The evolution of structural domains from scoping study to operations for the Meadowbank Mine – Amaruq Site

ROCKENG 2025
23rd Canadian Rock Mechanics Symposium

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ABSTRACT
Agnico Eagle Mines operates the Meadowbank Mine - Amaruq Site in the Canadian Arctic. The open pit and underground gold mine is hosted in a folded ore body and the complex rock mass structure strongly influences open pit slope and underground excavation performance.

Structural domains were defined for areas with similar structural characteristics and refined over time as the mine moved quickly from engineering studies to operations. The structural domains reflect advances in the geological understanding of the deposit, the contribution of data collection programs, and, eventually, the observed excavation performance. Data collection at Amaruq has included over 9,000 m of oriented core drilling as well as open pit and underground mapping.

This paper discusses how the structural domains were defined, how they have evolved over time, and how they have influenced the design and operation of the open pit and underground mine at Amaruq. Lessons learned through this process that may be applicable to other projects and mines are also discussed and summarized.

RÉSUMÉ
Mines Agnico Eagle exploite la mine Meadowbank et plus précisément le site satellite d'Amaruq dans l'Arctique canadien. La mine d'or à ciel ouvert et la mine souterraine sont situées dans un dépôt minéralisé plissé et la structure complexe du massif rocheux influence fortement la stabilité des pentes de la fosse ainsi que la performance des excavations souterraines.

Des domaines structuraux ont été définis pour des zones présentant des caractéristiques structurales similaires et ceux-ci ont été raffinés au fur et à mesure que la mine complétait rapidement les études d'ingénierie et débutait l'opération. Ces domaines structuraux reflètent le développement de la compréhension géologique du gisement, la contribution des programmes de collecte de données et, finalement, la performance d'excavation observée. La collecte de données à Amaruq inclut plus de 9 000 m de forage orienté ainsi que la cartographie de terrain de la mine à ciel ouvert et souterraine.

Cet article explique comment les domaines structuraux ont été définis, comment ils ont évolué au fil du temps et comment ils ont influencé la conception et l'exploitation de la mine à ciel ouvert et souterraine d'Amaruq. Les leçons tirées de ce processus, qui pourraient être applicables à d'autres projets et mines, sont également présentées et résumées.

1 INTRODUCTION

Agnico Eagle Mines (AEM) operates the Meadowbank Mine in the Canadian Arctic. The satellite Amaruq Site (Figure 1) is located 50 km west of the Meadowbank Mine and contains several gold deposits that are being mined using open pit and underground mining methods, including the Whale Tail deposit. The Whale Tail open pit is currently 150 m deep, with an ultimate planned depth of 250 m. The underground mine is located directly below the open pit and is approximately 1,100 m along strike and is planned to extend to a depth of 610 m below surface (Figure 2). The open pit and the majority of the underground mine are located within permafrost.

The timeline from the start of the engineering studies to operations for the Whale Tail deposit was relatively short, with a conceptual study completed for the open pit in 2015 and commercial operations beginning in 2019. Similarly, a scoping study was completed for the underground mine in 2016, an exploration ramp commenced in 2017, and underground commercial production started in 2022.

Figure 1. Amaruq site location

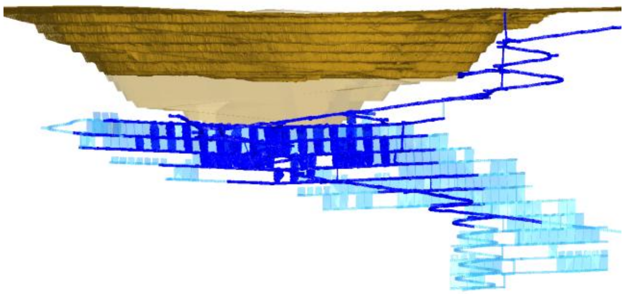


Figure 2. Whale Tail open pit and underground mine. Existing excavations are represented by dark colours and planned excavations by lighter colours.

The Whale Tail deposit is relatively shallow and the rock mass quality is generally Good (RMR_{89} 60 to 80). The orientation and characteristics of the rock mass structure are the main factors controlling the open pit slope and underground excavation performance. Understanding the structural characteristics of the deposit are key to optimizing the mine design and providing rock mechanics recommendations that are practical and help the operation be both profitable and safe for the workers.

This paper summarizes the structural domain definition process, explains how the structural understanding of the Whale Tail deposit has evolved over time, and how it was used to optimize the design of the open pit and underground mine from the conceptual study to operations. The paper concludes with some lessons learned from over 10 years of work gaining an understanding of this complex deposit.

2 DEFINING STRUCTURAL DOMAINS

Structural domains are used to group rock masses with similar structural characteristics and are a key part of the geomechanical model developed for the site. The domains are used during the mine design process to predict possible open pit slope or underground failure mechanisms and to identify the likely geomechanical hazards that will need to be managed.

The domain definition process is iterative, starting with limited data during conceptual studies and then evolving over time as new data becomes available and the rock mass understanding improves through advanced engineering studies and into operations. The number of iterations and resources allocated to refine the domains will depend on the spatial complexity of the deposit and the influence that these variations have on the excavation performance and mine economics. The more complicated the structural environment, the more effort is required to define it and the more likely it is that significant changes will occur over time.

In general, the large- and small-scale structural characteristics of a deposit can be influenced by a number of geological factors including, but not limited to, lithology, the nature of the mineralization, deformation and folding events, and faulting. The interactions between these factors need to be understood with the goal of identifying the key geological controls and spatial dependencies so that structural domain boundaries can be established and the relevant geomechanical characteristics defined (Mathis, 2016).

Each iteration of the domain definition process typically involves several key steps. For an initial assessment, these steps may include:

- Discussing the current geological and structural understanding of the deposit with the site's geology team.
- Creating a conceptual model of the expected structural characteristics of the deposit.
- Testing the conceptual model using the regional structural trends, core photos, mapping, oriented core data and/or televiewer survey data.
- Spatially separating areas with similar structural characteristics into domains, noting any areas where there is uncertainty or limited data.
- Collecting additional structural data to reduce uncertainty and improve characterization.

The model should be refined as further information becomes available, including observations of the excavation performance during operations.

3 AMARUQ SITE GEOLOGY AND STRUCTURE

3.1 Geology and Mineralization

The Whale Tail deposit is made up of a metamorphosed sediment and volcanic package which consists of Greywacke, Mafic Volcanics, two Komatiite units (Ultramafic Soapstone), Iron Formation, and Chert. A Diorite unit is located to the south of the deposit. A plan and cross-section through the deposit is shown on Figure 3.

The gold mineralization is associated with a system of quartz veining and silica flooding within the Chert and along the contact of the Iron Formation and Komatiite.

3.2 Structure

The Whale Tail deposit is folded and has a complicated structural history. The lithology contacts strike east-west and rotate at the eastern end of the deposit to strike northeast-southwest. These structures dip moderately to the south/southeast at surface and then overturn a number of times at depth. The rock mass is folded at all scales, from centimeter size folds to bench scale folds to deposit scale folds (Figure 3 and Figure 4). The sediments and volcanics are characterized by a prominent foliation. The open discontinuities along the foliation have a significant influence on open pit slope and underground excavation performance. Other less prominent joint sets are also present and can locally impact slope and underground excavation performance.

4 OPEN PIT CONCEPTUAL STUDY

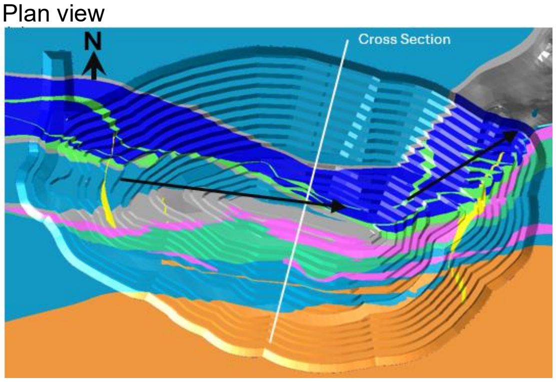
Discontinuity orientation data were not available for the initial conceptual study of the Whale Tail open pit. As a result, the initial characterization of the rock mass structure relied on deposit-scale structural trends identified by the

AEM geology team. Four structural orientations were assumed:

- Lithology contacts striking east-west and dipping to the south. The dominant small-scale structure (i.e. foliation) was assumed to be parallel to the contacts.
- Regional ductile structures striking northeast-southwest and dipping to the southeast.
- Regional faulting striking northwest-southeast and dipping to the southwest.
- Sub-horizontal discontinuities identified in a review of core photos

These four general orientations were used to define a single structural domain that formed the basis of the conceptual level open pit stability assessments and design recommendations.

(a) Plan view



(b) Cross section view

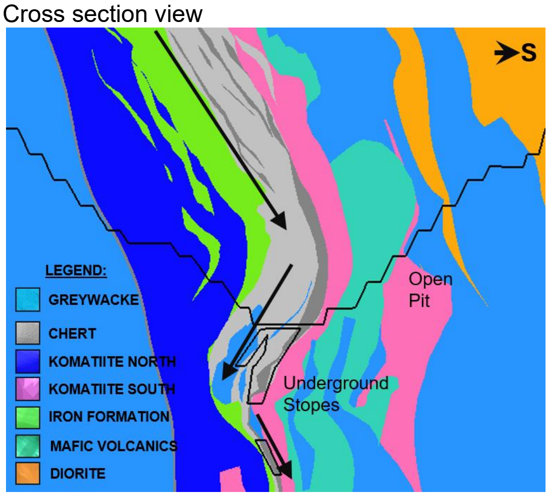
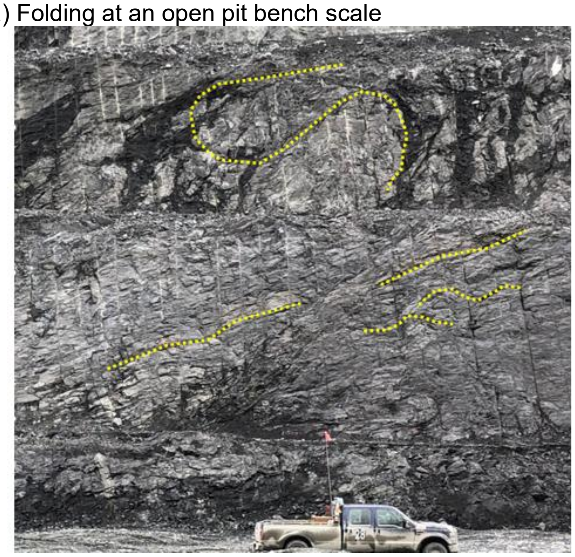


Figure 3. Geological model showing lithological variations and large-scale folding trends (black arrows) relative to the open pit and underground mine plan: (a) Plan view with lithology cut to the open pit design, (b) Cross section view though the open pit and underground

5 OPEN PIT ENGINEERING STUDIES

After the completion of the conceptual study, the project advanced through pre-feasibility and feasibility engineering studies. As part of these studies, site investigation programs with orientated core drilling were completed to collect discontinuity orientation data. The data were reviewed and used to refine the number, position, and characteristics of the structural domains. Details of this process are included in the following sub-sections.

(a) Folding at an open pit bench scale



(b) Folding at the core scale

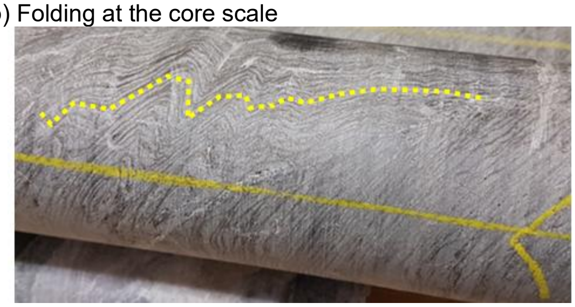


Figure 4. Examples of folding (outlined in yellow) in the Komatiite at different scales: (a) Bench height (21 m) scale fold, (b) Centimeter scale folds in NQ core.

5.1 Data Collection

Two site investigation programs were completed in 2015 and 2016. A total of 4,655 m of oriented core were collected from 18 drillholes. The drillholes all intersected the proposed final open pit walls and eight of the drillholes extended to depth to collect information in proximity to the planned underground workings.

Televiewers were assessed as an option for collecting drillhole discontinuity orientation data; however, they were considered impractical due to the permafrost conditions. In permafrost, televiewer surveys need to be conducted immediately after the drillhole is completed and before it freezes closed. This eliminates the value in being able to conduct surveys on previously drilled holes.

5.2 Geological Evolution

During this phase of the work, the geological understanding of the deposit was rapidly changing and improving. In particular, lithology units were changed and updated as more drilling was completed. It also became clear that the deposit had sustained multiple deformation events, however the timing and effect of these individual events was not yet known.

The geology and geomechanical engineering teams continued to believe in this phase of the work that the foliation would generally follow the large-scale trends defined by the lithology contacts. The regional faults and ductile structures from the conceptual study were re-interpreted as a series of low RQD corridors parallel to the mineralization (referred to as high strain structures) and ductile shears along the lithology contacts. In addition, a series of sub-vertical lamprophyre dykes (striking north-south) and five faults (in a variety of orientations) were added during the feasibility work. It was also noted that the rock mass structure of the Diorite was blocky, as opposed to being folded like the remainder of the deposit.

5.3 Observed Rock Mass Structure

The oriented core drilling data were used to confirm that the foliation was typically parallel to the large-scale lithology contacts in the deposit. The discontinuity orientation data from each drillhole were divided into several stereonets based on variations in the orientation of the lithology contacts observed in the lithology model. The data were then compared to the average orientation of those lithology contacts (Figure 5).

The data were also reviewed by lithology to see if any differences could be noted. It was believed at the time that the foliation in the relatively weak Komatiite was oriented in a slightly different direction than the other lithologies, however, there were limited data, the geological interpretation did not support a deviation in orientation, and the level of study did not warrant further investigation into this question at the time.

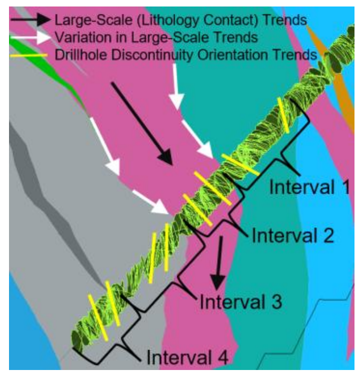
In addition to the foliation (Set A), a sub-horizontal joint set (Joint Set C), and a joint set parallel to the lamprophyre dikes (Joint Set D) were identified. Several minor concentrations of joints were also recognized that were not prominent enough to be joint sets and these were referred to as preferred orientations (PO).

In some drillholes, the most prominent joint set was observed to be dipping opposite to the large-scale lithology contacts. These drillholes were reviewed for errors and ultimately additional drillholes were completed to confirm initial observations. The orientation of this set would eventually influence the design for a portion of the south wall of the open pit. Despite numerous discussions there is no current geological explanation for the observed variations.

5.4 Structural Domain Iterations

During the study phase, there were three iterations of the open pit structural domains. Each one included more data and incorporated a more refined understanding of the geological history of the deposit. The general division of the domains was based on the orientation of the foliation and the large-scale structural trends, as well as lithology. Stereonets were developed for each domain and their boundaries defined relative to the final wall of the proposed open pit (Figure 6). This structural domain definition was used as the basis for the kinematic analyses to define the open pit slope geometry. A key design assumption during each of the study phases was that the bench is expected to break to the foliation where the benches are located sub-parallel (within approximately 20°) to the foliation. In these cases, the foliation would control the achievable bench face angle.

(a) Cross section



(b) Stereonets of drillhole orientation data

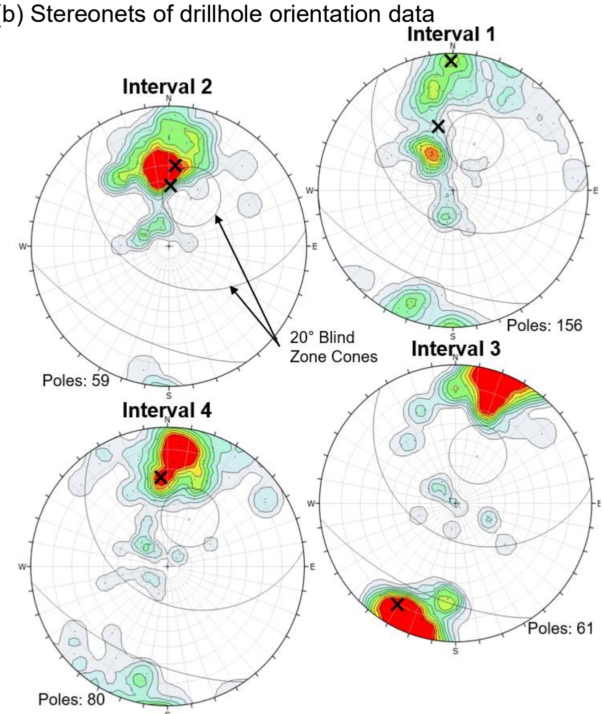


Figure 5. Drillhole discontinuity orientation data compared to large-scale lithology contacts: (a) Cross section showing lithology and drillhole discontinuity orientation data (b) Stereonets of drillhole discontinuity orientation data for

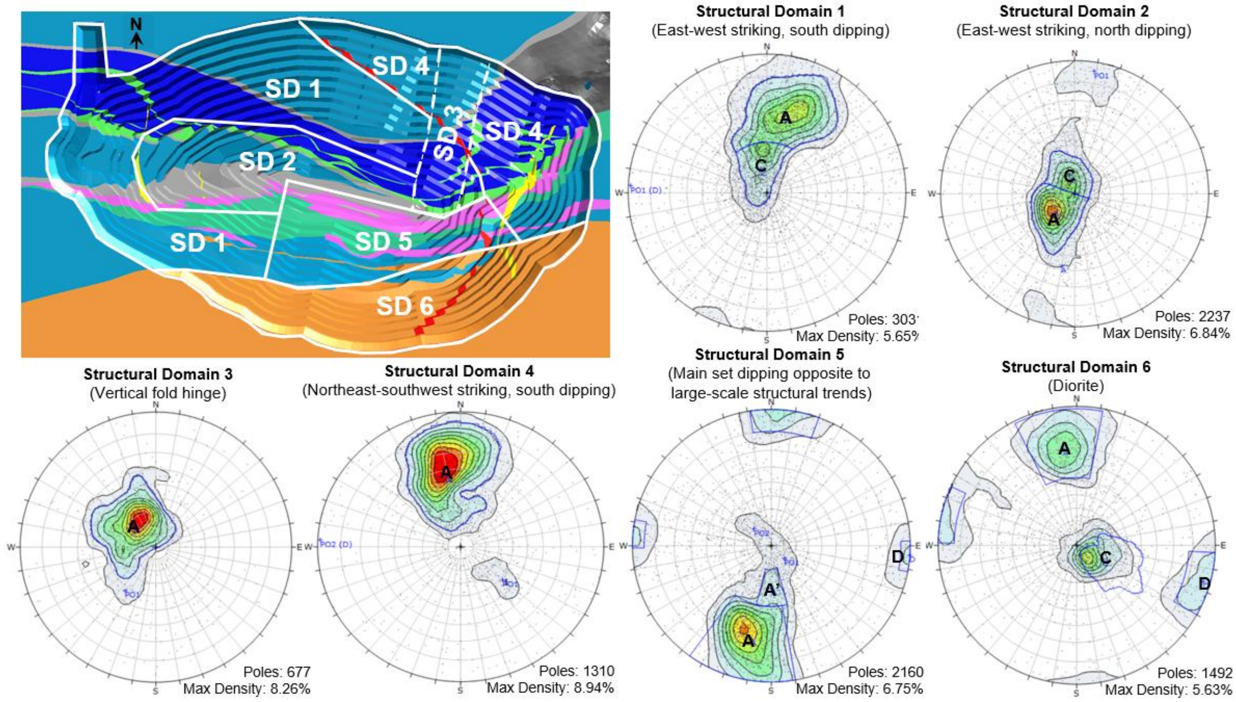


Figure 6. Structural domains used to support initial construction of the Whale Tail open pit

each interval. The orientation of the lithology contacts is shown with a black X.

Additional data and improvements in the understanding of the structural domains led to more confidence in the open pit design, which generally allowed for steeper slope designs. As an example, in the scoping study (which was only based on the first geomechanical site investigation program), the north wall of the open pit had a design inter-ramp angle (IRA) of 41°. For the pre-feasibility study, the second geomechanical site investigation program had been completed, and the additional oriented core data allowed the IRA to be increased to 43° in the upper wall and 52° in the lower wall. For initial construction, a few additional targeted drillholes were completed and the joint sets adjusted, which allowed the IRA for part of the upper north wall to be increased to 46° (with part of the wall kept at 43°). The lower wall had an IRA between 52° and 53°. These increases in IRA have a significant positive impact on the stripping ratio and open pit economics.

6 INITIAL OPEN PIT DEVELOPMENT

When the open with into development exposures of the rock mass were mapped and provided the opportunity for the structural domains to be verified and adjusted. Since the open pit was in early production there was still time to refine the domain boundaries and the associated slope geometry recommendations.

6.1 Data Collection

During this time, additional data were collected from wall mapping and targeted oriented core drillholes to confirm the structural domains from the study phase and obtain additional data in areas where there was limited coverage. Spot and window mapping programs were completed in areas where there was access to the benches. Digital mapping was also conducted using 3D LiDAR scans of the bench faces in areas where access was not available or the benches were not safe to approach. Several bench-scale kinematic failures were also back-analysed to verify the understanding of the rock mass structure and the open pit slope design.

6.2 Evolution of Geological Understanding

During the initial development of the open pit a detailed study was completed on the structural history of the deposit (Valette et al. 2020). It was determined that there were five key deformation events in the deposit's history. The first three deformation events resulted in the folding geometry observed at Amaruq. Deformation events one and two caused the folding observed in the large-scale lithology trends and foliation (S1/S2). The third deformation event caused a secondary shallow dipping foliation (S3) that is only observed in the Komatiite due to its lower strength and stiffness.

6.3 Structural Domain Update

The updated understanding of the geological history and additional data led to a more detailed review of the rock mass structure within the Komatiite. The foliation in the Komatiite was found to be rotated and more folded than the other lithologies due to the additional S3 folding, which was defined as a separate joint set. This updated understanding justified the creation of structural sub-domains for the Komatiite in Structural Domains 1, 2 and 4 (an example is shown in Figure 7). Significant exposures of Komatiite (more than two benches) were expected in the open pit for each of these domains.

6.4 Impacts on Open Pit Design and Observed Slope Performance

The updated structural domains for the Komatiite required some of the open pit stability analyses to be revised. The foliation continued to be the most prominent structure; however, the bench design was adjusted to account for differences in the foliation orientation between the Komatiite and the other lithologies. For example, in the north wall of the open pit, the area with an IRA of 43° was reduced and used only for areas with significant exposures of Komatiite, where the foliation was expected to be parallel to the open pit wall. The remainder of the north wall design included IRA values between of 46° and 53°. Since these changes were made early in the mine life, the mine planners were able to accommodate these adjustments in the updated mine plan.

In areas where the strike of the foliation was sub-parallel to the bench orientation (within approximately 20°), the benches failed back to the foliation in the Komatiite (as anticipated during the study stage). In the other units where the foliation was stronger, the achievable bench face angles could be steeper than the foliation.

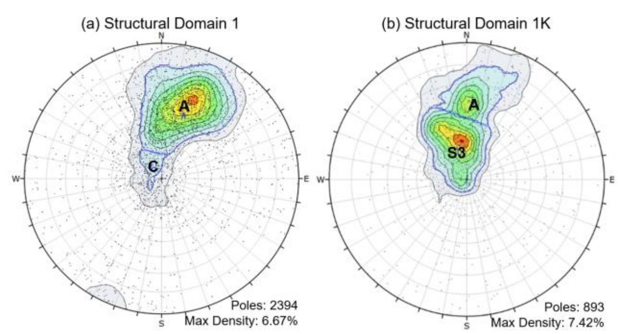


Figure 7. Structural Domain 1 updated domains: (a) 1 - All lithologies excluding Komatiite, (b) 1K - Komatiite.

7 ONGOING OPEN PIT DEVELOPMENT

As the open pit continued to develop, additional structural mapping and data were collected as needed to refine the structural domains in specific areas of concern.

One of these areas was the lower northeast wall of the open pit. Structures associated with zones of reduced rock mass quality in the upper portion of the wall required increased bench widths, lower bench face angles and shorter bench heights. These adjustments reduced the IRA to 34° and resulted in the lower portion of the open pit becoming smaller with reduced ore recovery. To increase production in the lower slope, the local orientation of the foliation needed to be understood so the bench design could be optimized. This area did not have any specific orientation data, and therefore there was justification to complete an additional oriented drillhole, detailed open pit mapping, and mapping from digital scans.

The new orientation data indicated that the foliation was rotating along the wall and the strike of the foliation in the lower Northeast wall was between the strike of Structural Domains 1K and 4K. Due to the sensitivity of design to the strike of the foliation, a sub domain (1Kb) was created and used in updated stability analyses for this area. The new sub-domain allowed for the IRA to be increased to 46° where the foliation was not parallel to the wall orientation. Where the foliation was parallel to the wall orientation an IRA of 27° was expected to be required, which would significantly decrease ore recovery. As a result, the mine proposed a novel solution to mine the benches at an IRA of 40° during the winter when the ground is frozen and then buttress the slope to provide confinement. This approach is based on experience in other parts of the Whale Tail open pit (Tremblay et al., 2024).

8 UNDERGROUND DEVELOPMENT

The initial scoping and pre-feasibility study work for the underground built on the work completed for the open pit and assumed that the foliation followed the large-scale lithology contacts.

As the underground decline was advanced and mining levels were being excavated, structural mapping data were collected to confirm that the domains observed in the open pit continued to depth. It was expected that the open pit structural domain definition would need to be adjusted to account for the smaller scale of the underground excavations which can be more sensitive to minor joint sets (e.g., controlling pillar corners, forming wedges, etc.) (Barnett and Carter, 2020).

8.1 Data Collection

As indicated, discontinuity orientation data from eight of the open pit geomechanical oriented core drillholes were initially available to cover areas of the planned underground mine. Additional geomechanical drillholes were then completed from underground exploration bays to provide additional data in key areas, such as the crown pillar between the open pit and underground mine. A total of 12 drillholes with a total of 2,360 m of oriented core were completed and used to support the underground studies.

The underground development associated with the transverse open stoping mining method provided opportunities early in the mine development to complete several significant mapping programs in footwall accesses drives and drawpoints. The underground mapping allowed the variation in foliation orientation (and other joint sets) to be tracked along strike and with depth.

8.2 Underground Structural Observations and Domains

The completed mapping confirmed that the folding observed in the open pit (Figure 3) continued with depth and that the foliation is generally parallel to the large-scale lithology contacts.

A joint set (Joint Set B) striking perpendicular to the foliation was observed. This joint set was not expected, as it was not prominent in the open pit and had not influenced the performance of the open pit slopes. The drillhole orientation data was reviewed in greater detail and Joint Set B was observed in low concentrations in the drillholes biased against the foliation.

Three minor joint sets were also observed underground influencing pillar and excavation performance. Similarly to Joint Set B, these joint sets were not picked up in the open pit due to their limited prominence and the fact that they did not negatively affect open pit slope performance. The sets were labelled Minor Joint Sets E, F, and G.

The mapping data for each of the underground joints was collected and reviewed. The percentage of mapping locations with each joint set by lithology is shown in Table 1. Some random (R) discontinuities were also mapped. The table shows which joint sets are most common in each of the lithologies. The data were used to better understand the rock mass characteristics and which joints sets are most likely to impact underground performance in each lithology.

The underground domains followed the trend from the open pit and were based on the main orientation of the large-scale structural trends. The Komatiite was separated out from the other lithologies, and Joint Sets B, E, F and G were included in the stereonets to delineate the new sets.

8.3 Impacts on Underground Design and Excavation Performance

Like the open pit, the adverse ground conditions underground are structurally driven. To assess which joint sets or combinations of sets were contributing to poor excavation performance and/or wedge formation, mapping programs started recording which sets were controlling opening performance and in which locations (i.e. back, wall, pillar corner, etc.). The results of the data collection are shown in Table 2, where the percentage of mapping locations controlled by each joint set is summarized by lithology. Examples of the structure controlling the underground openings are shown in Figure 8. As expected, the foliation (Set A) is the most prominent control on opening performance in each of the lithologies, with the other joint sets exerting less influence on excavation performance. These data were used to refine the ground support design basis.

Table 1. Percentage of mapping locations with each joint set by lithology

Lithology	Number of Mapping Locations	A[1]	B	C	S3	D	E	F	G	R
Komatiite	32	81%	25%	13%	50%	28%	16%	6%	6%	6%
Mafic Volcanics	48	81%	54%	23%	0%	56%	2%	4%	19%	8%
Greywacke	11	82%	36%	55%	0%	73%	0%	0%	9%	18%
Chert and Iron Formation	9	78%	44%	56%	11%	56%	0%	11%	11%	11%

[1] Foliation A is likely present at all mapping locations, however it is not always possible to collect discontinuity orientation data at each location.

Table 2. Percentage of mapping locations that were controlled by each joint set

Lithology	Number of Mapping Locations[1]	A	B	C	S3	D	E	F	G	R
Komatiite	26	31%	0%	0%	15%	0%	8%	0%	0%	0%
Mafic Volcanics	41	34%	15%	5%	0%	17%	0%	0%	2%	0%
Greywacke	6	17%	0%	0%	0%	0%	0%	0%	0%	0%
Chert and Iron Formation	8	38%	25%	25%	0%	13%	0%	0%	0%	0%

[1] Table only contains mapping locations which include comments on whether structure was controlling the opening profile or not.

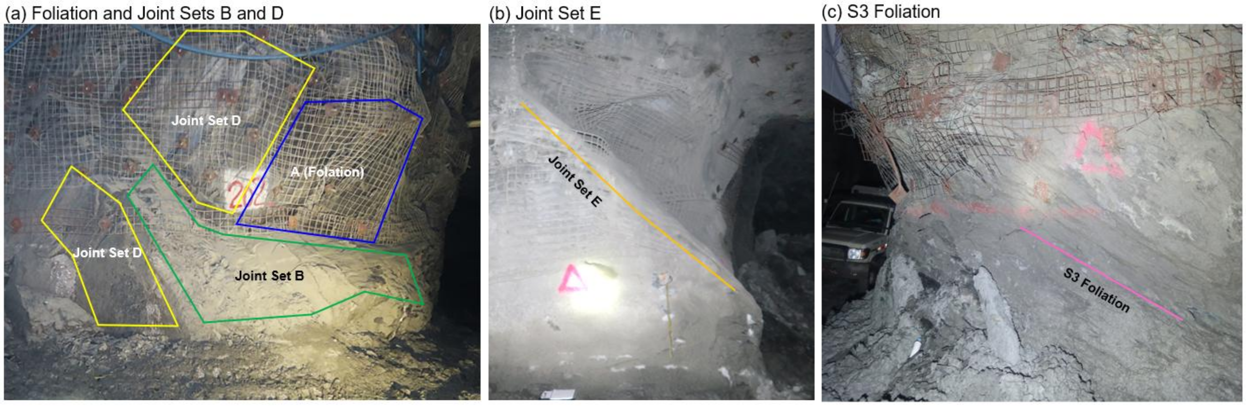


Figure 8. Structure controlling underground pillar corners (a) wedge formed on the foliation and Joint Sets B and D, (b) Joint Set E, (c) S3 foliation

9 CONCLUSIONS AND KEY LESSONS LEARNED

The evolution of the structural domains for the Whale Tail deposit over a decade of engineering studies and operations has led to a number of lessons being learned that are relevant to other projects and operations. These include the following:

- Input from the geology team is critical to the development and refinement of the structural domains. Open and regular communication with the team significantly contributes to the structural understanding of the deposit, which is needed to complete the work in a timely way. Similarly, the development of the structural domains also helps advance the geological understanding of the deposit.
- Drillhole orientation data should be reviewed on a drillhole-by-drillhole basis, compared to adjacent drillholes, and evaluated collectively to get a full understanding of the variability in the structural environment.
- Domains need to be based on data from multiple complementary sources, including drillhole orientation data, surface mapping, and excavation mapping to confirm the structural characteristics at different scales.
- Optimizing the domains over the life of the mine is an important part of the design process and results in increased safety and more reliable production.
- During operations, mine plans evolve and it is possible that detailed data may not be available for parts of the updated mine plan. Therefore, additional data collection is required to update the structural domains and to provide a confident design.

In addition, structural domains need to be defined in such a way that they distinguish meaningful differences, are practical to implement, and are appropriate for the level of study. Considerations include the following:

- Level of study – Lower levels of studies will typically have broader domains that cover the most significant structural trends. As the study advances, variations or anomalies in the domains can be broken out based on an increased understanding of the deposit.
- Sufficient data – As the level of study advances, increased data are required to ensure that there is adequate confidence in the structural domains to support the required design work.
- Spatial definition – The spatial extents of the domains need to be defined in 3D space so that the recommendations can be applied to the correct zones or sectors of the mine by the planning team. As such, the domain definition needs to utilize rock mass characteristics and models that can be realistically defined and updated in 3D over time.
- Number of Domains – The number of the domains needs to adequately distinguish between areas that are likely to perform differently without creating so many domains that the mine planners struggle to implement the associated recommendations in a practical and consistent way. In addition, it becomes increasingly possible as the number of domains increase that distinctions are being made that will not materially impact the appropriateness of the overall mine plan.
- Domain Joint Sets – The domain needs to be appropriate for the scale of the excavation being designed. Open pits will typically have domains based on the most prominent and/or persistent structural orientations since they are most likely to control wall performance. In contrast, underground domains will likely include distinctions between minor joint sets since they can influence excavation performance.

10 ACKNOWLEDGEMENTS

The authors would like to acknowledge Agnico Eagle Mines for allowing this work to be published. This work was a collaborative effort that included significant contributions from AEM's Geology and Rock Mechanics groups. Early input from AEM's Jonthan Servais and Véronique Falmagne were key to the success of this study.

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