. Non-continuous 2nd and 3rd order faults cannot be projected to the future pit depth. These smaller-scale structures may be described as part of the rock mass characteristics (inferred dashed faults), such as frequency, continuity, orientation and physical properties.

High order faults such as those shown in heavy linework in Figure 3-11 commonly define domain boundaries that can be projected with confidence for hundreds of metres. Deeper drillhole intersections of those faults maintain high confidence in the interpreted continuity where large intersection widths have been encountered.

Most domains include 2nd or 3rd order structures that have limited continuity yet need to be included in any geotechnical analyses of the new data-deficient domain. The interpretation that a domain extends into an area with limited informing data can be accomplished by assigning the known characteristic fabric to the data-deficient parts of the domain (Barnett and Carter, 2020). A stereonet analysis should be conducted to check for consistency between the data-rich and data-poor sections of a domain and assess if the data in the data-deficient section should be included in the analysis. For design purposes, the known characteristics (frequency, continuity, orientation, physical properties) of major and minor faults and structures can be extrapolated to the entire domain.

4 Geological Modelling

4.1 Overview

The mineralogical and physical properties of the rock are fundamental controls on the mechanical behavior of the rock mass, and often influence the nature of the faults and folds systems such that the structural patterns and properties change. This section will discuss the process of defining lithological domains and alteration domains, in context of the geotechnical model. Structural geology is part of a geological model, but not discussed further in this section. Importantly, the structural interpretation is dependant on the geological model, so should be developed concurrently with the geological model.

It should be recognized that the geotechnical design needs one representation of reality, which is essentially a combination of the lithological, structural and alteration models (Figure 4-1) that may be dependant on each other. The alteration model may therefore be developed as an spatially overlapping model superimposed on the geological model. Structural model zones may similarly be created overlapping the lithological model. Final geotechnical properties used for analysis, relating to rock strength, fracture frequency and joint condition, are derived from the appropriate litho-structural-alteration domains representing the rock mass component of interest (Figure 4-1). The geotechnical domain boundaries are therefore selected by informed geologists and geotechnical engineers, and typically transferred into a block model for further numerical analysis. A rock fabric model may similarly be integrated into the model and used to represent anisotropy in slope stability analyses. Hydrology and stress regime models are typically also used in the stability analyses.

4.2 Lithological Modelling

4.2.1 Pre-Modelling Lithology Domains

As described in Section 3.5.1, the geological model objective is to provide a simplified representation of the physical properties of the subsurface since there is no way to measure the true detail exhaustively (Wellmon and Caumon, 2018). The key lithological units need to be defined prior to modeling, those being the units that are important to the geotechnical domaining of the open pit. A lithological domain can be defined as a volume of rock mass that has similar overall lithology characteristics, bounded by lithology domains of different characteristics.

A lithological model is therefore by definition a domain model representing lithological units of similar mineralogical and/or textural composition, at a scale and accuracy appropriate for the objectives of the model. A lithological domain may also be a zone with a specific range in hardness or anisotropy variations (e.g. sedimentary sequence with a certain bedding orientation in a pit wall; Barnett and Carter, 2020). It is also important that lithological contacts may represent anisotropies in the pit, for example, dyke contacts or unconformities.

3-D lithological modeling utilizes similar datasets to 3-D structural modeling, with the primary input datasets being:

- Pit wall and bench geological mapping;

- Drill core lithological logging; and
- Downhole geochemical and/or geophysical data

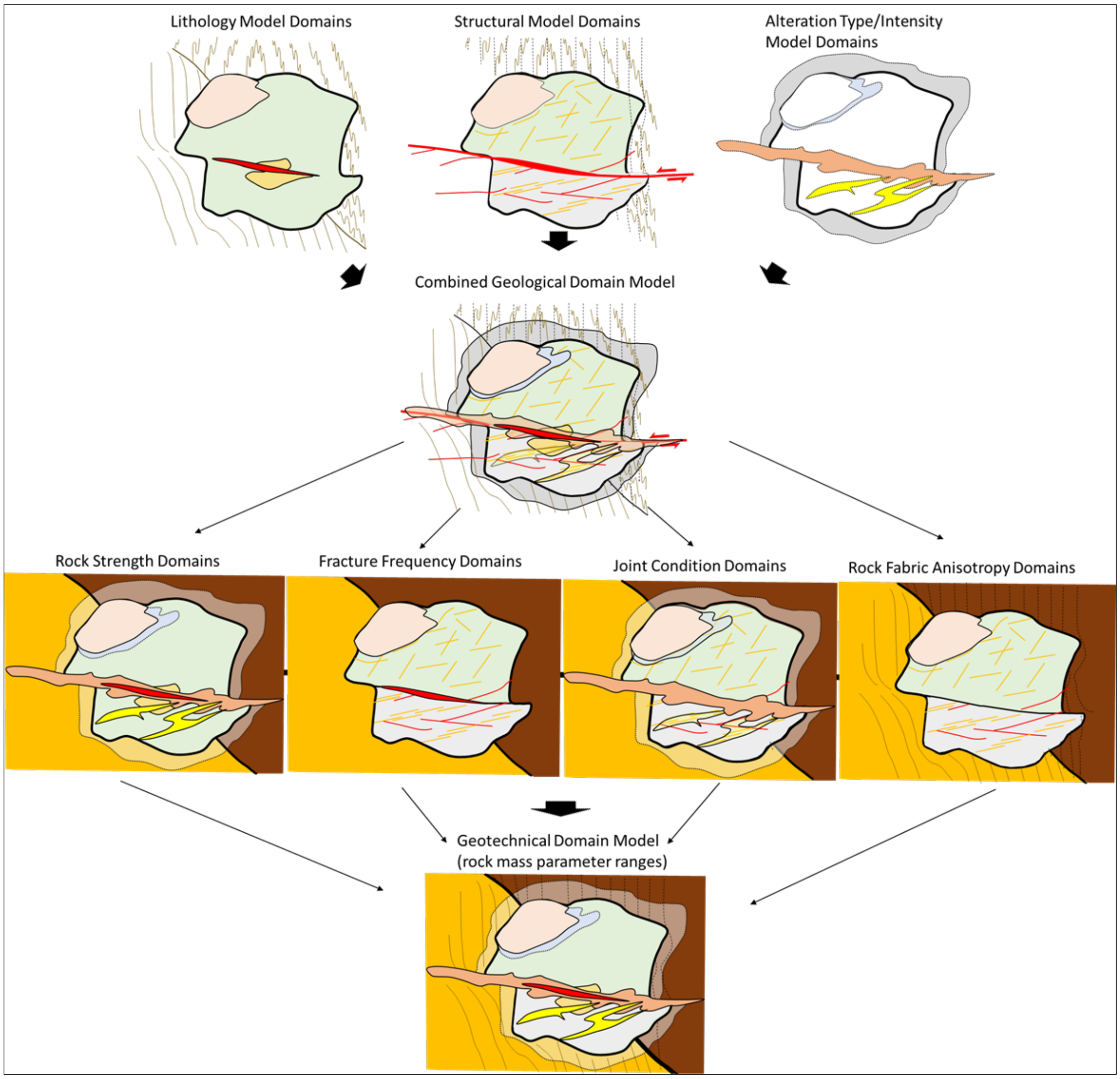


Figure 4-1: Process of domain model development and integration, starting with the geological components of lithology, structure and alteration. The geological domains may then be selectively used for grouping rock mass parameters that can be analyzed in the geotechnical domain model for slope design purposes.

Mapping and logging remains a fundamental tool for representing the spatial distribution of lithological units and their interaction with structures. Geological and lithological mapping should always be accompanied by a geological cross-section, to ensure the map is balanced.

Lithological core logging tends to split rock types into more detailed subdivisions than mapping, due to the difference in scale of the observations. Detailed core logging may be useful for detailed 3D modeling; however, typically rock types are grouped into domains that are relevant to the end-user engineer. Core logging data should always be checked for reliability, especially for long-lived operations where the lithological understanding or core logging practices may have changed over time. This is best conducted by reviewing the data in 3-D. Consistency between loggers, training and quality control is an ongoing, critical initiative.

The distribution of lithologies should be reviewed in 3-D, typically for the entire mine. Examining the distribution of each major lithology relative to the open pit in terms of:

1. Do they have a certain geometry/distribution?
2. Are they folded or offset by certain structures?
3. How do they relate to known stability issues in the pit/geotechnical parameters/domains?

The validity of lithological core logging can be compared to downhole geochemical or geophysical data, variations in which may be related to lithological changes. Whole-rock geochemical data can be used to define certain elemental ratios for volcanic, intrusive, sedimentary, or metamorphic rock types. The application of geochemical techniques is well-defined in Halley, (2014) and Halley et al. (2016). Geophysical logs, (e.g., gamma-logs, magnetic susceptibility, conductivity) can be useful for defining geophysical variations that may be related to lithological changes. These may be variations in density, magnetism, or conductivity for example.

4.2.2 Lithology Domain Modeling Process

Best practice 3-D lithological domain modeling utilizes software based stratigraphic modeling methods, which incorporate geological rules that define how lithological units interact with each other (e.g., age relationships, crosscutting relationships, intrusive contacts, unconformities). For this, the age relationships must be defined and this can be based on:

- Geological understanding of the area/open pit;
- Relationships observed during geological mapping; and
- 3-D distribution of lithologies

The first examples of stratigraphic/lithological modeling were seen in the software packages GoCad™ and Geomodeller™. Currently the most widely used software package for lithological modeling is Leapfrog Geo™. All stratigraphic modeling workflows can generate a model directly from core logging and surface mapping, so validated, error-free data sets and consistent logging codes are essential. All stratigraphic modeling workflows work by extracting contacts from the logging data and/or mapping, and then using these contact points to build a series of contact wireframes. The interactions between these wireframes are dictated by a user-defined chronology and various user defined and built-in geological constraints. These contacts can then be used to define lithological volumes (i.e. domains).

The resulting 3-D lithological model always should be integrated with the 3-D structural model. Modern 3-D software packages allow the integration of cross-cutting relationships between the structural and lithological models. For example, defining if a sedimentary sequence is offset by faulting but a younger dyke is not.

The integration of the 3-D lithological and structural models is essential as this combination will highlight errors in the continuity of lithological units across fault blocks. This process of “structural-balancing”, that being the interpreted restoration of the lithological units pre-faulting, is essential to all 3-D geological models.

This integration should also incorporate the influence of structures on the lithological domains. For example, a tight-spaced joint set may only occur in proximity to a given fault within a given lithology. Fold structures influence the geometry of the lithological domain boundary, whereas faults commonly offset the lithology domain and form part of the domain boundary.

4.3 Alteration Modelling

Geotechnical engineers and structural geologists have witnessed the compound impact of alteration and structure on wall stability, yet seldom they understand how to leverage existing alteration data sets to construct a 3-D alteration model that informs and enhances the reliability of geotechnical and structural domains.

The focus of this section is on presenting effective steps to identify and integrate alteration data sets and 3-D interpretations into the geotechnical domain models. It is beyond the scope of this paper to provide basic training or best practices in alteration mapping and logging. Only the alteration geology concepts that are directly pertinent to structural and geotechnical models are discussed here.

4.3.1 What Causes Alteration?

Alteration products affecting open pit mines fall into three genetic categories:

- Hypogene: Alteration that is produced by ascending hot fluids that are directly associated with ore genesis. Hypogene alteration assemblages can form broad halos as well as controlled corridors and chimneys controlled by faults and fault intersections, respectively.
- Supergene: Alteration produced by weathering in climates or paleo-climates where there is a pronounced alternation between hot and dry and humid seasons. Supergene alteration typically forms mantos which are controlled primarily by the paleo-topography, and may protrude at depth to form steeper, fault-controlled dyke- to cone-shaped zones.
- Anthropogenic: Mining induced alteration and degradation triggered by the increase in the surface area of rock that exposed to the present-day atmosphere; Anthropogenic alteration can develop within days to months of mining activity.

Supergene and anthropogenic alteration zones reduce rock strength by converting feldspars and other minerals into swelling clays. Supergene alteration includes deeply weathered rock profiles such as residual soil, saprolite, and transitional materials. Saprolite has well defined supergene mineral zones that impact rock quality, and which can be easily distinguished by infrared spectroscopy, and modelled in 3-D. It forms three main mineral zones:

1. An uppermost zone characterized by recrystallized halloysite;
2. An intermediate light-coloured layer of predominantly halloysite and gibbsite; and

3. A basal dark coloured manto of predominantly smectitic clays and poorest rock quality forming the transition to unweathered bedrock as well as steeper deeper protrusions that are controlled by fault permeability.

Sauders (2018) provides a concise overview of the challenges of characterizing transition rock materials and the impacts of transition rock on bench slope performance.

Hypogene alteration can increase rock strength in certain parts of a mine, e.g. through silicification and reduce it in other parts, e.g. resulting from argillic alteration.

4.3.2 Visible and Invisible Alteration

The alteration observed in a pit is a combination of microscopic to submicroscopic minerals, most of which cannot be identified by the naked eye.

Visible Alteration

A limited number of alteration minerals can be identified by a pit geologist or core logger using a loupe, silicon carbide scratcher, and/or hydrochloric acid as the main mineral identification tools. Common visibly identifiable alteration minerals include silica, clay/sericite, carbonates, ferromagnesian minerals chlorite (also a clay), epidote, actinolite/tremolite, and oxyhydroxides. In most cases, attempts to characterize the exact clay/sericite or oxyhydroxide mineral species with the aid of a loupe, scratcher, and acid are futile, and are more likely to generate noise than useful information for the alteration database.

In many cases it is possible to identify certain alteration colours and textures that may be diagnostic of an assemblage of visible and invisible alteration minerals. It is common to undertake visual and physical inspection of drillcore to identify depths of change in alteration signaled by changes in the physical geotechnical properties of the rock, such as fracture frequency and presence of clays. This can sometimes be done from core photographs.

It is preferable to map and log the few individual minerals that can be identified, than to use interpretative and ambiguous terms such as *propylitic* or *intermediate argillic*, as it is seldom evident what rock properties served as the basis for the assemblage interpretation. The geologist should bear in mind that it is possible to interpret the alteration assemblages on the basis of the individual minerals, but it is not possible to decompose the interpreted assemblages into alteration minerals in order to search for subtler trends.

Invisible Alteration

Invisible alteration consists of alteration minerals that are too fine grained or too subtle to be identified visually, and require routine in-situ semi-quantitative to quantitative analyses such as infrared spectroscopy (IRS) and portable X-ray diffraction (pXRF), or by a variety of laboratory techniques such as multielement geochemistry, transmitted light petrography, and X-Ray methods such as Rietveld (quantitative) and conventional X-Ray Diffraction (XRD), MLA, QemScan, which are offered by most commercial laboratories.

Often invisible alteration data has already been collected in mines and can be obtained from exploration geologists, metallurgists and geometallurgists.

4.3.3 Alteration Domain Modelling Steps

Step 1 – Defining the Purpose and Scale of the Alteration Domain Model

Like a lithological model, an alteration model is also by definition a domain model representing a zone of alteration of similar mineralogical composition, at a scale and accuracy appropriate for the objectives of the model. Unless the ultimate objective and scale of the alteration domain model is well understood and stated, it is possible for the interpreter to spend a large effort developing sophisticated alteration wireframes that do not add information that is pertinent to geotechnical studies. Alteration models can feed into geotech, resource, and metallurgy, and different criteria may be important for each discipline.

During this initial step, the interpreter must interact with the geologists and geotechnical engineers to understand what types of alteration can be expected (hypogene, supergene, or anthropogenic), what properties of the alteration must be characterized in order to add value to the structural and geotechnical domains, and what are the extents or scale of the alteration 3-D domain model.

Step 2 – Identifying and Importing Alteration Data

There are two groups of data that can be used to model alteration:

1. Pit maps and drill logs of visible alteration minerals and assemblages; and
2. Analytical data obtained on-site or from laboratory analyses.

Visible Alteration Data

Visible alteration is commonly mapped and logged in database and logging sheet structures that were not designed to optimize the tasks of importing into a 3-D model. Specifically, alteration data are frequently designed to be entered into data fields such as Alteration1, Alteration2, Alteration3, etc. This format encourages a mix of minerals, assemblages, textures, and intensities, precludes sorting by alteration mineral of interest, and requires a series of queries to convert the data set into a format that allows for realistic alteration models.

Additionally, generic and interpretative alteration assemblages rather than alteration minerals are commonly mapped and logged, precluding the interpretation of key visible alteration minerals.

In order to produce an unbiased alteration model, it is recommended to build each visually identifiable alteration mineral as a separate domain, and only upon completion of the mineral domains modelling, build the alteration assemblage domain models that are guided by the spatial coincidence of mineral wireframes.

The most common visible alteration minerals that can be identified are:

- Silica;
- Clay/sericite;
- Carbonates;
- Ferromagnesian minerals (epidote, chlorite, actinolite);
- Minerals specific to a mine, for example, sulphates, feldspars, biotite, topaz, etc.

Invisible Alteration Data

Because of the limitations in what can be identified visually, alteration surveys and models tend to rely more heavily on invisible than in visible alteration data sets. In that sense, the process of alteration modelling can be considered more data driven and makes more use of numeric interpolants than lithological or structural logging. In that sense, invisible alteration data can be efficiently modelled by a resource geologist who is accustomed to evaluating, modelling, and assigning confidence levels to the spatial distribution of metal concentrations.

Amongst routine alteration data types, IRS requires special attention, as it provides the most cost and time efficient method to obtain alteration mineral identification and characterization. IRS data can be collected in a traditional manner as point data from small pit samples. Recent developments in hyperspectral imagery that allow for continuous coverage of mineral species and characteristics in open pits are discussed in Stopka et al, 2020.

IRS data provides three main types of information:

1. The presence or absence of infrared-active alteration minerals such as illite, smectite, kaolinite, alunite, etc.
2. Numerical ranges that represent compositional variations in alteration minerals, such as Fe- to Fe-Mg to Mg-rich chlorite and carbonate, and Al- to Si-rich sericite.
3. Numerical ratios and values that can be used distinguish expanding clays from more stable and water-poor clay mineral species, amongst other alteration mineral characteristics.

Table 4-1: List of the IRS scalars that are commonly modelled in 3D and what those values and models represent.

Mineral Group	IRS Scalar	Proxy to
Sericite-Clay	wavelength 2200 depth 2200	sericite composition (paragonitic, muscovitic, illitic) sericite-clay abundance
Chlorite	wavelength 2250 depth 2250	chlorite composition (Fe-, Fe-Mg- or Mg-rich) chlorite abundance
Carbonate	wavelength 2350 depth 2350	carbonate composition (Fe-, Fe-Mg- or Mg-rich) carbonate abundance

The Spectral Geologist software reports the result of automated mineral interpretations as Mineral1, Mineral2, Mineral3. Direct modelling of Mineral1, Mineral2, and Mineral3 data columns lacks a geological significance. In order to model actual minerals such as phengite, paragonite, kaolinite, etc., the user must query The Spectral Geologist mineral identification columns for the mineral of interest. IRS scalars, on the other hand, can be directly input into numeric interpolants.

Step 3: Data Visualization and Exploration

Before starting the modelling process, it is important to understand the relative importance of supergene, anthropogenic, and hydrothermal alteration in the mine, and to examine how strongly the various alteration features and minerals are controlled by lithology. This is particularly important in mines where ore is hosted by lithologies that have a broad range of mineralogical and chemical compositions. For example, if ore is hosted partly in a felsic rock such as rhyodacite, and partly in a mafic rock such as basaltic andesite, the two host rocks will produce very different alteration minerals, characteristics, and intensities in response to the same alteration triggers. This occurs because of the differences between the original composition of the rock, i.e., the percentage of original aluminosilicate or ferromagnesian minerals that is available to be converted into alteration minerals. Boxplots of lithology by visual alteration intensity logged as a numeric range and boxplots of lithology by spectral absorption depths and indices can provide a good initial understanding of the lithological controls. In many cases an examination of boxplots is sufficient to define whether the entire dataset can be analyzed and modelled together, or if it is necessary to produce separate lithological domains prior to advancing the alteration modelling.

Once the lithological control is understood, the modelling software tools can be used to identify visible and invisible alteration halos and mantos, as well as narrow corridors of alteration controlled by first order faults or fault intersections.

It is recommended to start the exploratory analysis by searching for broad, halo- and manto-type patterns in visual alteration mineral groups (silica, sericite/clay, ferromagnesian minerals, oxyhydroxides, carbonates, and mine-specific minerals) as well as understanding the distribution of the most common IRS active minerals such as montmorillonite, saponite, kaolinite, illite, chlorite.

The next step is to identify the key invisible alteration features that may be used as a proxy to the presence of hydrophyle clay zones, and other lithologically or structurally controlled clays. Specifically, the D1900 (depth of the ~1900 nm IRS absorption feature) can be used as a measure of the relative amount of water in the clay mineral structure, with zones of deeper D1900 representing clays that have a greater tendency to swell, and zones of shallow D1900 representing more stable hypogene clays.

Step 4: Alteration Interpretation and Domain Model Development

It is recommended that the interpreter start by modelling a common visible alteration mineral species, and then constructs invisible alteration features that pertinent to the purpose of the alteration 3-D model. For instance, the interpreter may choose to start by building the mesh for logged clay/sericite. If strong/moderate/weak intensities were assigned, a filter for only moderate to high intensity clay/sericite may be created at first, then compared to a mesh of all logged clay/sericite, and only then start building meshes for the invisible alteration features associated with clay/sericite (namely, depth of the ~2200 nm absorption feature, sericite and kaolinite crystallinity, sericite composition on the basis of the 2200 nm absorption position). An alteration assemblage commonly has individual invisible alteration features that have slightly different spatial distributions.

Step 5 – Assigning Alteration Properties

Alteration properties that can be incorporated into the model include texture, intensity, abundance, and likelihood to weaken rock quality. In the pit the geologist assigns visual alteration intensities which are easily input as category data.

A challenge for geotechnical engineers rests in the geologists inability to define an absolute alteration intensity range that can be applied throughout a pit to develop alteration domains. This is because the gradational contacts, the lithological controls on alteration products, and the variable intensities typical of most alteration zones preclude reliable percentage estimations. This contrasts with sulphide percentage estimations, where a Geologist or Geotechnician can perform consistent and reliable estimations by comparing the rock to opaque mineral percentage charts.

Step 6 – Integrating the Alteration and Structural Models

Upon completion of the alteration model, the interpreter should conduct a second phase of exploration, focusing on identifying trends and cross-cutting relationships between modelled structure and alteration zones.

During this integration step, the interpreter will search for the following types of spatial and temporal relationships between modelled structure and alteration:

- Coeval fault and alteration form narrow to cone-shaped alteration zones that are strongest within the damage zone of a fault and grade outwards into unaltered rock.
- Faults that are truncated or bound alteration zones are interpreted as being younger than the alteration zone, and the fault kinematics information can be used to predict the location

of fault-displaced segments of alteration zones. Conversely, the identification of displaced alteration zones can provide information on a fault's net displacement.

- Linear or cross-shaped alteration zones controlled by fault intersections.

Alteration zones forming shallow level mantos that protrude downward surrounding faults can be interpreted as hypogene alteration caused by hot fluids ascending through faults then spreading laterally in permeable lithologies, or as supergene or anthropogenic alteration produced from cooler fluids that percolate from the surface downwards.

5 3D Model Reliability

5.1 Industry Status Overview

"All models are wrong, but some are useful" (Box, 1976).

The Guidelines for Open Pit Slope Design (Read and Stacey, 2009) calls for methodologies to better quantify the reliability of the structural geology features used as input into the geotechnical design. Reliability can be defined as the opposite of uncertainty (Venturini et al., 2019), but is more difficult to describe mathematically than uncertainty. In this section, we focus on challenges and solutions for defining uncertainty in the different structural components of the model.

This section also introduces workflows for building and communicating model uncertainty to the engineer (e.g. Deliveris et al., 2018) in an interactive manner that ensures the communication takes place effectively and in a focussed manner on the most critical elements of the pit design. As emphasized by Read and Stacy (2009), the geotechnical study components, like structural geology, do need to be compatible with the project development stages defined for resource reporting systems like CRIRSCO (international; http://www.crirsco.com) and similarly aligned codes like JORC (Australia; https://jorc.org) and NI 43-101 (Canada; https://www.bcsc.bc.ca/securities-law/law-and-policy/instruments-and-policies/4-distribution-requirements/current/43-101).

Adequate software tools for the statistical analysis of measurable parameters such as mineralization grades or orientations of structural planes or lineations are available in the mining industry and frequently applied. Practical industry tools are available to simultaneously apply spatial domaining decisions integrated with statistical analysis of numerical, categorical or azimuthal data, as part of decision-making workflows (e.g. ioGAS™, Leapfrog Geo™, GoCAD™). However, the application of appropriate domains in mining projects has not been consistent (Barnett and Carter, 2020).

No statistical software tools currently provide a practical way to quantify the uncertainty in the interpreted spatial arrangement of a 3-D geological system, including cross-cutting/timing relationships, magnitude and direction of structural displacement, continuity of fault segments, and waviness/roughness of any geological surface. Bistacchi et al. (2008) use GoCAD™ to show how a fault that is well constrained by data (data-driven) can be statistically described, but that the extrapolation of the fault at increasing distance from the data becomes a knowledge-driven interpretation based on experience of the geologist (Figure 5.1)The model uncertainty is influenced by the geological complexity of the area of interest, which can vary from very simple and predictable, to extremely complex and unpredictable.

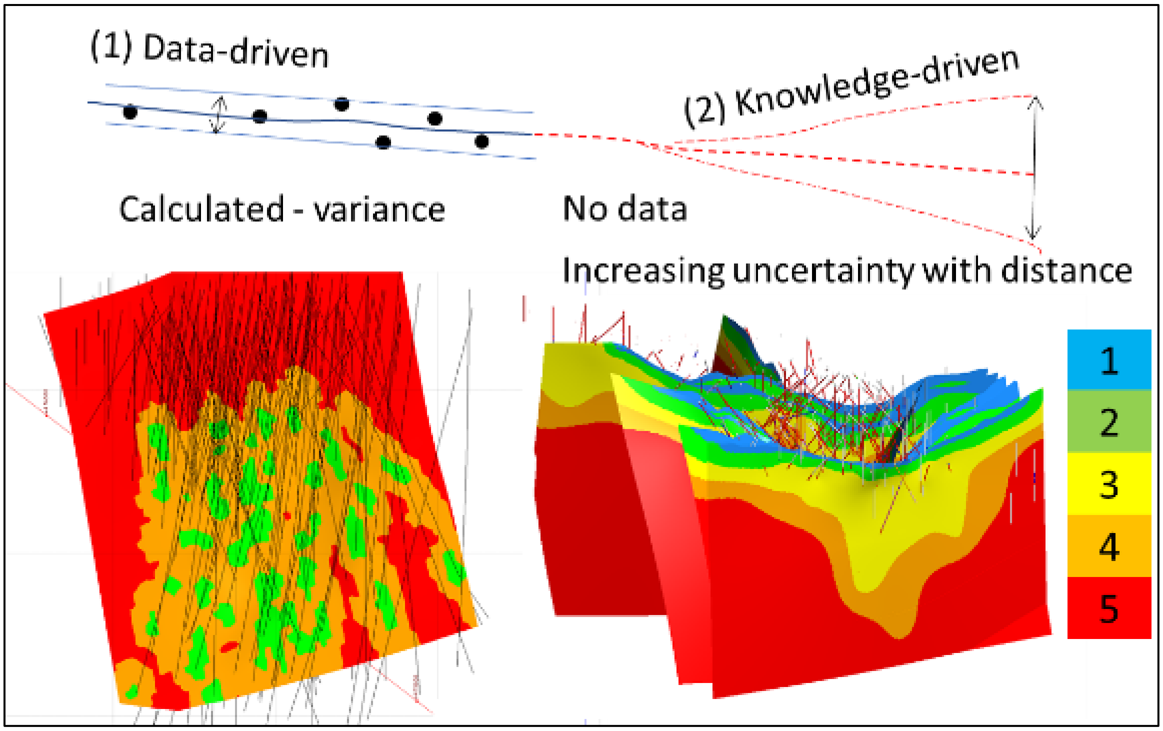


Figure 5-1: Visual representation of fault surface interpretations coloured by distance to data, illustrating where more data may be required to reduce uncertainty. Data-driven interpretations are well constrained by data, whereas the same structure may require knowledge-driven interpretation where there is less data.

5.2 Structural Model Reliability

5.2.1 Reducing Structural Model Uncertainty

Reducing Data Uncertainty

The least biased input into a model interpretation is the input data, so effort is required to reduce measurement error and subjectivity in primary information (e.g., Curtis, 2012). Types of data include positional, interval and trend data types. Depending on the source of data (e.g. mapping, logging, geophysical survey, laboratory analytical) the procedure for data collection is different and the instrument-associated accuracy errors are variable. Errors introduced by operator inexperience can be significant. Reducing errors for all the different data sources often requires specialized expertise and discussion of the possibilities are beyond the scope of this document but obtaining such expertise should be strongly considered.

Reducing Uncertainty by Increasing Structural Data Quantity

On-going data collection is necessary to challenge and reduce subjectivity in a 3-D geological model. Therefore, on-going mapping or drilling, with subsequent re-evaluation of the model in context of the new data, is necessary to reduce model bias and reduce risk in an active open pit. Good mapping data also includes constraints on fault displacement magnitudes and directions, stratigraphic thicknesses and locations where structures are observed to be absent. The known absence of structures helps constrain structural continuity bias. Similarly, more drill hole data with appropriate high-quality logging may reduce uncertainty. The required structural data for different stages of project development are indicated in Table 5-1, or alternatively see Carter (2018).

Table 5-1: Recommended Levels of Geotechnical Effort by Property Stage. From Read and Stacey (2009).

Project Stage					
Project Level Status	**Conceptual**	**Pre-feasibility**	**Feasibility**	**Design and Construction**	**Operations**
Geotechnical Level Status	**Level 1**	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Structural Model (Major Features)	Aerial photos and initial ground proofing.	Mine scale outcrop mapping; targeted oriented drilling; initial structural model.	Trench Mapping; infill oriented drilling; 3D structural model.	Refined Interpretation of 3D structural model.	Structural mapping on all pit benches; further refinement of 3D model.
Structural Model (Fabric)	Regional outcrop mapping	Mine scale outcrop mapping; targeted oriented drilling; database established; initial stereographic assessment of fabric data; initial structural domains Established.	Infill trench mapping and oriented drilling; enhancement of database; advanced stereographic assessment of fabric data; confirmation of structural domains.	Refined interpretation of fabric data and structural domains.	Structural mapping on all pit benches; further refinement of fabric data and structural domains.
Strength of Structural Defects	Literature values supplemented by index tests on core from geological drilling.	Laboratory direct shear tests of saw cut and defect samples selected from targeted mine scale drill holes and outcrops; database established; assessment of defect strength within initial structural domains.	Targeted sampling and laboratory testing; enhancement of database; detailed assessment and establishment of defect strengths within structural domains.	Selected sampling and laboratory testing and refinement of database.	Ongoing maintenance of database.

All undeveloped, structurally complex projects with limited surface exposure face the problem of how to obtain adequate data to reduce risk without drilling every possible fault (Carter, 1992; 2018). Information is required on the orientation, continuity and properties of each structure to assess the risk of each feature with regards to its possible impact on the future slope stability. However, it is not practical to drill enough intersections into every possible fault in a complex deposit to get data resolution adequate to quantify all risks comprehensively. Carter (2018) notes that the structural model must be robust enough to identify and describe mapped or drill-proven major and minor structural features and must also include lower confidence interpreted structures that may exist and impact the slope design. Such structures include data-constrained features that need to be interpreted a significant distance away from the data (Bistacchi et al., 2008). Even if these are low reliability structural interpretations, they still need to be included in the slope design process to guide “worst-case” scenario checks and decisions.

Use of geophysical datasets allow further options for refining the reliability of 3-D interpretation by application of inversion approaches (Wellmann and Caumon, 2018). More recent software allows automation and tighter integration of the 3-D wireframe model to the geophysical model.

Integrated Litho-structural Models

More complete integration of all data and geological knowledge leads to the filtering out of poor interpretations and the creation of better interpretations. Structural patterns influence the spatial distribution of lithological domains, so the observed distribution and geometry of lithological contacts can be used to guide the most likely structural interpretation, and vice versa. Structural model interpretations should therefore be integrated with lithological interpretations. Such integration will reduce model uncertainty. On projects where structural data is very limited, careful study and interpretation of lithology is the only way to infer structures. Similarly, interpretations that integrate alteration systems improve the overall interpretation.

Reducing Bias and Uncertainty by Peer Review

Reducing bias (see Section 5.3.1 below) during the 3-D interpretation phase is more challenging than reducing data uncertainty. Interpretation of deposits that have undergone technical studies and have publicly disclosed interpretations are subject to strong availability bias or anchoring bias (see Section 5.3.1 for description of bias types), as it is much easier to update an existing model without questioning its fundamental assumptions. Often the model will determine if the project is profitable or not, so for the investing company, confirmation bias or optimistic bias (Section 5.3.1) may play a significant role.

As an example, 3-D structural interpretations are commonly part of feasibility studies and based mostly from drill core data. A complex deformed deposit typically has many faults of different continuity that are equivocal to interpret and characterize from drilling data alone. A large fault oriented in an adverse direction can have impact on the stability of a slope, so there is strong temptation to reduce continuity or change the interpreted orientation of the fault. An optimistic model may seem a logical approach if there is limited data to show continuity or orientation.

In addition, many models that are poorly representative of the geology are built by persons who lack the necessary modelling experience or technical training.

It is therefore recommended to have iterative independent review during any geological model development, and a final review. The independence can help remove bias and identify quality problems. Multiple model reviewers, internal or external to the company, helps overcome availability bias, since different geologists have different preferred models based on different experiences.

Interpretations of lower confidence structures should also be created to guide on-going data collection programs such that potentially influential structures may be targeted for drilling to improve characterization of the fault and then better quantify the design risks. In complex structural environments no practically feasible amount of drilling will enable all structures to be fully characterized to mitigate all design risk factors (see Section 5.3.2 and Figure 5-4).

5.2.2 Quantifying Structural Model Reliability

Review of Active Mine Fault Models

Comprehensive verification of a structural fault model can be undertaken in active mine pits with rock exposures. Such an audit requires careful comparison of the interpreted fault wireframes to the actual rock exposures during a field visit. The audit takes consideration of compliance to:

- Fault pattern, including dip and strike, and typical fault system patterns;
- Continuity, noting visible trace lengths in exposures, and tendency for segmentation;
- Properties, such as the waviness, roughness of the plane, and the infill fault rock material; and
- Timing relationships, specifically for cross-cutting priorities.

Every modelled and observed fault is tabulated and labelled as compliant to observation or not for the two categories of Pattern and Continuity. Observed timing relationships are factored into the assessment of the Continuity compliance. Compliance to observation is then calculated as a percentage of reviewed faults. Not all faults in the mine need to be reviewed during such an audit, but a representative sample should be undertaken until the auditor has a clear understanding of the geological conditions. Examples of actual audit results are shown in Figure 5-2. The record for each observed and tabulated fault should be provided to the client for review.

Stereonets are also useful when validating existing structural models and their overall pattern reliability. If a structural model does not match any structural trends identified from stereonet analyses, the model may not be representative and therefore not very useful.

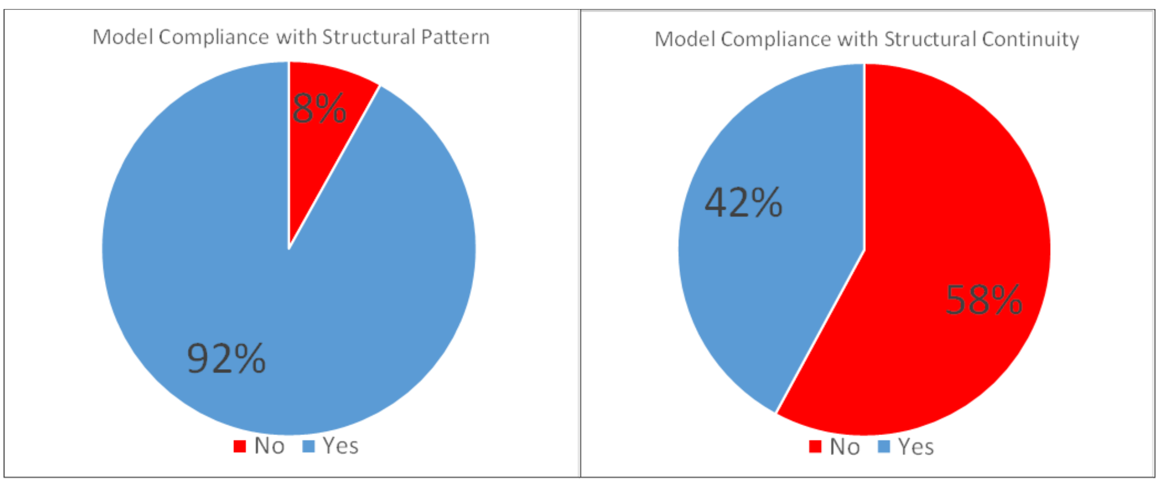


Figure 5-2: Example of a structural model review with results displayed graphically

Ideally the original geological modeller includes tabulation of fault model properties for review purposes. It may be necessary to additionally communicate observed errors or misunderstandings on fault properties to the downstream engineer relying on the information.

The structural pattern compliance and continuity compliance may be represented as percent values (Figure 5-4). These two values are averaged to create an operating mine structural model compliance percent (%) rating. The rating process could also be applied independently to different domains. This percent rating can also be used as an adjustment to overall model Reliability Rating described in Section 5.3.3 for Figure 5-6.

Review of Developing Projects

If rock outcrop is extensive and accessible, a similar structural model review process can be achieved as described in the paragraphs above and Figure 5-2. If outcrop is poor or inaccessible, the review process will rely on the reviewer’s structural experience and feedback may be more qualitative. The review focus should be on whether the model conforms to realistic structural patterns driven by an appropriate conceptual model, and whether the model is based on adequate data (such a drilling data). If not derived from adequate data, then the reviewer should assess how the confidence in the model is communicated to the necessary users.

Early exploration or scoping level projects commonly ignore brittle structural features unrelated to the mineralization. It is important that the technical reports include descriptions of the likely geometries, continuities and physical properties of brittle structures and rock fabrics, including first-order structures that may impact the stability of the proposed pit shell (Carter, 2018). Typically, a pre-mining geotechnical review will look for faults that may be parallel and behind the slope face at a similar or shallower angle to the planned design slope angle. Such faults can have a significant impact on the slope design and project economics (Carter, 2018; Murphy and Barnett, 2018).

Fortescue Metals Group Ltd. utilize a structural model reliability assessment matrix (Figure 5-3) on projects from early scoping to operations (J. Dixon, pers.comm.). A score weighting per model component is not provided but could logically be organised to derive a value between 0 and 100. Such a score could be considered a “measure” of the Reliability of the overall model. The scoring provides a systematic review process that likely identifies strengths and weaknesses in the different model components, to inform the geotechnical engineer, or from which corrective actions can be derived.

		Structural Model Reliability Assessment Matrix				
		Reliability Rating				
		Very Low	Low	Moderate	High	Very High
Model Component	Mapping Data	No mapping data available	Regional mapping data only with little/no project specific mapping completed, area under cover - poor level of detail.	Internal or staged designs mapped informing final slope design, some with 3D imagery. Stratigraphy partially subdivided, some shale bands identified. Digitised in Vulcan, measurements in Acquire. Data imported to Vulcan		All faces physically mapped and digitised using 3D imagery. Stratigraphy sub-divided, shale bands identified. Strat and structures correlated with adjoining benches. Digitized in Vulcan and measurements in Acquire.
	Drilling Type & distribution	Exploration RC only		Exploration RC and limited Diamond, some diamond holes with TV - few holes behind pit design.	Exploration RC and limited Diamond, TV in some RC and diamond holes. A number of holes in locations that inform pit design.	Targeted structural RC with TV and full assays, sufficient to inform sectional interp, Targeted geotechnical diamond program coverage of Geotech domain with good spread to inform spatial variability and pit design.
	Drilling Density	> 300m		100 - 200m		Overall ~50m X 50m with structural rc 3 - 4 holes every 3 sections 50 - 80m behind pit design.
	Core Logging	Logging completed by untrained person with limited QA/QC		Logging completed by trained person with routine QA/QC by geotechnical engineer		Logging completed by competent geotechnical engineer with peer reviewed QA/QC
	Downhole Survey Data	Majority (>50%) of holes with no downhole survey - severe impact on interp and confidence data.		Majority (>80%) of holes with downhole survey (Gyro +/- Mag dev) - moderate negative impact on interp and confidence data.		Collars surveyed, majority (>95%) of holes with full downhole survey (Gyro +/- Mag dev) c/w full gamma suite.
	Interpretation	Resource model only, implicit model, no structural interpretation.		Structural interpretation done but limited by lack of data (data types available geol log, TV, assay, geophysics but limited coverage) Weathering estimated only (no surface) Mineralisation available from block model.	Structural interpretation complete with good data (data types available geol log, TV, assay, geophysics coverage) Weathering, mineralisation and Confidence layers available. Stereonets to define domain structural sets	High confidence interpretation, all data aligns (geol log, TV, assay, geophysics, mapping). Data density supports confidence, weathering, mineralisation and confidence layers done. Shale bands and structures can be interpreted. Sub-division of detrital, or other low strength units if present. Stereonets to define domain structural sets with set statistics. Model Peer review completed
	Data Management	Data is not managed (e.g paper logs with limited or no input code standardisation)		Database used but no built in validation (data entry from paper logs)	Database used with direct field PC logging with inpit validation codes	All data stored and routinely 3rd party validated in database (geotech engineer validated against benchmark values)

Figure 5-3: Example of a Structural Model Reliability Assessment Matrix (courtesy of Fortescue Metals Group Ltd.)

5.3 Geological Model Reliability

5.3.1 Uncertainty and Reliability

Read and Stacey (2009) define uncertainty in context of geotechnical design as having three components; namely geological, parametrical, and model uncertainty (also see Walker et al., 2003 for general model context). Geological uncertainty includes the appropriate identification of geological features and the spatial relationships between features, and sufficiently accurate measurement of the geometries. Parameter uncertainty refers to natural variability (or aleatoric uncertainty) of the rock mass parameters, defined by statistical variability. Model uncertainty includes the choices of workflows, analyses and assumptions made during the geotechnical design, which are subject to ignorance, errors and inaccuracies (or epistemic uncertainty). For the purpose of defining geological model uncertainty, we focus on the geological and parametrical aspects and break this down further.

The visualization and communication of uncertainties is an active field of research (Wellmann and Caumon, 2018; and numerous references therein). Savage et al. (2013) suggest placing confidence points on geological wireframes during model construction (Table 3-2), which can aid visualization of uncertainty. Wellman and Caumon (2018) summarize the approaches to communicating uncertainty in two forms:

1. Using visualization techniques, most commonly colour coding multiple realizations of a model on 2-D sections or morphing between realizations in movie form.
2. Using quantitative analysis followed by appropriate visualization of uncertainties (e.g. in graph form).

Such functionality is not fully available in geological modelling software commonly used in the mining industry that has traditionally focused on explicit interpretation and statistical tools for resource estimation. Implicit modelling techniques (most particularly Leapfrog Geo™ software) have reduced the time needed to build most geological models and very significantly reduced the time to update a model. Implicit modelling therefore does allow fairly rapid experimentation with testing simple ideas and changing curvature or volume of geological features (e.g. Barnett et al., 2018). Building a completely different conceptual model for testing purposes still requires significant time-based manual work that is commonly not financially supported in the mining industry.

Geological knowledge and experience are difficult to express in a quantitative and objective way. Geological data measurements are easier to quantify, but all geological observations themselves cannot be made without a framework of knowledge (Wellman and Caumon, 2018). Frodeman (1995) categorizes geological sciences as hermeneutic science with a strong interpretative character, such that many geological observations have a subjective component. The geological model is therefore influenced by a geologist's natural bias.

Bond et al. (2008) summarize several types of model development bias, including:

- Availability Bias: an interpretation that is most readily to mind and are familiar with.
- Anchoring Bias: accepting "expert" or dominant published opinion.
- Confirmation Bias: seeking only opinions or facts that support one's own hypothesis, or similarly interpreting the data to fit the hypothesis.
- Optimistic Bias: Interpreting in a manner that produces a more positive outcome for a study, such as interpreting greater continuity of mineralization controlling structures, or preferring to ignore conflicting data that may reduce positive project outcomes (after Krueger and Funder, D., 2004).

In summary, the following are uncertainties in geological model construction:

- Observed and measured data quality is subject to the geological knowledge of the observer who collected the data, who may have misunderstood what was measured because of lack of experience and training.
- There are measurement uncertainties in primary data (incl. position of measurement, accuracy of measurement, volume represented by the measurement) for both mapping and logging.
- Geological interpretation is impacted by biases. These are enhanced by linear geological model building workflows. A fixed choice on the overall conceptual model and any

significant interpretational decision points during model construction may force or overly influence subsequent decisions.

- Greater uncertainty exists for parts of a geological model interpretation that lack data, or in the extrapolation of a structural feature from data-rich areas to data-poor areas.
- Choice of interpretation software and model construction methodology, and the user's ability to access all available data for interpretation. For example, explicit and implicit wireframe construction workflows tend to produce different interpretational bias and different geometric and topological structure bias (Cowen, 2017). Different software functionality, complexity and user expertise influences the product.
- Quality of additional inputs, such as geophysical data (including quality of data, of processing, and of interpretation), and resolution and representativeness of the data (such as magnetic susceptibility) to the feature of interest. There may be an addition level of interpretation bias of geophysical data before it is included in a model as "data".

In conclusion, interpretational uncertainty in a geological model includes subjectivity from the data collection process through to the final 3-D model and cannot be quantified precisely. The more interpretational decisions that are made, the greater the uncertainty. This leads to an important additional conclusion, that models of geological environments with greater complexity (more cross-cutting relationships, non-planar contact geometries and variable continuities) therefore have greater uncertainty. This needs to be factored into consideration of geological model reliability.

5.3.2 Why Quantify Reliability?

An existing pit, or conceptual excavation design geometry should be assessed by an engineer to determine the risk of slope failure and impact to the project (Steffen et al., 2008). Geotechnical kinematic rock stability analyses can use numeric descriptions of the orientation, continuity and strength properties of structures as direct input into calculations. The more precisely the excavation geometry and statistical range in structural geology geometries are known, the more ideal the situation for the engineer and the more precise the analysis of the risk.

However, a geological modeller commonly deals with the challenge of a lack of data to constrain an interpretation, most typically on early development projects but also advanced projects with poorly sampled areas. Inadequate data sampling may occur because of time or financial limitations, data quality problems, physical access challenges, perhaps leading to sampling bias (Terzaghi, 1965), or excessive geological complexity. In these cases, quantifying Reliability of the geological inputs can be useful as an engineering input. The concept of practical data limitations and an optimal expenditure point is illustrated by Carter (1992) in Figure 5-4, with particular reference to geological complexity. Slope design and risk quantification must therefore incorporate uncertain 3-D interpretations and uncertainty in descriptive parameters of geological features.

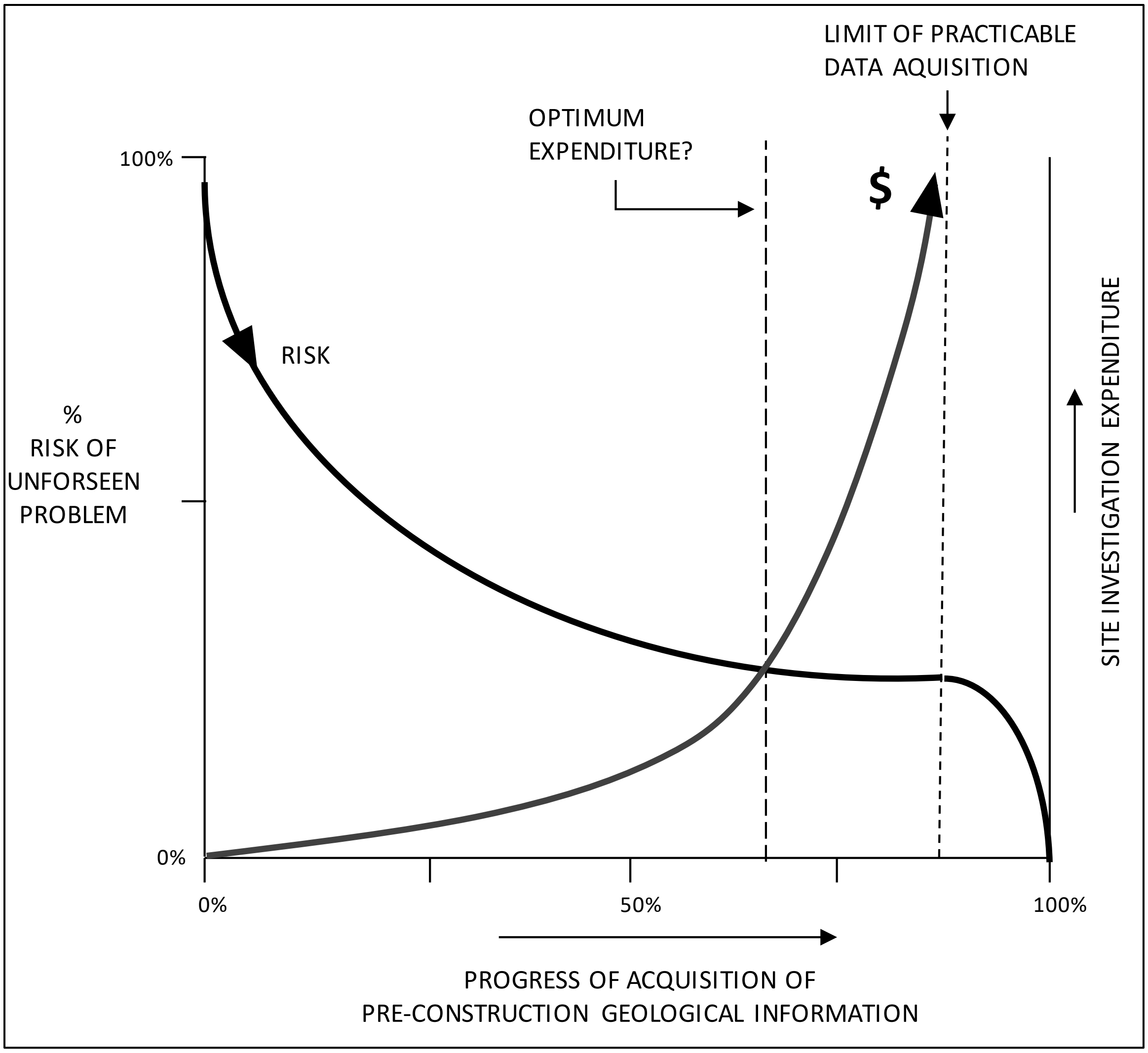


Figure 5-4: Inverse relationship between the geological risk that decreases as site investigation expenditure and geological knowledge increases. From Carter (1992)

An important objective of pre-construction site investigation is that the data gathering and 3-D interpretation identifies the most critical geological features that will impact the pit design. The optimum expenditure could therefore be considered that which is sufficient to identify the most critical geological features. Fookes (1968) notes that the rate of data collection needs to be sufficient to identify the critical information before it is too late for the project to adjust the design (Figure 5-5).

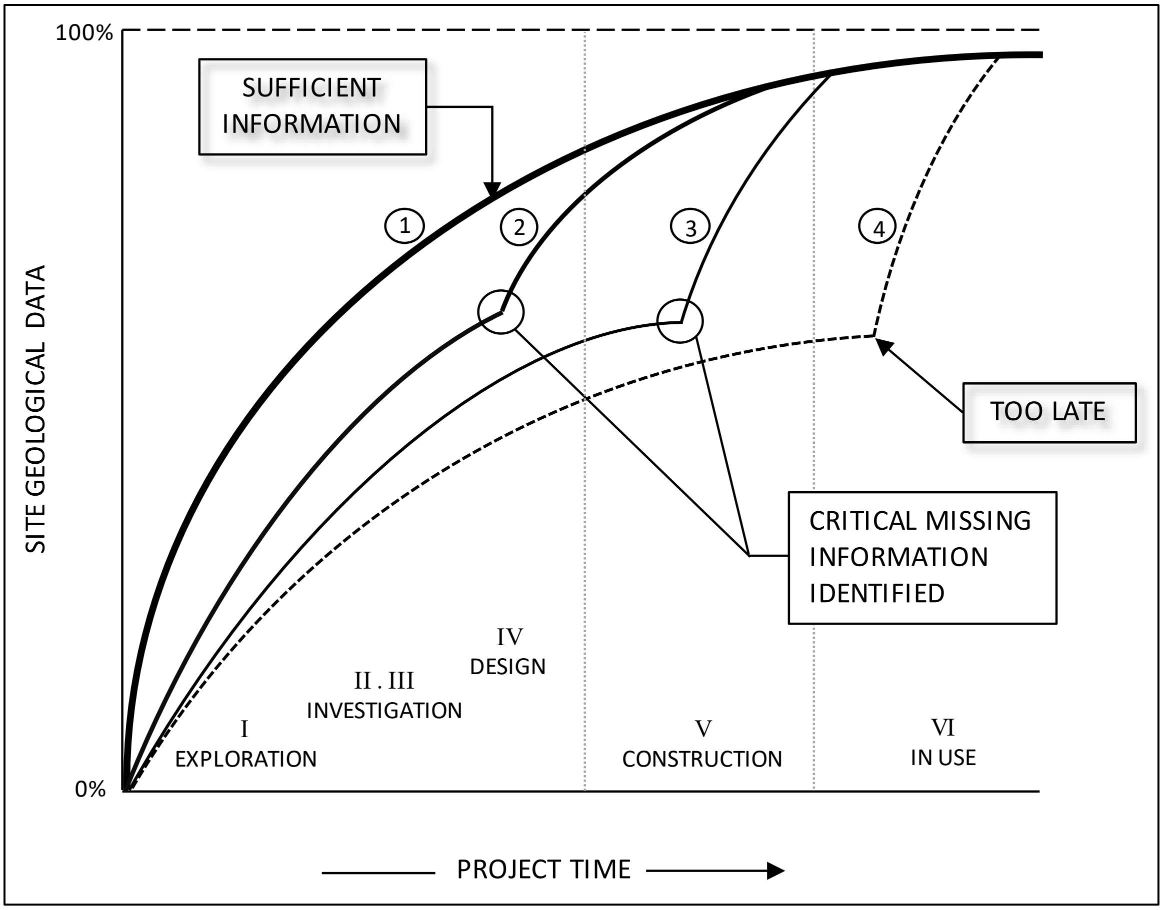


Figure 5-5: Typical mine project developments stages, showing the importance of undertaking adequate data collection. From Fookes (1968). There are increasingly severe financial implications to identifying the possible risks too late.

It may not always be useful attempting to quantify reliability. In early scoping or pre-feasibility design phases of the project, the uncertainty in the specific structural geometries may be high at most locations or all locations in the planned project area. In these cases, it may be most practical not to focus on building precisely inaccurate and potentially misleading wireframe models. Rather, the engineering design should conservatively include a broad understanding of the likely range in structural patterns, continuity and properties of the area of interest; which may be communicated in written text and/or illustrations. Similar situations may occur in certain mining scenarios, such as new mining extension projects or slope pushbacks, where access to the area of interest is restricted based on depth or social-political constraints.

5.3.3 Practical Application of Reliability (GMR)

The open pit mining industry needs a way to define the Reliability of geological models for input into pit slope design and risk/consequence decisions (Macciotta et al, 2020), such as the Geological Model Rating (GMR) of Perello et al. (2011; 2015). In this section we suggest a method for calculating a GMR for a 3-D interpretation of an open pit geological domain. However, this new Reliability Index is not fully tested nor the primary objective. The objective is to illustrate the potential impact of different factors on the Reliability of a 3-D structural model. We expect that GMR method presented below should evolve and improve with testing.

Based on the previous sections, to quantify model reliability, the main causative factors of geological model uncertainty are:

1. Natural geological complexity/variance with greater complexity creating uncertainty;
2. Lack of data, and the related problem of distance-to-data uncertainty;
3. Data quality-based uncertainty; and
4. Subjectivity and interpretative biases, including lack of expertise of the model builder

Section 5.3.1 establishes that the subjectivity in the geological sciences is too great to accurately and mathematically quantify uncertainty in geological interpretation. Practical application of the concept of reliability of geological models as input for engineering purposes must therefore be bridged through subjective quantifications.

Venturini et al. (2001; 2019; further discussed and developed by Perello et al., 2003, 2005, 2011, 2015, and Bianchi et al., 2009) presents a method for categorizing and quantifying the Reliability of geological models in order to address challenges in the tunneling industry where contractual issues are experienced related to unexpected subsurface conditions and their financial impacts and schedule delays. Their recommended model Reliability index (the R-Index, which performs the same function as a GMR) can be included into Geotechnical Baseline Reports as a way to fairly allocate risk and the associated costs between the contractor and owner.

The Reliability can be applied to an entire geological model, or a single domain, or specific study area of interest. Three open pit mine cases studies are presented in Appendix B as illustrations of the process described here.

Step 1: Quantifying Geological Complexity (System Parameter)

Geological complexity is considered by Venturini et al. (2019) to vary based on "geological context (sedimentary, plutonic, metamorphic), tectonics (no deformation, folding, faulting, shearing), geodynamics (compression, extension, uplifting), morpho-dynamic (belts, marine, slope, plane, glacial, etc.)" and other possible factors. They propose a biaxial categorization with increasing complexity from sedimentary, to magmatic, to metamorphic context on one axis, and increasing structural complexity from unfolded to strongly deformed on a second axis. On this table, a numeric classification scale from 1 to 12 in order of increased complexity is suggested, where 1 is least complex and 12 is most complex. This is a simplification of the Reliability approach defined by Perello (2011), who define the lithological complexity, ductile deformation complexity and brittle deformation complexity as the fundamental input parameters into defining the GMR.

In this document, we have further simplified the complexity table to a rating from 1 (most complex) to 10 (least complex; Table 5-2). For the GMR calculation, the geologist needs to pick a value from Table 5-2 that is most representative of the geological domain that is being evaluated. The chosen value (1 to 10) is subjective within the defined value ranges. For the purpose of geomechanical studies, geological complexity does not always translate into geomechanical complexity (Perello et al., 2011). For example, a complex granitic intrusion within a gneissic rock will not necessarily have significant rheological contrast. So, the complexity (or simplicity) described in Table 5-2 must consider the geomechanical implications rather than just the geological variations. Examples of estimated complexity for different mines around the world are provided in Appendix B.

Table 5-2: Simplified numerical categorization of geological simplicity (as opposed to complexity) . Modified from Venturini et al. (2019)

Deformation Type	Sedimentary	Magmatic / Alteration System	Deformed Metamorphic Complex
Undeformed	VL - L **(10 - 8)**	L - M **(8 - 6)**	
Faulted	L - M **(8 - 6)**	L - H **(7 - 5)**	
Folded + Faulted	L - H **(7 - 5)**	M - H **(6 - 4)**	M - VH **(5 - 2)**
Folded + Faulted + Sheared	M - H **(6 - 4)**	M - VH **(5 - 2)**	VH - EH **(3 - 1)**

Complexity descriptors: V = Very L = Low M = Medium H = High E = Extremely

The lowest complexity geological systems (e.g. complexity 10 to 5; Table 5-2) may plausibly be drilled adequately enough to identify all geological features that may pose risk to the project, whereas with increasing complexity (e.g. categories 4 to 1, for example) each more complex setting would include increasing geological unknowns that cannot be practically mitigated by drilling (Figure 5-4).

Alteration systems are usually associated with magmatic intrusions (grouped together in Table 5-2) and can be complex to observe and measure and to model in 3-D. Alteration domains are strongly dependant on alteration intensity and that intensity is spatially variable. It is common for a simple bubble type “grade shell” estimation to be applied to modelling alteration intensity. The alteration intensity variations should consider the influence of confirmed lithological boundary controls, lithological property variations, structural features and structural domains. The reliability of the alteration model will therefore be dependant on the controlling geological features, as well as the observations or measurements taken.

The highest complexity geological environments are a product of a prolonged deformation history, including exposure of early deep crustal metamorphic environments and often overprinting brittle and ductile deformation. Such complex geology is summarized as deformed metamorphic complex in Table 5-2.

It is also important to realize that the complexity of a lithology or alteration domain is commonly strongly scale-dependant and therefore project objective-dependant. A regional lithological model of a sedimentary sequence can be very simple, layered, and undeformed. In contrast, at a sub-metre scale that same sedimentary sequence can be extremely complex and unpredictable, with intercalated, cross-bedded or disturbed units. It is therefore important to clearly define the scale of the project objectives and the scale of the required geological model prior to data collection and modelling. In this way an appropriate complexity rating can be applied.

Step 2: Quantifying Data Quality Uncertainty (Investigation Parameter)

The GMR includes a methodology to determine the reliability of the data used in a geological model, essentially based on a comprehensive audit of the data sources. Perello (2011) considers measurable components of the data collection, such as:

- Drilling Potential Quality (DPQ): including spacing of holes, % cored holes, inclusion of televiewer data, and intersection with area of interest;
- Mapping Potential Quality (MPQ): including area and scale of mapping, outcrop percentage, data collection method;
- Geophysics Potential Quality (GPQ): including length and interval of lines, method resolution, distance to of AOI.

These quality parameters are then used by Perello (2011) in global interaction matrices after Jiao and Hudson (1995) and Hudson and Jiao (1996) to determine weighted factors that can be applied to the lithology, ductile and brittle geology ratings.

In this document we have modified these quality parameters to be more applicable to open pit data collections systems (Table 5-3). We also simplify the calculation process by removing the weighted matrices approach, which is not an accessible workflow and technology for most mining geologists. MPQ and DPQ are each given a rating out of 10, and then averaged to get a final rating. GPQ is used only as an adjustment to DPQ.

The main measurable for MPQ is the percent mapping data coverage of all the final benches, or outcrop in the planned pit footprint. However, one adjustment is applied. The mapping quality is optimal for the benefit of 3-D modelling only if a pattern mapping approach is undertaken (as per Section 2.3). A 50% reduction on the MPQ is applied proportionally to any mapping that is not pattern mapping. Photogrammetry can be utilized for pattern mapping and therefore may contribute favourably the percent mapping coverage, so long as it is of adequate resolution and quality. Note that photogrammetry mapping without confirmatory in-pit mapping of structural orientation and kinematics is not adequate, and a certain reasonable subjectivity in application of a rating is required.

The DPQ is dependant on average drilling spacing across pit domain footprint area (by definition the drillholes should be logged), and also on the percent of oriented core that is well oriented (the orientation line must align over 3 runs within 10-degree error to be considered aligned; Kramer Bernhard et al., 2020). The drilling spacing rating is calculated using the chosen geology complexity value as input, as more complex geology requires closer spacing. The rating must be capped at the maximum value of 10, if the calculation produces a larger value. Only relevant drillholes spatially located within the geological model domain should be used in the calculation. If the drill holes are mostly oriented in one direction and unlikely to sample the most relevant geological trends adequately (Terzagi, 1967), it may be reasonable to downgrade the rating.

Poorly oriented core gets no recognition as it creates uncertainty in the model rather than building Reliability. Acoustic and optical televiewer can be used to improve or replace oriented drill core data, as long as the necessary data can be obtained at adequate quality. Necessary data is project dependant and may include lithology, alteration and faults including core zones and damage zones (Figure 3-7) that can be recognized and described by a geologist (most mines do not have the skills to do this; Kramer Bernhard et al., 2020).

Geophysics is not a commonly applied data collection technique in open pits but can be useful. The GPQ is therefore not applied as a separate investigation parameter, but rather applied as and adjustment factor to the DPQ. As long as the geophysics data was collected over a relevant spatial location within the pit domain, used a geophysical method that provides adequate resolution to resolve structures and contacts, and the product can be tied and verified to drillhole data, then it would reduce data uncertainty between drillholes. In this case, the DPQ is increased by a factor of 1.5.

Table 5-3: The Investigation Parameter calculates the quality of the data inputs into the 3-D model, and can be applied as a modification to the Geological Model Rating (GMR). MPQ and DPQ are calculated separately and then averaged.

Data Quality – Investigation Parameter = [MPQ + DPQ] ÷ 2			
Mapping Quality (MPQ) 1 to 10	Bench / Outcrop scale 15x15 m footprint %		Calcs % ÷ 10
	Adjustment	Pattern mapping method	No adjust.
		Point mapping method	x 0.5
Drilling Quality (DPQ) 1 to 10	(DHS Rating + OCQ Rating) ÷ 2 = DPQ Rating	DHS Rating *(maximum value =10)* Drillhole Spacing (m) along slope	(350 x Complexity -1500) ÷ Spacing *Complexity cannot be less than 5*
		OCQ Rating Oriented Core / ATV/OTV Quality Orientation line aligned over 3 runs within 10 deg error = good (otherwise poor) ATV/OTV must have QAQC, adequate resolution and classified by structure type	% Good ÷ 10
	Adjustment Only if relevant	GPQ - Geophysical investigations (a) spatially within pit footprint, (b) adequate resolution to distinguish structure (c) tied to some drillholes	x 1.5 DPQ cannot exceed 10

Step 3: Quantifying Quality of Model Interpretation Process (Interpretation Quality)

Model peer review and auditing is an important part of mine geological model workflows (Figure 1-1; Figure 3-5). Perello (2011) includes an input to the GMR that is based on the quality of the 3-D interpretation, which they consider one of the most difficult parts of the evaluation. They consider whether:

a) A conceptual model has been used and consistently applied to the interpretation,

b) The interpretation is based on data or overly extrapolated, and

c) The years of experience of the interpreter.

We have adopted the same measurements but have chosen not to include an adjustment for the experience of the interpreter, as this depends on the type of experience and training undertaken by the interpreter. Table 5-4 explains the criteria for the rating adjustment and has slightly expanded explanations from the original source table. The modification factor of around 0.8 for overly extrapolated interpretations is based on calibrated sensitivity studies (Perello, 2011). In Step 4 below, we suggest a modification for active mines where more detailed verification can be undertaken.

Table 5-4: Interpretation Parameter, to assess the quality of interpretation. Modified after Perello et al., 2011

Category	Criteria Description	Rating
Extrapolation Criteria	Genetic interpretation based on well documented observations. Structures and contacts should be constrained by mapping and drilling data at intervals consistent with the complexity of the geology.	1
	Genetic interpretation sometimes not based on well documented observations. Consideration of pattern and continuity not always maintained.	0.9
	Geometric extrapolation prevalent with poor genetical interpretation. Structural continuity significantly over-interpreted with poor recognition of cross-cutting relationships.	0.8
Conceptual Model	All elements of the model included in the frame of one or more structural or lithostratigraphic association; conceptual models and analogues for associations used are well documented and well described in literature.	1
	Partial use of the conceptual structural or lithostratigraphic associations concept.	0.9
	No use of the structural associations concept; conceptual models use unclear, or confused mixture of conceptual models.	0.8

The Interpretation Quality rating (IQ) is the average of the Extrapolation Criteria rating and Conceptual Model rating in Table 5-4.

To undertake the review in Table 5-4, it is necessary for the reviewer to visually look at the intersections supporting each lithological contact or fault. The process can be made simpler if the modeller provides a Structural Matrix (Figure 3-5) and control point database (Table 3-1) for the modelled faults. Similarly, control point databases can include lithological or alteration domain contact points from drill holes or mapping. The relevant intersection points can therefore be pre-prepared for the review process.

Certain parts of a model may be supported by more abundant data than other parts, and even well constrained geological structures are often projected away from the data to parts of the model with limited or no data constraints. In such cases, for visualization and peer review purposes, it can be valuable to use numerical estimation/interpolation techniques to determine the data density and/or distance to data for the modelled features (Bistacchi et al., 2008). Most 3-D modelling software allow the user to “paint” the geological wireframes with the colour based on distance or data density, thereby enabling the user to subjectively gauge or numerically quantify uncertainty in the interpretation (Figure 3-4). For example, model components located beyond specific distances may be categorized as lower confidence, depending on geological model complexity.

Finalization of a Reliability Index

The proposed final Reliability calculation is a significant simplification of that used in the civil tunnel industry. Its value is to explore the parameters that impact model Reliability towards the goal of improving the model quality. Through this process the geologist and engineer will better understand what the risks are.

A summary of the overall calculation process is shown in Figure 5-6. The structural Pattern and Compliance % values (from Section 5.2.2) can be averaged to create an operating mine structural model compliance rating (OMA) used as an adjustment to the overall model Reliability Rating described in Section 5.2.3.

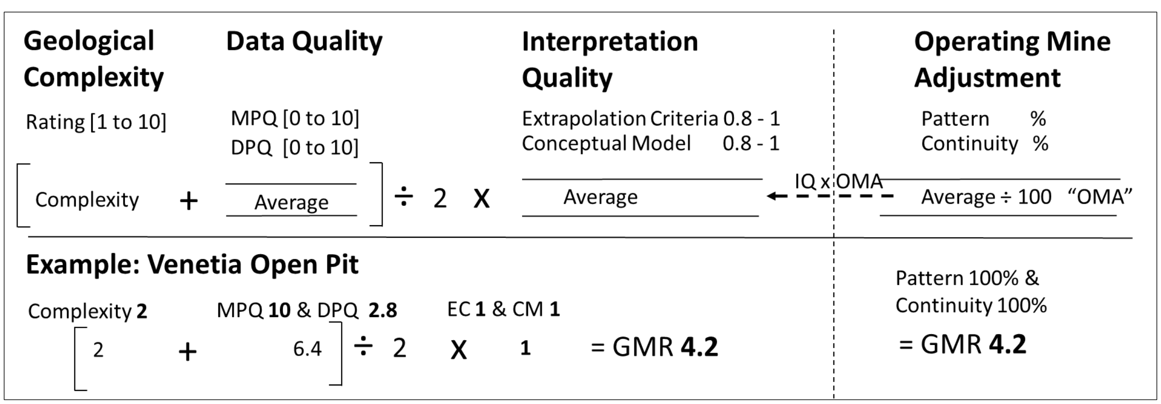


Figure 5-6: Final summary calculation workflow for a “Reliability” index concerning a structural model interpretation of an open pit, based on easily obtainable parameters. Following the workflow should inform the user of the primary concerns that should be considered. Each of the input parameters are obtained from the following images, Table 5-2, Table 5-3, Table 5-4 and Figure 5-2.

5.4 Geological Model Handover to Geotechnical Engineer

The geotechnical engineer should be involved from the original conception of the project to define the project and model objectives and needs to review and approve the model prior to project completion. A geological model is inclusive of lithology and alteration domains, and structural geology. In providing the litho-structural model to the slope design engineer, the geologist should consider, quantify (if possible) and communicate the following aspects of the model reliability:

- The possible variation in orientation of each structure as compared to the modelled orientation (inclusive of faults, shear zones, folds and foliations).
- The likely variation in properties of each fault. Maybe useful to communicate possible variation in transmissivity, width, breccia/ gouge percentage. Clarify if the modelled structural features are discrete features, or domains or volumes with isotropic or anisotropic rock mass properties. Practically, it is usually the weakest rock mass component that is used in geotechnical analysis.
- Describe the interpreted continuity of the faults and whether it is more appropriate to represent the faults as realistic segmented wireframes or continuous wireframes representing a consistent fabric (section 3.4).
- Uncertainties in the contact location and internal properties of lithological domains. These can be provided using confidence points (section 3.2.4; Savage et al., 2013). Discuss variance/uncertainty of fold hinge location, amplitude, wavelength and fold style.
- Uncertainties in the domain boundary and internal properties of domains (section 3.5; Carter and Barnett, 2021), including modelled alteration intensities, if relevant.

The communication to the engineer should include a report explaining the model development process, limitations and assumptions, typically in report format and preferably also verbally. As discussed in Section 3.2.4, the handover process can be improved by providing information via a Structural Matrix (Figure 3-5) and control point database (Table 3-1) for structures, and lithological and alteration domain contacts.

For the engineer, the review and approval process involves determining applicability of the model as guidance or input into the engineering analysis and design. In receiving the model from the geologist, the engineer should determine the following:

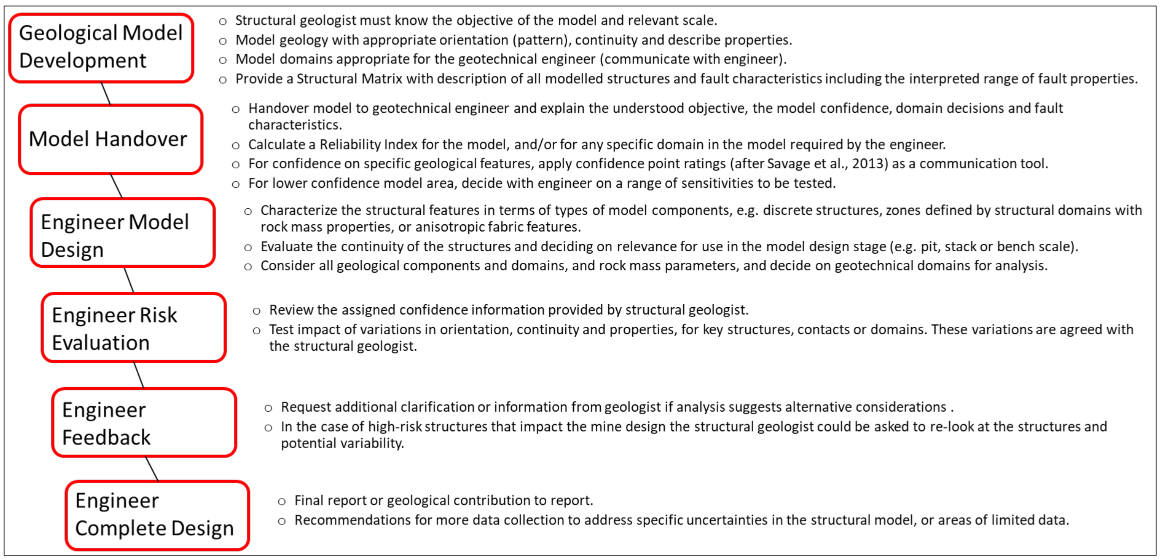
- The assigned confidence information for the structures, and lithological and alteration domain contacts.
- Test the geotechnical impact of variations in orientation, continuity and properties, for key structures, and lithological and alteration domains.
- Request additional clarification or information from the structural geologist if analysis suggests alternative considerations. In the case of high-risk structures that impact the

mine design, the structural geologist could be asked to refine interpretations of specific structures and their potential variability. It may be necessary to create multiple versions of an uncertain structure to test the impact of different possible orientations on the engineering design.

- Provide recommendations for more data collection to address specific uncertainties in the structural model, or areas of limited data.

A recommended handover workflow is provided in Figure 5.7, to ensure transfer of understanding and a feedback process to optimize and achieve most appropriate geotechnical analysis.

Figure 5-7: Geological/structural model handover to geotechnical engineer



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All data used as source material plus the text, tables, figures, and attachments of this document have been reviewed and prepared in accordance with generally accepted professional engineering and environmental practices.

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Appendix A:

Short Reference for

Technical Aspects of Structural Geology

Short Reference for Technical Aspects of Structural Geology

This Appendix is provided as a basic guide to describe much of the structural geology terminology used in the document, as well as for further describing some of the data collection expectations required during mapping. It is recommended that the reader refer to the McClay handbook on mapping (McCLay, 2013) and Fossen (2016) for more comprehensive and illustrated general structural geology.

In all cases it is recommended to take planar orientation measurements in dip and dip direction notation, since strike and dip convention varies and requires excellent metadata management for as long as the data is required.

1 Fundamental Fault Characteristics: Pattern, Continuity, Properties

Understanding faults, fault systems, and shear zones is fundamental to mining, as these structures are commonly associated with zones of geotechnical weakness. Rock deformation is commonly, if not generally, discontinuous on the scale of mapping, i.e., faults and shear zones are the typical products of rock deformation under a very wide range of conditions.

We tend to think of faults as being the latest structures to form, especially in multiply folded metamorphic rocks. However, faults (and shear zones) may form during any part of the deformation history and are deformed by later deformation events.

Understanding faults and shear zones in an open pit, requires:

- Mapping and interpreting the shape of fault surface in 3-D;
- Determining direction and sense of displacement on the fault;
- Mapping and interpreting the pattern of faults in 3-D; and
- Determining timing and movement history

1.1 Mapping Faults in 3-D

Faults and shear zones should be mapped just as assiduously as other rock units — especially in view of their potential importance for geotechnical domaining and design. Faults are not always straight and are commonly irregular, so they should be mapped in the pit by following them along strike and down-dip.

A fault set is a collection of faults of similar orientation analogously to the geotechnical definition of a discontinuity (joint or fracture) “set”. A single fault system may contain multiple fault sets of different orders of importance and orientations. All faults within a fault system have worked harmoniously to accommodate the displacement across the fault system. In order to understand, develop, and communicate a fault's geometry and displacement through a 3-D model, the geologist must be familiar with typical fault geometries that occur under compression, tension and shear strain. In other words, the geologist should be trained to identify and understand typical deformation patterns that are diagnostic of certain tectonic environments.

In addition, the geologist must be able to determine the kinematic indicators that can help understand the shear sense of the fault system, and be prepared to identify evidence for single or multiple activations of a fault under different tectonic stresses. These fundamental observations from pit benches, surface outcrops, and from oriented drill core should be the basis of any structural model.

Faults are generally represented on a map as straight to gently curved lines, and that is often as much as some geologists think about fault shapes. It is most important to realise the following points:

- Faults are commonly curved, sharply bent, rough, branching and/or en-echelon (De Joussineau and Aydin, 2007; Fossen, H., 2020).
- Every bend, branch, undulation, and step in a fault requires that the surrounding rocks deform in response to the irregularity, this often results in significant variations in jointing and damage around the fault itself.

Faults form three-dimensional linked arrays that move co-operatively to accomplish "balanced" deformation of rock masses. These arrays are usually regular and belong to a limited set of pattern "types" that reflect tectonic environment (extensional, compressional and strike-slip; Davis et al. 2011).

A key aspect of fault mapping for determining fault patterns and tectonic setting is to determine the nature of fault intersections. Always take care to determine whether intersecting faults merge (i.e., appear to be members of a single array or pattern) or cross (one fault clearly displacing the other), acknowledging that faults part of one active system can locally mutually displace each other. Identify and show intersecting faults on a map with clear cross-cutting relationships indicating different timing.

The comments above on fault patterns are particularly pertinent to interpretation of Landsat or regional geophysical data. Too often, the 'lineament' approach is taken to such interpretations, without critical evaluation of the relationships of lineaments to faults, of lineaments and faults to each other, and of the patterns of lineaments. All too many published interpretations show cross-cutting lineaments and faults with no mutual offset.

Fault system mapping data should record (Groshong, 2006; McClay, 2013):

1. Sufficient measurements of the different fault orientations within a fault system to precisely constrain the pattern. This may include second- or third-order structures that help define kinematics, like Riedel shears (Price and Cosgrove, 1990; Katz et al., 2004). and may be found within damage zones.

2. Continuity of the different fault sets in the system, including possible presence of fault segmentation with intact, partially breached, or doubly-breached relays. Breaching occurs when originally separate fault segments link up (Figure 1-1), creating a more continuous fault.
3. Properties of the faults, including fault infill material, width, water flow, fault plane roughness/complexity, persistence, and intensity and symmetry/asymmetry of the fractured damage zone.
4. Kinematic indicators, which most commonly consist of slickensides/slickenfibres, Riedel fractures, vein and dyke cross-cutting relationships, rotated objects.
5. Timing relationships, such as with other faults, folds, vein systems, intrusive rocks or alteration systems.

The following two contrasting situations are commonly encountered when attempting to map faults in an open pit:

- The faults are well exposed and can be analysed directly in pit walls and benches to determine their direction and sense of shear; these faults can be mapped in just the same way as any other geological feature — by following them along strike and down-dip.
- The faults are not exposed in the open pit, but their existence is inferred based on geological relationships of the adjacent rocks or that observed in drillcore. The best way to define the position and shape of non-outcropping faults is to look for continuity of faults between drill holes, or map abrupt changes in the continuity of stratigraphic units, intrusions, or the orientation of contacts and internal features such as bedding.

1.2 Structural Logging of Faults

Core logging of fault should record the same data as listed above for mapping. For the purpose of aiding final fault system interpretation in 3-D modelling, Kramer Bernhard et al. (2020) propose five structural observational categories (classes) that should be distinguished during structural logging. The fault classes are listed in order of probable increasing distance from the centre of the fault zone and decreasing confidence for truly constituting a fault:

- **Class 1**: Tectonic breccia and/or fault gouge – interpreted as fault core zone; high-confidence indicator of faulting. Similarly, brittle-ductile or ductile shear zones can be grouped into the class, or sub-class.
- **Class 2:** Fault plane with slickenlines or observed displacement – represents a fault plane, either within or forming the outer boundaries of the fault core zone; high-confidence indicator of faulting.
- **Class 3**: Unusual alteration and/or intense fracturing – interpreted as the fault damage zone, relay zone, or fault termination zone; medium confidence indicator of faulting.
- **Class 4:** Rubble core – may be related to mechanical damage from poor drilling quality, which may be caused by presence of a fault; very low confidence indicator of faulting.

- **Class 5:** Strong clay or other unusual non-cohesive alteration, or texture-destructive clay/saprolite/residual soil of unknown origin (customized per project to capture poorly understood, additional geological features that may be related to faulting) – interpreted as potential highly permeable zone; low to very low confidence of faulting.

Alternative categories may be customized to the specific project but should convey both textural observation and a level confidence for use by the geological modeller. The structural class data can also be collected from high resolution core box photographs. Although time consuming, structural class data can also be inferred from detailed observational records in text format.

1.3 How do faults form?

Faults and shear zones represent localised brittle and ductile deformation, respectively. They form as the response of the rock mass to differential stress. They initiate with orientations that are largely controlled by the orientations of the principal stress directions (e.g., Anderson, 1951).

Faults grow by repeated seismic rupture and by more continuous aseismic creep, displacement accumulates over time, and faults tend to get longer and taller. Faults can grow from small fractures that propagate laterally and vertically as they accumulate slip, or they can grow by reactivation of pre-existing structures such as older joints or faults (Fossen, 2020).

Isolated faults tend to show a gradual increase in displacement from a tip line towards a central point, and ideally the tip line is more or less elliptical (Figure 1-1). As faults grow, the linkage of faults and fractures occurs at almost any scale, from the linkage of microcracks to form mesoscopic shear fractures (Reches and Lockner, 1994; Crider, 2015, Figure 1-1). Linkage is a fundamental process of fault growth and can be observed in any tectonic regime and setting, including thrust (Nicol et al., 2002), strike-slip (Woodcock and Fisher, 1986) and various extensional settings. Fault linkage controls the formation of jogs, undulations, and steps within the fault profile. The geometry of connecting fault segments formed during fault linkage is known as a relay zone.

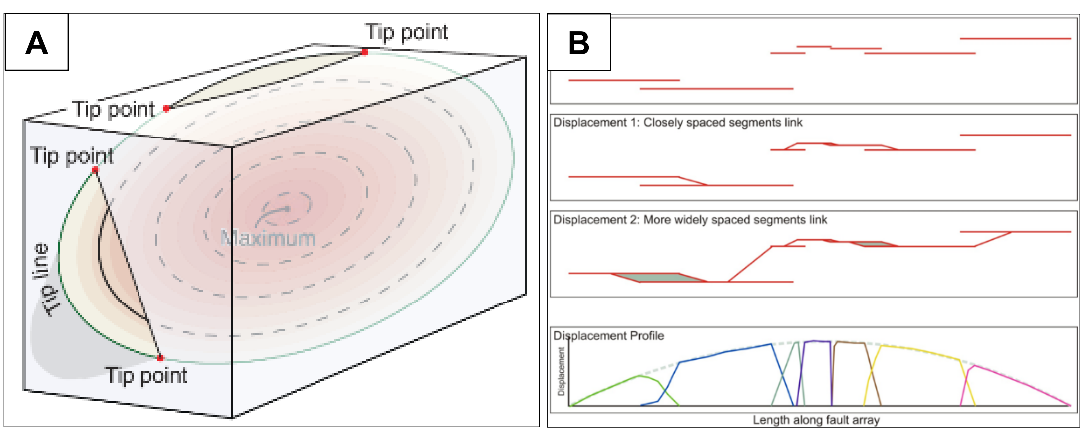

Figure 1-1: Displacement contours on a fault, idealized schematic model (A), modified after Barnett et al (1987). Conceptual growth of a fault, indicating fault linkage with increased displacement, and showing the displacement gradient from tip line to tip line (B).

1.4 What Do Fault Rocks Look Like?

Faults may have significantly different appearances in outcrop, depending principally on the:

- Pressure and temperature conditions under which they formed;
- Amount of water that accompanied deformation; and
- Minerals in the rocks being deformed along the fault.

Most fault rocks are characterized by either:

- Regular arrays of fractures, narrow shears or cataclasite in brittle fault/shear zones; most of the shear fractures are parallel or at a low angle to the orientation of the fault zone.
- More intense foliation than in the surrounding rocks; the shear foliation in these ductile fault/shear zones is sub-parallel to the local orientation of the fault/shear.

Faults are typically sub-divided into either brittle faults or ductile shear zones (note that some sources differ on this nomenclature).

Faults formed in a brittle environment by shearing and grinding of rocks during fault movement are characterized by zones of breccia, gouge, and cataclasite (Figure 1-2):

- Fault breccias and gouge (a fine powder or clay) form from comminution processes (shearing and crushing) during fault movement. They consist of rock fragments that are weakly cohesive unless cemented by fluid ingress syn- or post-deformation.
- Cataclasite is a fault rock also with matrix formed by crushed microfragments, but annealed by higher pressure and temperatures.
- Very rapid (seismic) fault movement in dry rocks can melt the wall-rocks and produce the glassy rock pseudotachylite.
- Dilational (implosion, hydrothermal) breccias consist of clasts of wall-rock suspended in a cement (usually quartz or carbonate) deposited from hydrothermal fluid, and may be spatially associated with a fault.

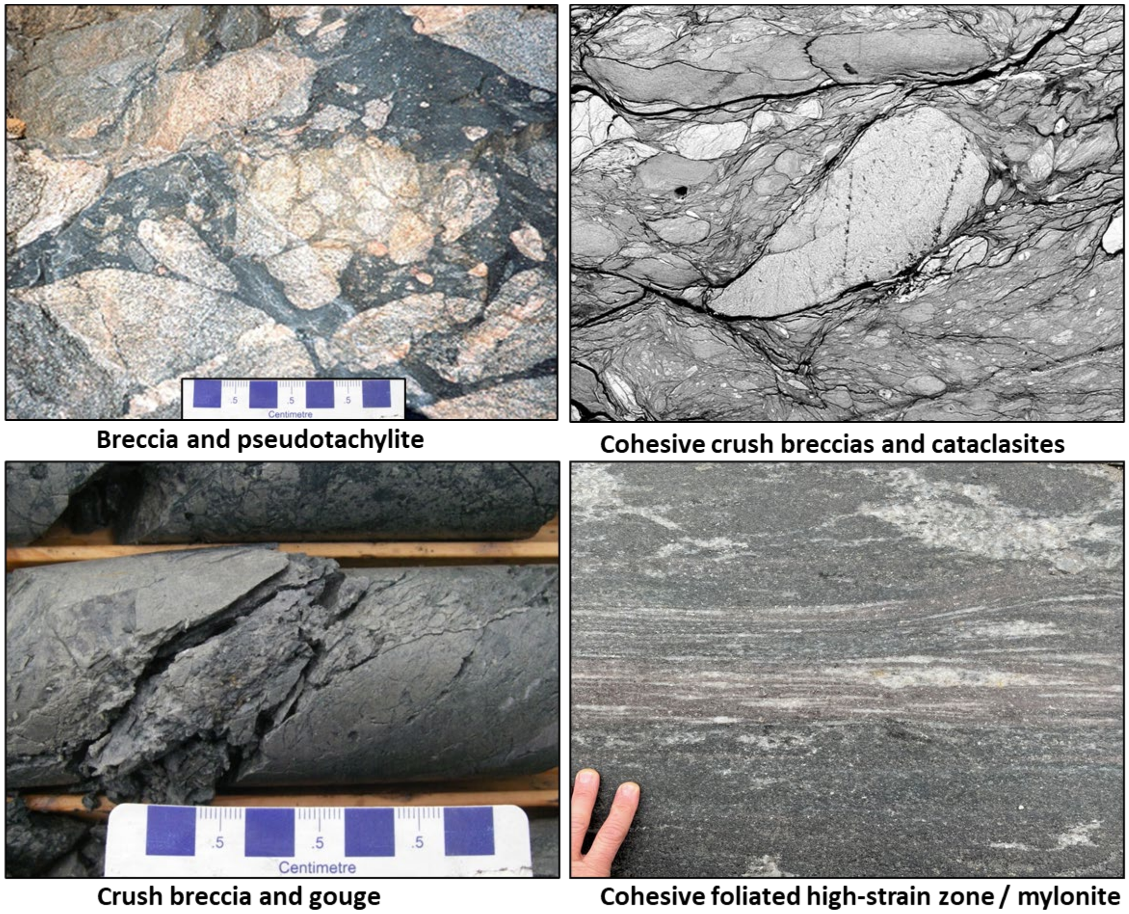

Figure 1-2: Examples of fault rock types, as labelled. Cataclasite (top right) view width is approximately 1 cm wide.

Shear zones (sometimes referred to as ductile fault zones) form in a ductile deformation environment and are characterized by strongly developed planar fabrics and commonly also linear fabrics. The key to mapping shear zones within a deformed package of rocks is the recognition and tracing out of zones of more intense foliation/lineation. Ductile deformation tends to increase with depth, though deformation rates and water activity also contribute. Many shear zones show evidence of both brittle and ductile behaviour, due to:

- Variation in deformation rate with time;
- Changes in pressure, temperature, or water activity with time; and
- Variations in the rheology of individual minerals

The internal anatomy of many faults or fault zones fits the simple two-fold classification of a central fault core and an enveloping damage zone (Caine et al., 1996; Figure 1-3). The fault core consists of highly sheared rocks that may be represented by fault gouge, cataclasite or breccia in which the original structure of the rock has been strongly masked or destroyed (Fossen, 2020).

A fault core is sometimes completely surrounded by the damage zone, which is a zone of relatively low-displacement structures, notably shear fractures, but also veins (mineral filled extension fractures), short joints, deformation bands and/or stylolites (Fossen, 2020). Large faults may also contain smaller faults with their own damage zones, contained within the large damage zone of the first-order fault. Hence, the definition of a damage zone is to some extent scale-dependent (Fossen, 2020). It is common to refer to the largest observed faults as first-order faults, then next smallest size of faults that link into the same fault system are referred to as second-order faults, and similarly for third-order faults, etc. Common fault description terminology is listed in Table 1-1.

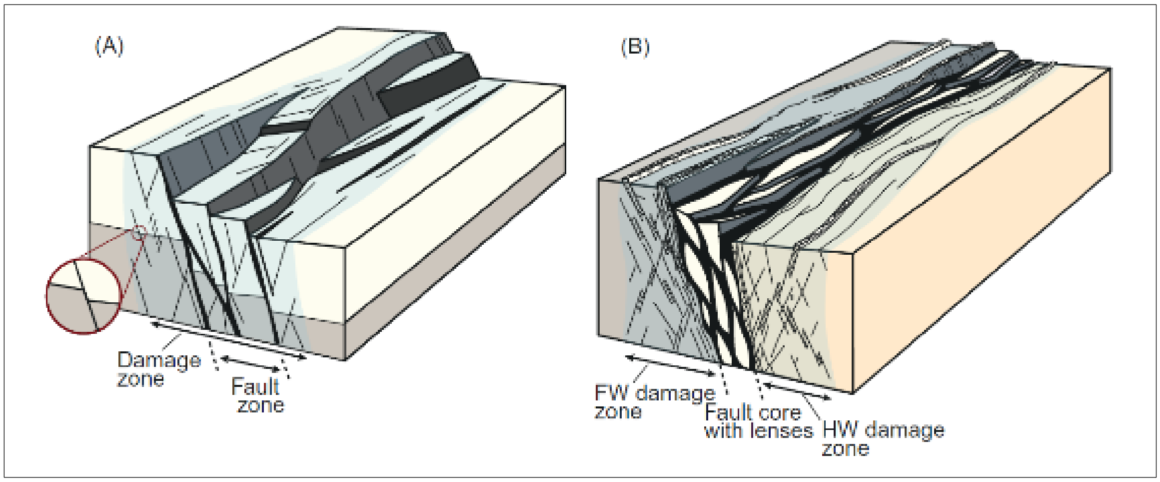

Figure 1-3: Examples of a complete fault and its different elements. (A) Slip localized on two or more narrow high strain zones (slip surfaces or fault cores shown in black). A subsidiary footwall shear fracture is highlighted. (B) High-displacement fault showing a more extensively sheared central core with a surrounding low-strain damage zone. Source: Fossen (2020).

1.5 Fault Type Terminology

Faults are described as either strike-slip (i.e., horizontal displacement) or dip-slip (i.e., up- or down-dip displacement), or oblique-slip faults (i.e. a combination of vertical and horizontal slip) (Figure 1-4). Faults should never be drawn on a geological map unless an attempt is made to determine the direction, sense, and amount of displacement. Determining the sense of displacement or shear on a fault/shear zone is a kinematic analysis and particularly important for understanding the influence of faults on map patterns and for predicting geometry of faults and related features (folds, foliations, fractures, second and third order faults etc.). Magnitude of displacement can be estimated from outcrop and map-scale features.

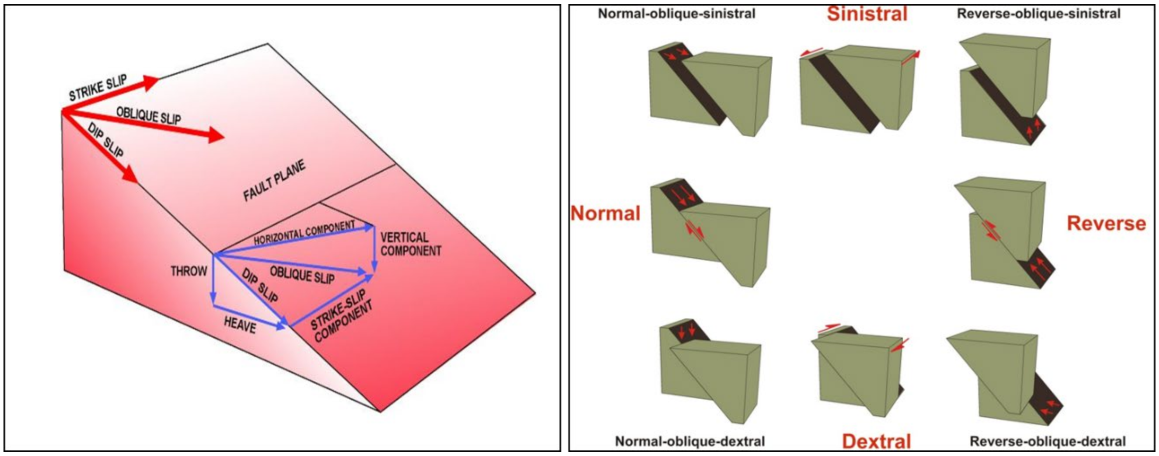

Figure 1-4: Illustration of basic fault displacement terminology.

The local direction of displacement on a fault or shear zone is best determined from outcrop observations of lineations (slickenlines, fibre growths, stretching lineations) within the fault zone. The sense of displacement on faults is best determined by outcrop and microscopic features (steps on slickenside surfaces, asymmetrical blasts and clasts, bending of earlier foliations, S/C fabrics, etc.).

The only way of reliably determining/estimating the amount of displacement on a fault/shear zone is using the measured offset of markers/rock units across the fault (i.e., fault reconstruction), but constrained with a direction of movement, such as from slickenlines or slickenfibres.

Table 1-1: Common Fault Terminology

Term	Description
Hanging wall block	The fault block overlying a non-vertical fault.
Footwall block	The fault block underlying a non-vertical fault.
Décollement fault	A low-angle fault in the basement rocks, onto which upper-crust faults sole.
Listric fault	A fault that is steeply dipping in its upper portions, becoming progressively more shallow dipping with depth.
Dip-slip fault	Movement direction parallel to dip of fault plane.
Strike-slip fault	Movement parallel to strike of fault plane.
Oblique-slip fault	Movement direction has components of both dip-slip and strike-slip on the fault plane.
Net slip	The distance on the fault surface between 2 equivalent points before faulting; equals the vector sum of the strike slip and the dip slip.
Reverse fault	A dip-slip fault by which the hanging wall block has moved upwards relative to the footwall block.
Thrust fault	A low-angle (<30 degree) reverse fault with a large displacement of the hanging wall rocks.
Normal fault	A dip-slip fault by which the hanging wall block has moved downwards relative to the footwall block

Translational fault	No rotation of the fault blocks occurs during fault movement. Strictly applied only to segments of faults.
Rotational fault	The fault blocks rotate during fault movement, so that rotation takes place around a pivot point on the fault plane.
Scissor fault	A rotational fault for which the sense of displacement is reversed across a pivot point of zero slip, the amount of displacement increasing away from this point.
Detachment fault	A low-angle normal fault, formed due to the gravitational instability of an uplifted block, along which there is considerable horizontal displacement
Conjugate faults	A cross-cutting set of fault planes which ideally intersect at angles of 60° and 120°, and have both left-handed and right-handed shear senses.
Riedel Shears	System of smaller faults that form in the principal displacement zone of a fault zone. They are named and identified by their angle to the principal fault and used to determine the direction of the maximum compressive stress (Price and Cosgrove, 1990; Davis et al., 2000)

2 Fundamental Fold Characteristics

The basic goal of structural analysis in folded rocks is to determine the shape, orientation, and position of large folds from exposures within the open pit or the surrounding vicinity of the open pit. In most areas, it is not possible to directly observe km-scale folds while standing in the field, since generally only a small part of any fold is exposed as outcrop. However, the existence and general form of larger folds can commonly be inferred by analysing the shape and orientation of outcrop-scale structures that are related to larger folds in systematic and predictable ways.

2.1 Fold Formation

Folds can form in a variety of ways. They are commonly associated with faults systems and associated deformation systems in compressional, extensional and strike-slip tectonic environments. This section does not discuss these differences. This section also does not discuss interference folding between older and younger fold systems. It is recommended refer to Ramsay et al. (1983), or Fossen (2016; 2020).

2.2 Mapping Folds

Folds are best mapped by mapping the rock units that define them. The data to be mapped to allow structural analysis should be focussed on resolving the orientation relationships of bedding and foliation, and fold vergence.

Similarly, fold systems contain multiple folds of similar trend and plunge. Folds and faults may have developed as part of a single deformation event, in which they accommodated the strain together. Faults and folds should be evaluated to determine whether (a) their syngenetic timing resulted in holistic pattern, or (b) they formed in different events, producing cross-cutting relationships.

Pit fold system mapping should record:

1. Orientations of limbs, crest line (top of the fold), hinge-lines / fold axes (plunge) of folded layers, axial plane, interlimb angles.
2. Amplitude and wavelengths of largest scale folds (up to pit scale), and smaller parasitic folds.
3. Orientation, spacing, mineralogy, and continuity of axial planar foliation, which may be locally fanned in orientation, and may be continuous or discontinuous, depending upon rock composition.
4. Timing relative to other folds, faults, vein systems, intrusive rocks or alteration systems.
5. It may also be important to capture dip isogons (Ramsay, 1967), depending on objective.

2.3 Terminology of Folds and Related Structures

Folds are generally described according to shape and orientation (Figure 2-1; Table 2-1; Table 2-2). The orientation of a fold is defined by the orientation of its axial plane (axial surface) and axis (Figure 2-1). Therefore, these two features should be measured systematically during geological mapping. The orientations of both of these structural elements must be recorded, as neither on its own provides a complete description of the orientation of a fold:

- The fold axial plane is planar feature and its orientation is therefore recorded as a strike and dip, or preferably dip and dip direction.
- The fold axis is a linear feature and its orientation is therefore recorded as a trend (plunge direction) and plunge, with the trend recorded in the down-plunge direction.

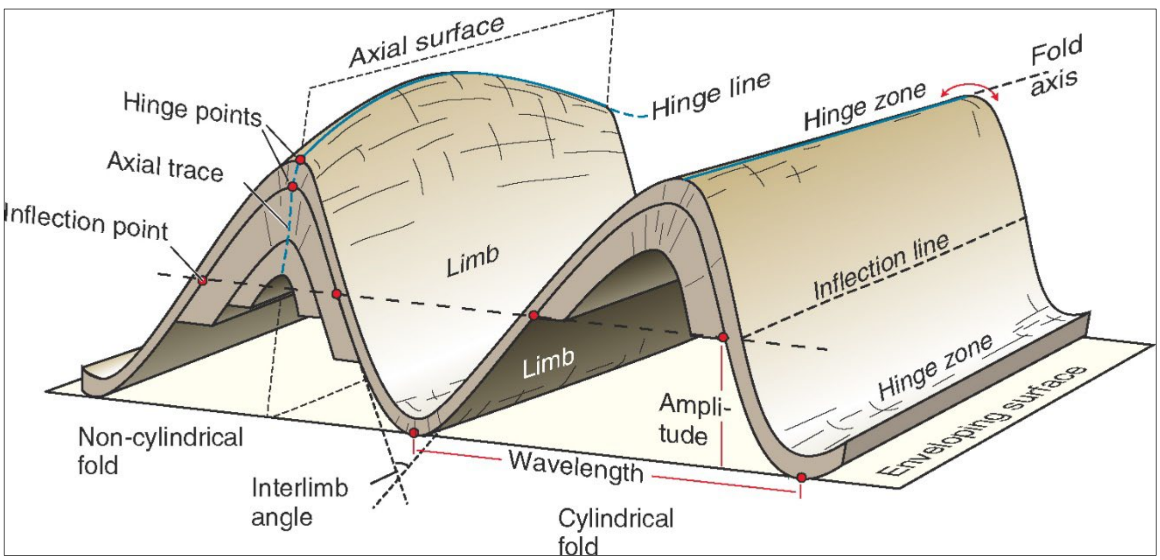

Figure 2-1: Fold examples showing the key elements of fold geometry. From Fossen (2016).

Folds may be classified by their shape — remembering that the true shape can be observed only in profile perpendicular to their plunge. The shapes of folds are generally defined by their interlimb angle and amplitude (Ramsay, 1967; Fossen, 2016). The amplitude and wavelength of folds are commonly related to the layer thickness (as well as layer competency), thinner layers generally making smaller fold wavelengths and amplitudes.

Folds with shallow to moderately plunging axes and moderately to steeply dipping axial planes can be described as synforms, antiforms, synclines and anticlines. Synforms close downwards and anticlines upwards, regardless of the relative ages of the folded units. If the relative ages of the folded units are known, the terms “syncline” (units get progressively older away from the axial surface) and “anticline” (units get progressively younger away from the axial surface) may be used.

Folds may also be classified based on the relative length of their limbs into symmetrical and asymmetrical. This is important for relating the folds to larger folds (Section 12). Symmetrical folds occur in the hinges of larger folds and have:

- Planar median surfaces;
- Axial planes perpendicular to their median surfaces; and
- Bilateral symmetry about their axial planes

Asymmetrical folds occur in the limbs of larger folds have limbs of unequal length and are referred to as “S” or “Z” folds, depending on their asymmetrical appearance.

Table 2-1: Fold Classification by Dip of Axial Surface (Ramsay, 1967)

Axial Surface Dip	Fold Type
90-80°	upright
80-60°	steeply inclined
60-30°	moderately inclined
30-10°	gently inclined
10-0°	recumbent

Table 2-2: Fold Classification by Plunge (Ramsay, 1967)

Plunge Angle	Fold Type
0°	horizontal
0-10°	sub-horizontal
30-60°	moderately plunging
60-80°	steeply plunging
90°	vertical

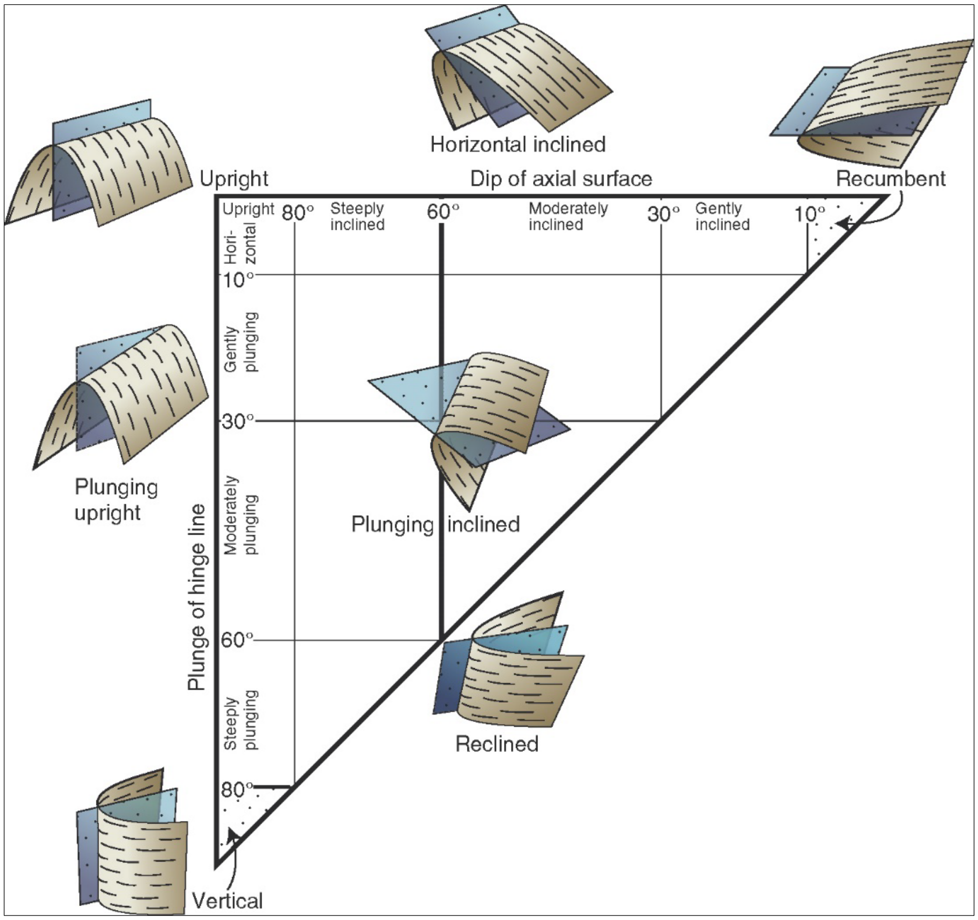

Figure 2-2: Modified Fleuty's classification of fold description (Fossen, 2016, after Fleuty, 1964).

A list of commonly used fold system terminology is provided in Table 2-3.

Table 2-3: Fold Terminology

Term	**Description**
Hinge point	The point of minimum radius of curvature of a fold
Hinge line	The locus of hinge points on a folded surface
Inflection point	The point on a fold profile at which the rate of change of a slope is zero
Median surface	The plane joining successive lines of inflection of the folded surface
Crest and trough	The high and low points, respectively, of a fold with a dipping axial surface.
Amplitude	The distance parallel to axial plane, when looking at the folds in profile, between the antiform and synform hinges. This definition assumes that the folds are symmetrical
Wavelength	The distance, when looking at the folds in profile, between nearest antiform or synform hinges. This definition assumes that the folds are symmetrical
Profile plane	The plane perpendicular to the fold axis

<table>
<tr><th>Term</th><th colspan="2">Description</th></tr>
<tr><td>Axial surface</td><td colspan="2">The surface joining the hinge lines of a set of nested folds Irrespective of whether the folds are cylindrical or not, the axial surface may or may not be planar.</td></tr>
<tr><td>Axial plane</td><td colspan="2">A planar axial surface</td></tr>
<tr><td>Axial trace</td><td colspan="2">Line representing the intersection of the axial surface and another surface (e.g., Earth's surface or the profile plane).</td></tr>
<tr><td>Enveloping surface</td><td colspan="2">Line tangential to the hinges of a group of related folds</td></tr>
<tr><td>Synform</td><td colspan="2">A fold in which the limbs close downward</td></tr>
<tr><td>Antiform</td><td colspan="2">A fold in which the limbs close upward</td></tr>
<tr><td>Syncline</td><td colspan="2">A fold with younger rocks in its core</td></tr>
<tr><td>Anticline</td><td colspan="2">A fold with older rocks in its core</td></tr>
<tr><td>Overturned fold</td><td colspan="2">A fold that has been tilted, so that both limbs dip in the same direction</td></tr>
<tr><td>Vertical fold</td><td>A fold with a (nearly) vertical hinge line</td><td rowspan="3">See Figure 2-1</td></tr>
<tr><td>Reclined fold</td><td>A fold with a gently dipping axial surface</td></tr>
<tr><td>Recumbent fold</td><td>A fold with a (nearly) horizontal axial surface</td></tr>
<tr><td>Interlimb angle</td><td colspan="2">The angle between adjacent fold limbs</td></tr>
<tr><td>Fold axis</td><td colspan="2">A straight, hypothetical line that lies along the hinge of a fold. Its attitude determines the orientation of the fold Only cylindrical folds or cylindrical segments of folds can really have fold axes. The fold axis approximates the trace of the fold, since it is defined as being perfectly straight. The hinge line is different, as it follows the actual trace of the fold.</td></tr>
<tr><td>Cylindrical folds</td><td colspan="2">Folds with straight, parallel hinge lines Non-cylindrical folds: Folds with hinge lines that are not straight and parallel).</td></tr>
<tr><td>Cylindroidal folds</td><td colspan="2">Folds that are approximately cylindrical. Though no real fold is perfectly cylindrical, many folds closely approximate this shape, at least for part of their length.</td></tr>
<tr><td>Symmetrical folds</td><td colspan="2">Folds with (1) planar median surfaces, (2) axial planes perpendicular to their median surfaces, and (3) bilateral symmetry about their axial planes</td></tr>
<tr><td>Asymmetrical folds</td><td colspan="2">Folds that do not meet the three criteria for symmetrical folds</td></tr>
</table>

2.4 Axial-Surface (Axial-Plane) Cleavages/Foliations

Folds that result from compressional deformation and shortening form foliations approximately perpendicular to the direction of shortening/compression. Foliations are approximately parallel to the axial planes of folds of the same deformation phase (Figure 2-3), however, foliations may refract to a high angle. The refraction in a multi-layered rock, e.g. turbidites is common and is controlled by competency contrast. Foliations are defined by aligned platy minerals such as biotite and white mica, as well as compositional differences between layers (especially in `recrystallize in orientations sub-parallel to the fold axial plane. The intensity of foliation in each rock type partially reflects the amount of deformation, but also depends factors such as mineralogy and fluid availability.

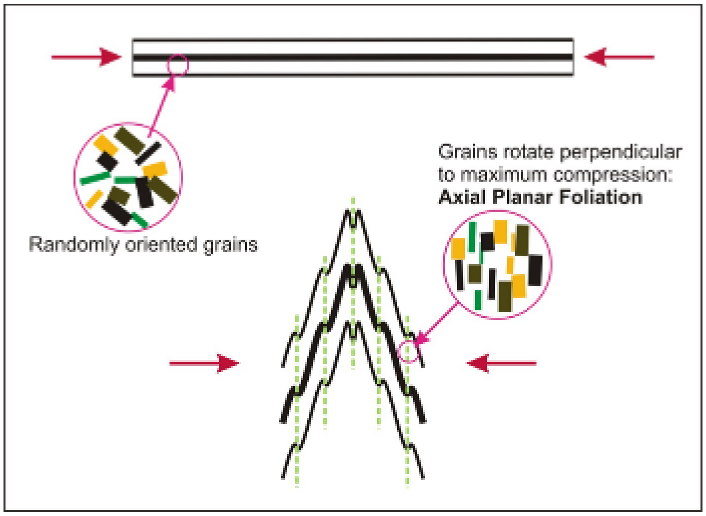

Figure 2-3: Schematic formation of an axial planar foliation during folding

Systematic recording of the orientation of axial planar foliations, as well as bedding, is an important aspect of the mapping of folded rocks.

An axial plane foliation approximately bisects the angle between the fold limbs, so that the relative dips of bedding and foliation can be used to determine your position on the fold. In overturned folds, the bedding on the overturned limb dips more steeply than the foliation (Figure 2-4:). Foliation and bedding are perpendicular in fold hinges and make smaller angles on the limbs. The tighter the fold, the lower the bedding/foliation angle on the limbs, and the higher the proportion of low-angle, limb bedding/foliation intersections.

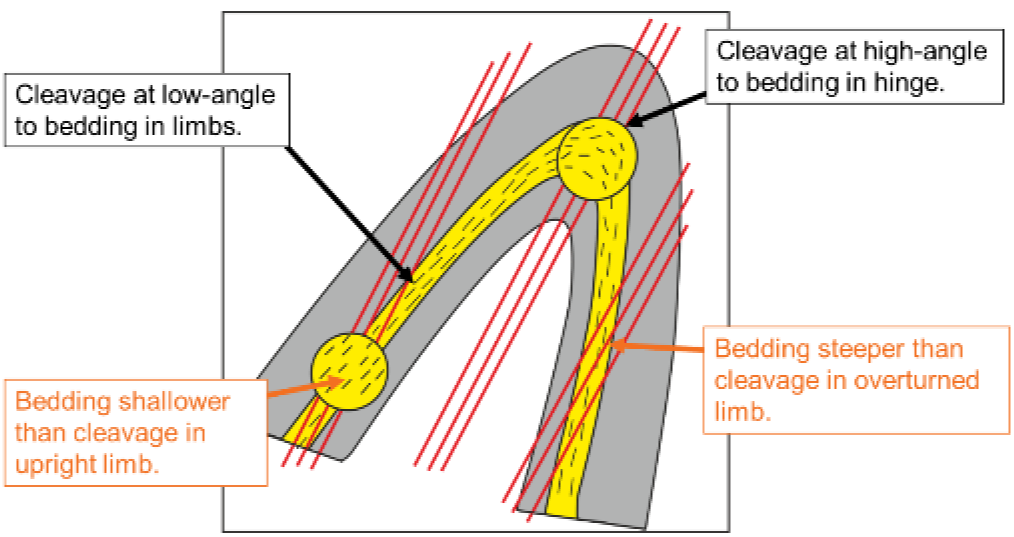

Figure 2-4: Fold vergence based on bedding and cleavage orientations (red lines) in an antiform

Bedding and foliation intersect in a line parallel to the axis or hinge of the fold. Bedding/foliation intersections (usually seen as bedding lineations on a foliation surface) are thus measures of the plunges of folds.

The orientation relationship between bedding and foliation in outcrop and small-scale folds is asymmetrical and therefore a form of vergence that can be used to locate fold hinges, as discussed below.

2.5 Parasitic Folds and Fold Vergence

Large folds are commonly associated with smaller, outcrop-scale parasitic folds, the orientation of the axes and axial planes of the parasitic folds approximating the orientation of the axis and axial plane of the larger fold (Figure 2-1: Fold examples showing the key elements of fold geometry. From Fossen (2016).; Figure 2-5). By measuring the orientation of the axes and axial planes of parasitic folds, the geometry of the larger-scale parent fold can be inferred.

This is because the two limbs of an ideal fold are mirror images of one another, and this symmetry relationship is a powerful tool for determining the position of an outcrop-scale fold on a large structure. Small folds on the limbs of a larger fold are generally asymmetrical, and the sense of asymmetry or vergence of the small folds is used to locate large fold hinges (Figure 2-4). The asymmetrical relationship between bedding and the axial planes of parasitic folds changes across the hinge of the larger-scale parent fold.

In the hinge of the larger fold, the limbs of the parasitic folds are close to symmetrical about their axial planes. The change in the asymmetry of the parasitic folds across the hinge of the larger parent fold is commonly referred to as a change in vergence. The parasitic folds are said to “verge” towards the hinge of the parent fold. The asymmetry of folds can be conveniently described as either "S" or "Z" shaped when looking down-plunge and used to locate fold hinges. Symmetrical parasitic folds in the hinge area of the large fold are called "M" (for antiform) or “W” (for synform) folds. By recording the asymmetry or vergence of parasitic folds it is possible to determine the position of the hinge of the larger parent fold without direct observation of the hinge itself (Figure 2-5).

Comparisons of fold asymmetry must be made looking in the same direction down the fold plunge, because the asymmetry of a fold switches when viewed in opposite directions along the hinge.

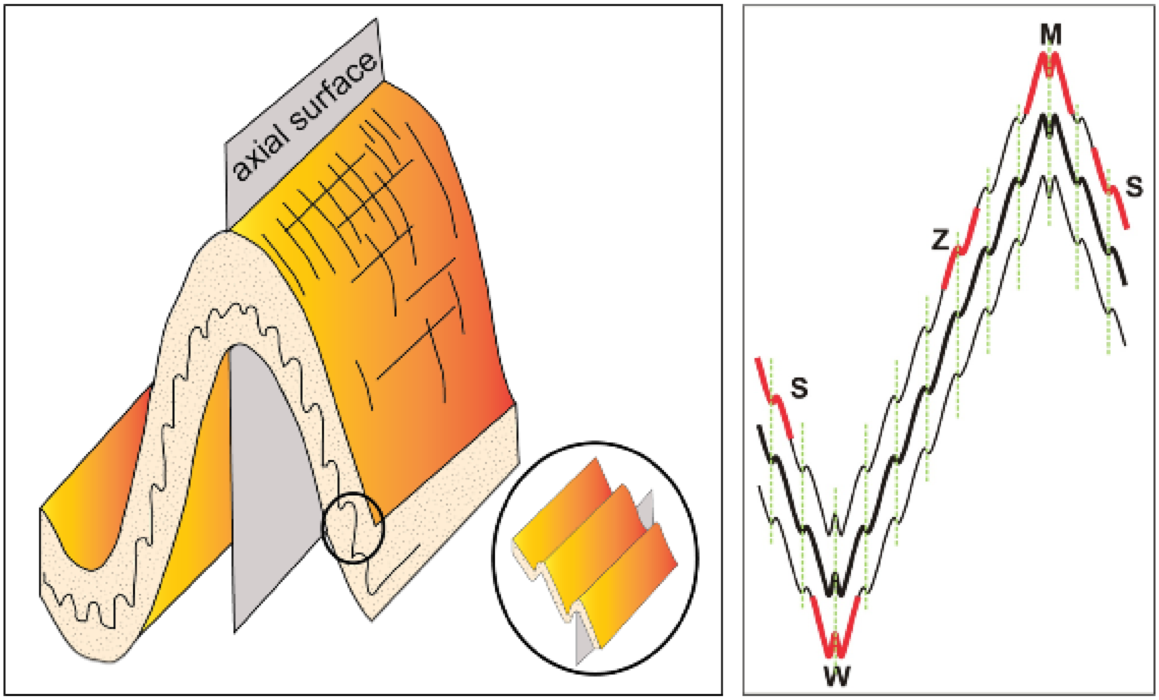

Figure 2-5: Schematic representation of parasitic folding and fold vergence based on parasitic folds

2.6 Intersection Lineations as Indicators of Fold Axes

Intersection lineations result from the intersection of two planar structures and are mainly useful in unravelling the geometry of folded rocks as they are parallel to the axes of folds. The most obvious intersection lineations are bedding/foliation (bedding/cleavage) intersections, which represent the plunge of the folds in the deformation event that formed the foliation. These intersection lineations are very useful as they provide an indication of the fold plunge no matter where on the fold they are measured.