Critical fault characterisation and modelling for geotechnical slope design at a large open pit gold and copper mine

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Abstract

Phu Bia Mining Limited's (PBM's) Phu Kham gold and copper mine in the Lao People's Democratic Republic (Laos) has been operating since 2008. An open pit approximately 2.2 km by 1.2 km has been developed, with excavated slopes up to 560 m high in mountainous terrain. The mine is structurally very complex, and to aid geotechnical design a detailed structural model was developed over several years by a consultant geologist.

As the structural model evolved and became more complex, two issues emerged. One was that the model was overly complex, with numerous faults of interest to structural geology but only a few that were geotechnically significant. The second was that a specialist structural geologist was required to visit the site and provide updates on a campaign basis, making the model ill-suited to the rapidly changing mining environment.

A process was developed for PBM's site geotechnical team to manage a simplified model comprising only faults that are geotechnically critical. A process for mapping, modelling and recording structures critical to pit stability ensured that critical faults were continuously monitored and updated, allowing for proactive management of geotechnical risks.

The first stage of development was to establish a standardised critical fault characterisation process to ensure consistency in fault identification, analysis, assessment of risks and mitigation strategies. The second stage involved a standardisation of the fault mapping and modelling process to ensure consistency and reliability. The third stage was to establish and maintain a database of critical faults confirmed through geotechnical drilling, historical failure, and in-pit and photogrammetry mapping.

A simplified, fit-for-purpose Leapfrog fault model was produced by combining these elements. This enabled site geotechnical personnel to manage and update the database to enhance the accuracy and reliability of geotechnical assessments, leading to safer and more efficient mining operations.

Keywords: *structural model, geological modelling, fault mapping, fault characterisation, geotechnical design, slope stability*

1   Introduction

Phu Bia Mining Limited (PBM) is a Laos-based subsidiary of the PanAust Limited Group that owns and operates the Phu Kham mine (PKM) gold and copper mine, located in Laos and approximately 100 km northeast of the capital, Vientiane. Mining began in 2008 and an open pit approximately 2.2 km-long by 1.2 km-wide and up to 560 m-deep has been developed. The mine operates in a tropical monsoon environment and is geologically and structurally complex, presenting challenges both for geotechnical slope design and day-to-day operations.

A specialist consultant geologist from Solid Geology was engaged by PBM in 2015 to compile a detailed working structural geological model (Solid Geology 2015) to assist with geotechnical slope design, which

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ultimately was developed in Leapfrog software with ongoing developments to June 2022. The structural geology model was a valuable resource for geotechnical design. However, its complexity required the specialist expertise and Leapfrog software skills of the consultant structural geologist. Infrequent updates to the model were made on site mapping campaigns. This limited the model's practical use for the site geotechnical team in mapping structures as they became exposed and maintaining the model as a working resource for short-term design.

A key issue faced by the site geotechnical team was the large number of faults. Many of these were of geological interest but were not geotechnically significant: i.e. they did not define lithological boundaries, contribute to past or potential failure mechanisms, or correlate with known slope instabilities. Without a clear framework for filtering such faults and systematically updating the model it remained overly complex for the site team to manage or use effectively in day-to-day operations.

PBM sought to simplify the model and make it more readily accessible to the site geotechnical team, to enable them to maintain an up-to-date model that can be used to respond to the needs of the rapidly changing mining environment. This paper describes how a standardised workflow for capturing fault data was developed, a critical fault database was established and made accessible to non-Leapfrog users, and a more simplified Leapfrog structural model was provided so site personnel can own the site's geotechnical processes and manage the model update internally.

2 Geotechnical conditions

2.1 Geology

The geology of the PKM deposit is described by Backhouse (2004), Tate (2005) and Solid Geology (2015), and regional geological context is described by Soysouvanh et al. (2016) and Leaman et al. (2019). The site is characterised by a thrust stack composed of various lithological units, with major northeast-dipping thrust structures forming the overall geometry of the deposit. Figure 1 shows an example cross-section using Solid Geology's February 2022 model. These thrusts bound imbricate slices of different lithologies that generally young to the southwest, except for blocks of conglomerate which likely originate from the basal Khorat red bed sequence. The lithological sequence from southwest to northeast comprises:

- Khorat red beds (Jurassic–Cretaceous)

- basal coarse clastic sequence including conglomerates (Jurassic)

- Lower Permian diorite and volcaniclastic sequence (mineralised)

- limestone (Devonian–Carboniferous)

- tuff and diorite sequence in the Haul Road Anomaly (HRA) mining area (Lower Permian)

- granite (Silurian).

The structural and lithological complexity of the site is further compounded by extensive post-Khorat deformation. The main foliation dips subparallel to the thrust stack, while some internal thrusts are rotated into steep orientations, suggesting that the apparent steep geometry of the deposit may represent a reorientation of an originally subparallel mineralised system.

The geology of PKM reflects multiple phases of deformation, including folding of the thrust stack and the development of an antiformal-syncline fold in the Khorat red beds in the western pit wall. This complex geological history presents unique challenges for geotechnical stability and necessitates ongoing structural and lithological model updates to inform safe mining practices.
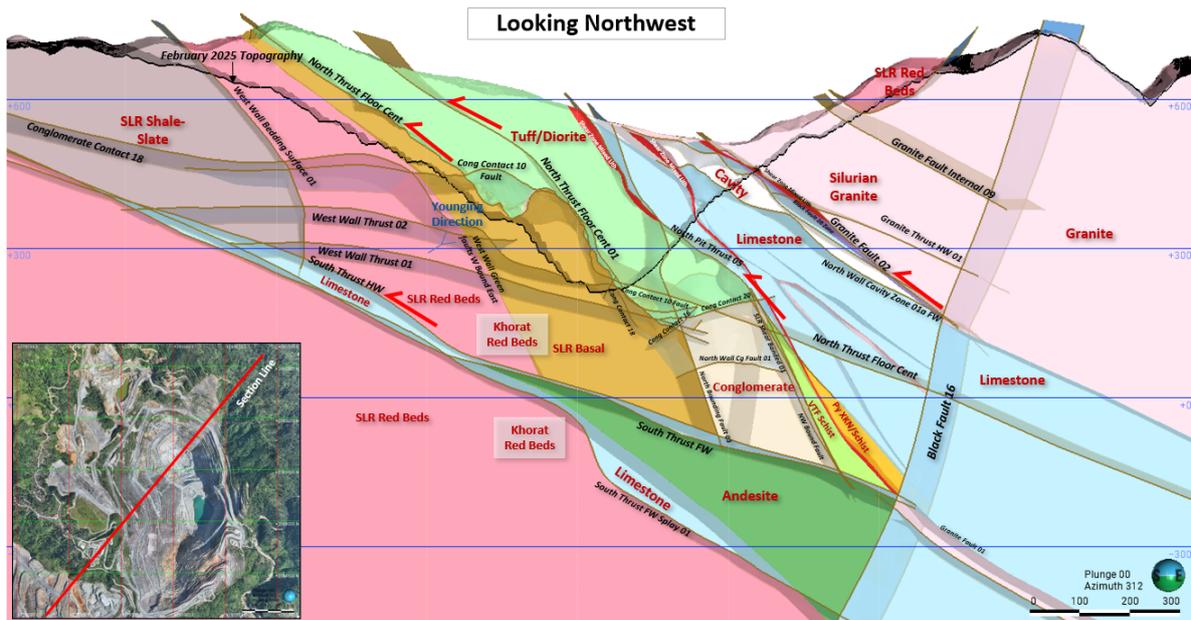
Figure 1   Cross-section of the Phu Kham mine fault network: overview plan (inset) as modelled by Solid Geology

2.2   Stability controls

The Solid Geology June 2022 Leapfrog model contained 273 faults, only a fraction of which are geotechnically significant. Faults are the predominant control of inter-ramp and overall slope stability, which is sometimes also controlled by shearing or compression of weaker foliated units such as tuff.

Figure 2 shows an example of faults in the northern wall of the mine forming an active-passive mechanism in the toe region with the weaker tuff (in green) subject to compression and shearing.

Figure 3 shows a plan view of the southern wall region where several failures occurred since late 2017, due largely to complex interactions of thrust and extensional faults, sometimes in combination with weaker and weathered materials. These are examples of where the Solid Geology 2022 model was valuable as a basis for long-term geotechnical assessments. However, the complexity of the model limited the site geotechnical team's ability to update and use it on a regular basis for short-term assessments.
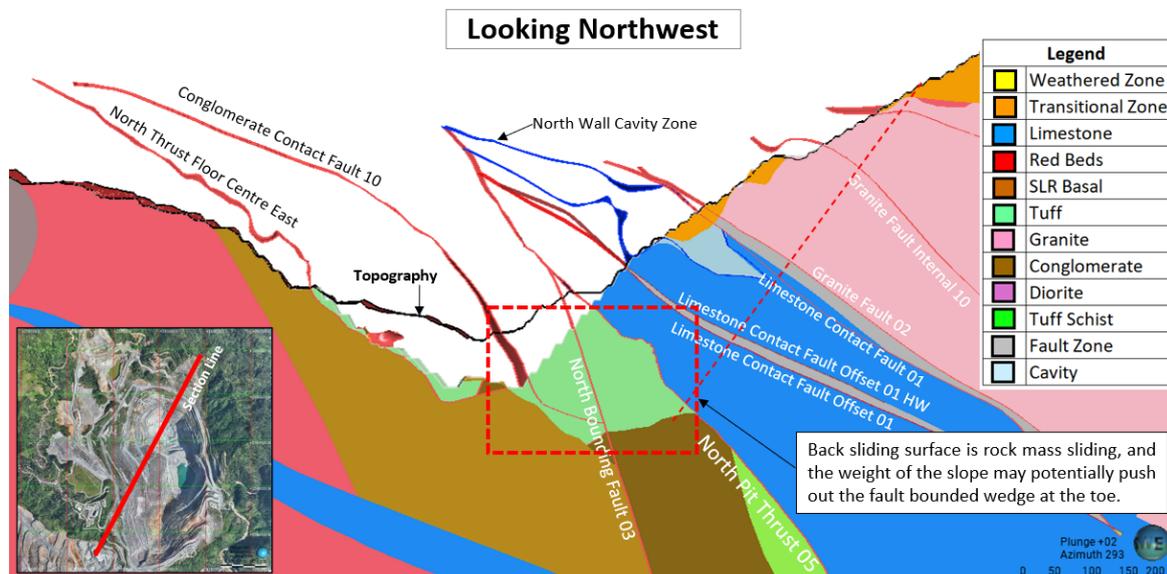

Figure 2   Active-passive failure mechanism for the Stage 11 region

Figure 3   South wall failures due to faults

2.3   Fault characterisation

Faults are categorised visually from drillcore intersections using a classification system of categories 1 to 4. Figure 4 shows an example, with the fault categories included as a table within the figure. Photo logging is a useful tool for reviewing the key characteristics of fault and sheared zones as it enables the geotechnical engineers to capture the features of the fault zone and surrounding damage zone. Figure 4 shows the fault characterisation system used for a selected major fault, with examples of fault categories 1, 2 and 3. The categories are based on visible features like the amount of shearing, gouge material and surrounding rock damage. This standardised approach ensures everyone logs faults consistently and helps the site team quickly identify which faults are likely to affect slope stability. It also forms the basis for deciding which faults are important enough to include in the critical fault database.
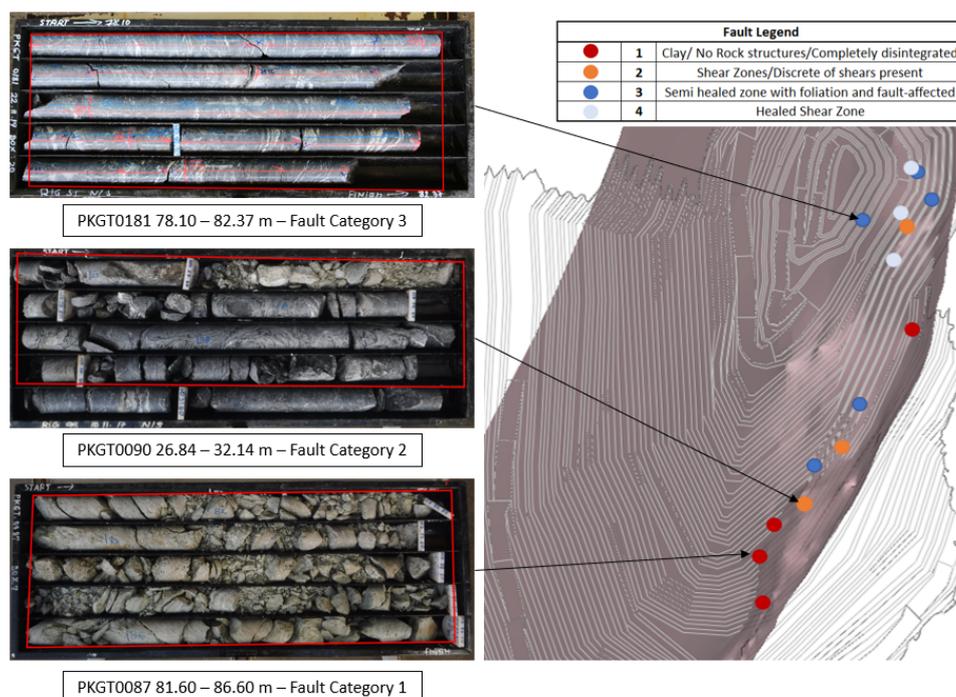

Fault Legend		
🔴	1	Clay/ No Rock structures/Completely disintegrated
🟠	2	Shear Zones/Discrete of shears present
🔵	3	Semi healed zone with foliation and fault-affected
🔵	4	Healed Shear Zone

PKGT0181 78.10 – 82.37 m – Fault Category 3

PKGT0090 26.84 – 32.14 m – Fault Category 2

PKGT0087 81.60 – 86.60 m – Fault Category 1

Figure 4   Example of fault characterisation

3 Critical fault model development

3.1 Stage 1: Fault characterisation and workflow

To identify faults that are geotechnically significant, the critical faults workflow is established at PKM and shown in Figure 5. The workflow is used to standardise the process in narrowing down the critical faults based on fault characterisation (categories 1 to 4) described in Section 2.3. This process is also used to establish a critical fault database to be used throughout the process.
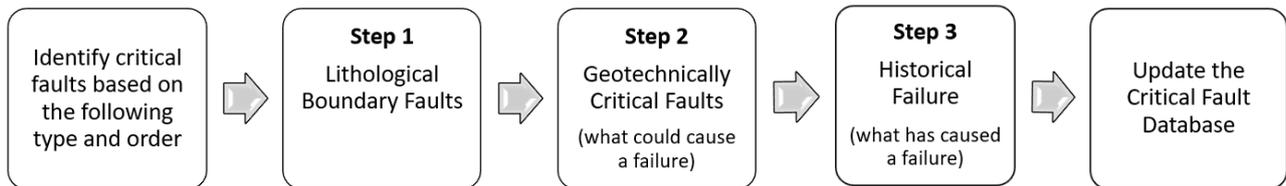

Figure 5 Identification of the critical faults workflow

Three types of critical faults have been identified based on the following order: lithological boundary faults, geotechnically critical faults, and faults involved in historical slope failures.

Before proceeding with the first step, a first-pass assessment of the critical faults is done by excluding faults that do not intersect the pit design, especially those are in the mined-out region.

3.1.1 Lithological boundary faults

Lithological boundary faults are the faults that form boundaries for geological units or geotechnical domains. An example is shown in Figure 6 and has proven to be of geotechnical significance.

The faults that form lithological boundaries are geotechnically critical as they form domain boundaries. For PKM, all the lithological boundary faults daylight into the slope and it is recommended that those which intersect the pit designs or lie within 100 m of the pit wall are first identified as critical faults.
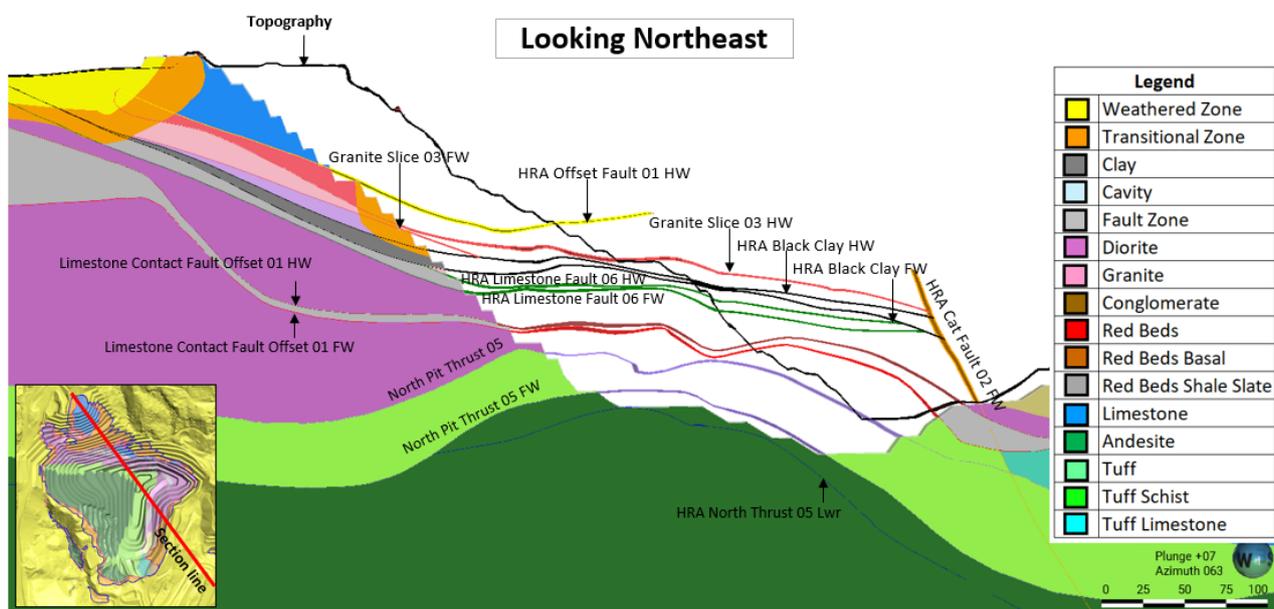

Figure 6 Lithological boundary faults in the Stage 14 satellite pit

3.1.2   Geotechnically critical faults

Geotechnically critical faults are defined as those that can potentially cause or be involved in a failure. Potential failure mechanisms are identified to be where the interaction between the wall orientation and pit design are within the 30° range, and faults dipping into the pit at 30°. Faults that are within this range are given priority for critical faults and stability assessment.

For geotechnically critical faults, fault orientations are analysed against the pit design. The four failure mechanisms used to identify the critical faults at PKM are planar, wedge, toppling and active-passive wedge failure. An example is shown in Figure 7. Lithological boundary faults that are included in the critical faults list are assessed for each potential failure mechanism.

These also commonly interact with rock mass foliation and joints to form potential failure mechanisms. Foliation is characterised as part of geotechnical stability assessments but is outside the scope of this paper.
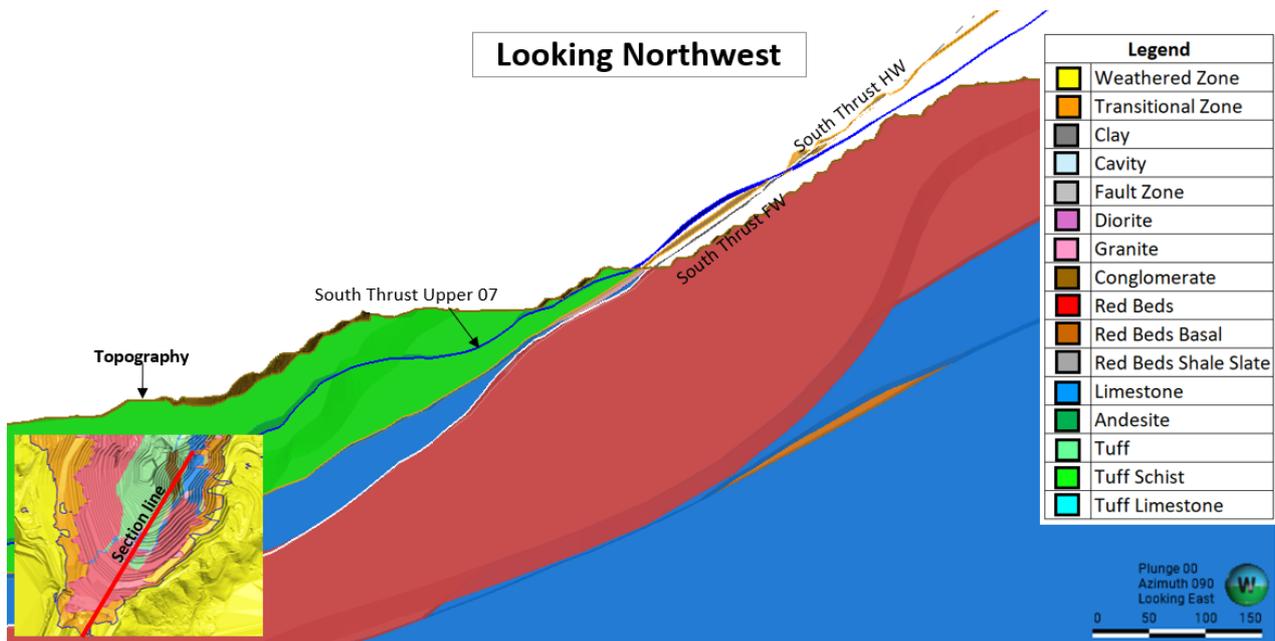

Figure 7   Example of geotechnically critical faults forming a planar sliding failure

3.1.3   Historical failure faults

The historical failure database provides a basis for identifying any additional geotechnically critical faults by identifying any faults that have been associated with failures. This part of the process begins with identified critical faults; historical failures that are within 50 m of the pit design and are associated with persistent failures up to an inter-ramp scale. For any failures not associated with identified critical faults, the search is expanded to include those faults that were initially classed as non-critical.

This is an iterative step that is part of the ongoing fault modelling process to: ensure that recent failures are assessed against known faults; incorporate any faults previously classed as non-critical; and identify any new faults to be included in the critical fault database. Figure 8 shows two examples: (1) a fault that caused a historical failure; and (2) large-volume historical failures that were associated with faults previously not classified as critical.
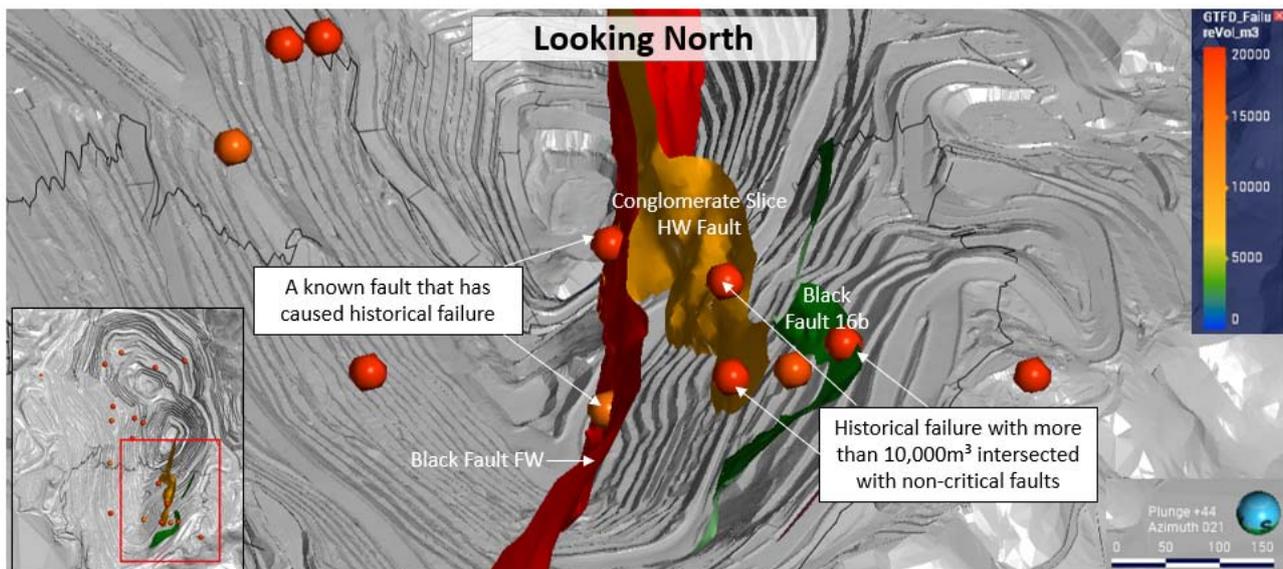
Figure 8   Review of historical failure data against faults deemed non-critical as part of Stage 1

3.1.4   Critical database

All critical faults identified are then compiled into one critical fault database (Excel spreadsheet) which is the main output for Stage 1 of the process. An example is shown in Table 1. The critical fault database includes the fault name, pit design intersected, type of critical fault and potential failure mode. This enables site personnel to update the critical fault database when there is a significant geological or geotechnical model update, pit design change or a pit slope failure, and is typically conducted once or twice yearly.

Table 1   Critical faults database in the early stage of development

Stage 14 critical faults	Type of critical fault	Potential failure mode	Does it form a failure with another fault in combination?	Final critical fault
Granite Slice 03 FW	Lithology boundary	Wedge	Granite Slice 03 FW, Granite Slice 03 HW, HRA Black Clay FW, HRA Black Clay HW, and HRA Offset Fault 01 FW	Granite Slice 03 FW
Granite Slice 03 HW	Lithology boundary	Wedge		Granite Slice 03 FW
HRA Black Clay FW	Lithology boundary	Wedge		HRA Black Clay FW
HRA Black Clay HW	Lithology boundary	Wedge		HRA Black Clay FW
HRA Offset Fault 01 FW	Lithology boundary	Wedge		HRA Offset Fault 01 FW
HRA Cat Fault 02 FW	Lithology boundary	Toppling	No	HRA Cat Fault 02 FW
HRA Mud VTF 01 FW	Lithology boundary	Rock mass	No	HRA Mud VTF 01 FW

3.2   Stage 2: Fault modelling process

3.2.1   Leapfrog database management

Solid Geology's structural and lithology models were constructed to serve different purposes and contained different fault networks, creating complexity and difficulty in integrating them into the geotechnical design process. These were consolidated into a master structural model containing all current critical faults. The master structural model is where faults are updated, and involved two key aspects:

- The underlying fault network relationships within the original Solid Geology model are preserved and updated in the background, simplifying the front-end process while preserving the original model.

- Areas of interest are created as sub-geology models in the Leapfrog software, each linked to the master structural model and allowing specific areas of the mine to be targeted for updates.

3.2.2   Overview of the fault modelling process

Stage 2 involves standardisation of fault modelling in Leapfrog software to ensure a streamlined and standardised process for the site geotechnical team, and improved consistency and reliability in fault data. The fault modelling workflow process for Stage 2 is summarised below:

- Step 1: review geotechnical input based on the recommended data hierarchy.

- Step 2: update the fault network with all the reviewed control points.

3.2.3   Step 1: reviewing fault inputs and updating critical faults

3.2.3.1   Data hierarchy

Inputs for modelling faults are then reviewed, using the data hierarchy shown in Figure 9 and described in Table 2. The main inputs to the process are photogrammetry mapping and in-pit mapping, each involving expert structural geology interpretation by Solid Geology. These are efficient and cost-effective methods that can be carried out onsite on an ongoing basis.
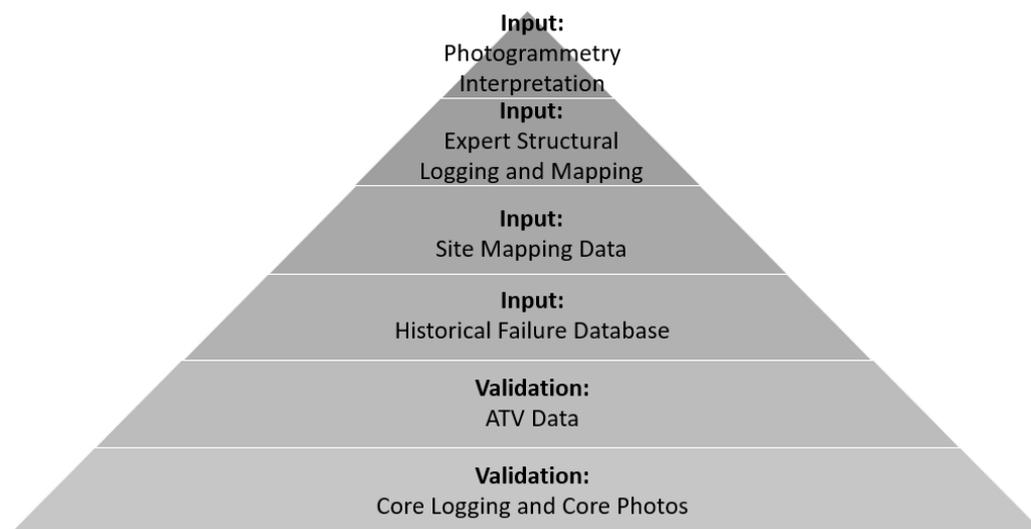

Figure 9   Data hierarchy for geotechnical data collection

The steps involve reviewing the inputs from newly obtained data from the top down in the data hierarchy, followed by checks against the structural data:

1. High-resolution geotechnical photogrammetry files, expert structural interpretation and logging and mapping are assessed first as inputs for modelling critical faults. Photogrammetry data supersedes structural logging and mapping where the photogrammetry is based on newer data.

2. Historical failures are captured as inputs by the review process discussed in Section 3.1.3.

3. This is followed by checking faults against acoustic televiewer (ATV) data, noting that ATV is a lower precedence of data that provides a check. ATV data must be checked to see if there are other (competing) data points at the same locations or close by.

4. Finally, logging and validation of a diamond drillcore is undertaken. The geotechnical logging is completed to site logging standard and validation is conducted to verify the fault that has been modelled. This is done by using the rock quality designation (RQD) data, structure measurements and core photos to validate that the fault zone and structure orientation matches the modelled critical fault of interest. The photo logging based on fault characterisation as described in Section 2.3 is then completed to establish the fault thickness of the critical faults.

Table 2   Geotechnical data hierarchy for fault modelling inputs

Data type	Description	Priority
Photogrammetry interpretation	High-resolution, continuous pit wall capture; primary structural input for Leapfrog modelling	High
Expert structural logging and mapping	Field-based structural data from experienced geologists; used to interpret and validate key faults	High
Site mapping data	Pit-based observations; supplementary input for fault surface definition	High
Historical failure database	Used to identify historically failed structures and validate critical fault selection	High
ATV data	Acoustic televiewer images; support verification of logged structures in boreholes	Moderate
Core logging and core photos	Visual and photographic confirmation of fault zones, rock quality designation and structural features in the core	Moderate

3.2.3.2   Photogrammetry and structural interpretation

High-resolution photogrammetry is used as the main method of geotechnical structural data collection and updating of the fault model as it provides continuous records of exposure in the pit and is highly accurate. It also enables the geotechnical engineer to gain data in mining areas that are unsafe and inaccessible. Figure 10 shows an example where the fault intersection is digitised as polylines and points in Leapfrog, which are then used to verify and update the modelled fault.
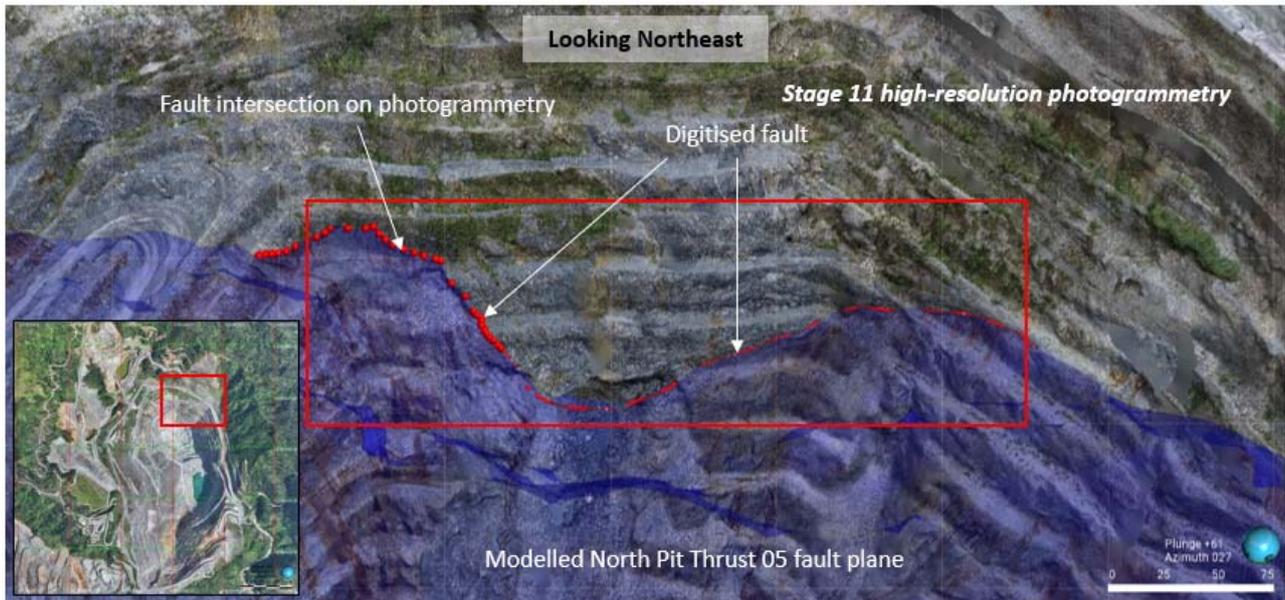
Figure 10   Verification of digitised fault polylines against the current fault surfaces

3.2.3.3   In-pit mapping

Mapping data is collected onsite based on the priority of critical faults, and the data is imported into Leapfrog as points with structural types and orientation values. Once the pit mapping data has been reviewed and deemed necessary for addition as control points, the pit mapping data is changed to polyline format and added into the fault network in the master structural model. The mapping data is reviewed against the modelled fault, as shown in Figure 11.

If there is a newly exposed fault that has not previously been modelled, the new fault will be mapped based on in-pit mapping data and high-resolution photogrammetry, and modelled as fault planes. This is common in localised areas for faults that are not typically intersected in diamond drillholes. The newly modelled fault will be peer reviewed by the site geotechnical team and added to the critical faults workflow as described in Section 3.1 to establish whether the fault is deemed critical.
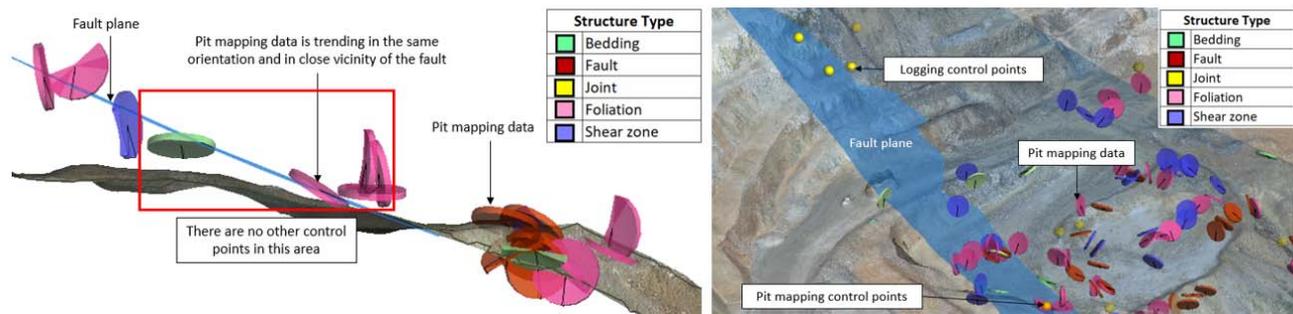

Figure 11   Verification of pit mapping against the fault of interest

3.2.4   Step 2: updating the fault network with new control points

Reviewed geotechnical data (photogrammetry, structural interpretation control points, mapping, ATV and RQD data) that have been established as control points are added to the master structural data, with naming conventions maintained based on the source. The control points can be in polylines/points or fault mesh format and will be automatically updated in the fault network in the master structural model.

3.3   Stage 3: database management and updating

After updating fault networks with new control points in Leapfrog software, Stage 3 involves exporting the controlling points out of Leapfrog software and updating the fault register. For record keeping within the geotechnical team, a fault register is used to track most-recently updated faults and associated controlling data (points, lines, intervals), and important datasets for fault interpretations (mapping, drillhole logs, photogrammetry, recent failure). The fault register is important to streamline the process and track which faults have been updated.

4   Implementation and benefits

The implementation of a standardised critical fault characterisation and modelling workflow at PKM has added significant value to the geotechnical slope design process in both operational and geotechnical design review processes. This value is realised through practical improvements on data collection and management, collaboration with other operational departments and geotechnical hazard awareness.

4.1   Consistency and accessibility

The creation of the critical fault database (example shown in Figure 9) as a fault register to accompany the simplified Leapfrog model has significantly improved the consistency and accessibility of fault data management at the site. The system is designed to be simple and streamlined, and to provide a master reference for critical faults across each mining area, enabling the geotechnical team to quickly identify and communicate geotechnical hazards.

The critical fault database acts as the overarching system for tracking and managing faults by region. It ensures all key personnel – including geotechnical engineers, mappers and mine planners – are aligned and working from a single source of truth. Faults are systematically categorised by type, potential failure mode and proximity to pit designs, providing clarity in geotechnical risk assessments and planning discussions.

Importantly, the system is accessible by non-Leapfrog users such as operations, planning and hydrogeology teams. This broader access has allowed critical fault information to be shared in real time, which facilitates more proactive decision-making for other departments, especially during the geotechnical slope design review process.

4.2   Targeted fault management

With the implementation of a structured, three-step filtering process – considering lithological boundary faults, geotechnically critical faults, and faults associated with historical or recent failures – the site team has been able to reduce the fault list to a more focused and meaningful fault dataset. This has directly standardised and improved the face mapping process. Mappers now prioritise critical faults identified in the database using exported traces from the Leapfrog model to guide their fieldwork. This targeted approach enables more efficient data collection, improves the consistency of structural interpretations and ensures that mapping directly supports slope stability assessments. By focusing on the faults most likely to impact geotechnical performance, the geotechnical team can allocate resources more effectively and produce more actionable data for operational decision-making.

4.3   Streamlined hazard communication

The critical fault maps generated through this workflow have become a powerful tool for enhancing both geotechnical communication and operational decision-making. The visual outputs – fault maps grouped by region and failure type – provide clear, actionable insights to operational and mine planning teams. Importantly, they have also become highly effective in visually communicating geotechnical hazards to operations teams. The maps simplify complex critical geotechnical information and make it easier for operators to understand what faults they are working near as mining progresses. An example of this is shown in Figure 12 below, which displays critical faults in the Stage 11 area of the mine.

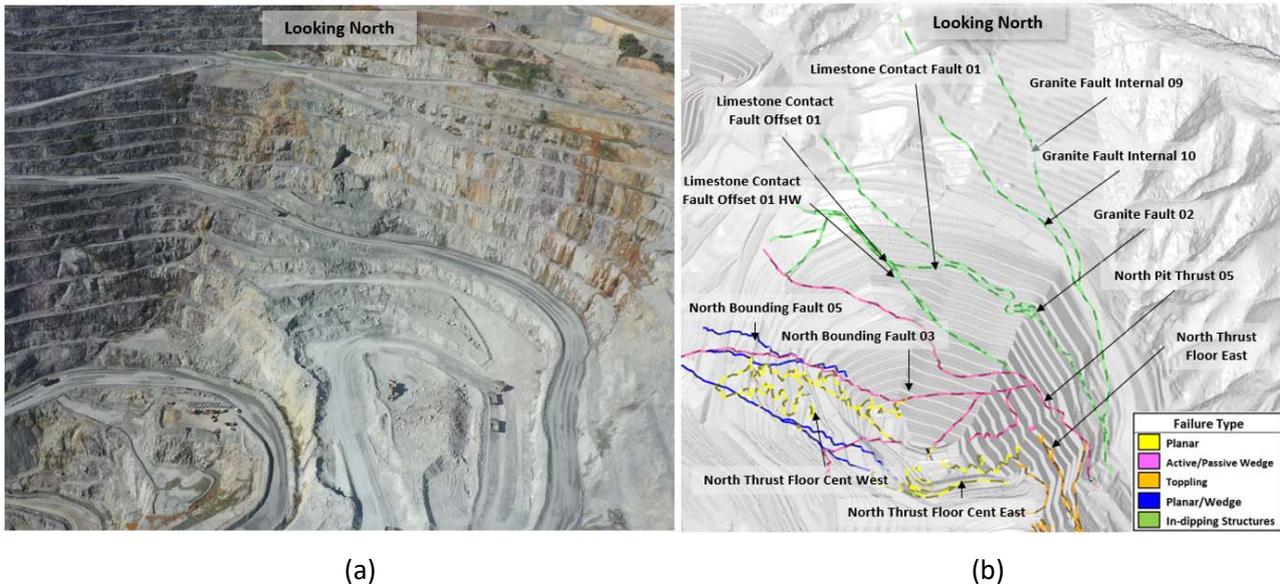(a)   (b)

**Figure 12 (a) High-resolution drone imagery of the Stage 11 wall; (b) Critical faults are displayed by their
potential failure type in the Stage 11 region**

4.4   Hazard mitigation planning

The value of this approach is exemplified at PBM's other mine, Ban Houayxai (BHX), where the same workflow
has been adopted. At BHX, this system has proven its value in real-time operations. Several faults were
flagged as critical during early design risk assessments, with an example in Figure 13 showing the intersection
of South Pit Fault 017 with the pit, resulting in planar failure. Although the operations team could not fully
redesign around the problematic faults due to pit constraints, early identification enabled the team to
prepare effective contingency plans.

When these faults began showing signs of activation around the pit, the geotechnical team was able to trigger
timely interventions – halting mining and deferring ore extraction in high-risk areas. This proactive response
helped the operations team avoid more serious outcomes. Without the critical fault workflow in place, these
risks may have gone unrecognised until failure occurred. Figure 14 presents a cross-section of the failure,
highlighting the fault's planar failure mode and its proximity to the main access ramp. Following this event,
the ramp was successfully rerouted to allow mining to continue while the failure clean-up was safely
managed – an outcome made possible through early discussions between the geotechnical and operations
teams, facilitated by the critical faults workflow.

Since that incident there has been a noticeable cultural shift in how the BHX operations team engages with
geotechnical input. Instead of being passively informed, operations teams are now actively involved,
including engaging on risk reduction measures that can be taken around known faults, such as allocating drill
pad space to confirm uncertain fault geometries and adjusting designs to remove unstable hanging walls.

The critical faults workflow has initiated significant collaborative processes with the operational team, and
risks are now addressed before designs are finalised. There are clear plans in place for safely managing critical
faults during mining. This integration of fault risk into early-stage planning has fundamentally improved
communication between the geotechnical and operations teams.

(a)   (b)
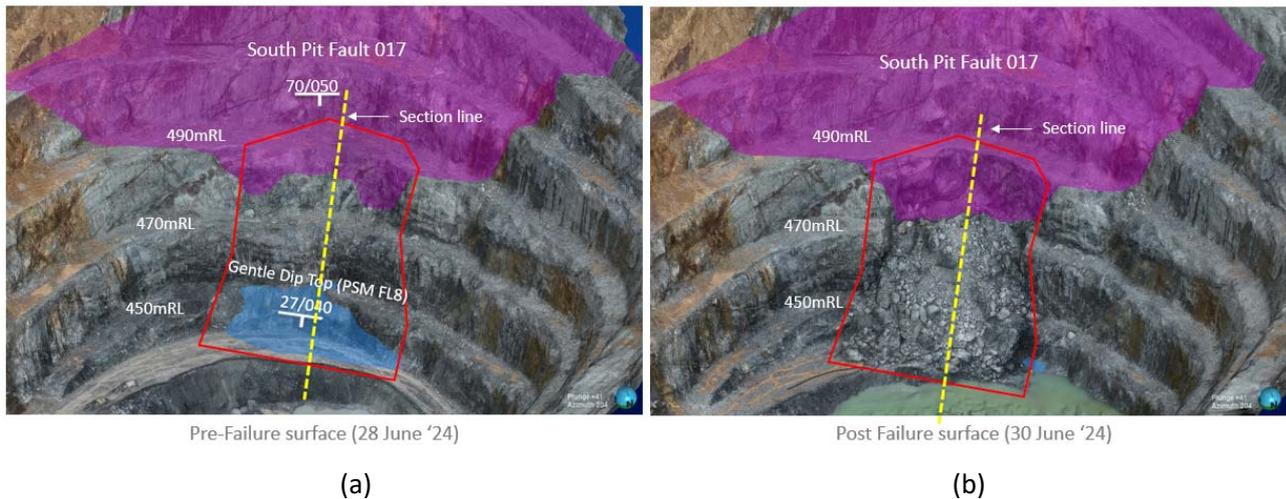
Figure 13 (a) Pre-failure wall at Ban Houayxai mine showing the critical faults and pit intersection; (b) Post-failure showing the result of the critical faults and pit intersection
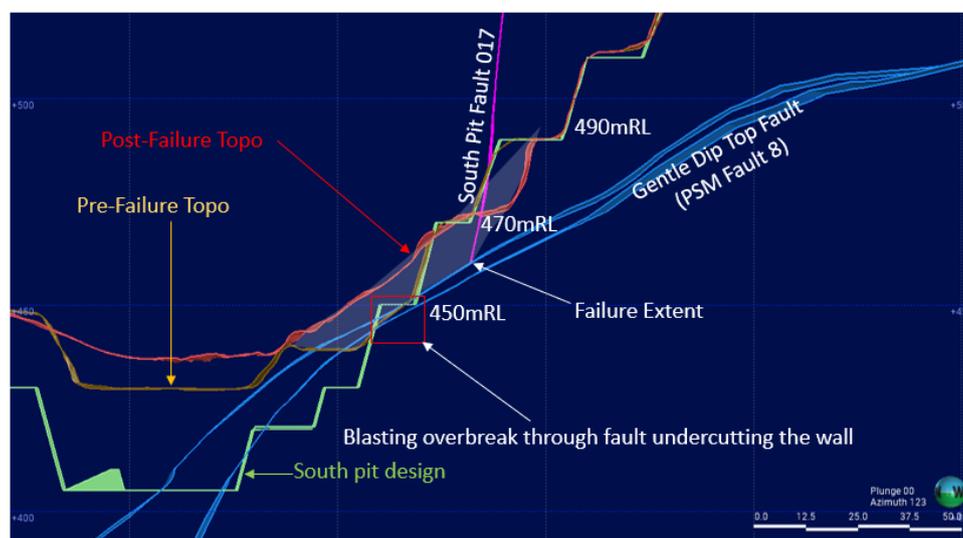

Figure 14 Cross-section showing the critical faults and pit intersection at Ban Houayxai mine

4.5   Empowerment and ownership

The simplified critical fault workflow and the establishment of a site-owned master structural model in Leapfrog shifted responsibility from external consultants to the site-based geotechnical team. This transition not only improved operational capability in providing support to the operational team, but also reduced long-term costs associated with outsourcing model updates. The workflow enables fault updates to be made efficiently, which ensures that the fault network remains aligned as the mine activity progresses and new faults are uncovered. With the new system in place, the geotechnical team can now easily prioritise and focus on critical faults by region, rather than having to navigate the entire fault network of 273 faults.

More importantly, this approach does not replace or discard the original model developed by Solid Geology. All historical data and interpretations are preserved within the Leapfrog file. The new workflow retains the integrity of the existing structural model but empowers the site team to maintain and update it independently. The process has been trialled and tested on several critical faults, and has proven to be effective, robust and repeatable in practice.

5 Conclusion

This project successfully delivered a practical and standardised approach to critical fault characterisation, modelling and ground truthing at PBM PKM. A structured workflow for fault data capture was developed, enabling consistent and accurate identification of geotechnically significant structures across all mining stages. The establishment of a critical fault database and fault register now allows the site team to maintain a real-time record of key fault structures, improving geotechnical mapping and hazard awareness.

Importantly, the underlying fault network and relationships of the original Leapfrog model are preserved and updated in the background, while the master structural model simplifies usability for daily operations. This balance of geotechnical complexity and practical application ensures the model is both reliable and adaptable.

This process has also driven a cultural shift towards proactive geotechnical hazard management. The geotechnical site team now incorporates recent failures and historical data into ongoing updates, with clear examples – such as the early identification and management of the South Pit Fault 017 – highlighting its effectiveness.

Simplifying the geological and geotechnical complexity has ensured that the fault network at PBM is not only accurate but is also practical for site use. This has enabled the site team to regularly update the fault network to keep data current while reducing reliance on external consultants and improving the site team's capabilities in providing geotechnical support to operations in a fast-paced environment. PBM is now better positioned to address structural risks and maintain safer, more efficient mining operations.

Acknowledgement

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