Risk Mitigation through Design Optimization Utilizing Seasonal Effects under Arctic Conditions at the Amaruq Mine

Christian Tremblay *Rock Mechanics Coordinator, Agnico-Eagle Mines, Baker Lake, Canada*

Ben Peacock *Specialist Engineer, Knight Piésold, North Bay, Canada*

Véronique Falmagne *Senior Advisor Mining, Agnico-Eagle Mines, Rouyn-Noranda, Canada*

K.S. Kalenchuk *President and Principal Consultant, RockEng Inc., Kingston, Canada*

Erik Bellefleur *Mine Planning Coordinator, Agnico-Eagle Mines, Baker Lake, Canada*

Abstract

Agnico Eagle Mines is currently operating the Amaruq Mine located in the Canadian Artic. Since the beginning of the open pit operations, a series of bench-scale failures and rockfalls have occurred during the freshet and summer months (May to September). These instabilities can be correlated with a prominent and very weak komatiite unit. The komatiite is an ultramafic rock commonly altered to a chlorite carbonate shist. The domain is strongly anisotropic and rock mass competency is highly variable. High strain zones within the komatiite, which are identified in core as zones of low RQD, with shearing or gouge are impacting the slope performance locally.

This paper presents the geological and geotechnical site characterization, emphasizing the challenging komatiite conditions including the impact of the high-strain structures. An overview of the historic slope performance and failure mechanisms is provided, with focus on the influence of the seasonal effect and how the mine plan has been adjusted to take advantage of more favorable frozen conditions. The evolution of the pit slope design in response to kinematic analyses and numerical modelling is presented as well as the strategic design updates and tactical measures implemented to mitigate risk through the life of mine.

1 Introduction

Agnico Eagle Mines Meadowbank Division (AEM) has been established in the Canadian Arctic since 2009. The Meadowbank Complex includes the Meadowbank Mine and the satellite Amaruq Mine which is located 63 km away (Figure 1). Mining is currently focussed on the Amaruq Mine which consists of the Whale Tail and IVR narrow vein gold deposits. Commercial ore production began in 2019 in the Whale Tail and IVR open pits and an underground mine below the Whale Tail deposit came on stream in 2022 (Figure 2). The geomechanical design inputs to the design of the open pits was provided by Knight Piésold Ltd. (KP). This paper will focus on the Whale Tail open pit, which is

1100 m long, 675 m wide, 290 m deep and being mined in three phases. Note that all orientations presented in this paper are relative to mine grid, which is rotated 39° counterclockwise from true north.

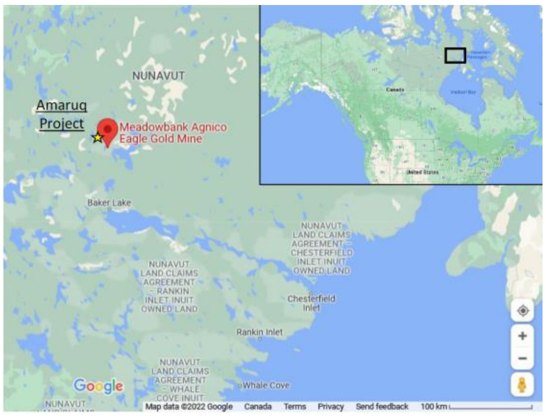

Figure 1 : Amaruq Mine Location

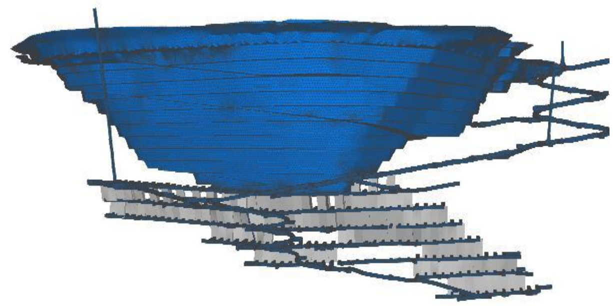

Figure 2 : Whale Tail Open Pit and Underground Mine

2 Background Information

2.1 Geology

The main lithologies within the Whale Tail open pit are described below and shown relative to the final open pit slopes on Figure 3.

- **Greywacke:** The most common lithology which hosts the deposit and is also internal to it.
- **Mafic Volcanics:** Present along the southern limit of the deposit and consists of basalt.
- **Komatiite:** The Komatiite consists of a North and a South limb that bound the northern and southern limits of the deposit. Commonly altered to a chlorite-talc-carbonate schist (soapstone) with chaotic carbonate veining and can be locally altered with biotite. The Komatiite is characterised by variable rock mass quality and can be faulted.
- **Iron Formation:** Primarily located along the contact of the Komatiite and Chert.
- **Chert:** A sedimentary unit consisting of interbedded bands of Chert, sediments, and thin beds of iron formation. The Chert is associated with several of the mineralized zones.
- **Diorite:** An unmineralized intrusive unit located to the south of the deposit.

A series of high-strain structures have been identified at the deposit and are predominantly located within the Komatiite and near to the lithological contacts. These structures can be brittle, with gouge and rubble, or associated with intervals of intense foliation. The gold mineralization is associated with a system of quartz veins, typically within the Chert. Replacement mineralization has also occured within the Iron Formation.

2.2 Permafrost Conditions

The seasonal temperature variation at the mine is extreme, ranging from +20°C in summer to -30°C in winter on average. The Whale Tail pit is predominantly located within permanently frozen ground referred to as permafrost. However, the open pit was established below the northern end of Whale Tail Lake and areas of talik (unfrozen ground) are present in the upper south, northeast and northwest walls below the former lake. The distribution of the talik within the slopes has been evaluated using thermistors and numerical thermal models (Figure 5). Furthermore, seasonal temperature variations result in an active layer along the surface of the open pit slopes where the rock mass thaws each spring and freezes each fall.

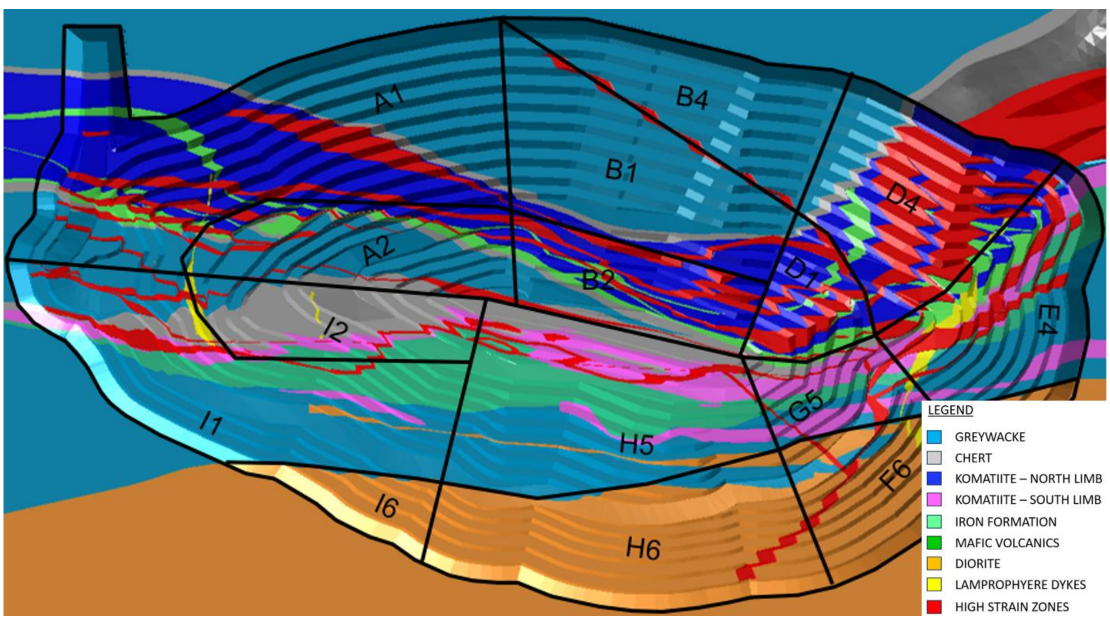

Figure 3 : Lithologies and High-Strain Structures

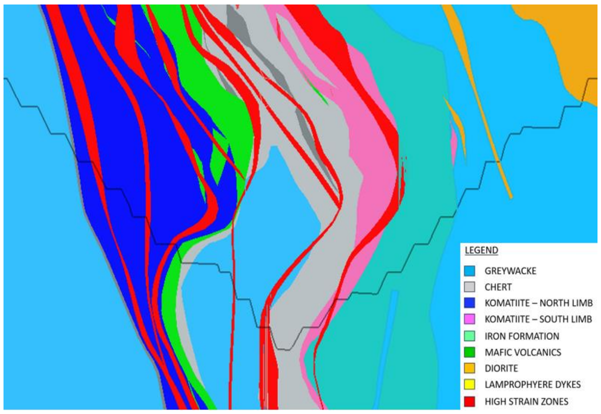

Figure 4 : Typical Cross Section

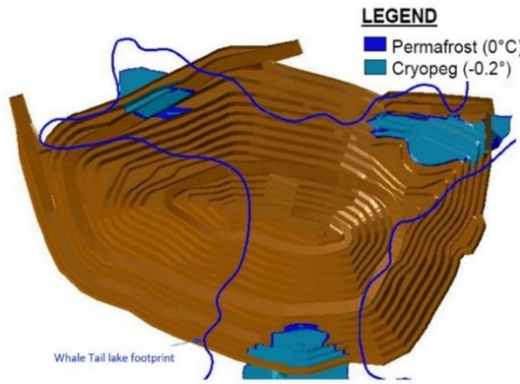

Figure 5: Predicted Talik Within Open Pit Slopes

3 Rock Mass Characteristics

The geomechanical properties of the rock masses forming the open pit slopes have been characterized through a series of site investigation programs as well as on-going in-pit mapping. This includes approximately 4,000 m of geomechanical logging and core orientation from 19 drillholes and a comprehensive program of laboratory testing. including 136 Uniaxial Compressive Strength (UCS), 71 Triaxial Compressive Strength (TCS), 82 Brazilian Tensile Strength (BTS), and 24 Direct Shear (DS) tests. Additional discontinuity orientation data have been collected over time through structural mapping and LiDAR scans of the bench faces.

The rock mass structure at the Whale Tail deposit is complex. The deposit has experienced several deformation events and is characterized by folding at multiple scales. Except for the Diorite, which is blocky, the rock mass is characterized by a prominent foliation sub-parallel to the lithology contacts. The orientation of this foliation varies with the folding of the deposit. In the upper portion of the pit, the foliation strikes approximately east-west and dips to the south. The foliation overturns and dips to the north in the lower portion of the pit. The strike of the foliation rotates approximately 30° counterclockwise at a vertical fold axis in the eastern third of the open pit. A sub-horizontal joint set and a widely spaced north-south striking sub-vertical set cross-cut the foliation. A total of six structural domains were initially defined using the discontinuity orientation data and the contacts in the lithology model in an effort to capture this variability at a scale practical for open pit slope design (Figure 3). It was recognized that smaller-scale folding results in local variations within the slope.

Lithology is the primary control on the intact properties and rock mass quality. Therefore, rock mass quality domains were primarily defined on this basis (Table 1). The Komatiite is of lower and more variable rock mass quality than the other domains. Early in the design process it was recognized as a key unit likely to dominate the slope performance. Considerable effort was put into understanding the possible influence of geochemistry, alteration, the high-strain structures, and spatial controls on this variability. Based on the outcome of this work, an anisotropic strength model was selected for the Komatiite consisting of alternating weak and strong layers. The weak layers accounted for the high-strain structures within the Komatiite which vary from gouge-rich rubble zones to intervals of intense foliation.

Table 1 : Rock Mass Quality Domains and Rock Mass Characteristics

Domain		Intact Rock Properties				Joint Properties		Rock Mass Properties		
		mi	UCS (MPa)	Unit Weight (g/cm^3)	Unit Weight (kN/m^3)	Friction Angle (°)	Cohesion (MPa)	RMR_{89}	GSI	Q'
Diorite	Surface to 80 mbgs	20	130	2.82	27.7	35	0	65	60	5.2
	> 80 mbgs							70	65	8.1
Greywacke		13	120	2.81	27.6	35	0	65	60	6.6
Chert		10	130	2.89	28.4	35	0	65	60	5.6
Iron Formation		9	105	3.12	30.6	35	0	65	60	4.1
Komatiite	Strong Layer	8	50	2.86	28.1	30	0	60	55	3.8
	Weak Layer							40	35	N/A

4 Initial Open Pit Slope Design

The original evaluation of the achievable open pit slope geometry was based on a combination of kinematic and limit-equilibrium analyses, complemented by 2D numerical analyses, rockfall analyses, and a review of the performance of the existing open pit slopes at the Meadowbank site. The potential for kinematic planar failures on the foliation was identified as a limiting condition in many of the design sectors. Rock mass quality was not expected to limit the resulting slope angles at the planned inter-ramp slope heights. Territorial regulations specify a minimum catch bench width of 8 m. This was increased to reflect the backbreak expected due to both kinematic failures and operational factors. The resulting slope geometry recommendations ranged as follows:

- Bench Height (BH): 21 m established in three 7m benches
- Bench Face Angle (BFA): 65 to 75°

- Catch Bench Width (CBW): 10 to 13 m
- Inter-Ramp Angle (IRA): 43 to 53°
- Maximum Inter-Ramp Height: 175 m

The northeast wall of the open pit, which is a focus of this paper, is within the Komatiite and coincides with several high-strain structures. The foliation was expected to strike approximately 45° relative to the wall and the kinematic analyses suggested that it would not control the slope geometry. The catch bench width was increased to account for the expectation of increased back break due to the presence of the Komatiite and high-strain structures. The design recommendations were for a BFA of 75° and CBW of 10.5 m, resulting in an IRA of 52°.

5 2019 to 2021 - Overview of Slope Failures

The Whale Tail open pit experienced several bench-scale failures and rockfalls between 2019 and 2021. A total of 30 individual events were documented from 2019 to 2021 (Figure 6). Some of these events represented the progression of an existing instability and were grouped into 20 failures. These 20 failures can be broadly grouped into three categories:

Phase 2 South Wall: Localized planar failures ranging in size from approximately 200 to 1,700 tonnes occurred along lithology contacts and random discontinuities. These represent approximately 30% of the failures. The slope performance was consistent with expectations and it was concluded that no design modifications were required. The failures will be mined out by the final Phase 3 pushback of the South Wall into the Diorite.

Phase 1 North Wall: This interim wall was established in the Komatiite parallel to the foliation. The bench face was established at a steeper angle than the dip of the foliation and failed back to it in a series of planar and wedge failures. The failures were aggravated by the presence of the high-strain zones within the Komatiite. The cumulative failures ranged in size from approximately 50 to 1,100 tonnes and represent approximately 50% of the total. These failures affected open pit production, but will be mined out when establishing the final pit walls.

Phase 3 Northeast Wall: A series of planar failures occurred along the foliation in the Komatiite, in some cases breaking through the weak rock mass to form a wedge-like geometry. The cumulative failures ranged in size from approximately 1,000 to 6,600 tonnes. The slope in this sector of the open did not perform as expected . The failures are attributed to a rotation in both the foliation strike and wall orientation, aggravated by the presence of the high-strain zones and a reduction in rock mass quality in the Komatiite.

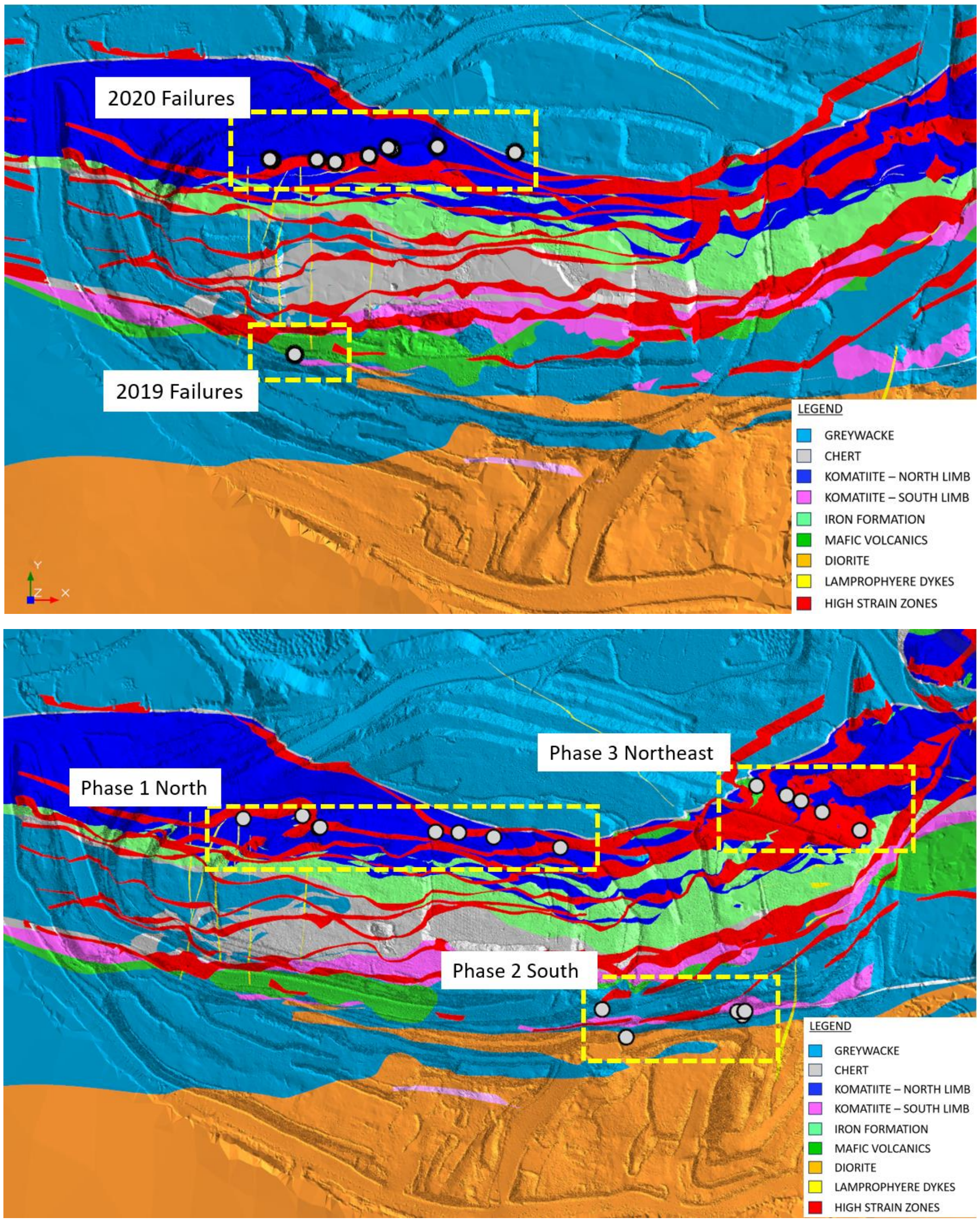

Figure 6: Overview of Slope Failures – 2019 & 2020 (Top) and 2021 (Bottom)

These slopes failures were initially managed through a series of tactical measures, including safety berms, temporary step-out and enhanced slope monitoring. The slope failures were then reviewed, and key observations are summarized below and shown on Figure 7.

- 85% of the failures have occurred within the Komatiite unit
- 90% of the failures are planar failures or a combination of planar and rock mass failure
- The individual failure events are relatively small, with more than 80% less than 1,000 tonnes, and occur rapidly.
- The failures occurred exclusively during the spring freshet and summer months (June to August), with most failures occurring in June at the onset of the freshet and diminishing in frequency over July and August.
- Benches established in the winter typically performed well until failing during the spring freshet. This is attributed to a combination of the thawing of the rock mass and the presence of rainfall/surface water infiltration. In many cases, the foliation was observed to be undercut when the bench was established but the bench face could not be scaled back to the foliation when the rock mass was frozen. Notably, it was possible to maintain a BFA of 55° in areas where the foliation was parallel to the slope and dipping at 40° while the rock mass was frozen.
- Approximately 35% of the failures occurred on the same day as a rainfall event, and almost 50% of the failures occurred within two days of a rainfall event. The larger failures were more likely to occur during a rainfall event. Water flowing down the slope was also observed to erode the high-strain structures, locally undercutting the bench faces.
- Approximately 50% of the failures occurred in or within 20 m of the modelled talik, representing 70% of the total failure tonnage. It is possible that the unfrozen rock mass allowed water to infiltrate deeper into the benches and contribute to the failures.

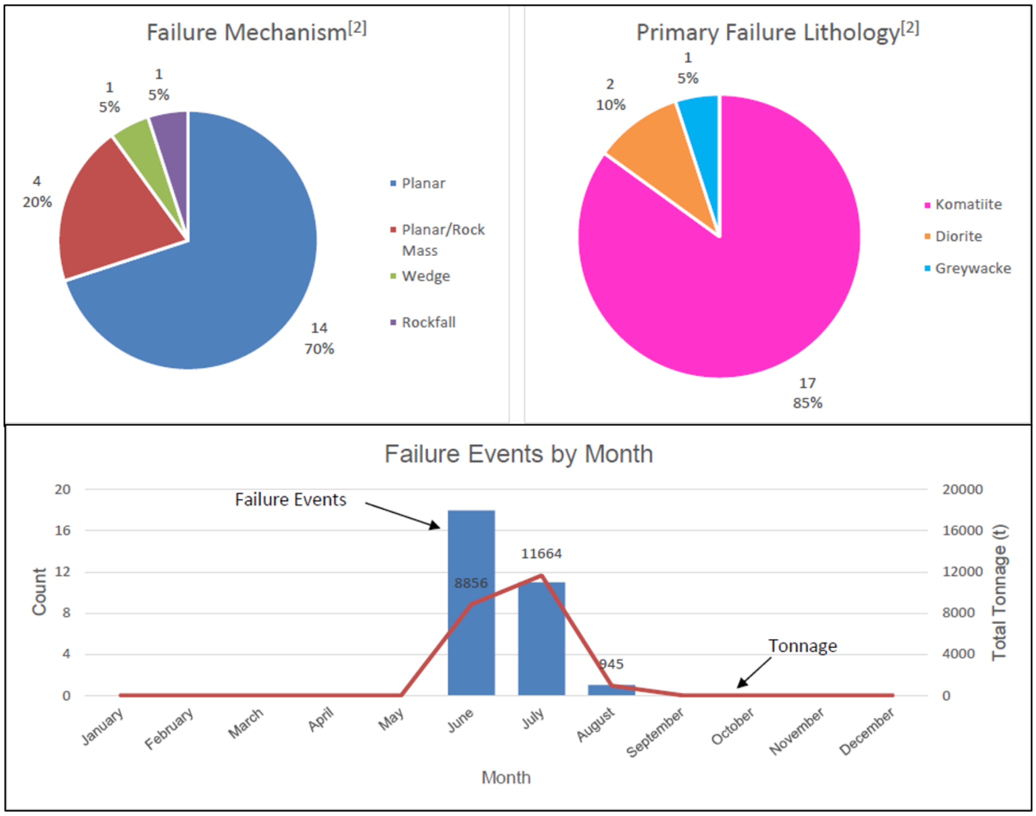

Figure 7 : 2019 to 2021 Failure Statistics

6 Changes to Mining Practices and Slope Design

In response to the 2019, 2020 and 2021 slope failures, AEM initiated a review of the slope performance and open pit slope geometry recommendations in collaboration with KP and two external reviewers with the goal of assessing whether design and operational changes were required. Being relatively early in the mine life, with few final walls exposed but the slope performance well documented, the timing was ideal to reassess the initial design assumptions. The entire pit was considered but the focus was on the Phase 1 North Wall and Phase 3 Northeast Wall.

6.1 Phase 1 North Wall

As an interim wall, specific slope stability analyses and slope geometry recommendations were not developed for the Phase 1 North Wall. The slope geometry recommendations developed for the final wall in an adjacent design sector were applied to this sector, consisting of a 65° BFA, 10.5 m catch bench width and 21 m bench height. However, the Phase 1 North Wall strikes parallel to the foliation whereas the wall in the other design sector cross-cuts it (Figure 8). This rotation in the orientation of the wall was not considered when the design recommendations were carried over and resulted in the planar failures that occurred (Figure 9). This was an important reminder that the planning and engineering team need to be aware of the inputs and assumptions underlying the stability analyses and to exercise caution when design sectors are represented as 3D solids.

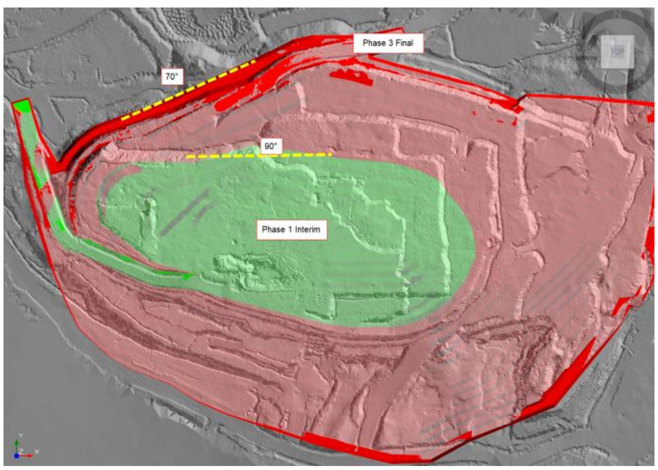

Figure 8: Wall Orientation of Phase 1 North Wall vs Phase 3

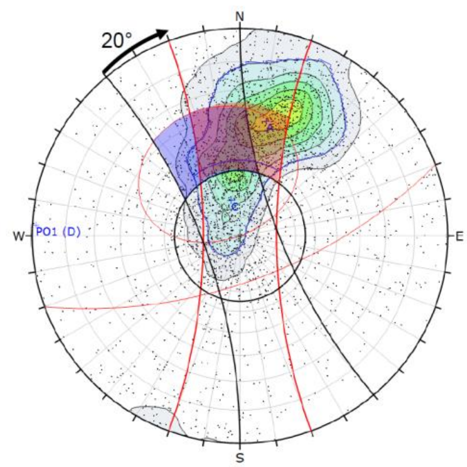

Figure 9: Kinematic Analysis Review of Wall Orientation

After an evaluation of several different options, AEM decided to re-establish the wall in the Komatiite with a pushback. From a geomechanical risk perspective, the optimal scenario would have been to mine the wall back into the more competent Greywacke which will form the final wall. However, this scenario was not economically attractive. Slope geometry recommendations specific to this interim wall were developed based on detailed kinematic analyses, resulting in a BFA of 55°, CBW of 11 m and a 21 m BH. It was understood that the new slope geometry would reduce both the frequency and size of the failures along this wall but would not eliminate them due to the variability in the orientation of the foliation within the komatiite.

Since the introduction of slope geometry recommendations specific to this interim wall, the slope performance has generally been consistent with expectations. During freshet, failures continue to occur in sections of the benches that were established over the previous winter. Considering this recurrent pattern, the mine geotechnical and planning teams re-sequenced the remainder of Phase 1 to prioritize mining of the Komatiite and Phase 1 North Wall during winter and to ensure that mine operations were offset from the wall with a step-out and safety berms during the subsequent freshet and summer period. Phase 1 was safely and successfully completed.

6.2 Phase 3 Northeast Wall

During the 2021 freshet, the wall established in the northeast corner of the pit during the previous winter failed extensively (Figure 10). There were no safety hazards as the geotechnical team had closed the area preventively before the onset of freshet, based on the previous performance of the komatiite and the local concentration of high-strain zones in the area.

Figure 10 : 2021 – Phase 3 Northwest Wall Before Freshet (Left) & During Freshet (Right)

As mining advances, the only ramp into the pit will eventually cross the lower part of this sector; frequent bench scale failures or the occurrence of an inter-ramp scale failure could lead to a loss of access. Un-mitigated failure in this area therefore posed a significant risk to the operation. Based on a detailed review of the slope performance, it was concluded that the orientation of the foliation and the rock mass quality of the Komatiite were not consistent with the expectations for this sector. The characterization of the Komatiite was refined, and the limit-equilibrium and kinematic stability analyses updated to re-assess the slope design. Due to the elevated geomechanical risk, the complicated geology, and curved slope geometry, a 3D numerical analysis was completed for this sector. The numerical model also allowed future interactions with the underground mine to be considered.

6.2.1 Revised Characterization of the Komatiite

The original characterization of the Komatiite as alternating weak and strong layers proved to be an oversimplification of a complex and variable rock mass. A decision was made to consider the Komatiite as a grouped, weaker unit. At the same time, an improved understanding of the deposit geology identified differences in the frequency and size of the high-strain structures between the eastern and western portions of the deposit. The Komatiite was divided accordingly into East and West domains. The East Komatiite forms the upper part of the Northeast wall and is generally of lower rock mass quality (attributed to more frequent and wider high-strain structures), while the West Komatiite forms the lower part of the Northeast wall and is generally of higher rock mass quality.

The design UCS of 50 MPa for the Komatiite was previously based on the average of the laboratory UCS test results. During the review it was concluded that the tested samples were likely biased towards the intervals of more competent Komatiite due to the difficulty in obtaining samples of sufficient length. As a result, the intact strength of the Komatiite was revisited using the Schmidt hammer data collected on a run-by-run basis during the geomechanical logging. Based on these data, the design UCS was revised to 40 MPa for the West Komatiite and 35 MPa for the East Komatiite.

The shear strength of the open foliation was initially defined as frictional strength of 30° based on both the line of best fit through the direct shear test results (peak strength) and JRC and JCS measurements using the Barton-Bandis shear strength criterion. The peak strength direct shear test results defined an envelope of frictional strengths that ranged from 20° to 35°. For the updated stability analyses, the lower bound frictional strength of 20° was considered in addition to the original design value of 30°. The strengthening effect of the frozen rock mass was not explicitly considered in the analyses as the focus was on the long-term slope performance (i.e., after the rock mass forming the benches had thawed). The updated rock mass parameters for the Komatiite are presented in Table 2. These revised parameters formed the basis for updates to the stability analyses (Section 6.2.2) which ultimately resulted in changes to the slope geometry.

Table 2 : Updated Komatiite Rock Mass Parameters

Domain		Intact Rock Properties			Joint Properties		Rock Mass Properties	
		mi	UCS (MPa)	Tensile Strength (MPa)	Friction Angle (°)	Cohesion (MPa)	RMR_{89}	GSI
Komatiite	West	8	40	-4	20	0	60	55
	East						45	40

The rock mass structure in the sector was reviewed using mapping data, LiDAR scans of the failures, and discontinuity orientation data from a new geomechanical drillhole in the lower slope. The review also benefited an improved understanding of the deposit geology. Key outcomes included:

- The foliation exposed in the benches in the upper slope is rotated by about 20° relative to the discontinuity orientation data from the geomechanical drillholes in this sector. As a result, the foliation is locally sub-parallel to the exposed wall which partly explains the greater than expected frequency of slope failures. The mapping data were used to define a new structural domain in the upper wall.
- A secondary foliation is prominent in the Komatiite and dips at a shallow angle to the east. The primary foliation is sometimes rotated in the Komatiite relative to the other domains. As a result, the structural domains were divided between the Komatiite and non-Komatiite lithologies.
- The boundary between structural domains were revised to reflect the new discontinuity orientation data. A new structural domain was defined in the lower slope.

The revised structural domains are shown relative to the expected pit wall lithology in Figure 11 and can be compared to the original structural domains in Figure 3.

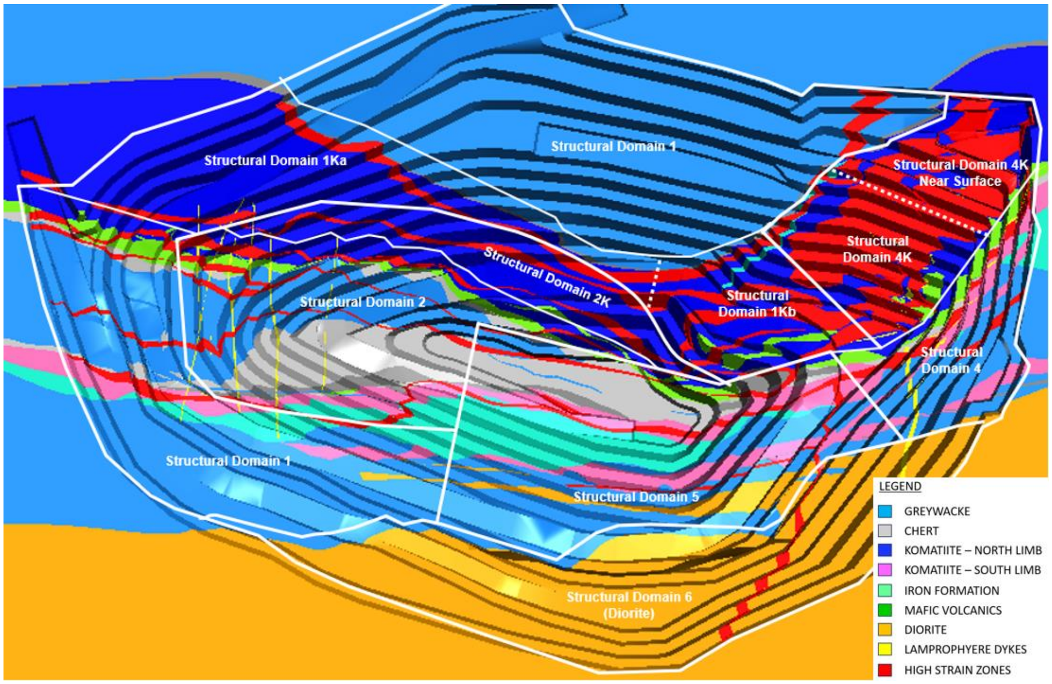

Figure 11 : Updated Structural Domains

6.2.2 Revised Stability Analyses and Slope Geometry

The kinematic and limit-equilibrium stability analyses were updated to reflect the improved understanding of the Komatiite characteristics and high-strain zones. The revised slope geometry recommendations developed for design sector 4K in the upper northeast wall consist of a 55° BFA, 11m CBW and 14m BH resulting in an IRA of 34°. The reduction in bench height from 21 to 14 m was made to reduce the exposure of personnel working in proximity to the wall to rockfall hazards. The width of the haul road width was also increased by 8 m to 36 m to allow the placement of a safety berm along the inside of the haul road.

In design sector 1Kb, in the lower northeast wall, the achievable slope geometry is sensitive to the orientation of the wall to the foliation. An IRA of 46°, based on a BFA of 65°, CBW of 10.5m, and BH of 21m is achievable where the wall cross-cuts the foliation (wall azimuth of 150°). IRAs less than 30° could be required where the wall is oriented parallel to the foliation (wall azimuth of 110°). Due to the economic impact of such a shallow IRA, alternative open pit designs and extraction sequences were considered for this design sector and the following measures were selected (Figure 12):

- Where possible, the wall orientation was adjusted to a more kinematically favourable orientation (i.e., azimuth of 150°) to allow for the steeper bench and inter-ramp geometry.
- Where the orientation of the wall could not be adjusted, (e.g., azimuth of 110°) the steeper geometry will still be used but the benches will be mined during the winter in order to take advantage of the strengthening effect of the frozen rock mass. These benches will be buttressed with rockfill prior to the spring thaw as they would otherwise fail back to the shallower IRA of 30°.
- The mine plan was sequenced so that no mining occurs against the Komatiite during the spring and summer months.
- Finally, visual and radar slope monitoring will continue to be key controls for managing the geomechanical risk.

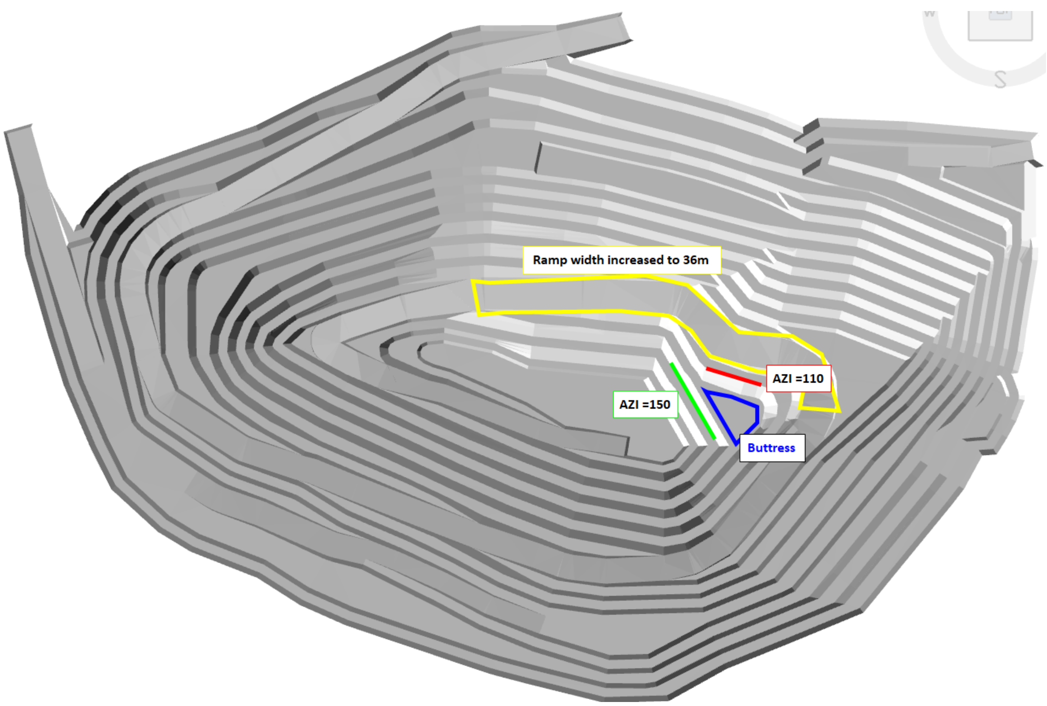

Figure 12: Tactical Slope Measures

6.2.3 Numerical Stability Analysis

A numerical model was developed in Flac3D by RockEng to back-analyze the performance of the pit slopes to date and forecast future performance over the mine life, including the impact of underground mining on the open pit slopes and vice-versa. The details of the model development and calibration approach are presented by Kalenchuk et al. (2024).

The results of the numerical models demonstrated that the proposed adjustments to the slope design and extraction sequence are achievable at a global scale based on the predicted yield, accumulated strain and stress states. The potential for multi-bench failure was identified where the Komatiite and high-strain structures will be exposed. Several design alternatives were analysed with the pit design and planning team and the optimal scenario was selected considering the impacts on ore recovery (losses) and scheduling delays while maintaining safe mining practices. The numerical modelling results provided additional justification for the slope design changes and tactical slope management measures.

7 Outcomes and Key Lessons Learned

As a result of the changes made to the slope design and operating practices, AEM has been able to continue safe and economic mining of the Whale Tail open pit. Slope instabilities continue to occur, but they are managed within existing processes.

Key geomechanical lessons learned over the course of mining in the Whale Tail pit include:

- Working closely with the Geology team is critical to understanding the rock mass structure within the deposit. This is an iterative process.
- Recognizing the seasonal nature of the failures in the Komatiite and optimizing the mine plan to limit mining activities in the vicinity of the Komatiite during freshet.
- Incorporating some flexibility into the mine plan to accommodate geomechanical risks (e.g., time and space for step-outs, increased ramp width, etc.). This can only be achieved with close cooperation between the geotechnical and the planning team.
- Clearly communicating of geomechanical risks to management and the planning team as soon as they can be reliably identified and understood.
- The importance of verifying the open pit slope design recommendations early in the mine life when there is more flexibility to adjust the open pit design (and on an on-going basis). The original design recommendations were by necessity primarily based on data from geomechanical drilling and preliminary geological modelling. While numerous drillholes

were completed, drilling ultimately only allows a small sample of the deposit to be characterized. The exposures in the open pit provided an invaluable opportunity to verify the rock mass characteristics and rock mass response during mining.

- The importance of ensuring the planning and engineering team are aware of the inputs and assumptions underlying the stability analyses.

References

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