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The development process of an applied geotechnical model for the Hemerdon deposit

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Abstract

The geotechnical model outlines the current engineering geological understanding of a deposit and provides a rational representation of the rock mass properties observed at the site. The primary purpose is to help inform subsequent slope stability modelling and by incorporating the geotechnical model into the analysis, engineers can evaluate the potential for slope failure and determine the optimal pit design that is safe while maximising efficiency.

However, if there are inconsistencies in the geotechnical model the pit designs created may not adequately account for potential risks and as a result, sub-optimal designs will be generated. These inconsistencies can arise from various factors such as insufficient site investigation or limitations in the analysis techniques employed. Therefore, a significant amount of effort is expended to collect and interpret data to justify the model parameters.

This paper outlines a methodology to develop the geotechnical model domains. It highlights an iterative approach which combines field observations, 3D models visualisations and the application of data visualisation techniques to justify model boundaries. The proposed method was applied to the development of the geotechnical model for the Hemerdon Mine, a tungsten deposit which is located in the southwest of the UK.

It is concluded that by using the techniques presented in this paper, engineers can develop robust geotechnical models which better reflect the rock mass conditions and therefore, improve the outcomes of subsequent slope stability modelling.

Keywords: *constructing geotechnical models, case studies, geotechnical characterisation*

1 Introduction

Holistically, a geotechnical model is used to divide rock into regions where the geotechnical conditions are expected to be similar to analyse the stability of pit slopes (de Bruyn 2021). More recently, approaches using either 3D models or block models have been used to define domains. As a result, a significant amount of time, effort, and money is spent collecting and interpreting data to justify the model parameters such as, geotechnical boundaries or rock mass properties.

The requirements for developing the geotechnical model have been discussed extensively in the recent literature (Barnett et al 2021; de Bruyn, 2021; Read & Stacey 2009; Read 2013; Weir et al. 2020). It is an evolving and iterative process whereby each of the constituent models: geological, structural, rock mass and hydrogeology are continually updated throughout the mine life.

This paper will discuss the development process of the geotechnical model for the Hemerdon Mine in Devon, England. This paper provides applied examples used to develop the geotechnical model and the considerations made when selecting model boundaries, parameters, and their limitations. Generally, the RMR_{89} (Bieniawski 1989) values have been used to highlight the techniques implemented. However, depending on the project and available information, this could be changed for any geotechnical data variable.

1.1 Geological setting

At a regional scale, the Hemerdon tungsten and tin deposit is hosted within a sub-vertical, granite–porphyry body known as the Hemerdon granite (Figure 1). The granites have intruded a Devonian-age volcano-sedimentary sequence and mafic intrusive rocks (locally termed 'killas'). Deformation during the Variscan orogeny resulted in a series of east–west striking folds followed by crustal relaxation and thinning which allowed for the intrusion of the granites and east–west striking faults that served as conduits for hydrothermal fluids (Tungsten West 2022).

The Hemerdon granite consists of a main north-northeast–south-southwest dyke with a strike length of 1,200 m and an average width of 150 m. The rock type (either killas or granite) has a major control on the rock mass strength. The fresh granite has a very strong massive unit whereas the killas is a jointed (blocky sugar-cube) unit with an anisotropic rock mass strength.

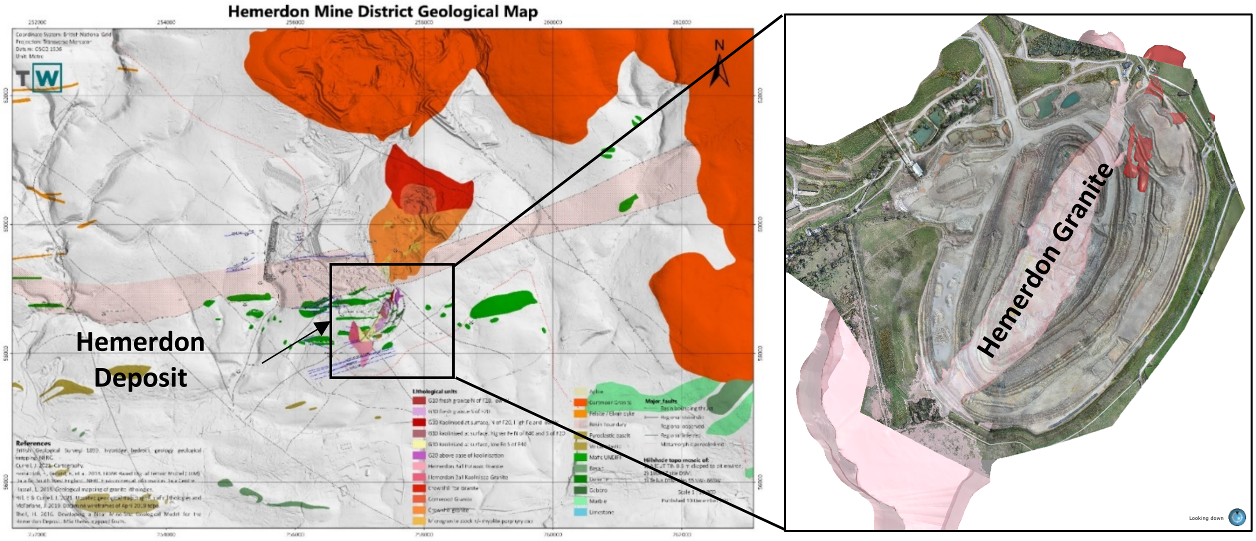


Figure 1 Geological setting of the Hemerdon deposit

2 Data

The first slope design for the Hemerdon deposit was completed in 1981 and since then, numerous data collection programs have been conducted to advance the geotechnical understanding of the deposit. The available data used to develop the geotechnical model for the Hemerdon deposit were:

- Lithology model.
- Weathering model.
- Alteration model.
- Major structural model.
- Minor structural model (downhole discontinuity measurements and pit mapping).
- Rock mass model which included:
    - Geotechnical rock mass logging from 14 drillholes covering approximately 3,000 m.
    - Geotechnical pit mapping of all accessible faces.
    - Laboratory test work.
    - Hydrogeological model which was developed by an external consultant.

3 Methodology

The key methodological steps used in this study are listed as follows (see Figure 2 for a visual outline):

3D data visualisation: Leapfrog was used to visualise the available data and constituent model boundaries to identify observable trends.

The lithology, weathering and alteration models were created by the mine geology team and the major structural model by an external consultant. Therefore, this initial stage was to become familiar with the various data sources and understand any limitations of the constituent models (Barnett et al 2021; de Bruyn 2021). This was completed via a combination of handover documents and verbal communication with the model creators.

Hypothesis testing: If a trend was observed, then statistical and graphical visualisation techniques were implemented to test possible relationships. Specific examples of the hypotheses developed and tested are outlined in Section 4.

In this study, Python was used for graphical visualisation which can rapidly create charts with numerical and categorical data. Using Python (or similar coding methods) has become significantly easier due to the advent of artificial intelligence which can create and correct the required code.

Geological context and linkage to field observation: The geological processes associated with the ore genesis for a specific deposit can often relate to the spatial distribution of rock quality (Eggers 2016). As a result, as hypotheses were generated and tested, they were supported by geological context and primary field observations.

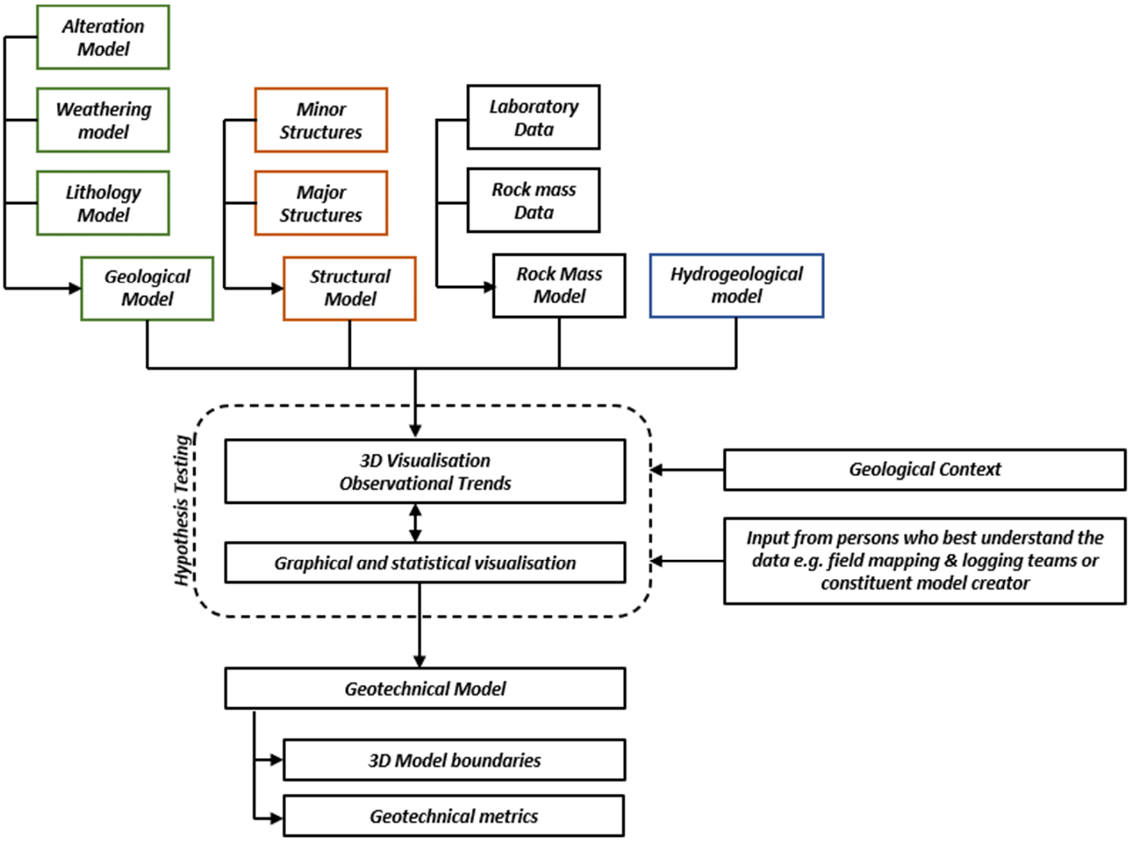


Figure 2 Methodology for geotechnical model hypothesis testing

4 Results

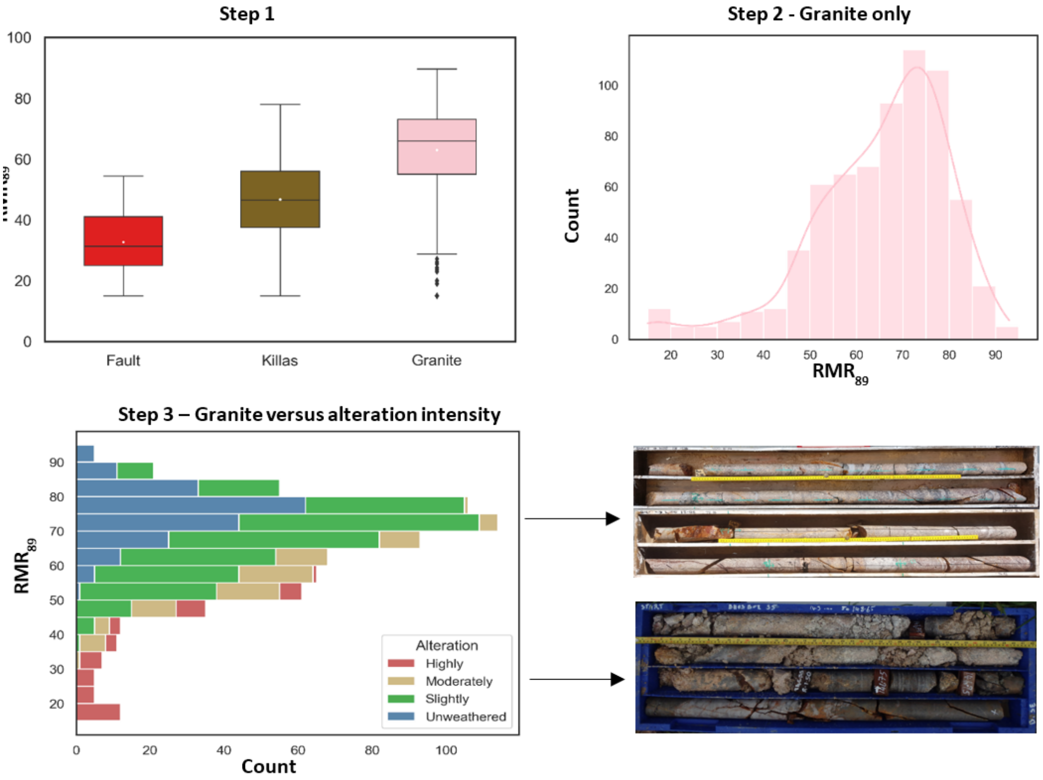
Four applied examples developed for the Hemerdon deposit geotechnical model are provided.

4.1 Lithology model

It was observed from the pit mapping and drillcore that the rock type (either killas or granite) had a major control on the rock mass strength and related geotechnical parameters. The fresh granite was expected to be a very strong massive unit, whereas the killas is a jointed blocky unit with an anisotropic rock mass strength.

Initially, the 3D geological model was reviewed and the geotechnical logging data was cross checked against the model domains in Leapfrog to ensure the correct logging codes had been applied. Following this, statistical visualisations were created using a boxplot for each lithology (Step 1, Figure 3). The results indicated:

- Killas had an average RMR_{89} of 48 ('fair' rock mass) with an interquartile range of 38–58.
- Granite had a higher average RMR_{89} of 65 ('good' rock mass) with an interquartile range of 57–76.
- The fault zones that intersected had much lower RMR_{89} values in the mid-30s ('poor' rock mass) which correlated to visual observations from drillcore and the open pit.



(a) (b)

Figure 3 (a) Box plot for RMR_{89} results for each lithology; (b) Histogram plot for RMR_{89} for the granite unit

The interquartile range within each lithology was expected to represent weathering or alteration (kaolinisation) of the rock mass. A histogram was created to further assess the RMR_{89} distribution within the granite unit which highlighted a left, negative skew in the data (Stage 2, Figure 3) and a second histogram was created, coloured by alteration intensity categories (Step 3, Figure 3). The results indicated that higher alteration intensities had lower RMR_{89} values which was investigated further within the alteration sub-model. Finally, the RMR_{89} results were compared to specific borehole core photograph intervals which supported the conclusion that lower RMR_{89} values in the granite were associated with kaolinisation alteration causing disintegration of the rock mass.

4.2 Weathering model

Weathering was hypothesised to reduce the rock mass strength with higher weathering intensities observed closer to the surface. The mine geology department had created surfaces to represent the base of completely oxidised (BOCO) and top of fresh rock (TOFR) for the resource estimation and validating these surfaces was required to ensure they represented depth-related changes in the rock mass quality. During the model handover process, it was identified that the primary geological logging codes were different to the engineering geological weathering intensity codes typically used to create the BOCO and TOFR.

Initially, the logged weathering grade was displayed in Leapfrog against the BOCO and TOFR surfaces for the available geotechnical drillholes and critical drillhole intersections were reviewed from the core photography (Stages 1 and 2, Figure 4). Following this, the RMR_{89} was plotted against elevation and colour-coded by weathering intensity (Stage 3, Figure 4). The results from the analysis were interpreted as:

- 200 mRL to 175 mRL had lower RMR_{89} values which related to the completely weathered material near surface which is more prominent in the killas unit. Following visual inspection of the core photographs, it was deemed that this material should not have a RMR_{89} rating and should be treated as a soil using Mohr–Coulomb failure criterion.
- 175 mRL to 120 mRL where the running RMR_{89} average steadily increases from ~45 to ~60 ('poor' to 'fair'). The increase in RMR_{89} is attributed to a reduction in rock mass weathering from moderately to slightly weathered.
- Poor quality RMR_{89} results below 100 mRL are attributed to intersections of weathered granite in drillhole WDD-14-003 in the south of the pit which is in close proximity to a major structure.
- Below 80 mRL the running RMR_{89} values are consistently above ~60 ('good' rock mass).
- Fault zone intersections were observed to have low RMR_{89} across a range of depths and generally logged as highly or moderately weathered.

Based on the results, the geotechnical weathering domains were aligned to BOCO and TOFR surfaces developed by the geology department as these adequately represented the changing rock mass quality due to weathering and were preferable to use rather than creating a new surface due to the wide spacing of geotechnically logged drillholes.

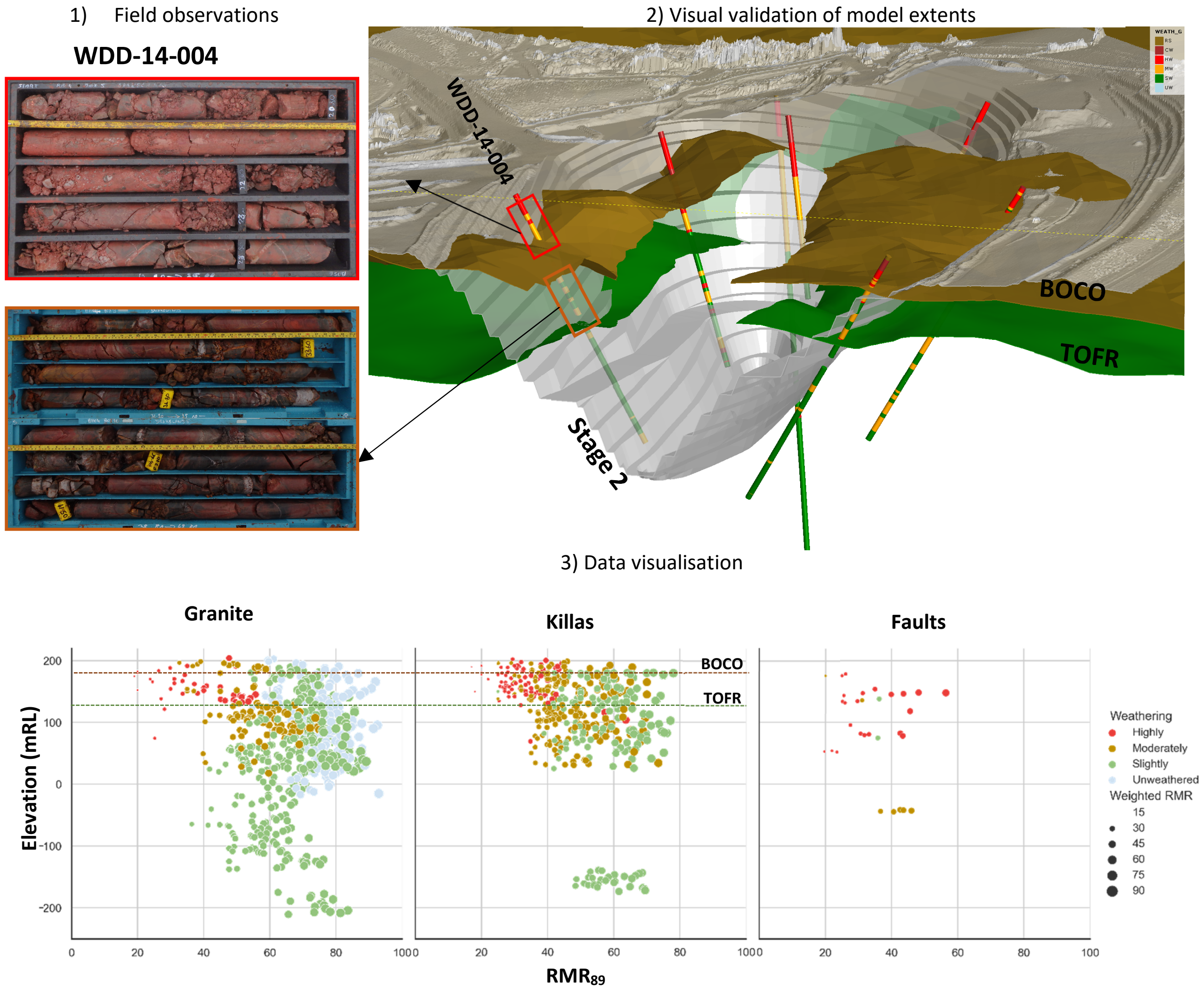


Figure 4 Visual comparison of weathering model (base of completely oxidised [BOCO] and top of fresh rock [TOFR]) to logging and core photographs

4.3 Rock fabric (minor structures)

The killas unit was expected to have three joint sets resulting in a blocky rock mass. A persistent bedding discontinuity set (~48°/150°) was observed across site which was shallower in the north (~40°) and steeper to the south (~50°). The granite was expected to be a massive unit with a persistent quartz vein set which hosts the mineralisation. Figure 5 outlines individual stereonets for each discontinuity type, mapping disks and form interpolant to visualise any changes in the structural orientation of discontinuities across the deposit. The key observations for each set were:

- Bedding
  - Bedding was consistently observed across the deposit orientated towards the southeast (dip direction of ~150°). Kinks in the dip orientation are observed in the form interpolant and are potentially related to block movements adjacent to the granite dyke intrusion.
  - The bedding planes dip at an average of ~45°; slightly shallower (~40°) in the north and steeper in south (~50°).

- Joints
    - Three joint sets were observed:
        - Joint Set 1 (a and b) was a steeply dipping set (~79°) typically towards the northeast (052°). In some areas the set is overturned (termed J1b) and dip towards the southwest at ~233°. Set J1a and b are orientated parallel to the regional fault structures.
        - Joint Set 2 was not frequently observed in the open pit and was primarily within an area in the east orientated at 84°/258°.
        - Joint Set 3 was aligned to the primary vein set (47°/335°) dipping to the northwest. Within the killas, the quartz infill has often crumbed away leaving a joint surface which has been identified during mapping. In other areas, the wall rock and quartz vein infill are both hard, however, a smooth discontinuity surface is present between the two materials.
- Veins
    - One vein set was identified in this geotechnical assessment. However, a swing in the contour plot was observed which likely represents other orientated veins within the swarm network.
    - Veins are more continuous and persistent in the granite. However, the vein set identified does extend into the killas rock mass.

Using these results, a kinematic stability assessment was completed at the bench scale to support the proposed bench-berm geometry. In addition, form interpolants were developed as these can be used to represent an anisotropic surface in 3D slope stability modelling packages.

4.4 Major structural model

Three major structural sets were identified at Hemerdon: regional northwest trending, north–south trending, and tourmaline structures.

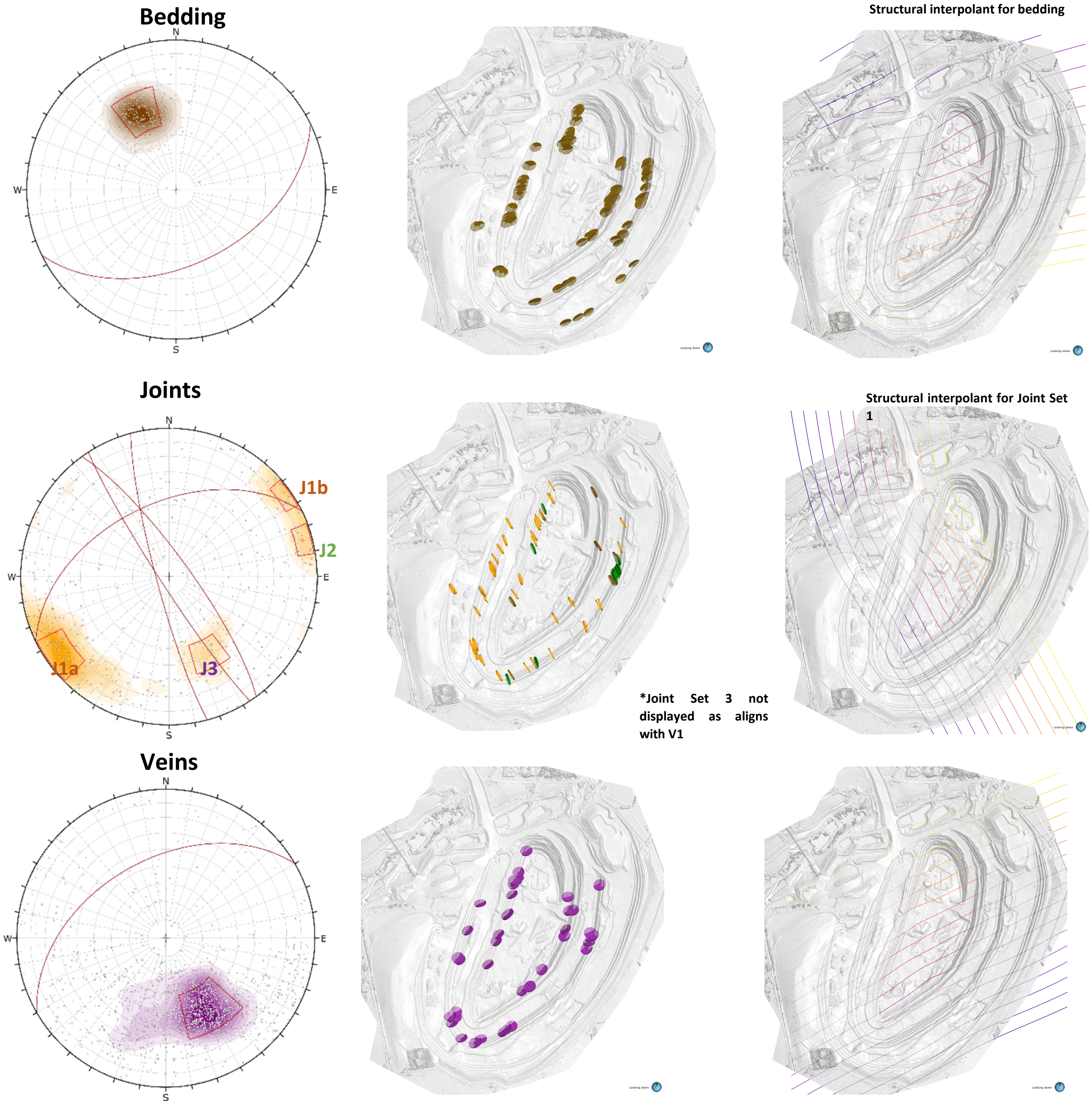
The northwest fault set dip at a steep angle and intersect the pit walls near perpendicular. Therefore, they were not individually expected to cause significant geotechnical risk. Generally, the faults were observed as discreet features with minimal fault gouge apart from F2 (formerly F40), F3 and F4. These structures typically had 0.2–0.5 m gouge core and ±2.5 m damaged zone either side of the fault plane.

The north–south structures were hypothesised to pose a significant risk as they were orientated parallel to the east and west pit walls and could act as a back-scarp release planes for a failure slip surface. In addition, due to the orientation, they were potentially under-represented in the dataset.

Tourmaline structures occurred as conspicuous, dark grey, moderate northwest and northeast-dipping structures and were associated with a late mineralising event. They commonly showed evidence of water seepage and were most likely reactivated as faults during late regional tectonics. The tourmaline structures were healed and not expected to cause significant geotechnical issues.

To assess the major structural model, observations and geotechnical descriptions were made of each structure in the open pit and visual validation of the 3D model was completed (Stages 1 and 2, Figure 6). Following this, the RMR_{89} drillhole and mapping data midpoints were used to calculate the distance from each data point to the major structure. The faults were combined into three structural sets:

1. Regional orientated structures northeast-dipping and northwest-trending faults (F1, F2, F3, F4, F5, F6, F8, F9 and F11).
2. North–south orientated structures (F7-NS, F10-NS, F12-NS, F13-NS, F14-NS and F15-NS).
3. Tourmaline faults (TV-1, TV2, TV3 and TV4).



*Joint Set 3 not displayed as aligns with V1

Figure 5 Visualisation of the minor structural sets at the Hemerdon deposit

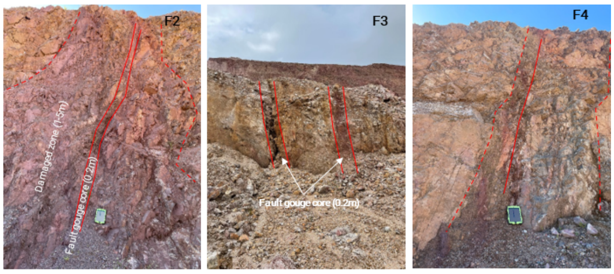
Hexbins (bivariate histograms) were created to represent the relationship between the distance from the structure and the RMR_{89} rating to quantify the damaged zones adjacent to major structure (Stage 3, Figure 6) with the following observation made:

- The regional faults (red) potentially had a bi-modal RMR_{89} distribution. The lower RMR_{89} range (20-30) observed within 5 m of a major structure and increases to 55–60 at 10 m is consistent with the field characterisation of F2, F3 and F4 (Stage 1, Figure 6). At this point the RMR_{89} value is similar to the mean value for the killas group. The higher range of RMR_{89} results around 55 are likely representative of minor discrete faults which have not affected the surrounding rock mass to the same extent.
- The north–south faults have RMR_{89} values of ~40 within 5 m increasing to 55 within 15 m of the structures. However, there is a significant distribution in the dataset which is potentially skewed due to most drillholes having been orientated down-dip of the fault set.

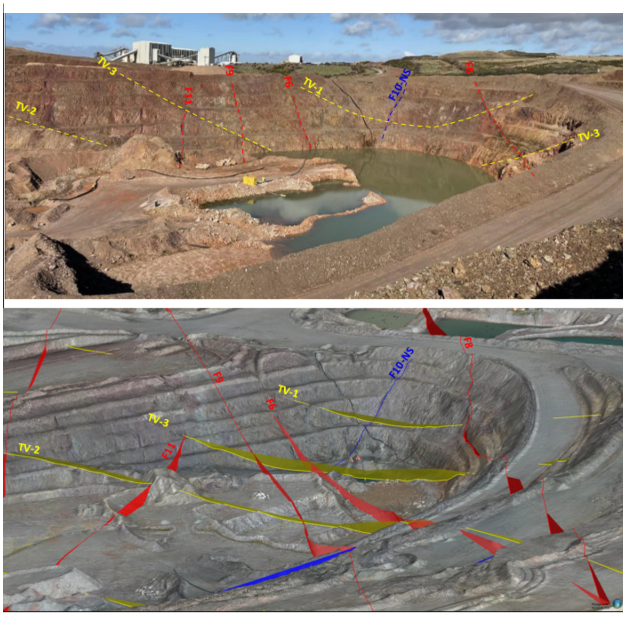
- The tourmaline faults have RMR_{89} values between 45–60 within 5 m of the structures. The RMR_{89} range remains constant as the distance increasing which indicates the tourmaline structures do not have a damaged zone. This observation agrees with the interpretation that the tourmaline structures are earlier faults and have been healed.

Based on these results, material properties were developed for each structural set that were then used in the stability analysis.

1) Field observation of individual fault structures



2) Visual validation of model extents



3) Data visualisation

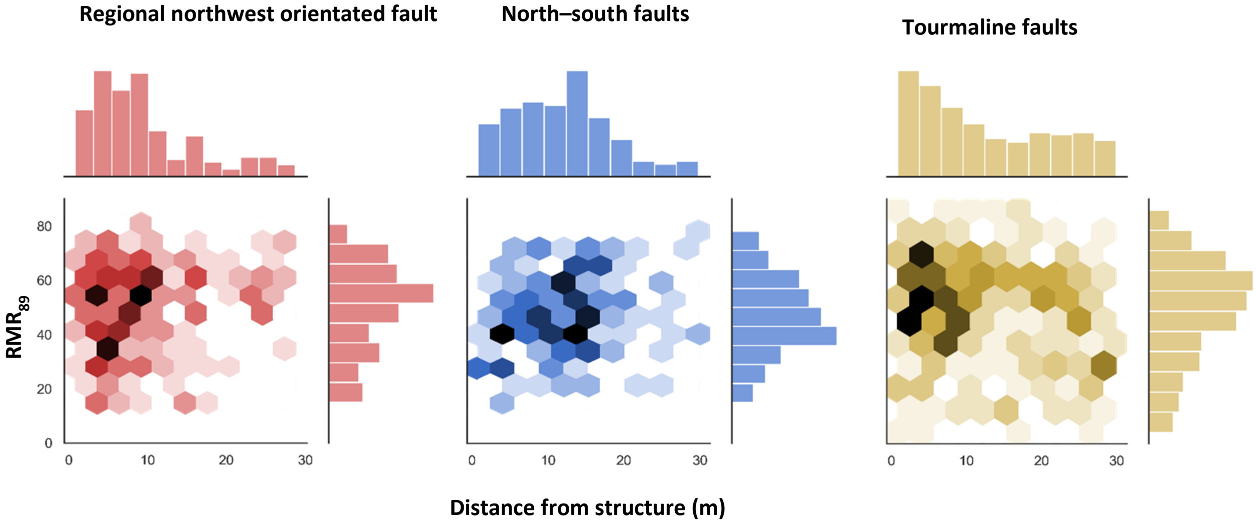


Figure 6 Geotechnical contextualisation of the major structural model

4.5 Geotechnical model

The geotechnical model was constructed and outlined in Figure 7. Two primary geotechnical domains were required for rock type (either killas or granite) which have a major control on the rock mass strength. Anisotropy was included for the killas unit which had a persistent bedding discontinuity set (~48°/150°). Following this, weathering in the killas and alteration of the granites have a significant impact on reducing the rock mass strength. Both processes are depth controlled with higher weathering and alteration intensities are observed closer to surface. Therefore, gradational depth-related geotechnical domains to account for decreasing weathering/alterations were required. The regional and north–south fault sets were included in the geotechnical model as these were expected to cause stability issues.

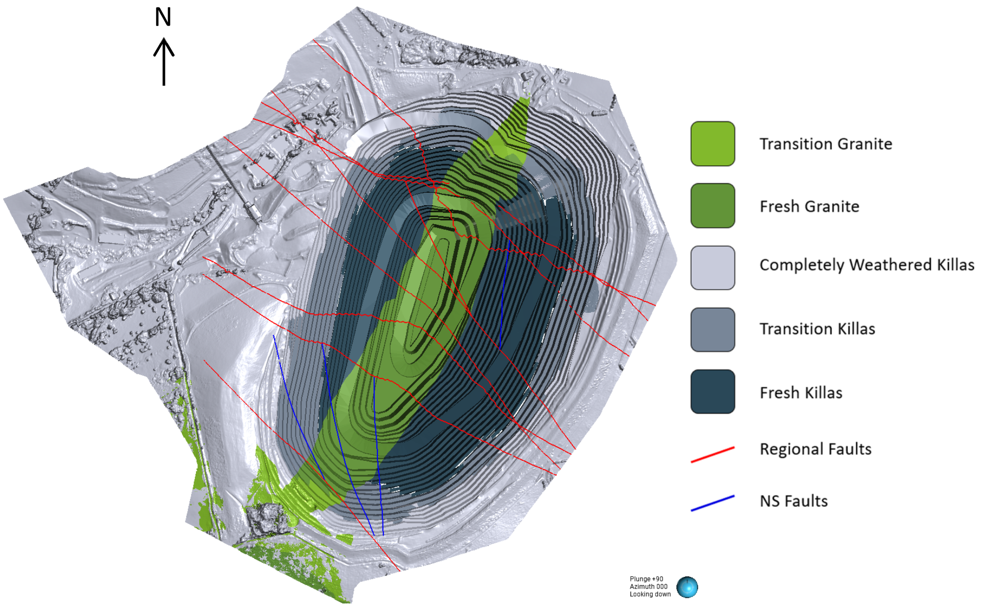


Figure 7 Geotechnical model for the Hemerdon deposit clipped to pit stage 3

5 Discussion

The geotechnical model is an essential tool for the safe design and operation of a mine. It provides a comprehensive understanding of the geotechnical conditions at the mine site which can be used to assess slope stability.

The development of a geotechnical model is a complex and iterative process that relies on a multidisciplinary team to collect and interpret a wide range of data for different purposes and needs. This is representative of modern mine technical teams where the constituent models are created and used by different teams. The added detail and complexity is welcomed, however, a key phase of work by a geotechnical engineer is to ensure that the limitations and purpose of the constituent models are conveyed to the end users (Barnett et al. 2021). At the Hemerdon deposit, the lithology, weathering and alteration models were created by the mine geology team and the major structural model by an external consultant. This paper highlights the importance of familiarity at the initial stages with the various data sources and gaining comprehensive understanding of any limitations of the constituent models (Barnett et al. 2021; de Bruyn 2021). For example, at Hemerdon, the major structural model was validated against observations from the open pit. Using the handover guidance developed by Barnett et al. (2021) can assist in this process.

Eggers (2016) and de Bruyn (2021) emphasised the importance for geotechnical engineers to understand the formation process of a deposit in relation to the geology, alteration, and structure. They also noted that the engineer developing the geotechnical model needs to observe the site conditions to effectively visualise the nature of the rock mass. This study highlights the importance of these requirements and that the justification for any model parameter developed through visual, statistical, or graphical methods needs to be supported by primary observations and geological context applicable to the deposit. Even with improved data visualisation techniques, development of geotechnical domains still requires engineering geological judgment (de Bruyn 2021).

Python was used in this study to develop graphical visualisations to test potential hypotheses controlling the rock quality. For example, at the Hemerdon deposit, this helped justify the use of model boundaries created by the mine geology team which could then be used in the geotechnical model. Further, as additional data becomes available and constituent models are updated, developing a methodology as outlined in this paper can assist the geotechnical engineer when validating newly acquired data. This is particularly important when the geology is complex or where the mining operations are changing. In addition, traditional Excel-based analysis can become slow and cumbersome for projects with very large geotechnical data sets.

It has been widely noted that advanced numerical stability models can be technically challenging, requiring significant resource and time to develop and run. However, as open pits become larger and increasingly geologically complex, these techniques will be required in predicting the rock mass behaviour (Vakili et al. 2020). Therefore, ensuring that the geotechnical model represents the expected conditions as closely as possible, as outlined in this paper, is vital to maximising the results of these analysis methods.

Once the geotechnical model has been developed, it is a practical tool to communicate complex geotechnical issues including risk or uncertainty to the wider mining team (i.e. geologists, structural geologists and mine planning engineers). The ability to view the geotechnical model is further enhanced via modern 3D software packages which can rapidly visualise multiple data sources simultaneously for interrogation. This approach is representative of the cross-disciplinary nature of modern mine technical services teams where the constituent models (e.g. lithology, alteration, or major structures) are often created and used by different teams for different purposes.

6 Conclusion

The methodology outlined in this paper highlights the iterative approach which combines field observations, 3D models visualisation and graphical techniques to justify geotechnical model boundaries. In addition, constituent models (e.g. lithology, alteration, or major structures) are often created and updated by separate subject matter experts for a variety of purposes. Therefore, by using Python (or similar coding methods) in conjunction of 3D modelling packages, it is possible to continually test potential hypotheses which may be controlling the rock quality and the location of domain boundaries as models are updated.

The ultimate aim of this process is to ensure that the geotechnical model accurately reflects the site conditions. This provides a greater potential to develop optimal pit designs, which are safe and as steep as possible to maximise recovery and mine profit.

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