SSIM 2023 – PM Dight (ed.)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-6-5
doi:10.36487/ACG_repo/2335_11

Geotechnical model development in a geologically complex porphyry setting: East Wall, Ok Tedi Mine, Papua New Guinea

BR Jones *PSM, Australia*

G Kennedy *PSM, Australia*

CL Alickson *Ok Tedi Mining Limited, Papua New Guinea*

G Pahina *Ok Tedi Mining Limited, Papua New Guinea*

Abstract

The Ok Tedi Copper-Gold Mine is one of the largest and most geotechnically challenging open cut pits in the world. The mine is the 'wettest' in the world and is situated in a complex geological setting typical of porphyry-style deposits. Fundamental to successful pit slope designs at Ok Tedi is the understanding of the geotechnical model, with the development of the East Wall cutback model presented in this paper. The cutback is complicated by the presence of important mine infrastructure near the crest of the pit wall and significant ore reserves hosted within the lower pit wall, dipping parallel with the design. A high confidence geotechnical model was therefore required to balance geotechnical stability with the steepest possible design to maximise ore recovery. Tight operational time frames and ore flow requirements further complicated the model development process, and meant investigations and assessments were undertaken during mining operations. To achieve this, the geotechnical model was developed and refined during mining using the mine engineering geological model (EGM) knowledge framework. An initial model was developed using available data which highlighted a very complex zone formed by regional-scale deformation and deposit-scale brecciation, alteration, weathering and adverse structure developed during multiple intrusion events. These resulted in poor rock mass conditions, with the wider poor zone being known as the Ok Ningi Weak Zone (ONWZ). The presence of faults and shears towards the base of the ONWZ was identified as a major risk to the design and further monitoring, investigation and assessment during mining was required. Accelerating slope movements observed in the prism data during mining and the exposure of discrete, persistent, low strength sub-horizontal faults and shears confirmed the risk that these features posed to the design. The EGM process was used to quantify the risk with additional targeted field mapping campaigns, and review of existing and new borehole data was used to update the geotechnical model. This work confirmed the presence of adverse faults and poor zones at the base of the ONWZ. However the tactile conditions and spatial distribution of these structures and zones were found to be highly variable, and with low strength infills localised to pockets and lenses. This work along, with subsequent analyses, confirmed that the design risks were acceptable; even leading to optimisation of the ONWZ into two subdomains, one of which was steepened to reflect the improved understanding of rock mass and structural conditions. The EGM framework was used successfully to underpin engineering decisions throughout the investigation, modelling, analysis and design process despite geotechnical and operational challenges. The outcome of the geotechnical model development process was an optimised slope design incorporating an understanding of the stability risks.

Keywords*: geotechnical model, engineering geological model, structural model, porphyry copper deposit*

1 Introduction

The Ok Tedi Copper-Gold Mine is located near the upper Ok Tedi River in the Star Mountains of the Western Province, Papua New Guinea, near the border with Indonesia. Owned and operated by Ok Tedi Mining Ltd, it is one of the largest and most geotechnically challenging open cut pits in the world. Since its opening in 1984 the mine has produced 5.17 Mt of copper, 15.9 moz of gold, and 36.4 moz of silver to the end of 2022.

Situated in a dynamic and complex geological environment typical of porphyry copper-gold (Cu-Au) deposits, the mine is one of the world's youngest major porphyry Cu-Au deposits (Pollard et al. 2021). It is also the 'wettest' mine in the world, receiving 8 to 10 m of annual rainfall. Rainfall is heavily influenced by topography and predominantly generated by convective thunderstorms of high intensity with limited duration (1 to 1.5 hours) and aerial extent (often less than 130 km^2). The high rainfall environment and insufficient sunshine consequently provide energy-limited conditions for evapotranspiration, and therefore high groundwater recharge and transient pore pressure conditions within the slopes. Pit slope heights are currently at around 850 m at the West Wall and 500 m at the East Wall. The management of large-scale instabilities in the West Wall has been the focus of recent geotechnical publications at Ok Tedi (e.g. Weir et al. 2018; Kennedy & Casagrande 2020; Casagrande et al. 2021).

These factors make geotechnical pit slope design challenging. Fundamental to the slope design process at Ok Tedi is ensuring a robust and comprehensive geotechnical model to understand controls and design risks. The geotechnical models are produced and updated during mining as an output from the project engineering geological model (EGM) knowledge framework. Development of the mine EGM has been significantly advanced over the past several years through targeted investigation campaigns and experienced engineering geological interpretation to better understand the complex geotechnical conditions.

This paper presents the geotechnical model developed for design of the central East Wall cutback at Ok Tedi, as shown in Figure 1. The development of the geotechnical model for the cutback was complicated by several geotechnical and operational challenges. These were addressed and the model was developed iteratively using the project EGM framework, resulting in an optimised pit slope design for the East Wall during mining.

2 Engineering geological model framework and methodology

The methodology used to develop the East Wall geotechnical model follows the work process for EGM development in rock engineering presented in Eggers & Bertuzzi (2020) and in Baynes & Parry (2022). The process is described as follows:

1. An initial geotechnical model is formulated for input into the engineering analysis and design for mining of the East Wall prior to mining, using available borehole and mapping data. This model described the character and spatial distribution of the rock mass and structural components to understand and identify the geological controls on pit slope stability. Due to tight operational time frames and the scale of geotechnical complexity, only a high-level understanding of the conditions and risks could be gained from borehole drilling. Additional observational data to evaluate these identified geological controls therefore needed to be gathered during mining.
2. Observational data obtained during mining is fed back into the EGM to assess the as-encountered conditions against those predicted, including:
   a. Slope performance, assessed from geotechnical monitoring data obtained from various instruments. Slope behaviour, particularly sensitivity to loading/disturbance events (i.e. rainfall, blasting, mining), which was carefully monitored and assessed.
   b. Data from the field mapping of benches and additional borehole drilling, including targeted field mapping focused on key rock mass units (RMUs) or major structures identified as controlling slope performance. Digital mapping of a series of 3D photogrammetry models were captured from an unmanned aerial vehicle to supplement the field mapping.
3. Geological factors controlling the distribution or influence of the distribution and changes in conditions are reviewed after iteration of the observational component of the EGM described in the previous step. RMUs are classified using existing description systems and their spatial distribution assessed. The location of major structures in the as-encountered conditions are spatially assessed against the latter to understand the interaction and distribution of RMUs and structural patterns.

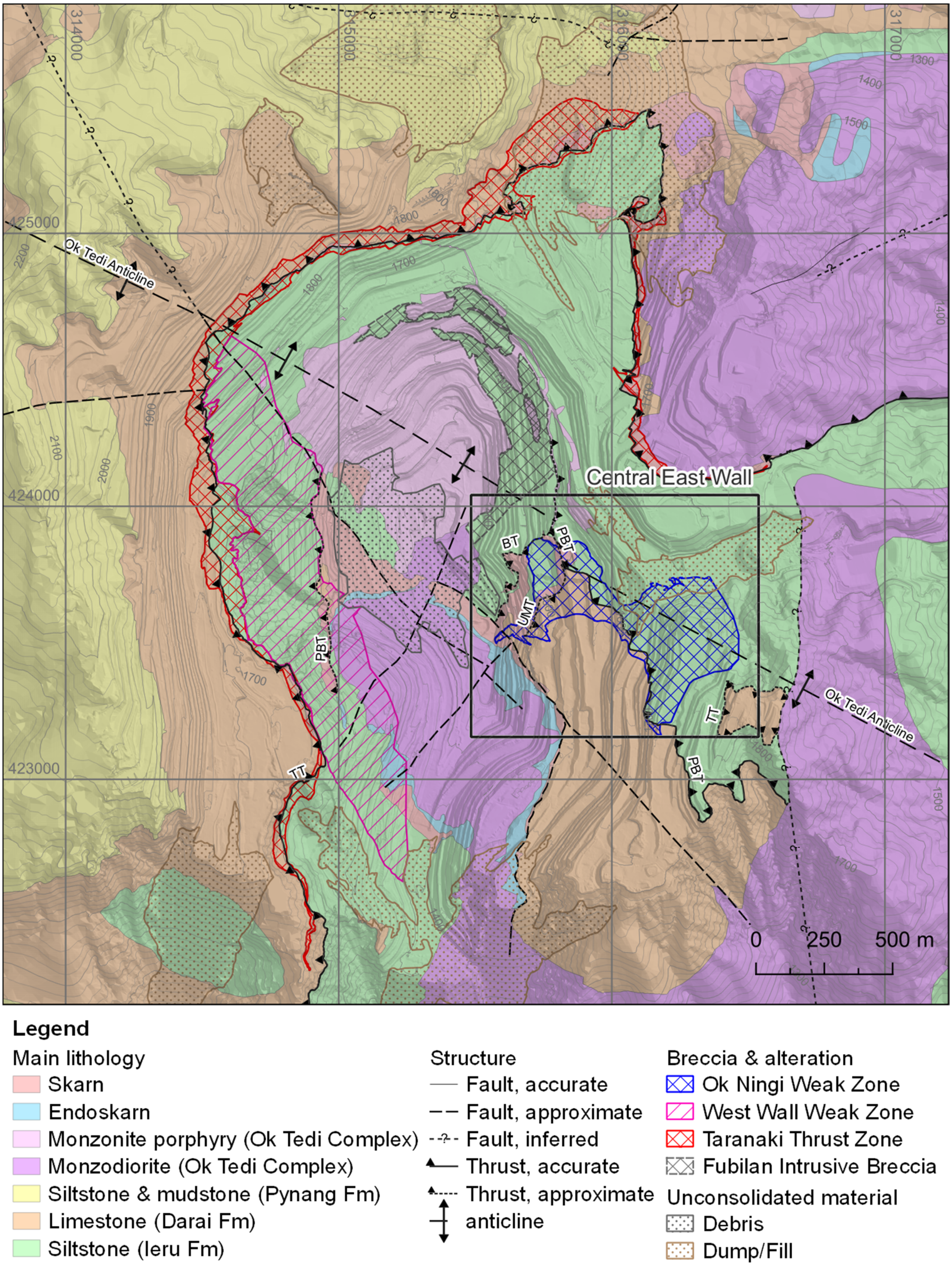

Figure 1 Geology plan of the Ok Tedi Mine area showing main lithologies and structures (modified from Pollard et al. 2021), as well as brecciation and alteration zones. TT = Taranaki thrust, PBT = Parrots Beak thrust, UMT = Upper Moscow thrust, BT = Basal thrust

4. A bespoke classification system is formulated to describe the character of major structures and assess their control on pit slope stability. The aim of the classification system is to describe different types of fault damage and infill in the major structures that influence the shear strength properties. The spatial distribution of each class type is assessed to formulate an understanding of how this controls the shear strength.
5. Major structures are parameterised by reviewing the structure classification system against existing triaxial testing undertaken on analogous material. Compiled laboratory test results and the characterisation of major structures are used to quantify the shear strength properties for input into numerical analysis to be re-run on the updated model.

3 Initial model

3.1 Tectonic setting and regional geology

Four main tectonic belts are recognised in New Guinea, comprising a northern belt of former accreted island arcs, a mobile belt of metamorphic rocks and ophiolites, a fold and thrust belt, and a southern stable platform or foreland sedimentary basin (Hill & Hall 2003). Ok Tedi is situated in the fold and thrust belt, which together with the mobile belt makes up the orogenic belt that forms the west-northwest-trending central mountain range along the spine of the island (Pollard et al. 2021). This orogenic belt formed on the leading edge of the Australian Plate through rapid late-Miocene convergence and, in the Pliocene, the margin became dominated by transpression which continues to the present day (Hill et al. 2002; Pollard et al. 2021). The fold and thrust belt consists of broad upright to overturned folds with generally east-southeast to west-northwest-trending fold axes and thrust sheets formed by southwest-directed thrusting (Mason 1994).

In the region of the Star Mountains, the oldest exposed rocks belong to the Jurassic Om Beds and Kuabgen Group. The most widespread sedimentary units include the Jurassic to Cretaceous Feing Group, late Cretaceous Ieru Formation, tertiary Darai Formation and Pnyang Formation, and the Pliocene Birim Formation (Pollard et al. 2021). Ok Tedi occurs along a north-northeast-trending zone of intermediate composition volcanic and intrusive rock suite emplaced in the New Guinea orogen during the Miocene and Pliocene (Large et al. 2018). The emplacement of these intrusive rocks coincides with the Ok Tedi Transfer, a linear zone orthogonal to regional strike (Hill et al. 2002).

3.2 Deposit-scale geology and mineralisation

The main lithologies, major regional- to district-scale structures, and primary zones of brecciation and alteration are shown in Figure 1 for the mine and annotated on an overview photograph of the central East Wall area in Figure 2. Primary sedimentary lithologies comprise siltstone of the Ieru Formation, limestone of the Darai Formation and siltstone/mudstone of the Pnyang Formation. Regional-scale deformation during the Miocene gave rise to several thrust faults and imbricate sheets located within the area. The northern part of the mine area is within the Ok Tedi anticline, and evidence for thrusting is observed as repetition of the Darai Formation and Ieru Formation along the Parrots Beak thrust south of the anticlinal axis.

Intrusive rocks comprise predominantly dioritic to monzonitic intrusions of the Ok Tedi Complex. Six main phases are recognised in the mine area, and from oldest to youngest are the Sydney Monzodiorite, Warsaw Monzodiorite, Kalgoorlie Monzodiorite, Ningi Quartz Monzonite Porphyry, Bonn Quartz Monzonite and Fubilan Quartz Monzonite Porphyry (Pollard et al. 2021). Little offset of the intrusive rocks suggests evidence of thrust displacement having occurred prior to emplacement of the intrusive rocks.

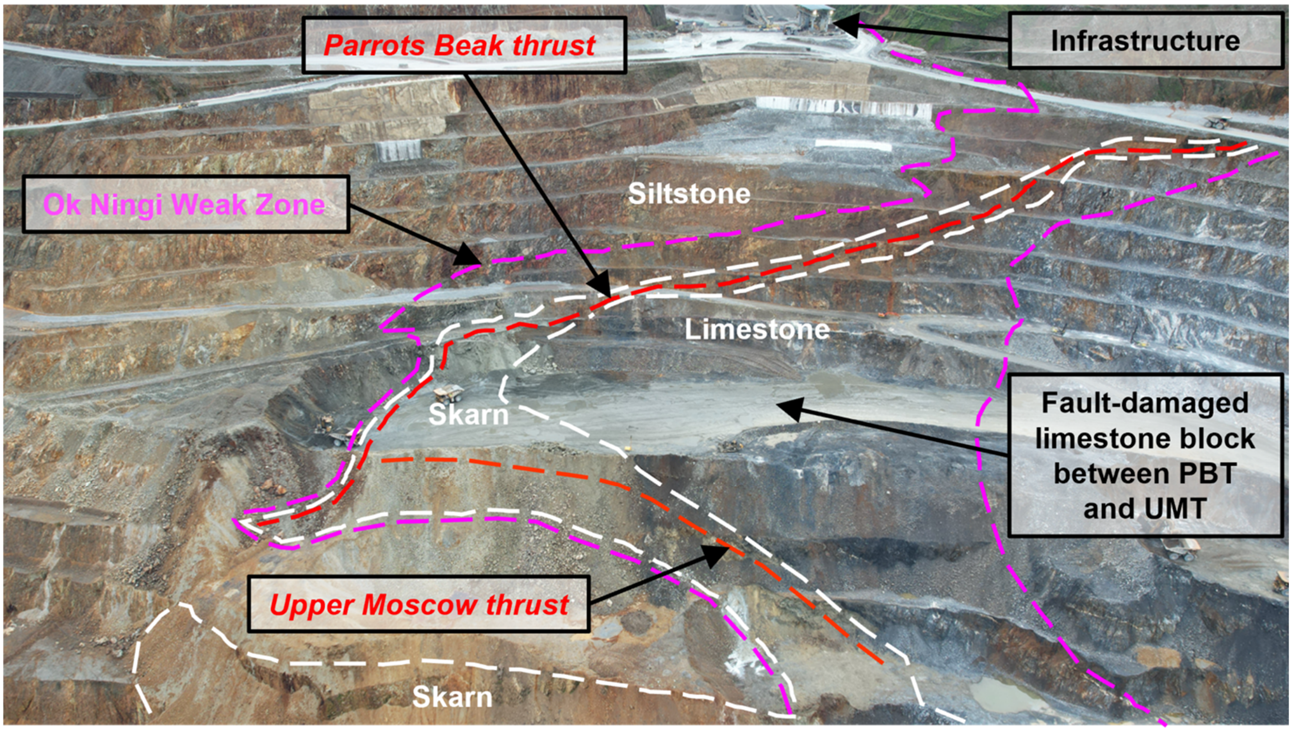

Figure 2 **Overview of the lithologies, major structures and Ok Ningi Weak Zone in the central East Wall**

Cu-Au mineralisation is associated with the emplacement of the intrusive rocks and occurs as disseminations, massive skarn bodies, vein infills, and endoskarn in igneous lithologies, and as associations with hydrothermal and intrusive breccias. Four main stages based on crosscutting relationships are recognised (Pollard et al. 2021):

1. Skarn-endoskarn and associated vein-style mineralisation in the Darai Formation limestone, Ieru Formation siltstone and Sydney Monzodiorite.
2. Porphyry-style veins and hydrothermal breccia within the Ningi Quartz Monzonite Porphyry, older monzodiorite intrusions and Ieru Formation siltstone.
3. Porphyry-style veins and breccias in the Fubilan Quartz Monzonite Porphyry and older intrusions.
4. Skarn-style mineralisation in the Darai Formation limestone along the Taranaki thrust.

Supergene processes resulted in development of the near-surface oxide gold deposit and underlying supergene-enriched copper zone that were the targets of early mining at Ok Tedi (Pollard et al. 2021).

The tectonic setting, alteration and brecciation results in several large zones of rock mass with poor geotechnical characteristics. At the East Wall, the Ok Ningi Weak Zone (ONWZ) comprises a zone of highly altered, fractured and variably brecciated (both hydrothermal and fault breccia) siltstone and limestone, as well as highly to completely decomposed skarns.

3.3 Major structures

Major thrust faults in the central East Wall include the Parrots Beak thrust (PBT), Upper Moscow thrust (UMT), and Basal thrust (BT). An imbricate sheet of Darai Formation limestone forms a 'thrust block' between the PBT and UMT. At the upper boundary the PBT comprises Ieru Formation siltstone in the hanging wall and Darai Formation limestone and skarn in the footwall. The PBT typically dips at shallow angles to the northeast, with a mean orientation of 16°/039.

The lower boundary of the thrust block is defined by the UMT where Darai Formation limestone and skarn presents in the hanging wall and Ieru Formation siltstone in the footwall. The UMT dips moderately towards the south-southwest, with a mean dip of 40°/190 and steepening up towards the faulted contact with the skarn where it turns sub-vertically. The UMT is a variably thick structure with an irregular shape on the macro-scale, and with an overall dip typically less than 35° towards the southwest. It pinches out towards the west, coincident with the faulted skarn contact between the monzodiorite and limestone, and converges and terminates at the footwall of the PBT in the north.

3.4 Rock mass units and the Ok Ningi Weak Zone

The rock mass at Ok Tedi has experienced a complex history of intrusions, alteration and faulting which has resulted in large variations of rock mass quality within each lithological unit. A total of 30 RMUs have therefore been designated within the current EGM at Ok Tedi. The series of RMU domains group areas of similar lithology, location, structure and rock mass quality. The RMU system divides lithologies into five classes where appropriate, with class 5 representing the worst and class 1 the best rock mass quality (Kennedy & Casagrande 2020). These classes have been developed from a statistically based set of field-generated geological strength index (GSI) values calibrated against representative core for all lithologies across the mine. Table 1 presents the RMUs for relevant lithologies present in the central East Wall, including Ieru Formation siltstone (IS), Darai Formation limestone (LS), and skarn/endoskarn (SK).

Table 1 Summary of rock mass units in the central East Wall. IS = Ieru Formation, LS = Darai Formation, SK = skarn/endoskarn, GSI = geological strength index, RF = rock fragments

Lithology	RMU class	RMU description	Description of shears	GSI		
				Ave.	Min.	Max.
IS	1	Broadly jointed	n/a	70	65	75
	2	Closely jointed	<5%	55	50	62
	3	Closely jointed, some shearing	Clay/RF to 300 mm	41	35	49
	4	Closely jointed and sheared	Clay/RF to 300 mm	29	24	35
	5	Sheared/fractured/brecciated	Clay/RF infills on shears spaced <1 m	20	15	24
LS	1	Massive to broadly jointed	n/a	68	65	72
	2	Closely jointed	<5%	57	47	65
	3	Closely jointed, some shearing or soil matrix. Also presents as healed brecciated rock, or blocky rock with soil veneers on joints	Clay/RF to 100 mm	39	33	46
	4	Closely jointed and sheared or soil matrix. Also presents as healed brecciated rock, or blocky rock with soil veneers on joints	Clay/RF to 100 mm	28	23	34
	5	Sheared/fractured/brecciated, soil matrix with rock clasts	Soil matrix with clasts	21	16	25
SK	1	Massive to broadly jointed	n/a	70	65	75
	2	Closely jointed	<5%	54	50	59
	3	Closely jointed, some shearing	Clay + RF to 400 mm	45	40	50
	4	Closely jointed and sheared	Clay + RF to 400 mm	30	25	35
	5	Sheared/fractured/brecciated	Soil matrix	17	15	30

Figure 1 and Figure 2 show the ONWZ in the central East Wall, which incorporates a zone of poor rock mass that has developed as a result of the geological history. The ONWZ is defined as a zone of highly altered and disturbed class 4 and class 5 rock comprising siltstone above the PBT, decomposed skarn, and a block of fault-damaged limestone between the PBT and UMT faults (see Figure 2).

3.5 Mining of the East Wall cutback and critical design risks

Mining of the current East Wall cutback commenced in 2021 following relocation of the crusher and mine offices. The final crest limit of the cutback is essentially set by the relocated infrastructure. Importantly for the mine, there is a high-grade skarn orebody dipping parallel with the pit design. A high confidence geotechnical model was therefore required to balance geotechnical stability with the steepest possible design to maximise ore recovery. Tight operational time frames and a requirement to maintain ore flow while other areas of the pit were being developed further complicated the cutback.

Producing a high confidence geotechnical model and pit slope design is challenging given the geological setting that has resulted in highly variable structural and rock mass conditions for the design as described in the initial model above. This is compounded by the requirement to ensure high confidence before mining begins, and using only mapping and limited borehole datasets. For this reason, the EGM process was adopted to allow efficient capture of information, updating of the geotechnical model and assessment of design risks during mining.

Geological and structural controls identified as stability risks to pit slope designs are identified as follows:

1. Highly altered and poor rock mass in the siltstone above the PBT.
2. Adverse orientation of the UMT and associated anisotropy of bedding, joints and shears in the surrounding zone as it daylights in the East Wall pit design.
3. The presence of discrete, persistent, low strength sub-horizontal to shallow-dipping shears proximal to the confluence of the UMT and PBT.
4. Steeply dipping jointing fabric forming a potential back scarp for instability.

4 Feedback of observational data during mining

4.1 Slope movement monitoring

A network of prisms was installed across the area, with displacement patterns closely observed during mining of the upper benches of the cutback. In addition to the rate of displacement, a particular focus was placed on identifying the sensitivity of the slope to the mining of each RMU and nearby loading or disturbance events such as rainfall, blasting and mining. Prism displacements between October 2022 and August 2023 are annotated in Figure 3 and indicate:

1. Subtle creep-style movements to October 2022 during mining of the upper benches.
2. Increasing creep-style movements between October and December 2022, coincident with exposure of the ONWZ.
3. Acceleration of movement immediately following blasting of a bench within the ONWZ in December 2022.
4. A regression of movements in February 2023 following a temporary pause in mining for two weeks.
5. Advanced creep-style movements have continued to date with some minor stick-slip movements.

Similar movement patterns were observed in both radar monitoring and inclinometer data.

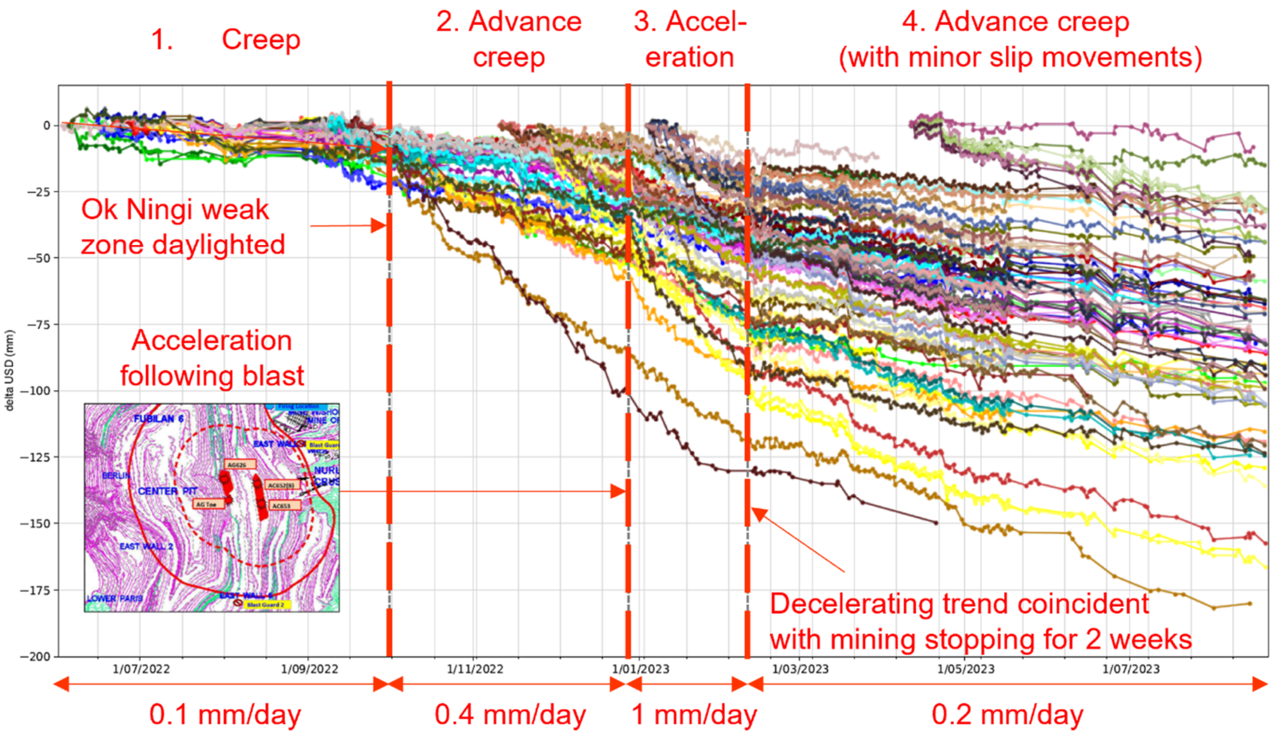

Figure 3 Prism monitoring showing typical slope movement patterns

4.2 Slope performance and critical failure mechanisms

The observed slope performance largely validated the conditions anticipated from the initial geotechnical model. The acceleration of movements from December 2022 following blasting confirmed the risk that sub-horizontal faults and shears posed to the design. An instability of the slope at the scale that it was in December 2022 was considered acceptable as it was shallow enough to not impact infrastructure. However, the potential for a larger deeper-seated mechanism at the base of the ONWZ and around the UMT was not acceptable due to the likely impact on infrastructure. The potential for sub-horizontal shears at the base of the ONWZ and around the UMT therefore needed to be quantified. Mining was temporarily paused to arrest the adverse movements and allow for reiteration of the EGM process and assessment of the potential for deeper-seated movements as conceptualised in Figure 4.

This was completed by review and further definition of poor rock mass conditions encountered around the PBT and confluence with the UMT (base of ONWZ), and the Darai Formation limestone between these major structures. Additional targeted field mapping focusing on assessing the GSI and logging RMUs for the relevant lithologies was undertaken. Major structures were logged and focused on characterising the orientation, pattern, geometry and tactile character of each. Digital mapping of 3D photogrammetry models was also undertaken to supplement data on the structural fabric.

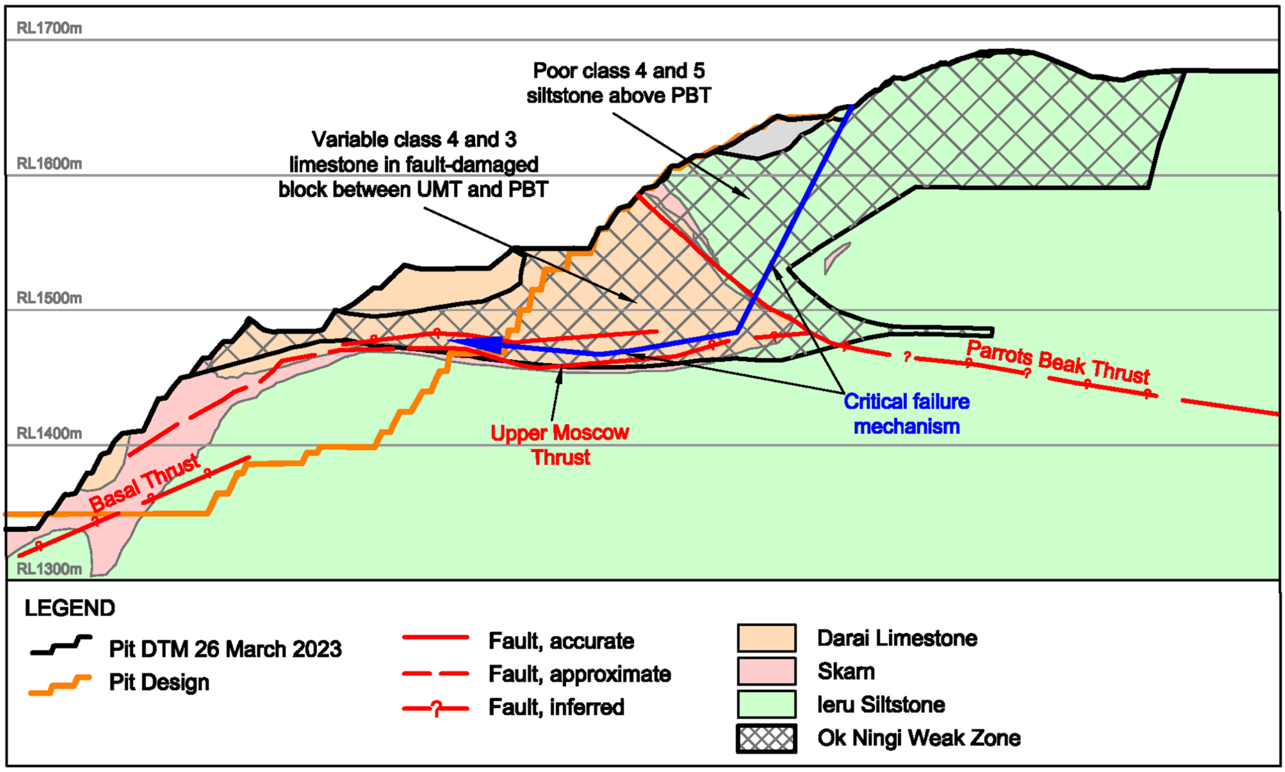

Figure 4 A potential deep-seated critical failure mechanism

5 Model iteration to assess a critical failure mechanism

5.1 Review of the spatial distribution of rock mass units

Figure 5 presents the RMU classes logged during the targeted GSI mapping campaigns and Figure 6 shows the RMUs initially logged within the boreholes. Figure 7 presents a photograph with the distribution of RMUs and major structures annotated.

The distribution of RMUs shows poor class 4 and class 5 siltstone above the PBT, which is typically closely jointed to sheared. Siltstone and skarn directly around the PBT comprises poor class 5 with localised pockets of class 3 skarn. Poor class 5 skarn and limestone surrounds the UMT. Variable poor class 4 with localised fair class 3 limestone is mapped between the thrusts, and rock mass quality improves to the south with fair to good class 3 to class 2 limestone dominating.

The targeted mapping confirmed that the initial ONWZ boundary is correct but also indicated slightly better rock mass conditions within the limestone. Therefore the ONWZ was subdivided into the following two RMU domains:

1. ONWZ – comprising highly altered, brecciated and decomposed poor rock mass conditions present above the PBT (siltstone) and directly surrounding the PBT (skarn, limestone) and UMT (skarn, limestone).
2. Ok Ningi Thrust Block (ONTB) – comprising closely jointed poor to fair rock mass conditions with variable proportions of shearing, fracturing and brecciation in the Darai Formation limestone thrust block between the PBT and UMT faults.

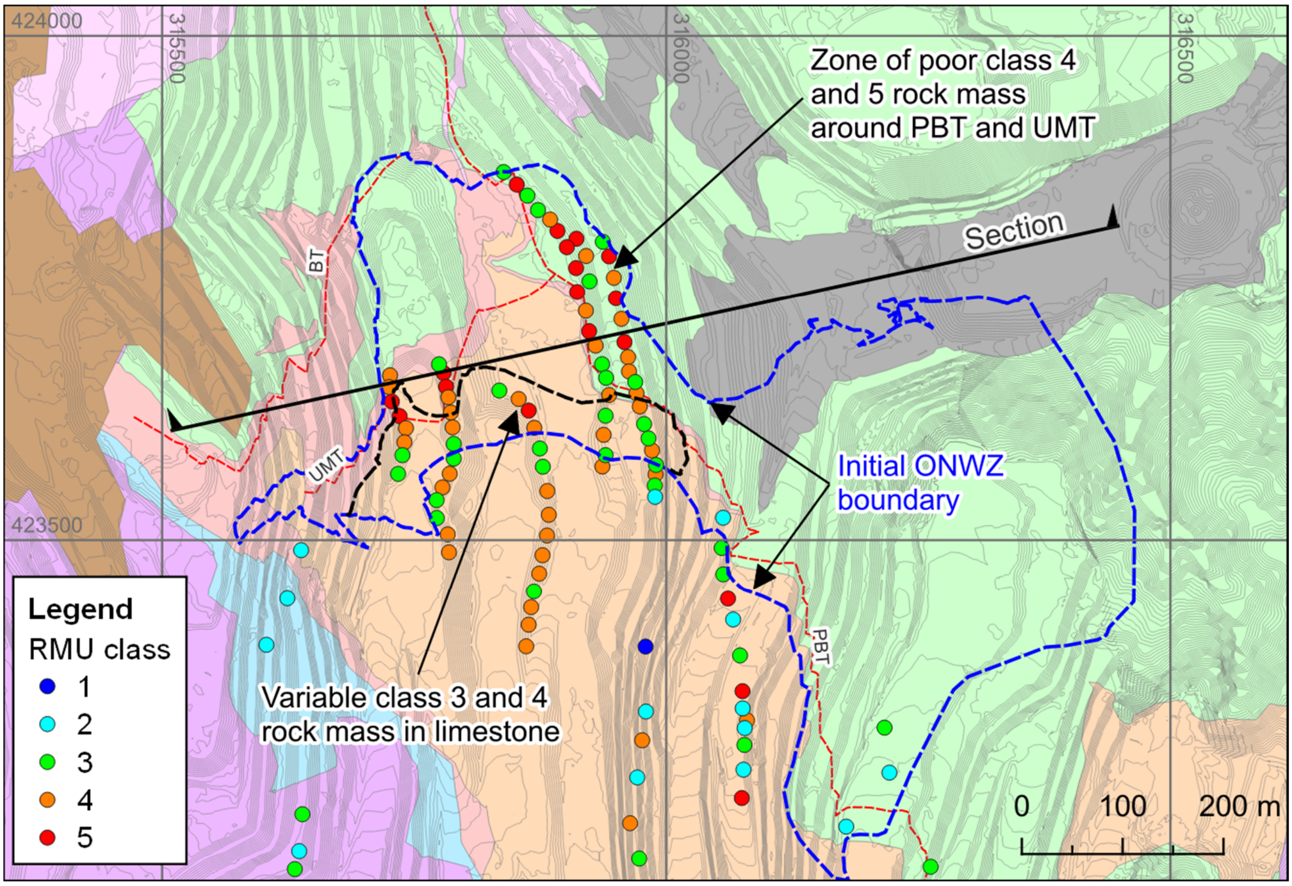

Figure 5 Distribution of RMUs from GSI field mapping locations in the central East Wall

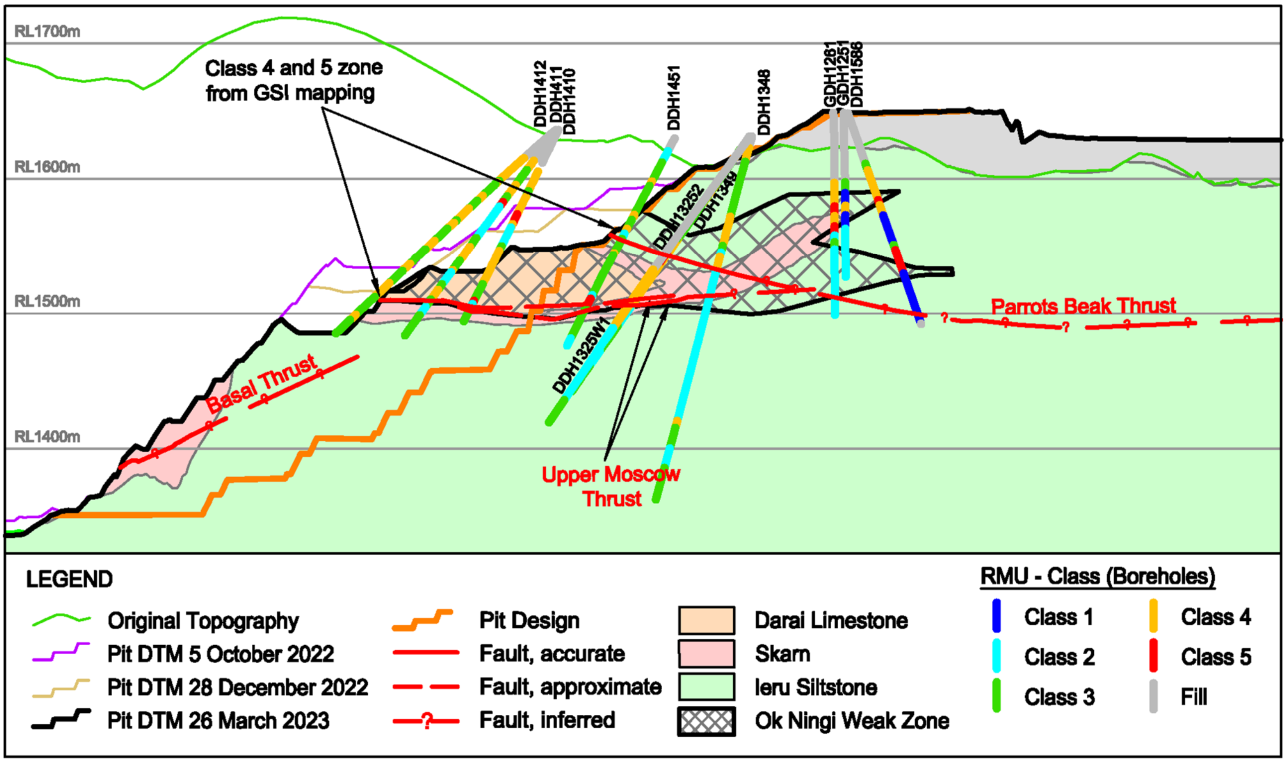

Figure 6 Section showing the distribution of RMU classes in boreholes

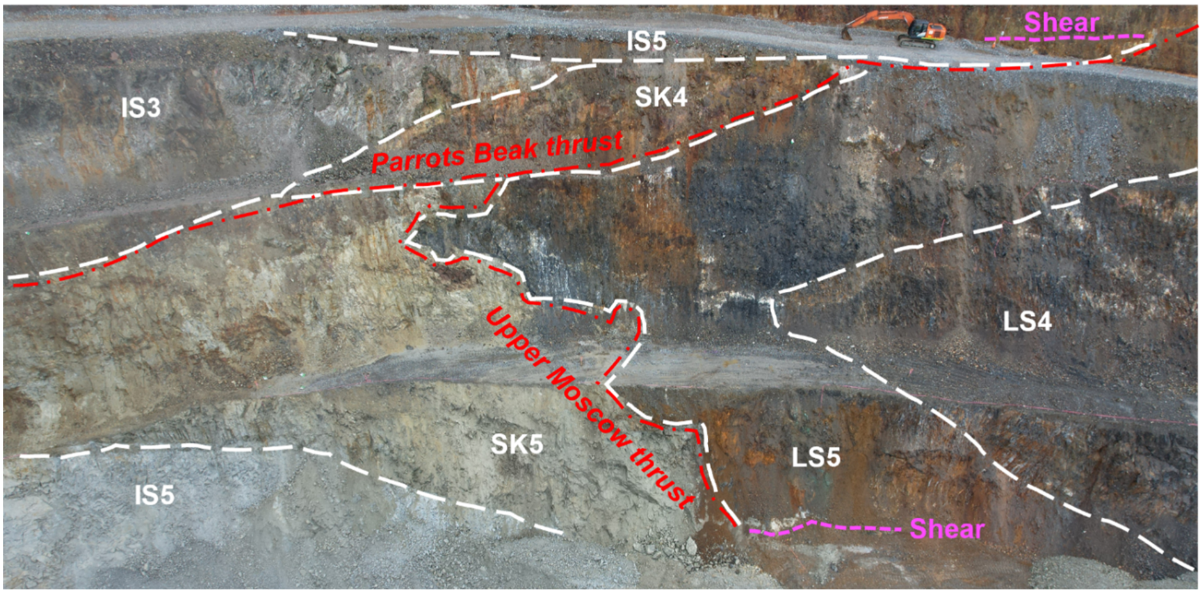

Figure 7 Annotated photograph showing the distribution of RMU classes and major structures

5.2 Assessment of structural controls

5.2.1 *Description and distribution of structural fabric patterns*

Structural measurements obtained from 3D photogrammetry models are shown in Figure 8 as an example of structural datasets obtained. Stereoplots for each lithology are presented and exemplify the typical structural patterns observed across the structural datasets:

- IS above the PBT comprises bedding dipping to the northeast and subparallel to the PBT. Shears are typically bedding-parallel to sub-horizontal, and in a moderately dipping joint set to the west-northwest and a steeply dipping joint set to the south-southwest. Field mapping described the horizontal shears as having thick infill comprising low strength light grey clay gouge.
- Darai Formation limestone thrust block (Lower Moscow) at the confluence of the PBT and UMT comprises shallow-dipping bedding towards the south to south-southwest, and shears that are typically bedding-parallel to sub-horizontal. Faults and associated joint sets are present, with a set dipping steeply towards the northwest and another set dipping moderately to steeply towards the west-southwest to south.
- Darai Formation limestone towards the south (Middle Moscow) comprises faults and associated joints, with a set dipping steeply to the northwest and another dipping moderately to steeply towards the west-southwest to southwest.

5.2.2 *Classification system to characterise the tactile infill condition of major structures*

Identification of individual major faults and shears in boreholes in the East Wall is complicated by two factors. Firstly, the presence of numerous other faults/splay faults with similar characteristics makes identification of the primary structure plane difficult by borehole drilling alone. Secondly, there is potential for the character of the fault to change spatially due to deformation and alteration associated with multiple intrusion events, as evidenced by the undulation and variability of the fabric within the UMT as annotated in Figure 7.

To better understand the variation, a classification system was developed to describe the character and distribution of major structure infill, which was then used to understand how these influence the structural shear strength properties. This was primarily developed to assess borehole data to allow comparison with the field observation of exposed bench faces. Infill character categories developed for the East Wall are presented in Table 2, which was used to classify all faults intersected by boreholes within the Ok Ningi area.

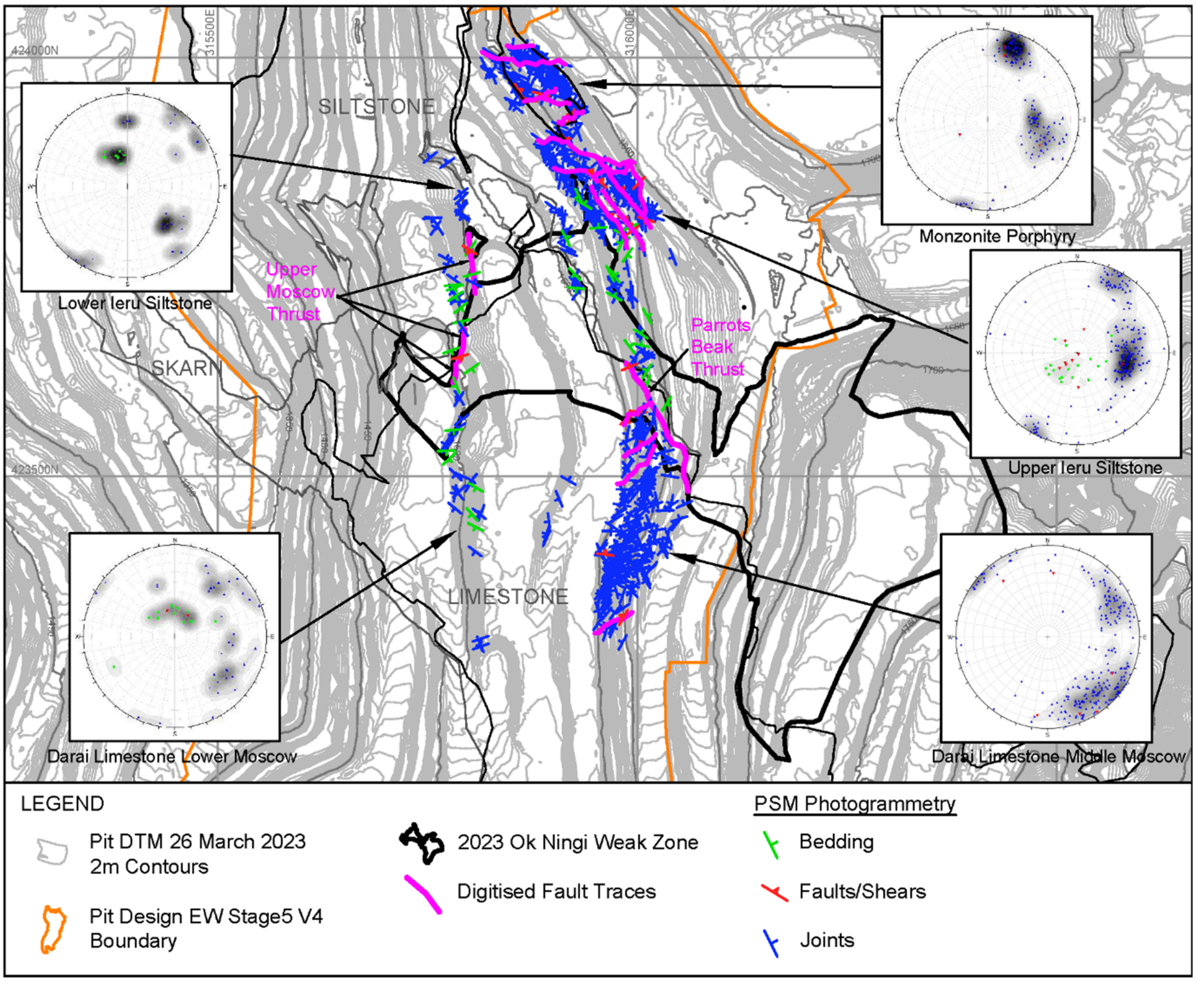

Figure 8 Distribution of structural fabric patterns from digital mapping of a 3D photogrammetry model

Table 2 Structure zone classification system developed for the East Wall

Shear strength description	Classification	Structure/zone infill description
	Clay gouge	Clay gouge or fines as the only component
Poor ↓	Clay, with crushed rock	Clay or fines, matrix-supported with angular disoriented rock fragments of variable sizes or chaotic breccia
	Crushed rock, with clay	Disoriented angular rock fragments of variable size or mosaic breccia, clast-supported with clay or fines as the secondary component
	Crushed rock	Angular rock fragments of variable size or fragmented rock or crackle breccia, with little to no matrix
Fair	Highly fractured	Intervals of closely spaced defects generally comprising core lengths <50 mm, or healed breccia
Poor (assumed)	Core loss/ cavity	Intervals of poor to no core recovery (>50% core loss), or intervals marked as cavities. Loss assumed to be clay or fine material washed out during drilling

5.2.3 Distribution of tactile infill conditions of major structures and zones

Figure 9 presents the distribution of the infill categories on Ok Ningi boreholes in section. The distribution of the infill categories shows that structures have a highly variable spatial distribution and character, with no single continuous fault infill along known structures being identified. This is interpreted as due to the discrete structures formed during regional-scale deformation having been subsequently deformed, altered and cindered at the deposit-scale during multiple intrusion events. Low strength clay gouge is present but rather as isolated pockets and lenses rather than being continuous over inter-ramp failure path scales, which is important given this is the major design risk.

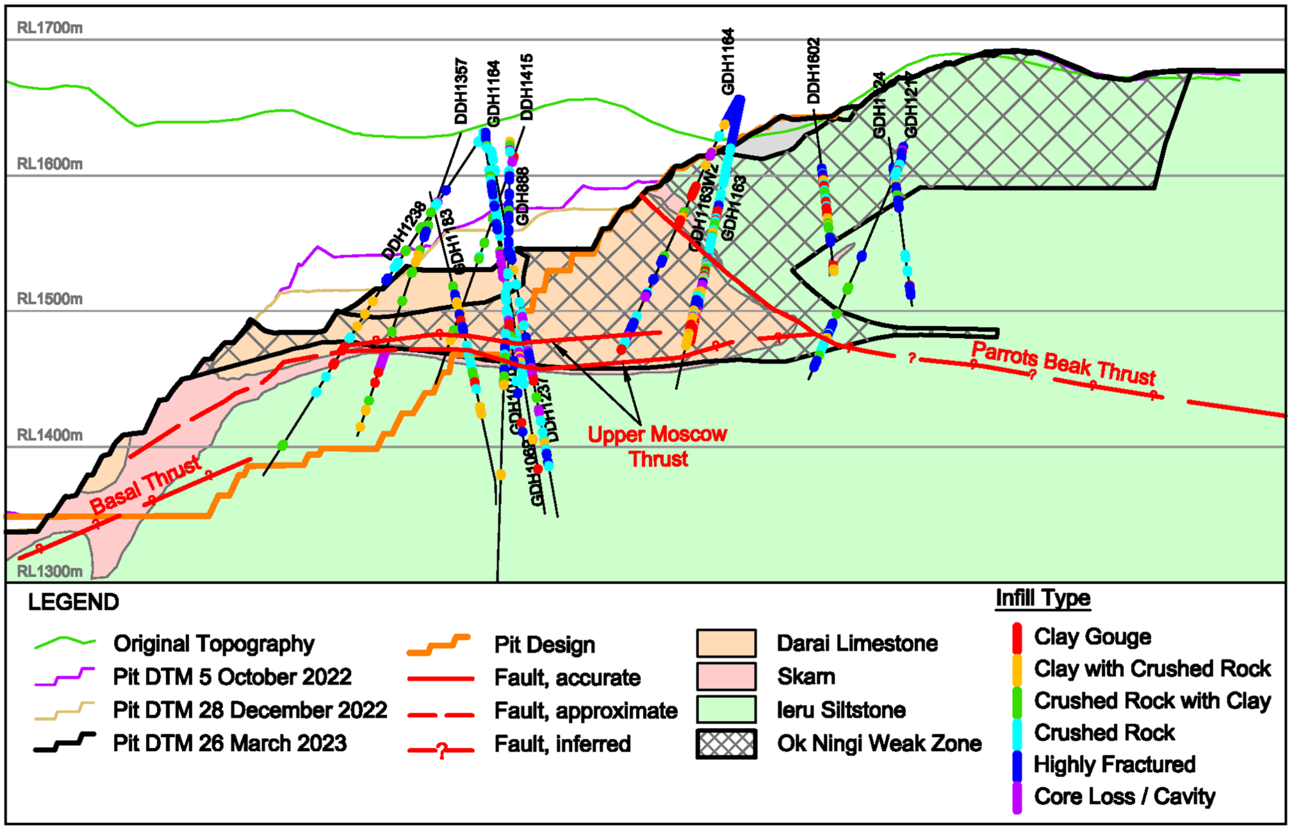

Figure 9 Showing distribution of the structure infill classifications on boreholes in section

5.2.4 Shear strength of structures and zones

Existing data on infill triaxial testing was reviewed to assign shear strength parameters to the structure categories. Figure 10 shows the range of shear strength results obtained from triaxial test results conducted on six samples in the central East Wall area. Structure infill categories were assigned shear strength parameters by distributing them within the range of parameters obtained from triaxial testing. Table 3 presents the assigned shear strength parameters for each category.

A weighted average of 30° and 10 kPa is calculated for intervals with clay/fines within the UMT fault due to the variable nature of the structures and based on the percentage of the total interval thickness. The weighted average represents an overall minimum shear strength for failure within this major structure zone comprising a variable character and strengths.

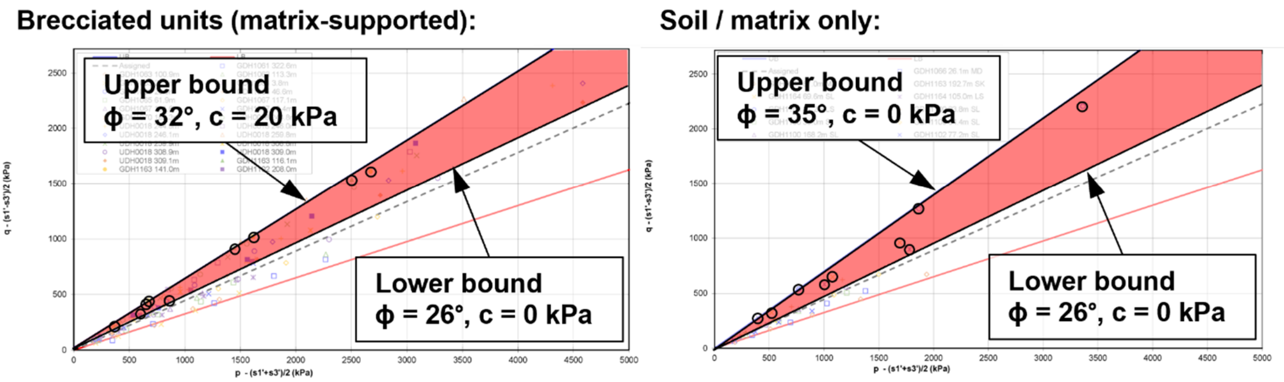

Figure 10 Shear strengths from triaxial testing of breccia and soil/matrix units. Samples from the central East Wall are circled, the upper and lower bounds annotated, and the range highlighted in red

Table 3 Assigned shear strengths for each structure category

Classification	% of total thickness	Shear strength description	Triaxial test range	Assigned parameters	
				Friction angle (°)	Cohesion (kPa)
Clay gouge	10	Poor	Lower bound	26	0
Clay, with crushed rock	5	↓	↓	28	10
Core loss/cavity	40			30	10
Crushed rock, with clay	3		Upper bound	35	20
Crushed rock	25	Fair	Assumed to be represented in rock mass strengths of the surrounding UMT zone		
Highly fractured	2				
Other/not classified	15	–			

5.3 Design optimisation

Stability analyses completed in 2D and 3D, and analysing a failure mechanism with basal sliding on a single persistent structure, indicated an:

- Unacceptable Factor of Safety for a basal fault equivalent to 'poor' shear strength (Table 3).
- Acceptable Factor of Safety for a basal fault equivalent to 'fair' shear strength (Table 3), and with potential for further steepening within the better-quality limestone rock mass within the ONTB.

Given the additional work completed during mining confirmed the basal faulting was equivalent to 'fair' shear strength classification across the scale relevant to the critical failure mechanism, the risk of large-scale instability was considered acceptable with continued extensive pit slope monitoring within the ONWZ subdomain. Within this subdomain both the bench angle of 50° and inter-ramp angle of 39° were considered to be as steep as possible, which was confirmed by stability analyses indicating a Factor of Safety close to 1.2 as well as observed slope performance.

Within the ONTB subdomain the slope was further optimised by increasing the bench face angle from 50° to 60°, which was achievable due to the marginally better rock mass conditions. This resulted in an increase in the design inter-ramp angle of 3°, which returned an acceptable Factor of Safety of 1.2 and resulted in significantly more high-grade ore being available for mining.

6 Conclusion

This paper has presented the geotechnical model for the central East Wall Ok Ningi area of the Ok Tedi mine, as well as the EGM process used for updating the geotechnical model during mining to address potential design risks. The Ok Ningi area is geotechnically very complex, with numerous regional-scale faults as well as late stage brecciation, alteration, weathering and structural overprints developed during multiple intrusion events. Due to the skarn orebody dipping parallel with the pit slope design and critical mine infrastructure located at the crest, it was considered crucial to ensure the design was as steep as possible to maximise ore recovery while also providing confidence that no instability large enough to impact the mine infrastructure could develop.

Additionally, significant time and data constraints for the initial slope design process meant there was a level of uncertainty in the geotechnical model and design assumptions as mining commenced. The initial geotechnical model did highlight risks to the design in the form of faults and shears towards the base of the ONWZ, which could act as a basal sliding surface if they were low strength, persistent defects. This emphasised the need for further monitoring, investigating and assessment during mining to address the design risks.

Accelerating slope movements observed in the prism data during mining and the exposure of discrete, persistent, low strength sub-horizontal faults and shears in the upper benches confirmed the risk that these features posed to the design. While instability of the upper benches was acceptable, a deeper-seated instability with a similar mechanism had the potential to impact the infrastructure and was therefore unacceptable.

The EGM process was used to quantify the risk with additional targeted field mapping campaigns, and the review of existing and new borehole data focused on faults and shears at the base of the ONWZ and updating of the geotechnical model. This work confirmed adversely oriented faulting at the base of the ONWZ, however, the tactile conditions and spatial distribution of these structures were found to be highly variable and with low strength infills localised to pockets and lenses. This work, along with subsequent analyses, confirmed that the design risks were acceptable and even led to optimisation of the ONWZ into two subdomains; one of which was steepened to reflect the improved understanding of rock mass and structural conditions.

The EGM framework was successfully used to underpin engineering decisions throughout the investigation, modelling, analysis and design process, despite fairly significant geotechnical and operational challenges. The outcome of the geotechnical model and updated stability analyses development process was a higher confidence design which increased ore recovery and safeguarded mine critical infrastructure at the crest.

Acknowledgement

The authors thank Ok Tedi Mining Ltd for permission to publish, and acknowledge the significant contribution of Tim Sullivan of PSM for his continued mentoring and guidance throughout the project. Further acknowledgement is given to the wider Ok Tedi geotechnical team for its contributions and assistance with data collection, as well as Madeline Kobler, Adam Irvine, Harrison Crooks and Megan Baker of PSM for their assistance with the ongoing model development.

References

Baynes, FJ & Parry, S 2022, *Guidelines for the Development and Application of Engineering Geological Models on Projects*, International Association for Engineering Geology and the Environment Commission, vol. 25, publication no. 1.

Casagrande, D, Klawitter, M & Koek, M 2021, 'Monitoring and risk-control of large-scale toppling failures-a case study from Ok Tedi', *IOP Conference Series: Earth and Environmental Science*, vol. 833, no. 3.

Eggers, MJ & Bertuzzi, R 2020, 'The engineering geological model', in R Bertuzzi (ed.), *Tunnel Design Handbook*, 4th edn, PSM, Sydney, pp. 5–13.

Hill, KC, Kendrick, RD, Crowhurst, PV, & Gow, PA 2002, 'Coppergold mineralisation in New Guinea: tectonics, lineaments, thermochronology and structure', *Australian Journal of Earth Sciences*, vol. 49, no. 4, pp. 737–752.

Hill, KC & Hall, R 2003, 'Mesozoic-Cenozoic evolution of Australia's New Guinea margin in a west Pacific context', *Defining Australia: the Australian Plate as Part of Planet Earth: Geological Society of America and Geological Society of Australia, joint publication,* vol. 372, pp. 265–290.

Kennedy, G & Casagrande, D 2020, 'Evolution and management of large-scale instability: a case study from Ok Tedi', in PM Dight (ed.), *Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 265–280, https://doi.org/10.36487/ACG_repo/2025_13

Large, SJE, von Quadt, A, Wotzlaw, JF, Guillong, M, & Heinrich, CA 2018, 'Magma evolution leading to porphyry Au-Cu mineralization at the Ok Tedi deposit, Papua New Guinea: trace element geochemistry and high-precision geochronology of igneous zircon', *Economic Geology*, vol. 113, no. 1, pp. 39–61.

Mason, RA 1994, *Structural Evolution of the Western Papuan Fold Belt, Papua New Guinea*, PhD thesis, University of London, London.

Pollard, PJ, Jongens, R, Stein, H, Fanning, CM, & Smillie, R 2021, 'Rapid formation of porphyry and skarn copper-gold mineralization in a postsubduction environment: Re-Os and U-Pb geochronology of the Ok Tedi Mine, Papua New Guinea', *Economic Geology*, vol. 116, no. 3, pp. 533–558.

Weir, FM, Smith, AG, Watton, J, Koek, M & Kuira, P 2018, 'Managing large scale failures – a case study from Ok Tedi mine, Papua New Guinea', *Slope Stability 2018: Proceeding of the XIV Congreso International de Energia y Recursos Minerales*, Sevilla, pp. 1394–1407.