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What happened to the structural model? A review of current open pit design practices and the development of structural models

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Abstract

In open pit mining, major geologic structures (faults and shear zones) play a significant role in slope stability assessment and open pit design. Commonly, however, open pits at the pre-feasibility, feasibility and development levels lack a structural fault model at an appropriate scale. The scale and confidence of the structural model, as well as the experience of the development team to perform field work, review drillcore, interpret data and build the model, is vital to the structural sub-model portion of the geotechnical model. Herein, we briefly review metadata from a series of publicly available pre-feasibility to feasibility-level open pit design reports and provide comments on the development and confidence of those models, if present.

We then present the methods used to develop a major structure model at the scale of an open pit development. This methodology includes a review of available data sources, a structural analysis, a model development and a confidence rating methodology. The methodology is also illustrated with a case history.

Keywords: *slope stability, structural model, open pit mining, confidence level, uncertainty, design stages*

1 Introduction

The objective of any open pit slope design is to provide an optimal excavation design that leads to the steepest possible open pit slopes while ensuring safety, ore recovery and financial returns are maximised. Weighed against this objective is the increased likelihood that steeper slopes perform poorly and have instability issues. Such slope stability failures could impact worker safety, ore recovery and ultimately the financial viability of the project (Read & Stacey 2009).

Generally, slope design takes into consideration an analysis of the overall slope stability of an open pit wall (i.e. all the benches and ramps from the pit floor to the surface), inter-ramp angle and height and the bench design (i.e. bench width, bench face angle, and bench height). Applying these parameters, the overall slope angle, inter-ramp angle and the bench face angles are designed based on achieving an acceptable Factor of Safety (FoS). From an operational perspective, open pit slopes at bench-scale are usually considered too conservative if no instabilities occur. As a result, some instability is expected and is planned to be controlled during open pit development (Read & Stacey 2009).

In the process of developing an optimum slope design, a well-defined 3D model of major structures needs to be included in the assessment. This paper discusses the following:

- The importance of a major structures model in slope stability optimisation.
- Results of a review assessing publicly available open pit mining project technical reports for the presence of a structural model.

- Methodologies that can be applied to complete a major structures model and fault confidence-level assessments.

Major open pit mine failures at the inter-ramp to overall scale are often the result of movement along large fault structures. This was the case for the 10 April 2013 failure of the Bingham Canyon pit wall, which occurred along a fault on the north-eastern wall of the open pit (Llano & Williams 2016). This failure was initially reported by news media to have cost one billion dollars to the operation (Pankow et al. 2014). Another good example of the impact of geological structures is the Randa rockslide in Switzerland. In the Randa rockslide, geological structures intersected to form a sliding plane and lateral release surfaces leading to failure (Stead & Wolter 2015).

2 Geotechnical model

The geotechnical model is the basis for all open pit slope design (Read & Stacey 2009) and comprises four sub-models, these are:

- Geological model.
- Structural model.
- Rock mass model.
- Hydrogeological model.

The sub-models that make up the geotechnical model are summarised in Figure 1, along with key data inputs.

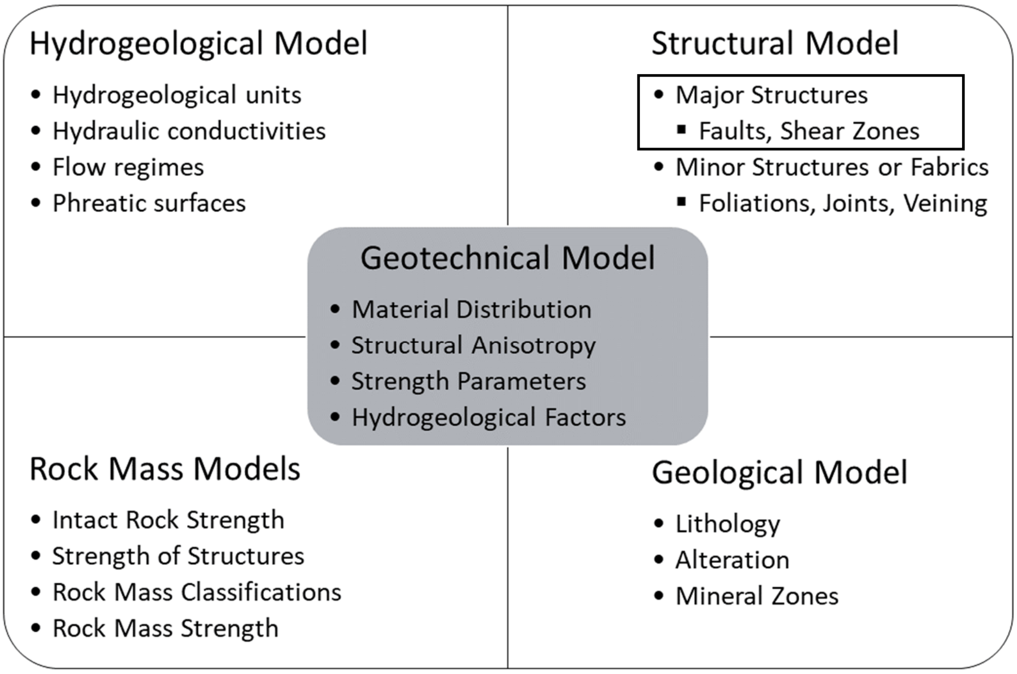

Figure 1 Geotechnical model, sub-models, and their key data inputs (adapted from Read & Stacey 2009)

3 Structural geology model

A structural geology model for open pit slope design is commonly divided firstly into the major structures (folds, faults and shear zones at the inter-ramp to overall pit scale) of the model and secondly into structural fabrics or discontinuities (generally bench-scale) model.

Herein, we focus on major structures at the inter-ramp to overall pit scale and their effect on open pit slope design. Faults are defined as any surface or zone that has undergone movement of one block of rock relative to the other. Major structures should be continuous both along strike, down dip and persist over multiple benches. Given scale of major structures, they are of the most concern to the stability of the inter-ramp and overall slope design.

3.1 Slope design methodology

As noted in Read & Stacey (2009) the formalised process of open pit slope design has been largely developed over the past 35 years. It includes:

- Development of the geotechnical model (including major structures).
- Division of the geotechnical model into domains (areas of similar anticipated rock mass characteristics and behaviour).
- Sub-division of the geotechnical domains into design sectors.
- Slope design for each design sectors at the bench, inter-ramp and overall slopes.

The following stability analysis is usually completed.

- Kinematic stability analysis – Stereographic analysis of discontinuity orientation data are conducted to identify kinematically possible failure modes. If structures are persistent enough to cut multiple benches, then kinematic failure modes at the inter-ramp scale must also be evaluated.
- Numerical modelling (rock mass stability) analyses – The overall FoS against large-scale, multi-bench rock mass failure is commonly evaluated using a 2D or 3D limit equilibrium and/or finite element modelling approach. This is usually completed at the inter-ramp and overall slope scales.

3.2 Major structures model and anisotropy

Structural features relative to their orientation and characteristics control rock mass strength and behaviour in terms of rock slope stability (Stead & Wolter 2015). Faulted rock masses may present anisotropic strength criterion during open pit design. In this case, understanding major structures and their rock mass strength is an important component of design. Figure 2 illustrates the effects of rock mass anisotropic strength in the analysis of a 200 m high rock slope in a Rocscience Slide 2D model (Read & Stacey 2009). As displayed in Figure 2, a weaker discontinuity daylighting out of the slope has a significant effect on the FoS of the slope.

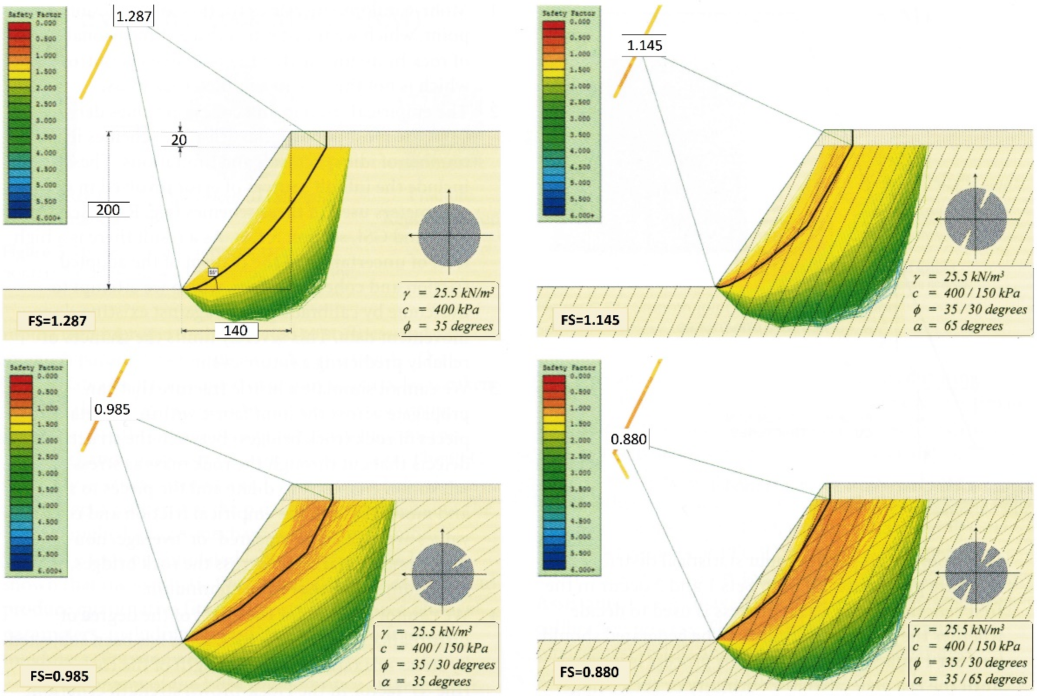

Figure 2 Factor of Safety of a 200 m rock slope, with different conditions of rock mass strength (after Read & Stacey 2009, Figure 5.48)

4 Technical report review

A total of 30 publicly available pre-feasibility and feasibility reports with a focus on open pit mining were reviewed as part of this study. The purpose of the review was to determine whether the study included a structural model related to major structures and, if so, whether the structural model was appropriate for the use and scale of the project.

Of the 30 reports reviewed, only five (17%) reported a structural model being completed and used in the open pit design. Further, despite, Read & Stacey (2009) stating, 'it is stressed that the task of erecting the structural model is one for an experienced structural geologist, rather than an exploration or mine geologist', only three of the five structural models were clearly developed by a team focused on structural geology with the intent of using the model for geomechanical mine design. It should be noted that this is not to say that the models developed by an exploration or mine geologist are wrong but rather that they are often focused on the geometry of the ore deposit and may not include structural model data directly applicable to open pit geomechanical mine design.

Of the reports reviewed, all of them included data on pit geology, rock mass characterisation, rock mass laboratory testing, and bench-scale fabric data. Therefore, the question remains, why has the design team proceeded without a structural model of major structures? Herein, we present a summary of the development of an open pit scale structural model; including key data inputs, modelling methods, data verification and a confidence rating system.

5 Structural model methodology

A structural geology model for open pit slope design is commonly divided into (a) major structures (folds, faults and shear zones at the inter-ramp to overall pit scale) model, and (b) structural fabrics or discontinuities.

5.1 Input data

Prior to beginning a major structures model for a project, the qualified structural geologist must familiarise themself with the structural and tectonic framework of the area. This is done by reviewing all relevant and available studies, at various scales, on topics such as regional/local tectonics, geology, exploration reports and structural geology. They will then have an initial conceptual idea regarding what to expect in the project area in terms of the types of potential structures, and their orientations, when modelling begins. An understanding of the development of structures due to tectonic processes over geological time is critical to ensure that fault cross-cutting relationships and linkages are modelled correctly.

Next, all relevant structural data, as well as other possible data that can be used for advancing structural interpretations, need to be compiled into a 3D format and reviewed. As a first step, the structural geologist needs to decide if the model will include only brittle structures or ductile structures or both. Brittle structures such as joints and faults develop due to rock fracturing or rock breaking, whereas ductile structures, including anticlines and synclines, are formed from rock bending (Fossen 2016).

The structural data type/set combinations available for each project are generally unique and will vary. Also, each dataset within a project commonly show variability in both data consistency and data quality; the structural geologist needs to assess and familiarise themself with each of these nuances so that they can be factored into fault interpretation decision-making and confidence level determinations. Examples of potentially useful data types for major structures modelling, as well as some potential data quality/consistency limitations for consideration, are listed in Table 1.

Table 1 Common data types used for major fault modelling

Data type	Possible criteria	Confidence understanding
Logged faults/gouge zones in drilling	Filter to a minimum downhole depth range	How does logging vary between drill programs loggers? Are noted faults dispersed into various tables, or perhaps not even transcribed from historic logs?
Low rock-quality designation (RQD) geotech intervals	To begin, consider RQD intervals of <50% to identify heavily damaged zones	How wide are the structures, and are they thick enough to be identified in low RQD? Perhaps a core photo review will be necessary. Are certain drill programs missing data?
Oriented core faults/gouge	Filter to the highest data quality, minimum downhole width, or specific orientations	Can data from some drilling programs be trusted over others?
Televiewer faults	Filter to a minimum downhole width or orientation	Is the televiewer data corrected for inclination, declination and/or mine grade correctly? Are measured faults reviewed and confirmed?
Independent core photo review and fault identification/ confirmation	Consider reviewing select core photo intervals for structures not identified in the drillhole database	Is the core photo of proper quality, and does it have depth markings?

Data type	Possible criteria	Confidence understanding
Topographic lineaments	Do they fit into structural framework? Compare to mapped lithologies	Is LiDAR available? Previously interpreted lineament analyses cannot always be taken as structures and must be re-evaluated with all other data
Geophysical lineaments	Disruptions/ irregularities	Scale of the survey
Surface and underground mapping	Review contact types for faulted contacts	How reliable is the existing structural mapping? Measurements and descriptions between programs must be reviewed validation can be conducted via a site visit
Historic interpretations/ information	This can be used in areas where no other data exists (i.e. old inaccessible workings) or to also confirm more recent work	How does it compare with all other available forms of data?
Lithology	Review the existing geological models and/or database litho coding for kinks or offsets	Is the drilling dense enough, and does it have the level of consistent logging to ensure geological offsets?

5.2 3D modelling methods

After all data has been compiled and reviewed, all available oriented fault measurements, available from mapping and oriented downhole data, should be reviewed in stereonets, and fault set orientations identified. As a first modelling pass, the orientations of the major fault sets should then be reviewed in 3D for any obvious correlations with other data sources (e.g. low RQD zones or logged faults).

After all data types have been reviewed and assessed in 3D and in a sectional format, structural trends can be tested and modelled. Following this, 3D fault plane or volume meshes can then be interpreted and/or correlated with the data, with most logged fault intervals, low RQD intervals and oriented faults identified in an oriented core/televiewer. The structural geologist begins modelling by systematically assessing the highest confidence and most correlative data and assigning them to individual fault models. Fault interpretations/orientations can then be compared with other data types and correlated/adjusted where applicable.

5.3 3D model validation

The structural geologist then subjects the model to various global validation tests to establish the overall level of confidence in the geological interpretation. In order of increasing confidence, validation tests include:

- Admissibility: geological structures in a deformed-state section or model should resemble real structures observable in outcrops in the area. The structural style of the model should reflect the rheology, metamorphic grade, state of strain and general tectonic environment of the area in question.
- Kinematic plausibility: the model should be qualitatively retro-deformable in a series of stages, consistent with the tectonic evolution of the region.

- Viability: a section or model to an undeformed state according to geometric criteria, such as footwall–hanging wall agreement, constant bed volume and consistent fault displacement (palinspastic restoration).

It should be noted that a model or section that passes all three validation tests is not necessarily correct; rather, it indicates that it represents a better interpretation than the alternative. In areas of sparse data, multiple valid models may exist. Additionally, some geometrical tests for viability (e.g. a balanced, or volume-constant, model/section) may not be applicable where there has been significant fault displacement beyond the boundaries of the model or out of the plane of the section. Volume-constant deformation may also not apply to ductile deformation at higher metamorphic grades.

5.4 Numeric fault confidence ranking

Once a 3D major fault model has been validated, an overall semi-quantitative confidence ranking for each major structure can be assigned. This method of assigning confidence levels to major brittle fault structures is considered a subjective assessment that relies on a structural geologist's technical competency and experience across a wide range of projects.

Structure confidence assessments reflect data points occurring along the entire strike and dip extents of each fault. Two confidence types are incorporated into a structure's overall confidence level. The first type of confidence is in the underlying data support for the interpretation, which includes input from the structural geologist's assessment of the amount of confidence for each data type, some examples of which are listed in Table 1 (e.g. diamond drillhole [DDH] logged faults, low RQD, topographic expression, magnetic expression). A score of 0–10 is given to each category of data type listed in Table 1, with 0 being no confidence or no data, and 10 being high-confidence. Table 2 shows numeric data confidence ranking assignments for each data type category (e.g. DDH logged faults, low RQD). For example, if a data type category (e.g. DDH logged) has a low data confidence level in competent structural geologist judgement, that particular data type category will receive a score from 1 to 3 in a confidence level calculation. It should be noted that the available data categories will vary between projects.

Furthermore, a full score of 10 would be assigned to a data category in an ideal situation. For example, for the logged fault category to score a 10, the logging dataset would need to show a high level of consistency in logging and distribution and clearly define the fault to the highest level possible for that specific data type.

Table 2 Confidence level scoring for each data type category

Confidence ranking value (s)	Data confidence level
0	None, or no data
1–3	Low
4–6	Moderate
7–10	High

The second type of confidence to be incorporated into the overall confidence of a structure involves the structural geologist using their project experience and geological judgement to compare and assess the confidence of each fault in the major structures model. For each fault, the geologist then assigns a 'geological judgement value' ranging from 0 to 50. This value will reflect how the structural geologist rates each fault, with all data types considered. For example, a fault that has perfect definition with respect to logged faults but ranks lower in the other data categories can be given a score of 50 to bring the structure into the highest confidence. Likewise, a fault with low data confidence, but with representation in all categories, can be assigned a lower geological judgement value. Data categories and the geological judgement value are then summed for each fault and divided by the total possible sum to determine a fault confidence percentage. The fault confidence scores are then determined from the confidence percentage according to the following criteria: 0–40% (low), 40–70% (medium) and >70% (high). The geological judgement value accounts for 50% of the total fault confidence rating, illustrating the importance of having geological structures modelled by a competent structural geologist.

6 Example case history

For an example of how to apply this methodology, we will present the major structures model developed for Marathon Gold Inc.'s feasibility-level Berry deposit, which belongs to Marathon Gold's Valentine Gold Project, located in Central Newfoundland, Canada, completed by Terrane Geoscience Inc (2022). An overview of the major structures model for Berry is shown in Figure 3, and fault confidences for a select range of faults are summarised in Table 3.

6.1 Confidence level of faults

As outlined in Table 3, five data types are involved in determining the confidence level of faults in this project: topographic expression, magnetic expression, DDH logged faults, low RQD, and DDH-oriented faults. For each data type category, a confidence value of 0–10 is given based on Table 2. A geological judgement value of 0–50 is then assigned per each fault as explained above. The total confidence level of each fault is sum up of data categories confidence value and geological judgement value. After determining total confidence value of faults, each fault can be labelled high, moderate, or low according to total confidence value.

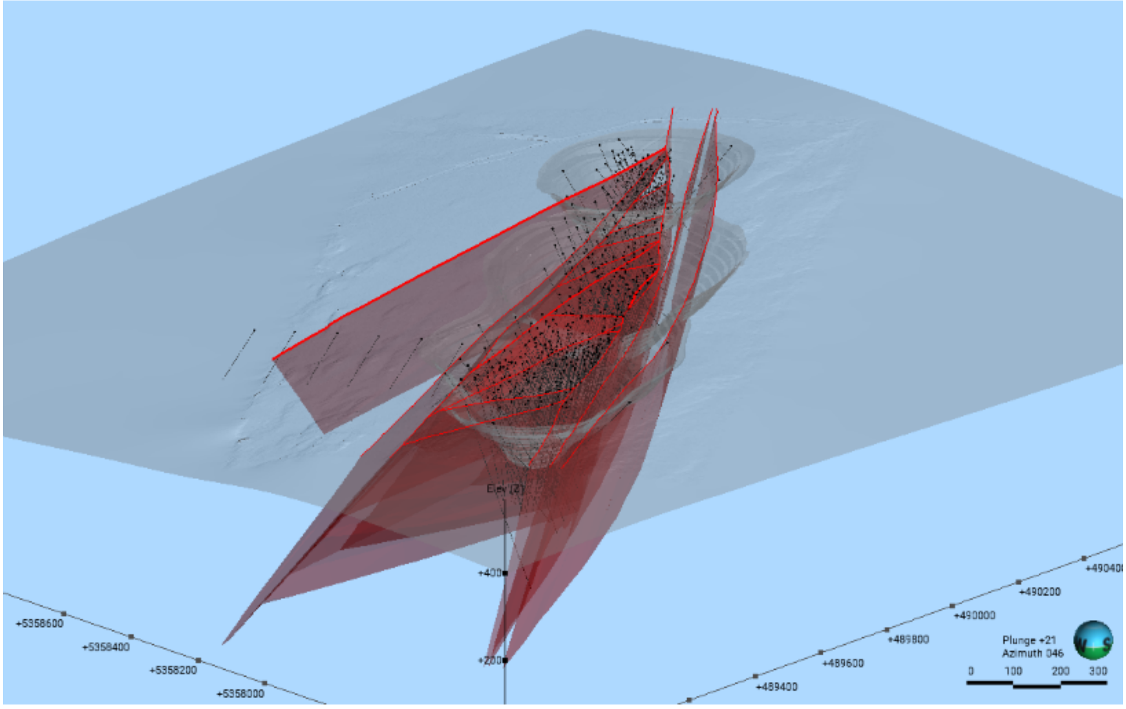

Figure 3 Berry deposit major structures model overview

Table 3 Major structure model for the Berry gold deposit – select fault confidence levels

Fault ID	Data type confidence (0–10 for each category)					Geological judgement (0–50)	Confidence (%)	Fault confidence assessment
	Topographic expression	Magnetic expression	DDH logged faults	Low RQD	DDH-oriented faults			
Fault 1	5	10	10	2	5	50	82	High
Fault 2	5	4	10	10	8	50	87	High
Fault 6	0	0	3	3	3	25	34	Low
Fault 11	0	1	2	3	7	40	53	Moderate

To elaborate further, Fault 1 (thrust fault) occurs at the contact between intrusive units to the north and a conglomerate unit to the south (Figure 4) and has a high level of definition from the geological logging; therefore, it was assigned a perfect score of 10 under the DDH logged fault category. In other data categories, the surface trace of Fault 1 shows a consistent but subdued topographic expression and was given a moderate confidence score of 5. The expression in the geophysical magnetics was as sharp as could be expected; therefore, it was given a score of 10. The structural geologist understands this fault to be ranked at a high level of overall confidence and assigns the highest score of 50, based on geological judgement.

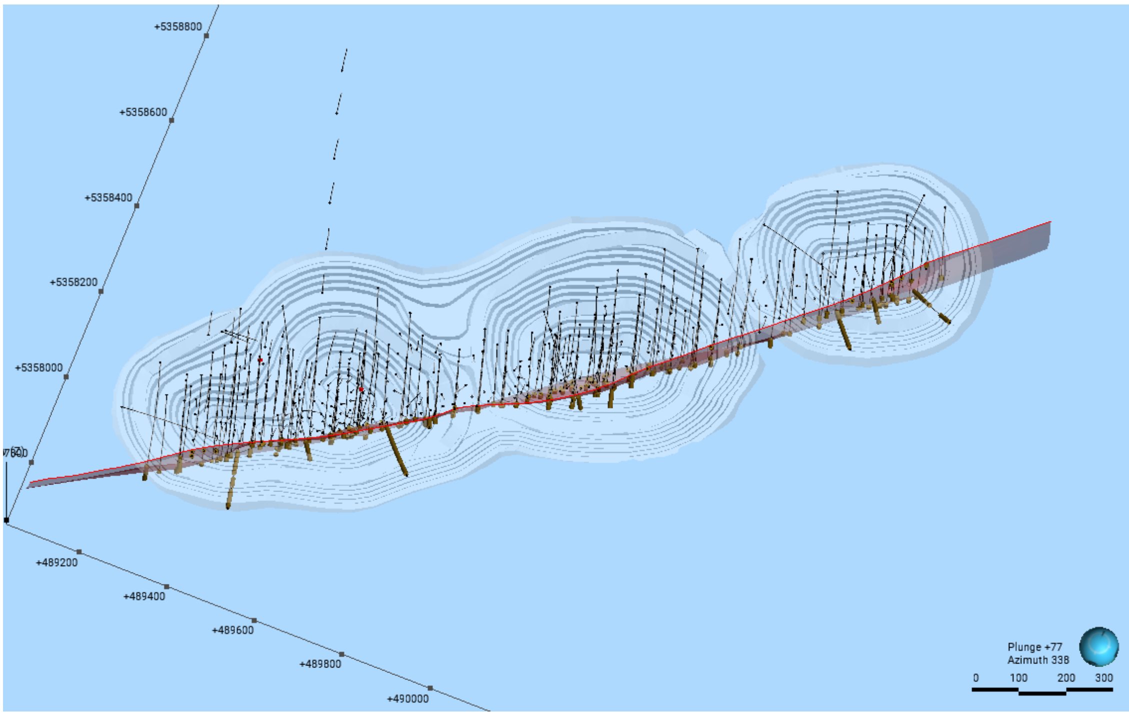

Figure 4 Fault 1 (Thrust Fault) with conglomerate intervals displayed

In the instance of high-confidence structure Fault 2 (Figure 5), there is a high level of definition in both the logged fault and low RQD data categories; it was therefore given a perfect score of 10 under each. Looking at the geological data, the structural geologist understands this fault to also be at the highest level of overall confidence and assigns a score of 50 for geological judgement.

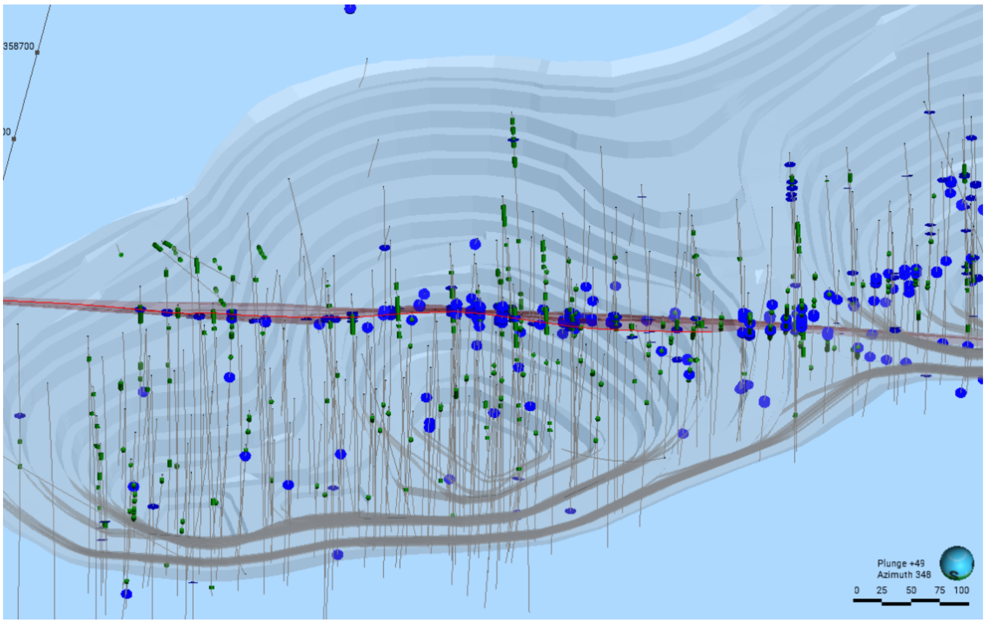

Figure 5 Fault 2 with logged fault (blue) and low RQD (green) intervals displayed

Fault 6 (Figure 6), a low- to medium-confidence structure, is defined by one oriented measurement and more sparsely distributed logged fault and low RQD intervals. Overall, due to the data density, the structural geologist understands this fault to be defined at a low to moderate range and assigns a score of 25 for geological judgement. This could perhaps be augmented to a higher level with an infill core photo review for potential faulting.

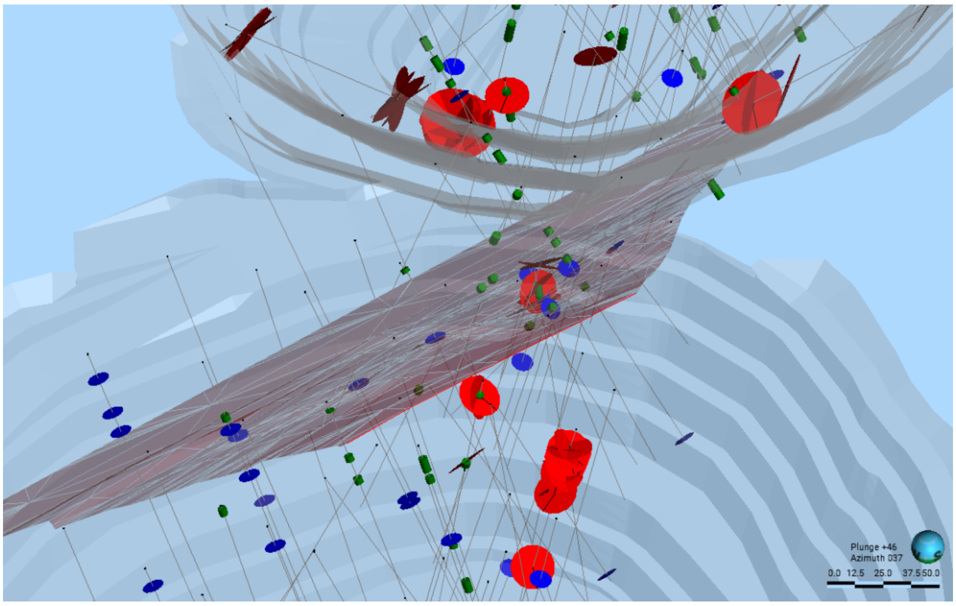

Figure 6 Fault 6 with logged faults (blue), oriented faults (red) and low RQD (green) intervals displayed

Fault 11 (Figure 7) has a similar amount of logged fault and low RQD data density as Fault 6; however, it contains three well-distributed interspersed oriented measurements. In light of this complementary data, a geological judgement score of 40 was assigned by the structural geologist to bring the fault closer to a medium level of confidence.

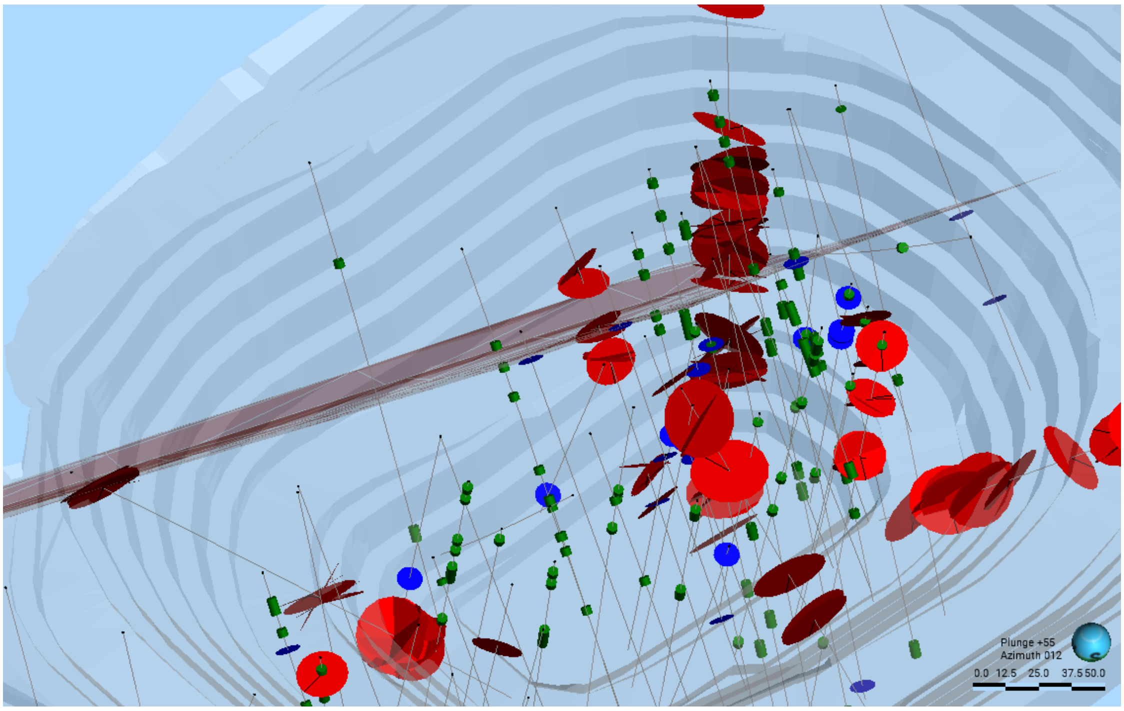

Figure 7 **Fault 11 with logged fault (blue), oriented faults (red) and low RQD (green) intervals displayed**

Once a fault model has been assigned an overall numeric confidence level, it can then be compared to the criteria required to meet the various stages of design (e.g. conceptual, pre-feasibility, feasibility and construction level). Table 4 summarises the data confidence levels required for each design stage (Read & Stacey 2009).

Table 4 **Levels of geotechnical effort and data confidence at project stages (Read & Stacey 2009)**

Item	**Project design stages**				
	Conceptual (Level 1)	**Pre-feasibility (Level 2)**	**Feasibility (Level 3)**	**Design and construction (Level 4)**	**Operations (Level 5)**
Overall confidence level of a geological structure	>20%	40–50%	45–70%	60–75%	>75%

6.2 3D confidence heat map

The numeric ranking system generally describes the overall confidence level across the entirety of a 3D fault interpretation; however, because the density of contributing data points is commonly variable across a fault model plane or solid, the attributed confidence levels from the numeric system tend to be more localised. To better communicate confidence variability across a 3D fault model interpretation to those working with it downstream, variations in fault confidence levels can also visualised using a 3D fault confidence heat map. This methodology is modified slightly from Owen et al. (2022). A 3D fault confidence heat map can be generated for each structure by performing a numeric distance evaluation (Leapfrog Geo software) to the contributing data points/types used to define the fault interpretation and/or to points/areas inserted by the structural geologist to reflect their best geological judgement on the 3D distribution of confidence levels for a given fault. An example of a 3D fault confidence heat map for Fault 1 (described above) at the Berry deposit is displayed in Figure 8. In this instance, confidence levels are a function of distance to informing data points with higher-confidence areas (red) occurring within 25 m of a contributing data point, medium-confidence areas (yellow) within 50 m, and lower confidence areas (blue) greater than 50 m from a data point. Distance criteria are always project specific.

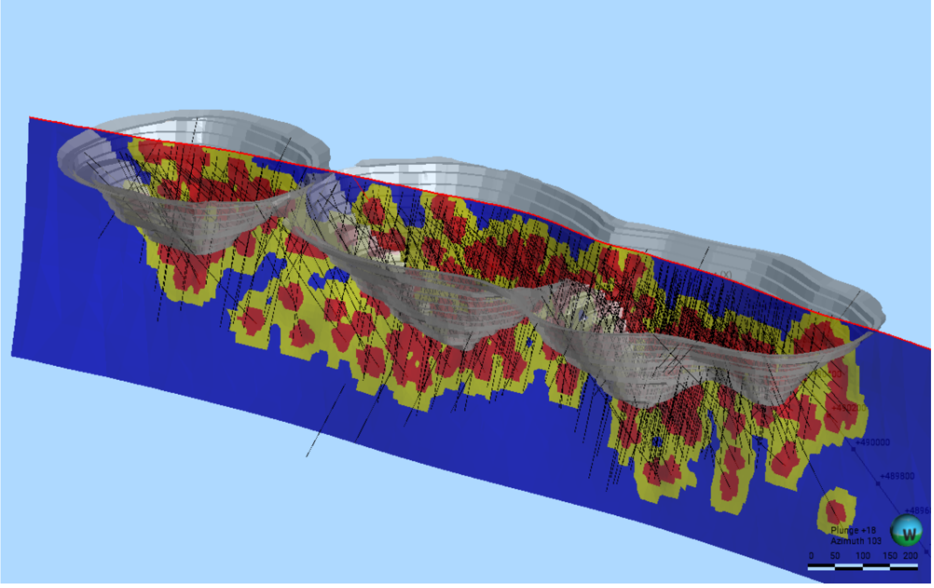

Figure 8 3D fault confidence heat map for Fault 1 at the Berry deposit. Confidences: high-confidence (red) areas located within 25 m of a data point; medium-confidence (yellow) areas located within 50 m of a data point; lower confidence (blue) areas located >50 m of a data point

7 Conclusion

A well-developed and accurate major structures model is necessary in order to develop an optimum open pit mine design that maximises project economics and provides a safe working environment. A review of 30 randomly selected and publicly available pre-feasibility and feasibility project technical reports showed that only 17% contained a major structures model in their slope stability design report. This illustrates a commonly neglected gap that needs to be highlighted. The 3D major structures model should be completed by an experienced structural geologist – working in collaboration with the exploration and rock mechanics engineering teams – who has worked on a wide range of projects with a focus on fault models for open pit geomechanical design. Herein, we have presented a summary of the development of an open pit scale structural model, including a summary of key data inputs, modelling methods, data verification and a confidence rating system.

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