https://doi.org/10.56295/1ACEG03

ENGINEERING GEOLOGY MODEL AS A TOOL FOR THE EFFECTIVE MANAGEMENT OF OPEN PIT SLOPES

F.M. Weir & M.J. Fowler
PSM

ABSTRACT

The engineering geology at every mine site has developed through complex interactions of geological processes over vast periods of time. The inherent variability between these processes and sites poses challenges in developing suitable pit slope designs due to both limited data and understanding, leading to uncertainty and associated risks.

Risk management for slope stability involves the identification, assessment, and mitigation of potential risks. A robust engineering geological model serves as an invaluable tool for effective risk management by providing insights into anticipated ground conditions. This paper provides a review of the engineering geology at three open pit mine sites from Australia and Southeast Asia. While the geological environment at each site is substantially different the underlying geological understanding enables effective slope design management and risk mitigation strategies. These strategies include the application of a geological model at a site in a highly active tectonic setting, showcasing how it facilitates identification of areas with elevated risk during operations.

The paper also presents how the engineering geology model at each site has evolved over time, particularly following slope instability events. The findings and guidelines presented herein provide valuable insights for professionals involved in slope design, enabling them to make informed decisions and enhance safety.

1 INTRODUCTION

For the design of an excavation, whether it is an open pit slope or a tunnel, an engineering model is required to represent ground conditions at a site. A critical element for the model is an appropriate understanding of the geology at the site. As highlighted by Eggers (2023), there is a trend in industry to focus on rock mass classification, with the geological component of the model often neglected, which can negatively impact the engineering design.

The management of open pit slopes in mining operations is essential for ensuring both the safety and efficiency of the excavation processes. The complexity and variability of geological conditions present significant challenges. These challenges emphasize the need for suitable engineering geological models.

An engineering geology model is a conceptual representation of the subsurface conditions at a specific site, used to support design, construction and inform risk management for a project. The primary components of the model include geology (lithology and alteration), structure, soil and rock mass, geomorphology and hydrogeology. The components of an engineering geology model are shown conceptually in Figure 1. The influence of each component on open pit slope design will vary with geological environment and site-specific ground conditions.

The complexity and variability in natural materials means that the formulation of the engineering geology model often relies on the experience of the practitioner. When developing slope designs, uncertainties and risk are always present. These uncertainties often manifest in the field of slope design, resulting in gaps and ambiguities that must be navigated. A fundamental understanding of the geological environment in terms of rock types and tectonic history can assist practitioners in predicting key failure mechanisms and likely slope performance.

At the Earth’s surface, there are three primary rock types: Sedimentary, Igneous, and Metamorphic. The method of formation and inherent character for each of these rock types have significant engineering and slope design implications. For each primary group, a case study is presented that illustrates some of the challenges in slope design for that rock type.

This paper explores the application of engineering geological models as tools for the effective management of open pit slopes. It focuses on three distinct mine sites located in Australia and Southeast Asia, each with unique geological settings and challenges. Through these case studies, the paper demonstrates how a robust understanding of the local geology can inform slope design and risk management practices.

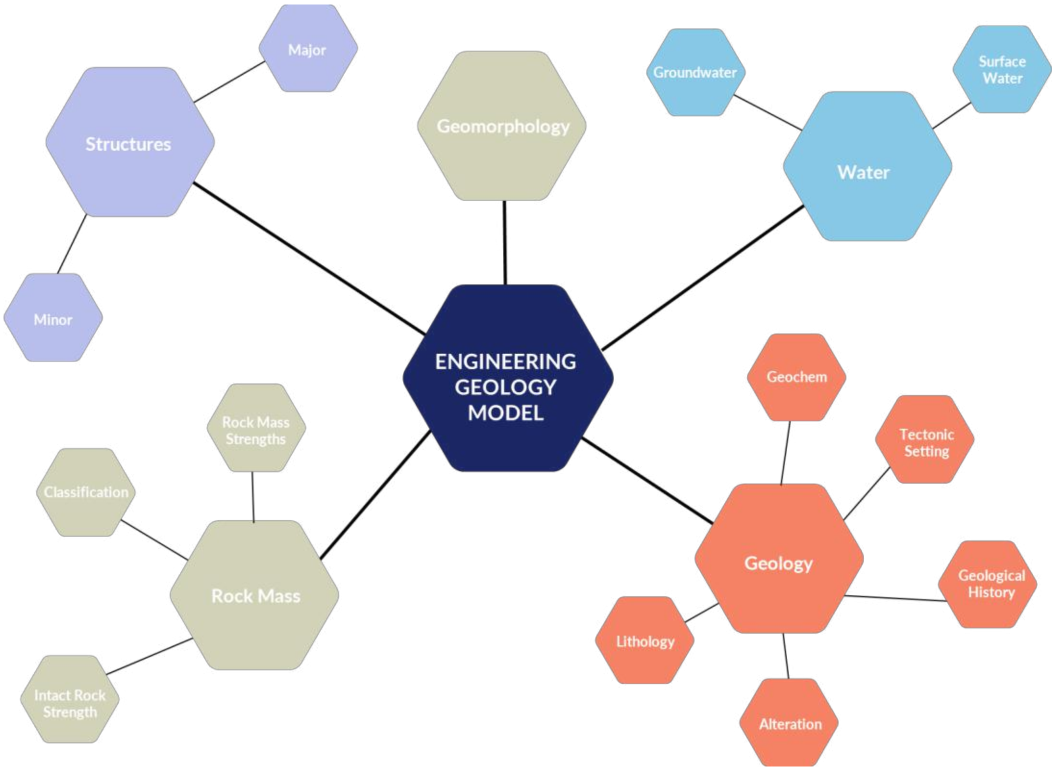

Figure 1: Conceptual understanding of the Engineering Model and its key components for open pit slope design

2 CASE STUDY SITE 1 – VOLCANIC ENVIRONMENT

2.1 Introduction

Volcanic geological environments are highly complex due to variable chemistry and rock characteristics, variable eruption styles and emplacement methods and the interaction of these with existing geomorphology. This means that volcanic igneous rocks are highly variable over short distances in depositional type, chemistry, strength and geotechnical behaviour (Weir, 2024). Adverse or irregular geological structures are also likely to be present. Examples include ring faults or dykes, faulting, autoclastic brecciation and curvi-linear jointing near intrusive plugs.

The geological complexity of these volcanic environments means that there is potentially large uncertainty in the engineering geology model. Case Study Site 1, presented here involved slope design at the base of the amphitheatre of a young strata volcano that has undergone sector collapse, multiple phases of alteration (propylitic, epithermal) and ongoing phreatomagmatic activity resulting in diatremes. This creates a geotechnically complex environment due to the co-incidence of complicated lithologies, alteration, structural, geothermal conditions, existing landslides and high seismicity. The amphitheatre forms a significant topographic feature that surrounds the active mining area and associated infrastructure with steep natural slopes, Figure 2. The existing open pit at the site is about 2.2 km long and 1.6 km wide with a depth of about 300 m (relative to sea level).

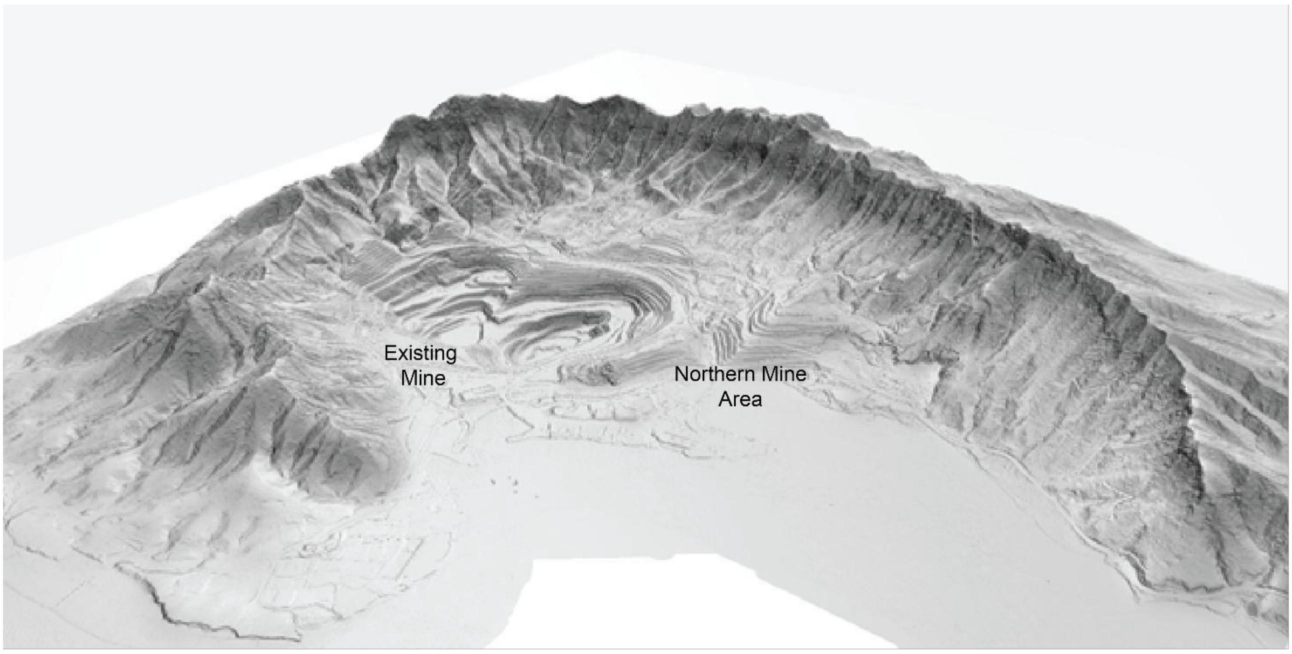

Figure 2: Oblique view towards the southwest of existing pit and volcanic amphitheatre, 2009 LIDAR surface (after Weir *et al.*, 2020)

2.2 Conceptual Model

The conceptual engineering geology model for the site was developed using modern analogues from similar volcanic environments and a combination of historical and current exposures at the mine. The modern analogues reviewed included Mt St Helens, a modern example of large-scale sector collapse of a strata volcano. The sector collapse (a large landslide), triggered by an earthquake, resulted in exposure of the magma chamber and an explosive eruption. Following this collapse, new volcanic activity commenced within the caldera. This modern example highlighted the dynamic, evolving, and overprinting nature of young volcanoes.

The sector collapse exposes the central core of the volcano to the atmosphere resulting in phreatomagmatic activity, the mixing of surface waters with magma and super-heated steam and water under pressure. The combination of reduced vertical stress due to the collapse unloading and phreatomagmatic activity is also associated with diatreme formation. Diatremes are generated by pulses of magma mixing with external water, rapid transfer of heat from magma to water, and explosion of the mixture. The diatreme contacts are typically sheared due to forceful emplacement and then compaction settlement.

Diatremes that form explosively may leave a crater. The crater can become deeper due to subsidence of the diatreme deposits. This subsidence cone or residual crater soon forms a Crater Lake, which is then often filled with epiclastic and/or fluvio-lacustrine sediments.

2.4 Diatremes at the Site

The geology at the site comprises a sequence of agglomerates, tuffs and basalts intruded by monzonite. The lithologies have typically been overprinted by various hydrothermal events, resulting in significant alteration from their primary rock types. The complicated geological history of multiple deformation episodes and pervasive alteration makes it difficult to distinguish among the twelve breccia types at the case study site and inhibits the development of a lithological model.

The soil and rock mass component of the engineering geology model for the site was developed from a framework of historical studies and recent site investigations. It represents the continuing evolution in the understanding of ground conditions. Early engineering geology models for the site were based around the existing southern mining area, where the geotechnical units were found to largely relate to the ore type/alteration model. However, as the model and mining progressed away from the volcano central core, the engineering model has evolved to incorporate the effects of late-stage phreatomagmatic activity and diatreme formation.

The first detailed characterisation of a large young diatreme at the case study site was by Blackwell (2010) in the existing mine area (L Diatreme, Figure 3). The diatreme is a polymictic, accretionary lapilli-bearing, matrix-supported breccia. It is largely unaltered, indicating a late-stage formation. Since 2010, with additional drilling data, model refinement has focused on the L Diatreme northern extent and character. Other similar "young" diatremes were subsequently identified in core. These breccia's are characterised by:

- Fine grained, grey matrix
- Low strength rock mass
- The absence of significant alteration overprinting
- Shallow, curved structures with low defect shear strengths
- Sheared, slickensided, clay infill planes along contacts.

The Northern Diatreme is the largest of the discordant breccia bodies modelled at the case study site, Figure 3. This diatreme will form a large portion of the final pit north wall. It is characterised as a polymictic matrix supported breccia with a dark grey muddy matrix and commonly white coloured andesitic clasts. The Northern Diatreme is overlain by weakly lithified, horizontally bedded sediments, interpreted as a Crater Lake deposit. The spatial relationship between the various rock mass units is highlighted in Figure 4.

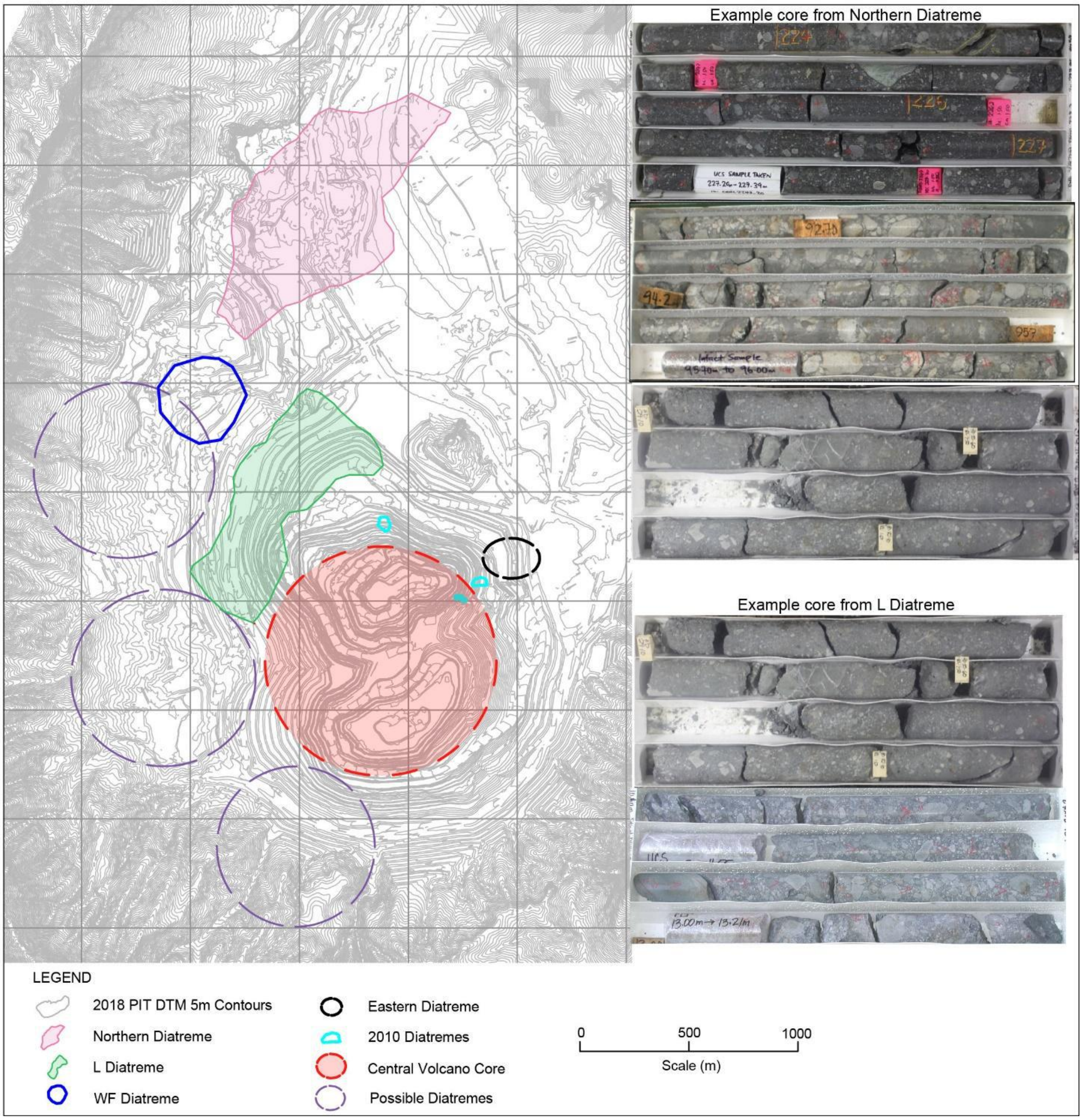

Figure 3: Identified and interpreted diatremes

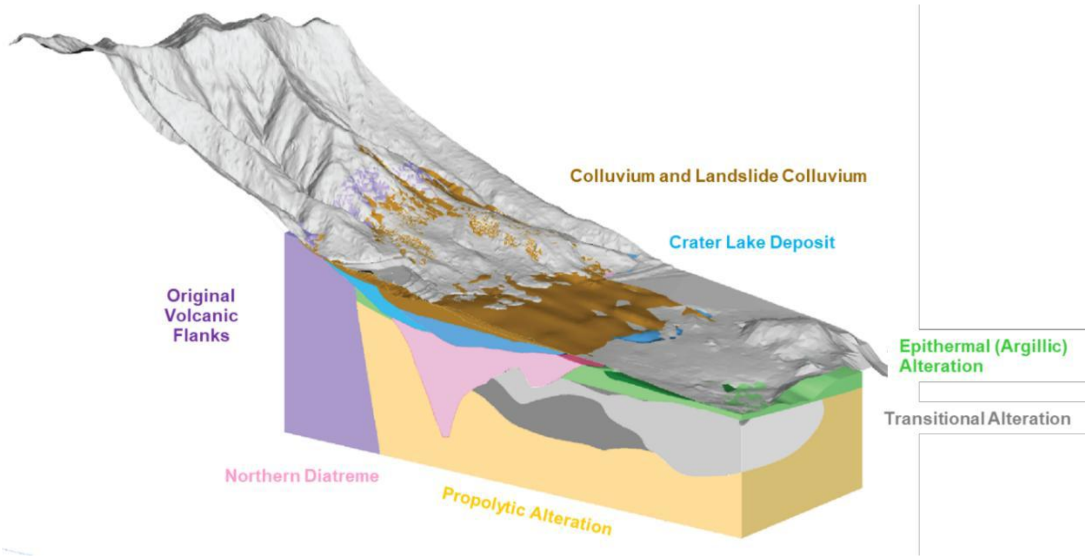

Figure 4: An oblique view of a slice through the 3D rock mass model, highlighting the relationship between the Northern Diatreme and surrounding alteration type rock mass units (after Weir *et al*., 2020)

A number of other possible young diatremes have also been inferred from the topography and exposures, Figure 3. These typically lie along the western side of the caldera. The location of the newly identified Eastern diatreme shows the potential for other young diatremes to also be present to the east of the central core. Importantly, young diatremes do not occur in the central core. The shape of the L and Northern diatremes (with a splayed sill feature extending to the north) and the location of other young diatremes implies that the underlying basement structures have played a role in the localisation of diatreme intrusions.

2.5 Importance for Pit Slope Design

A review of site-wide historical slope performance showed that large-scale pit slope instability to date has been related to diatremes (or highly altered argillics) with pore pressures also an important influence. The failure mechanisms relating to diatremes are variable but commonly include structure.

Adverse structure conditions occurred both within and at the contact young diatremes, this is consistent with the conceptual model. Exposures of the adverse structures show a shallow to moderate dip, curved, clay-filled and variably sheared with low strength. The exact location of any such structures is difficult to predict given the shape and variability in dip. The structures within the diatremes are interpreted as commonly emplacement related.

The keys for interpretation and prediction are to use the characteristic signatures of the younger diatremes to identify them. This is to understand the structural patterns associated with diatremes and where such structures typically develop then use borehole imaging data to build and refine the structure model for that location. The identification of the young diatremes from core photos is an important tool for predicting areas of increased risk of pit slope instability at this site.

This summary has focused on the role of diatremes in slope stability at the site. Weir et al., (2020) provides a more detailed review of the evolution of the engineering geology model at this particular site.

3 CASE STUDY SITE 2 – SEDIMENTARY ENVIRONMENT

3.1 Introduction

Case Study Site 2 is a stratiform sediment-hosted Zn-Pb deposit. The site is characterized by a thick sequence of siltstone beds and occasional breccia beds that have been variably folded and faulted. The intact strength is high (ISRM), and pit design is controlled by geological structures. Being a sedimentary deposit, bedding is a dominant structure type and is considered continuous on the pit scale, with the stratigraphic units able to be traced across the entire deposit. Consequently, bedding orientation is a critical control in structural domain definition, slope design and performance of the pit slopes.

Mining to date has predominantly progressed with a footwall parallel bedding and a steep high wall, Figure 5. The joint patterns at the site show a dominant set orthogonal to bedding, which is to be expected in a sedimentary environment. Mining at the site is proposed to progress as a series of cutbacks of the highwall. Substantial work has gone into identifying and defining the location of bedding folds where bedding in future cutbacks will dip out of the highwall. These folds are evident in the cross-section in Figure 5. The variation in joint orientations with these folds are also indicated.

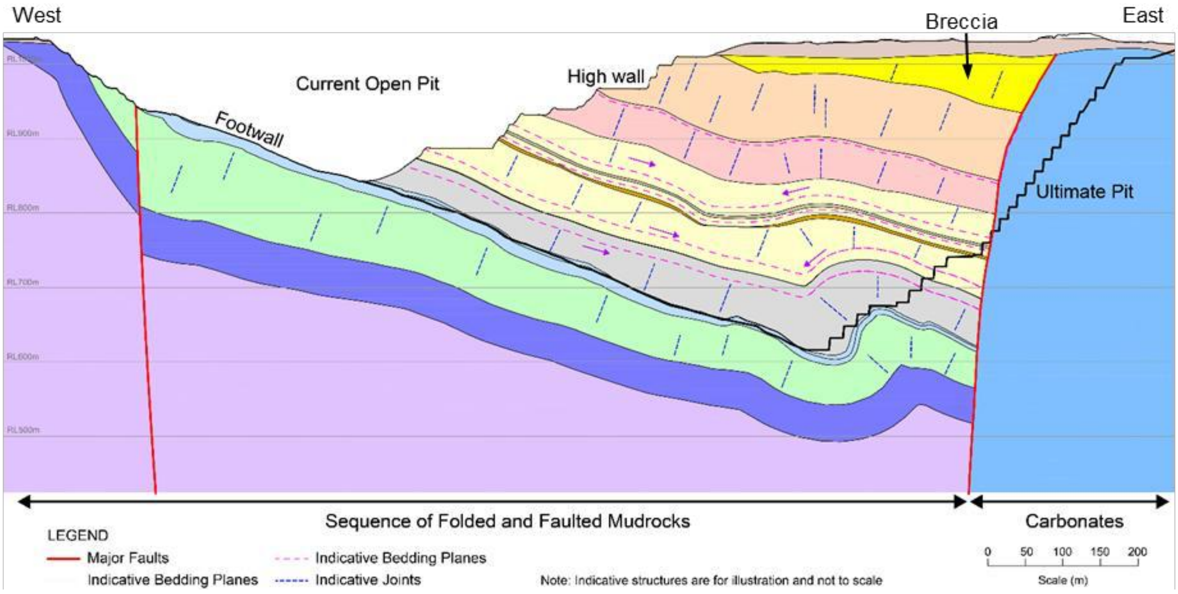

Figure 5: An East-West cross-section through a stratiform deposit showing primary stratigraphic units, bedding trends and indicative joint patterns

3.2 Instability Event

In June 2021 a multi-bench scale instability occurred in the southeast corner of the open pit. The instability developed over the course of one week, from initial detection of displacement to collapse. Geotechnical monitoring systems assisted with the identification, delineation, and safe management of the instability. The monitoring systems and management of the instability were presented by Heaven et al., 2022.

The instability occurred within a breccia unit at the top of the stratigraphic sequence, which had limited exposure in the pit wall prior to the event, Figure 5. The instability mechanism was interpreted to be step-path sliding on two closely spaced joint sets. Understanding of the ground conditions and instability mechanism was a critical element in the successful management and remediation of the slope.

3.3 Engineering Geology Model and Failure Mechanism

At the time of the instability a major study updating the engineering geology model and slope design recommendations was underway. Prior to this study data regarding the breccia unit was limited. The unit is a massive, polymictic breccia with sub-rounded clasts up to 2 to 3 m in length, Figure 6. Available data on intact strength for the breccia included field strength estimates, point load tests and unconfined compressive strength (UCS) tests. All three sources indicate for fresh rock there is a relatively high intact rock strength with values ranging between 80 and 200 MPa.

Prior to the instability the available structural data for the breccia unit consisted of limited oriented core from two boreholes. A high-resolution survey scan of the wall was completed one day prior to the instability. Photogrammetry mapping of the scan was conducted to better understand the structure orientations and conditions. The photogrammetry mapping shows two clear, joint sets that are adversely oriented for a northeast facing slope, Figure 6c. The fault plane that controlled the southern end of the instability is of a similar orientation to the dominant joint set, dipping towards the northwest (shown as red squares in Figure 6c).

Additional geotechnical drilling completed after the instability identified that the upper portion of the breccia shows an increased frequency of jointing. In addition, proximal to the fault there is a further increase in frequency of jointing and increased depth of iron staining on defects. Both at depth and away from the fault the joints are more widely spaced.

Seepage observed along structures in the pit face prior to the instability indicated a high ground water table and pore pressures acting on the slope. This was consistent with the conceptual hydrogeological model, where this area of the slope is understood to be mostly saturated with flows originating from overlying alluvial sediments associated with a nearby river. In upper units like the breccia there is groundwater recharge during the wet with subsequent slow recession during dry season.

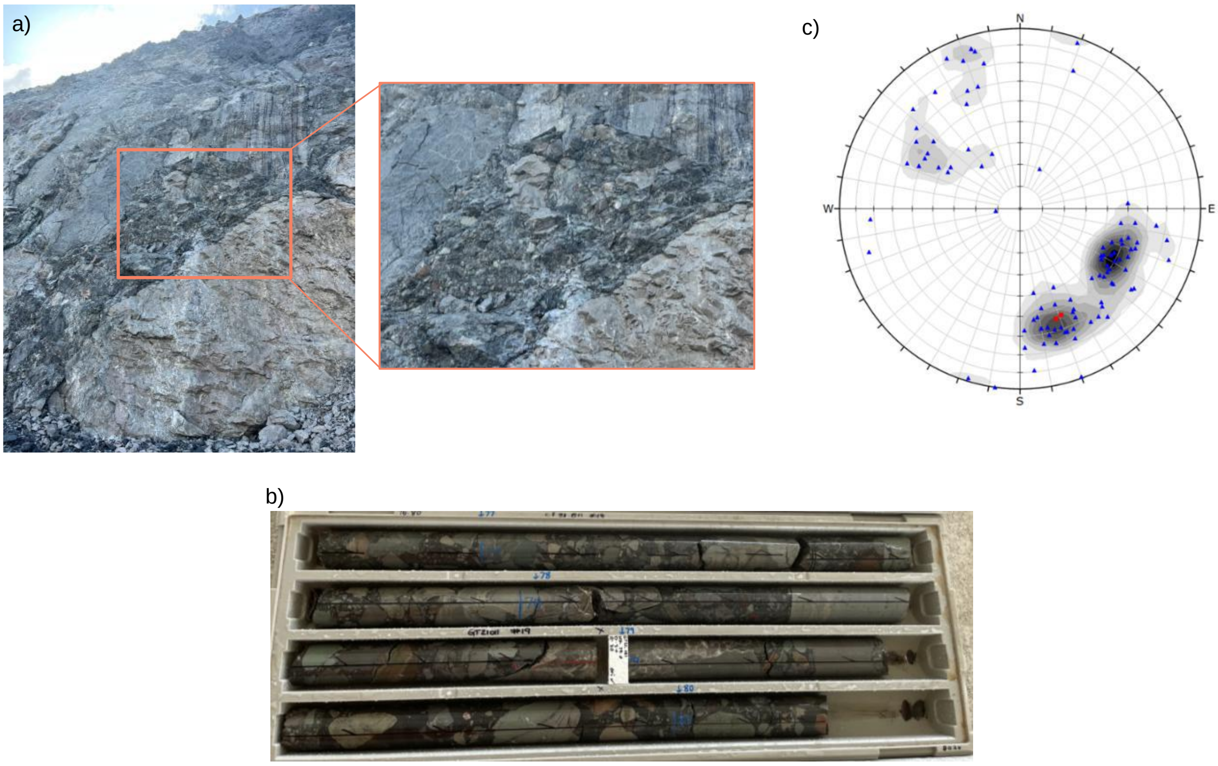

Figure 6: a) Example of the fresh polymictic breccia in recent bench face exposure, b) equivalent appearance in drill core and c) stereograph of defect orientations from remote mapping. Joints are shown in blue and faults in red. Stereograph is lower hemisphere, equal area

3.4 Failure Mechanism and Slope Management

The instability was interpreted to be structurally controlled, with the main sliding release on the southern side along a fault. The central and northern portions of the instability were likely step-path sliding along multiple closely spaced joint planes that dip out of the slope. The observations in subsequent geotechnical borehole core and bench face mapping suggest that the close spacing of the jointing was a result of proximity to a regional scale fault. The trigger for the instability was progressive mining towards the south along the slope toe which undercut some of the more persistent structures dipping out of the slope. Adverse ground water conditions also likely contributed.

A kinematic and statistical assessment of the defects was undertaken to assist reassessment of the pit slope design. This resulted in a reduction in both the bench and inter-ramp slope angles. With the adopted slope geometry there remained some risk of batter scale instability. To fully mitigate the risk of sliding due to the adversely oriented structures, the slope would have to be reoriented or flattened further. In addition, shallow batters can be difficult to execute with consideration to the limitations of drill and blast and excavation equipment. Consequently, the risk of batter scale instability was accepted and appropriately managed with the existing systems on site during mining.

The cutback was successfully completed in terms of achieving a stable inter-ramp slope. Irregular bench face geometries were experienced, largely due to the variable nature of the breccia with large, high strength clasts. Extensive seepage was again encountered during mining, which was addressed by installation of shallow horizontal drain holes.

In future cutback stages, with an increase in joint spacing away from the fault and use of the observational method the slope design was able to be steepened. This bench face steepening allowed a more practical mining approach and face development through variation to the blasting methods.

4 CASE STUDY SITE 3 – METAMORPHIC ENVIRONMENT

4.1 Introduction

Case Study Site 3 is a pegmatite lithium deposit, where the pegmatite has intruded into a regionally metamorphosed phyllite country rock, Figure 7. Pegmatite bodies enriched in spodumene are typically gently dipping, so the subvertical igneous body at this site is unusual (Phelps-Barber *et al.*, 2022; Weir *et al.*, 2023). Given the narrow, lenticular shape of the pegmatite the open pit slopes are predominantly within the surrounding country rock. A key characteristic for slope design in these rocks is the foliated texture due to directional stresses related to regional metamorphism. The authors became involved at this site after mining had commenced and geotechnical issues were encountered in terms of both slope performance and operations. The following sections review the engineering geology model for the site and the implications for slope design and operations.

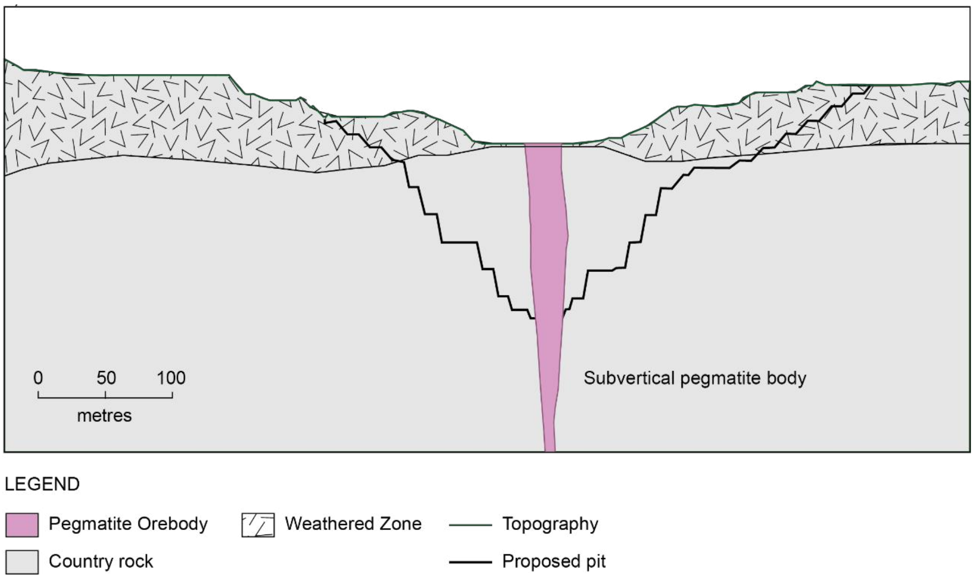

Figure 7: Cross-section through Case Study Site 3 with sub-vertical pegmatite body

4.2 Engineering Geology Model

Rock mass conditions are controlled by both the geology and surface processes at the site. The rock mass units comprise:

1. Weathered Zone - extremely weathered in-situ rock and residual soils. This zone is typically soil to low intact rock strength and is about 50 to 60 m thick. This zone is about 20 m thicker than was anticipated in pre-mining studies.
2. Fresh high strength rock - this consists of two units:
    a. Pegmatite and
    b. Metamorphosed country rock (phyllite).

The fresh rock for both the pegmatite and the phyllite has a high intact strength (>90 MPa). The presence of foliation in the phyllite country rock however results in a strong strength anisotropy. Consequently, it was important when undertaking testing that the foliation angle in relation to loading direction was carefully recorded.

The structural geology is critical to the engineering geology model and slope design for pegmatite deposits (Weir *et al.*, 2023). Two stereographs from Case Study Site 3 are presented in Figure 8. The stereographs show structures measured from oriented core of five boreholes through both pegmatite and the country rock. The pegmatite at the site is subvertical and striking north-northeast. The pegmatite stereograph shows shallowly dipping joints oriented perpendicular and parallel to the pegmatite body, which are interpreted as cooling and contact joints, respectively. Cooling related joints are oriented perpendicular and parallel to the dip of the pegmatite due to heat flow and a decrease in volume during cooling, Figure 8. Some of the jointing is of similar orientation to the meta-sedimentary country rock, Figure 8c and so may also be tectonic joints.

Within the phyllite foliation is subvertical and striking north-northeast, parallel to the pegmatite body, Figure 8c. It is likely that the magmatic fluid forming the pegmatite exploited the foliation as a plane of weakness during the intrusion event. The foliation forms closely spaced planes of weakness, particularly in the upper weathered zone, Figure 9a. Given the steep dip and character of the foliation, where the pit slopes are parallel to the foliation they are prone to flexural toppling style failures.

Standing water level observations from bores in 2021 indicate a depth to groundwater is about 0.5 to 1.6 mBGL (metres below ground level) during the wet season and between 4 to 12.5 mBGL during the dry season. The groundwater data and model are limited, particularly with regards to understanding of actual pore pressures currently acting in the slope. In addition, there are unlined mine water dams and sediment ponds directly to the south of the pit. It is considered highly likely that these structures are leaking and recharging the groundwater system, impacting slope stability.

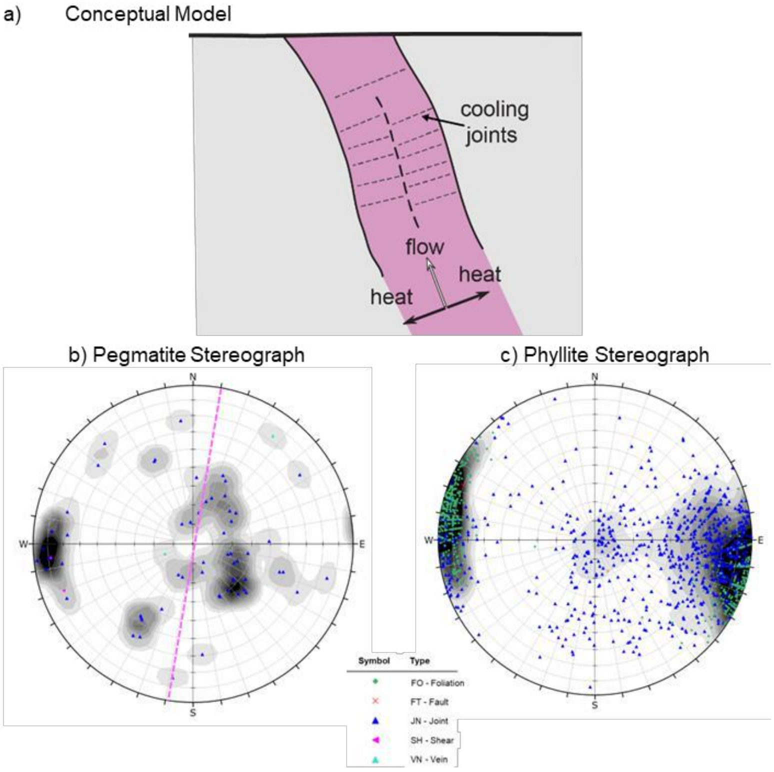

Figure 8: Pegmatite jointing patterns a) conceptual model of thermal (cooling) joints, Example structure conditions at Case Study Site 3 with stereographs from oriented core for b) Pegmatite and c) Phyllite Country Rock. Pink dashed line indicates strike of the pegmatite body. Stereographs are lower hemisphere, equal area

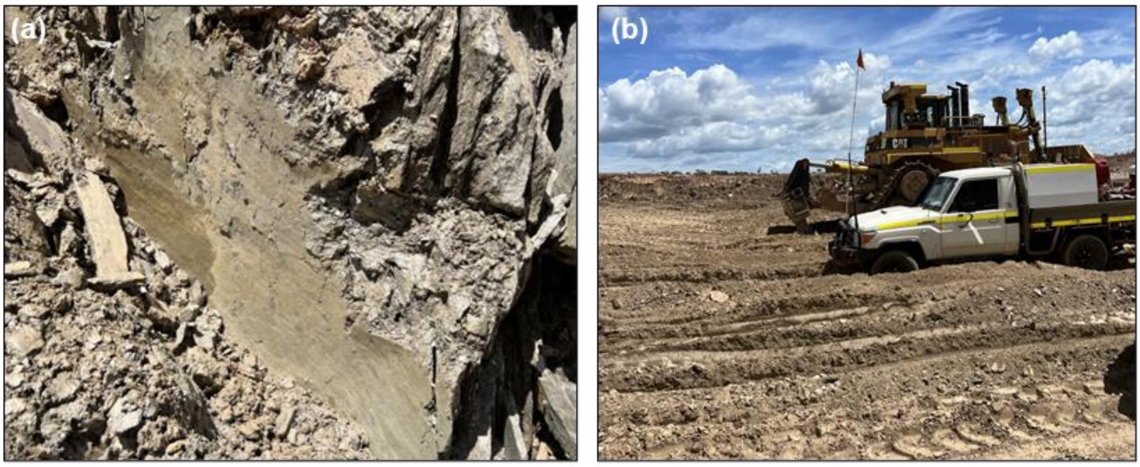

Figure 9: a) Example of a low strength foliation parting in weathered zone and (b) poor trafficability in dry conditions

4.3 Slope Design and Operational Implications

The critical failure mechanisms for consideration in slope design for each pit wall are summarised in Table 1. These were identified based on the engineering geology model and slope performance to date. To manage adverse slope performance due to toppling a small cutback and flattening of both bench face and the inter-ramp angle was undertaken for the upper weathered zone on the West wall.

Toppling failures are highly sensitive to pore pressures. To address this horizontal drain holes were also installed and lined with slotted pvc pipe to maintain the drain. The drain holes were effective at producing water and fitted with a reticulation system to capture the water and transport it to a lined sump on the end wall, rather than allowing the water to infiltrate back into the system.

Table 1: Failure Mechanisms

Pit Wall	Critical Failure Mechanism	Engineering Geology Controls
East and West Long walls	Toppling along foliation, as the pit is progressively excavated	Pervasive, closely spaced foliation in phyllite Minor faults and shears parallel to foliation Low intact strength in upper weathered zone Pore pressures
East wall	Planar sliding or wedges	Joints and shears parallel ot foliation Pore pressures
Northern and Southern End walls	One-sided wedges	Geometry and spacing of joints and foliation Pore pressures

There were other operational difficulties associated with excavation of the phyllite. The weathered phyllite is rich in micaceous minerals, which form micaceous silts and clays. These soils commonly exhibit a low in-situ density, are highly erodible and hydrophobic making dust control difficult. Durability of the slopes in the upper weathered zone is also low with slopes showing cracking and deformation with mining and exposure.

Trafficability is also a significant operational issue at the site in both dry and wet season, Figure 9b. This has resulted in significant cost associated with importing of material to the site for lining of the haul roads. A robust engineering geology model and understanding serves as a valuable tool for effective risk management by providing insights into anticipated ground conditions. These operational difficulties and associated costs could have been anticipated during early planning stages, given these are common issues associated with phyllite and other schistose rocks.

5 CONCLUSIONS

An engineering geology model is a conceptual representation of the subsurface conditions at a specific site, with the primary components of the model including geology (lithology and alteration), structure, soil and rock mass, and hydrogeology. This paper discusses the importance of engineering geology models for designing and managing open pit slopes, emphasizing risk management and the evolution of geological understanding across different mining sites. In particular, the paper emphasizes how a robust engineering geological model is an important tool for predicting likely slope failure mechanisms and aids in identifying and mitigating risks associated with slope stability in open pit mining.

The paper reviewed the engineering geology model at three open pit mine sites in Australia and Southeast Asia, highlighting how geological understanding varies yet enables effective risk mitigation strategies. Each geological environment presented posed unique challenges. In addition, the critical element of the engineering geology model (e.g. rock mass, structure or water) that influenced slope design and performance varied at each site.

The first case study focused on a volcanic site with complex geological conditions, underscoring the challenges in slope design due to high variability and potential instability from diatremes. The second case study examines a sediment-hosted deposit, where slope stability is influenced by geological structures such as bedding and faults. The third case study involved a pegmatite lithium deposit in metamorphosed rock, where foliation and groundwater conditions critically affect slope stability and operations.

Each case study illustrates how engineering geology models evolve over time, particularly after slope instability events, enhancing the understanding of ground conditions for design and management. The study highlights the need for a comprehensive geological understanding to anticipate operational difficulties and manage risks effectively in mining operations.

6 REFERENCES

Eggers, M.J. (2023). Engineering geological models in open pit slope engineering. *Proc. SSIM 2023: Third International Slope Stability in Mining Conference*, Australian Centre for Geomechanics, Perth, pp. 35-54, https://doi.org/10.36487/ACG_repo/2335_0.03.

Heaven, C., Weir, F.M., Fowler, M. and Farmer, M. (2022). Management and rehabilitation of a highwall slope instability. *Proc. Slope Stability 2022 Conference*, Tucson, Arizona USA, 17-21 October 2022.

Phelps-Barber, Z., Trench, A., and Groves, D. (2022). Recent pegmatite-hosted spodumene discoveries in Western Australia: insights for lithium exploration in Australia and globally. *Applied Earth Science*, 131 (2), 100-113.

Weir, F.M., Fowler, M.J., Sullivan, T.D., Kobler, M., and Bu, J. (2020). Evolution of a geotechnical model for slope design in an active volcanic environment. *Proc. of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 455-472.

Weir, F.M., Hemraj, D., Fowler, M.J., Watton, J.W., and Strang, D., (2023). Geotechnical slope design in hard rock lithium deposits. *Proc. SSIM 2023: Third International Slope Stability in Mining Conference*, Australian Centre for Geomechanics, Perth, pp. 449-458, https://doi.org/10.36487/ACG_repo/2335_28