SSIM 2025 - JJ Potter & J Wesseloo (eds)
© 2025 Australian Centre for Geomechanics, Perth, ISSN 3083-399X
doi:10.36487/ACG_repo/2535_26

Structural analysis and modelling in an evolving mineral resources operation

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Abstract

Optimising pit slope stability and reducing the strip ratio of a mining operation are two key tasks in geotechnical engineering. With a growing demand for minerals and an increasing cost associated with extraction, companies are constantly re-evaluating the viability of mineral deposits and challenging their geological understanding.

Within Rio Tinto Iron Ore, the structural geology (SG) team investigate and collect critical data, such as point-based orientations, mapping and geological inferences from adjacent pits to re-model deposits where previous interpretations have failed to account for structurally controlled slope failures. Utilising innovative data collection methods and data-driven investigation, SG aims to address the root causes of slope instability and the opportunity for improved mineral mining.

Resource drilling evaluation is often the majority source of data in bulk commodity extractions and will often bias data collection to a specific orientation with their vertical drilling orientation and regimented grid layout. This data bias can significantly reduce the capability to identify and qualify complexity, hence limiting confidence and reliability of the structural model which geotechnical design and decisions are built upon. Without the consideration of complexity and the capability of capturing the appropriate nature of geotechnical design domains, mining operations run the risk of inadequately designed slopes that may fail and potentially harm personnel.

Regional structural trends have been considered in conjunction with surface and in-pit mapping data to model multi-batter fold structures that were absent from previous iterations of the structural model. The structural model update is a 3D compilation of the upper Marra Mamba stratigraphy partitioned into six sub members and the detrital/bedrock contact spanning a model volume of ~6.25 × 2.50 × 3.80 km (length, width, breadth). Modelled stratigraphy in the Marra Mamba subunits are often defined by shale bands or packages amongst banded iron formation (BIF) units that are the target mineralised ore. A rheological contrast between the BIF and shale in the stratigraphy denotes potential anisotropic surfaces that are of concern in geotechnical design. The latest iteration of the structural model aims to address the issues of historical slope instability along planes of anisotropy and linking observed structures in the pit with the Pilbara regions deformational history.

Critical risks and opportunities have been identified in newly identified dip-slope and rock mass controlled sectors of the geotechnical design rather than a ubiquitous dip-slope sector across the previously adopted pit design. Such improvements forecast a reduced cost to operation and improved extraction of ore at depth.

Keywords: *structural geology, geotechnical design, optimisation, slope stability, risk mitigation*

1 Introduction

As of 2025, Rio Tinto Iron Ore operates across over 300 km of lateral extent in the Pilbara region located in the northwest of Western Australia. Referred to in this publication as Pit A, the paper explores application of

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advancements in structural geology (SG) data collection and technical investigation into slope stability for a high-grade iron ore deposit located in the Greater Brockman mine region. The Greater Brockman operation is situated in the western Hamersley Basin with Pit A situated along the northern limb of the Brockman Syncline (Figure 1) and primarily extracts iron minerals from the Hamersley Group sedimentary deposits known as the Marra Mamba Iron Formation and Brockman Iron formation (MacLeod et al. 1963; Trendall et al. 1970).

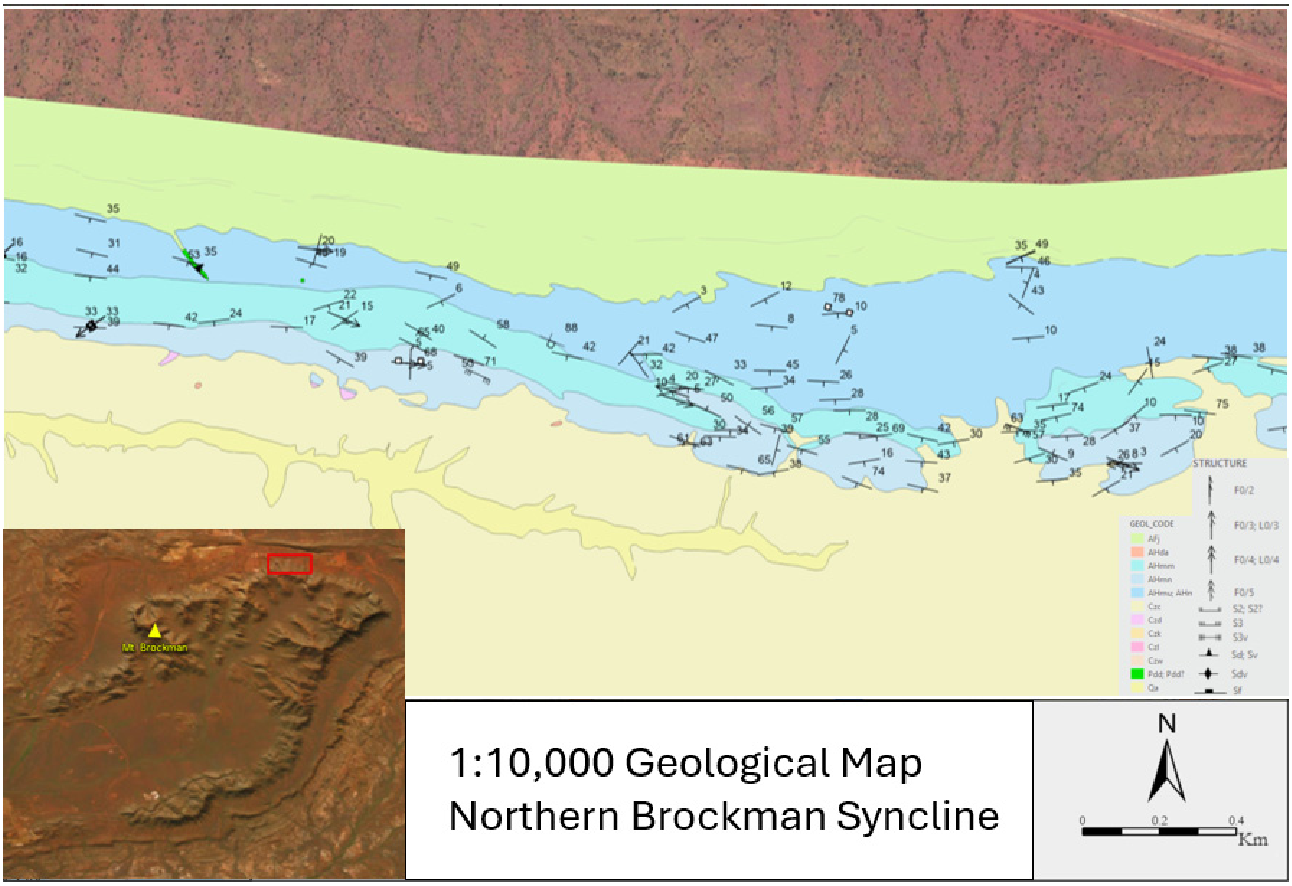

Figure 1 Geological map of the northern Brockman Syncline

The Hamersley Group (ca 2,630 to 2,450 Ma) is described by Kepert (2001) as an approximately 2.5 km thick sequence of deepwater chemical sediments, subordinate turbiditic sediments, and various intrusive and extrusive rocks. The western Hamersley Basin displays these deformed rocks in outcrop with clear preservation of regional tectonically driven shortening events such as the Ophthalmia Orogeny and Pan Handle Orogeny which are linked to the structural evolution and enrichment of Pilbara iron ore deposits.

The tectonic evolution of the basin is important from a SG perspective as it contextualises field data and mapping within a regional context. Observation and interpretation of regional structures are important as they can link orientation data trends to deformational phases and their relevant fold and fault structures. This same concept is equally as important when working at a smaller scale such as an operational pit or staged pit design. Furthermore, it is critical to combatting exploration phase data collection bias and further helps build a robust and confident structural model foundational to the geotechnical design and its execution (Read & Stacey 2009).

Resource drilling campaigns dominate the available data components in three-dimensional (3D) modelling with their associated geochemical and geological sample sets. They can often overlook the importance of orientation related data and potentially introduce uncertainty downstream. A resource geology model can often overlook orientation data sets in their inception for bulk commodity resources with a focus on assay grade data and its association with strata bound mineralisation. Downhole and field-based mapping orientation data continue to prove and champion importance in structural model builds with their ability to inform on sensitive design domains that are commonly overlooked in feasibility study phases. Such oversight introduces risk and uncertainty in design during mining. With the increased demand for high-grade (often structurally controlled) ore, the industry is facing a pertinent requirement to improve their orebody knowledge and provide models that service both economical and engineering disciplines.

Fundamentally, the SG team approaches operational problems with a problem-solving approach rooted in technical understanding and data collection. Detailed in the papers body are the results of implementing these techniques upon Pit A, with an ultimate strike length of ~6 km and an already approximately 20-year operational history. Pit A's design draws on an existing geological interpretation from a decade old structural model. The decade old model was translated to a new modelling software in 2020 with minimal deviation from its predecessor and thus warranted no design update or scrutiny.

In recent years, the pit encountered a series of batter to multi-batter scale instabilities that triggered investigation by the SG team in accordance with internal geotechnical safety and assurance standards. This problem also coincided with a proposition from Rio Tinto mine planning teams to implement a cutback design for the existing pit to recover additional high-grade ore at depth.

The rewards of doing so have been immense with four primary implications for geotechnical design practice:

1. providing sectors of rock mass controlled design in previously interpreted structurally controlled domains
2. the opportunity to optimise the slope angle for mineral recovery and reduced strip ratio
3. production of a 3D model with structures and geometries that can account for historic slope instabilities in structurally controlled domains where previous design assumptions failed
4. confidence evaluation of 3D model with distance to drilled stratigraphy intercepts and orientation measurements for informed decision-making during design optimisation.

2 Primary data collection and inherent bias

Committing to a resource grid drill campaign of vertical holes as the primary source of data collection is commonplace in bulk commodities such as iron ore. Although this is an effective way of proving a resource estimate it often bias's data collection to a specific orientation and significantly reduces the capability to identify and qualify structural complexity. This is especially true in the context of the Hamersley Basins, Marra Mamba Iron Formation, a ~2.7 Ga sedimentary deposit consisting of banded iron formations (BIF) and shale units (Trendall et al. 2004) that have rocks have preserved and endured multiple deformation events on an orogenic scale, resulting in complex fold systems and varying bedding geometry within the orebody (Tyler & Thorne 1990).

Consequently, these limitations and biases make it difficult to construct a realistic and coherent structural model that identifies adverse structural domains. Without the consideration of complexity and the capability of capturing these structural domains, mining operations run the risk of inadequately designed pit-slopes that may fail and potentially harm people.

For our analysed deposit the first unoriented evaluation holes were drilled in 1972 with subsequent programs in the 1970's expending further south with an ~50–100 m drill spacing and a lateral grid of 300–400 m spaced intervals. This evaluation grid makes up the first major study phase of the deposit and forms the initial geological interpretation of the system and its structural framework. Smaller infill programs continued in the 1980s and later in 1999 the resource grid was refined to 200 m spacing in the lateral extents of the prospect. Finally, in the early 2000s a final push was made to reduce the drill grid resolution to a 50 × 50 m drill spacing grid which often makes up the final evaluation phase of a study before the prospect is handed over for operational mining and further evaluation.

Prior to operation over 4,000 individual drill holes had been drilled with a significantly large proportion comprising of vertical orientated reverse-circulation drilling boreholes along a north–south grid. This skew toward vertical holes was recognised as a potential source of data bias during the 2023 modelling work by the SG team. During the investigation which comprised of a mapping and data collection campaign, in field observations recognised that recent slope instabilities in Pit A's north wall were occurring along shale bands in the stratigraphy. The shale bands acted as anisotropic planes of weakness and planar release planes for overlying material in the batter faces. Further, field mapping and unmanned aerial vehicle (UAV) photogrammetry displayed a northwest–southeast striking orientation trend associated with the shale bands and subsequent identification of a major fold corridor throughout the deposit.

3 Data collection and pit scale reconciliation

SGs at Rio Tinto Iron Ore are responsible for mapping newly mined batter faces as they are uncovered for the purpose of model reconciliation. The reconciliation process is a key part in identifying whether current interpretations are still relevant and fit for purpose for geotechnical design and a key reporting deliverable for our internal global technical standard for major hazard risk management.

In this case our original interpretation and design places majority of our north wall in a structurally controlled domain. Prior to our investigation and design updates in 2023, Pit A's north wall consisted of 10 individual design sectors (FW1–FW9), all of a structurally controlled nature (see Figure 2). Structurally controlled domains are sensitive to bedding dip angle and bedding anisotropy between shale and BIF units in the Mount Newman member, the youngest rock package in the Marra Mamba Iron Formation (Blockley et al. 1993).

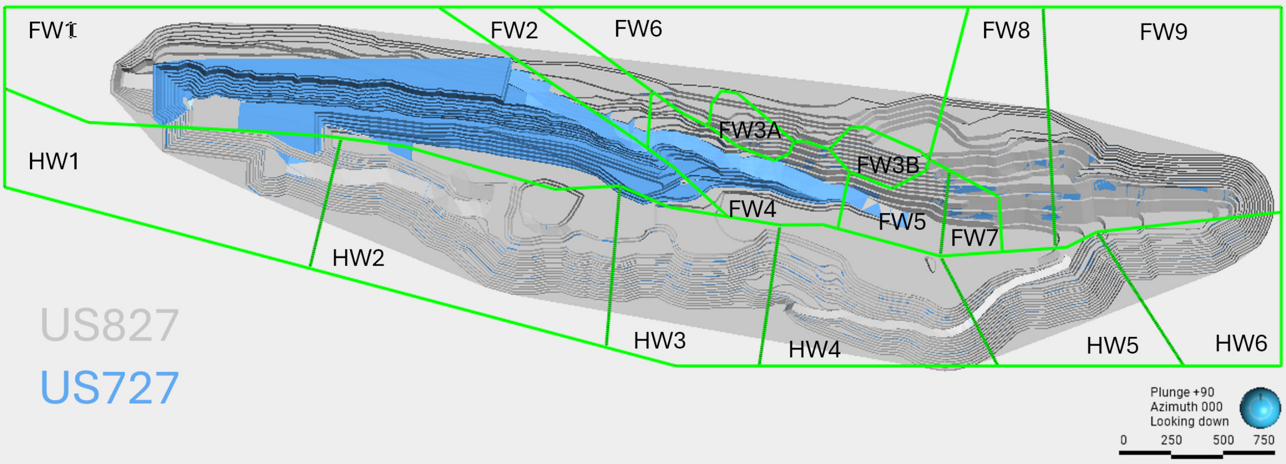

Figure 2 Pit A's geotechnical design domains superimposed onto stage design US727 and US827

The reconciliation process involves a direct comparison between currently adopted model versions and reality as outlined in both in-person structural mapping and UAV remote mapping. Both methods of mapping aim to capture geological and orientation data for the purposes of highlighting spatial and orientation deviations from the current adopted structural model. Utilising Rio Tinto Irone Ore's internal technical standards we can categorise the technical risk the reconciliation results pose based on a traffic light colour system, with green representing low risk, amber a moderate and red a significant risk to operations and the design. The traffic light system provides a high-level summary of where the technical risks lie across Rio Tinto Iron Ore's large Pilbara operation, spanning ~100 pits and thousands of mine designs and what level of risk is associated with slope stability impacts on the businesses delivery of ~360 Mt of iron ore annually.

From a SG delivery perspective, our geologists need to:

1. map newly uncovered benches in the operating pits
2. evaluate reconciliation of the structural model and report on conformance to current adopted structural model

3. update or produce new structural models if there is significant risk or issues in reconciliation outlined from the mapping results.

3.1 Structural mapping

Batter faces are typically 8–20 m high, limiting mapping measurements to the first 2 m of face exposure. Although this form of data collection is limited by personnel height and safe mapping conditions, the ability to discern textures in outcrop, collect confident structural measurements and kinematic indicators is invaluable. This is especially valid in high-grade deposits that experience a tremendous amount of alteration and mineralisation that can obscure the typical appearance of key rock types and units. In combination with sketching of the batter face the geologist can begin to contextualise the stratigraphy and structures to better understand how bench-scale features present themselves in the wall compared to the larger scale, regional deformation.

Figure 3 displays two mapping data sets collected by the SG team with large blue disks representing pre-mining-surface bedding orientation, small blue disks signify the bench-scale mapping campaign data, green lines and points major shale horizons and stratigraphic markers from digitised field sketches and UAV photogrammetry. These observations and data points allow the geologist and modeller to integrate said data into a structural model update or renewed geotechnical designs. The additional measurements in conjunction with stratigraphy interpretation and rock unit identification provide tie points to the modelled 3D surfaces and volumes and improve orientation confidence and spatial reconciliation. New data in the mapping and reconciliation process provides an opportunity to challenge the current interpretation and further build on the confidence of the model product once the data is understood and integrated into the overall interpretation.

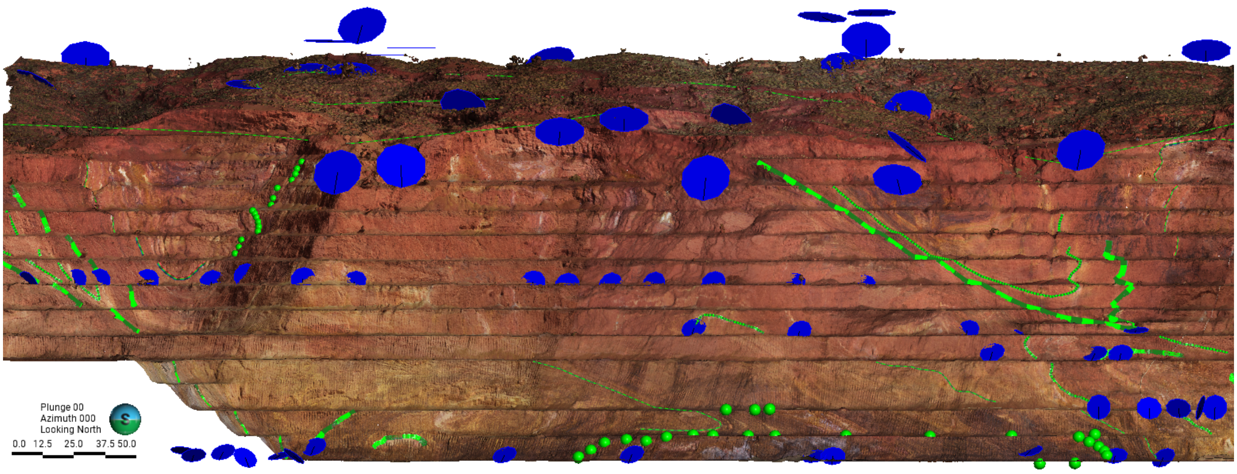

Figure 3 Surface mapping data (large blue disks), face mapping orientation data (small blue disks) and shale stratigraphy markers (green points and lines) projected on unmanned aerial vehicle photogrammetry in Leap Frog 3D modelling software

3.2 Drone photogrammetry and remote mapping

Remote structural mapping with the use of UAV photogrammetry techniques is one of the latest developments in data collection and reconciliation techniques (Dey et al. 2021). Utilising drone imagery and photogrammetry scanning methods we can produce 3D georeferenced reality models of pits requiring analysis (Thiele et al. 2017). It yields the benefits of a wider data array capture of slope faces (accessible and non-accessible) and removal of personnel from potential geotechnical hazards. To assist in the investigation of slope instabilities in Pit A, a high-resolution UAV scan was conducted on a recent slope instability and the surrounding bench faces (see Figure 4).

Figure 4 Unmanned aerial vehicle photogrammetry of latest Pit A slope instability post incident

With the wider scan the root cause of the failure was interpreted to be a planar sliding failure mechanism along a shale band within the Mount Newman member. The previous geotechnical design was unable to account for this instability due to poor stratigraphic reconciliation in the 2020 iteration of the structural model. With the use of the UAV imagery, 12 additional bedding orientation measurements were taken of the failure surface along with point-based location data of the day lighting shale band (see Figure 5). This data would then be integrated into the structural model update and ongoing geotechnical design analysis.

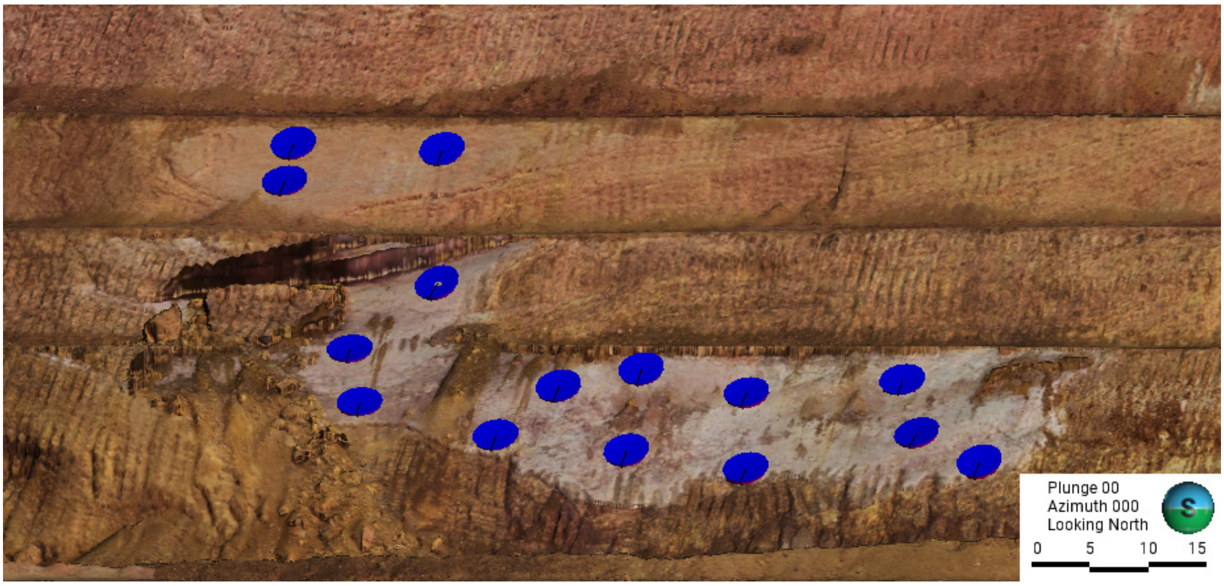

Figure 5 Textured mesh of unmanned aerial vehicle photogrammetry in Leap Frog modelling software with extracted bedding measurements (blue disks)

4 Results

Prior to mining the availability of targeted drilling data and orientation data collection was limited. In addition, modelling methodology was not rooted in structural understanding and modelling products often served both resource estimation and engineering customers. The lack of structural analysis and interpretation led to the interpretation of the broader system that Pit A lies in to be simplistic incapable of defining structures smaller than the dominating regional scale outcrop.

As outlined in Pit A, previous data biases could not adequately account for later deformational phases that were responsible for the reorientation of bedded stratigraphy coinciding with the north wall design. The interpretation of the system and adopted structural model were ultimately responsible for inadequate geotechnical design that resulted in slope instability. Synthesising regional and bench-scale data sets in conjunction with mapping campaigns resulted in a reinterpretation of the system from an east–west striking isoclinal syncline (Tyler & Thorne 1990) to an east–west isoclinal syncline with an overprinting northwest–southeast striking fold corridor pertaining to a later orogenic event likely consistent with the Pan Handle Fold Orogeny (Taylor et al. 2001). Across a single critical section and three design domains previously thought to be ubiquitously structurally controlled, the differences in structural model architecture in the 2020 and 2023 updated model were significant (see Figure 6 for cross-section location and Figure 7 for model comparison along section).

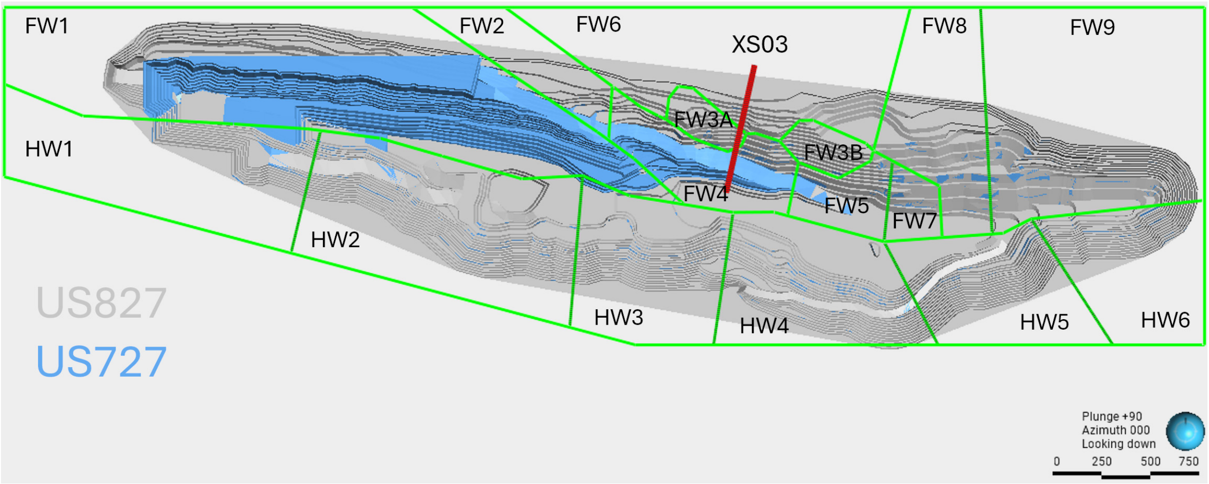

Figure 6 Critical cross-section 3 (XS03) location across Pit A

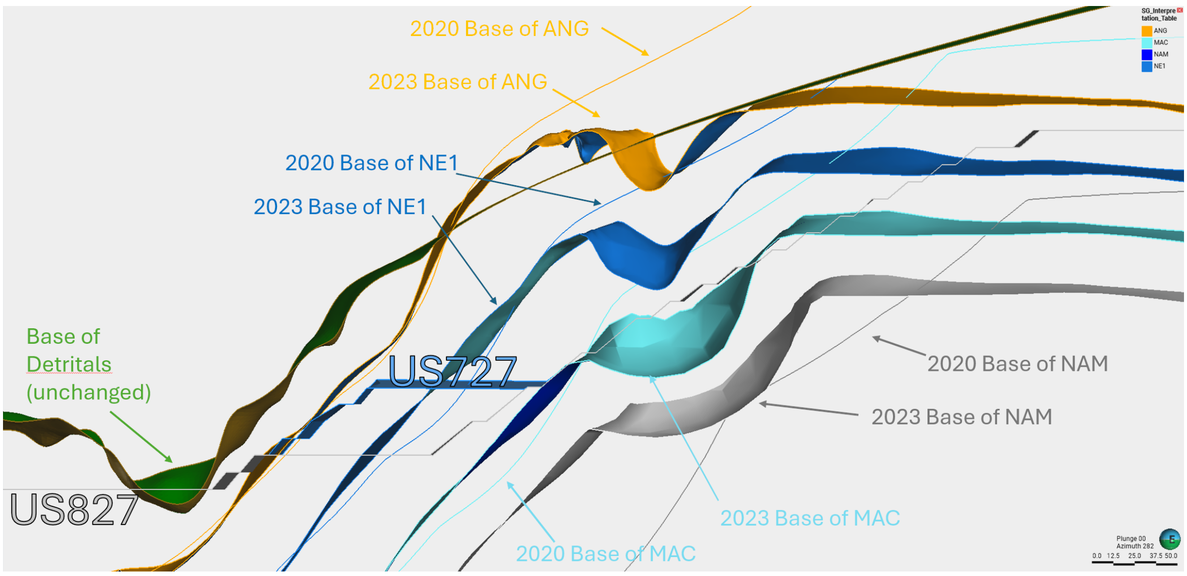

Figure 7 2020 and 2023 structural model wireframes along cross-section 3 (XS03), including four of six major subunits in the Marra Mamba Iron Formation

The realisation of a northwest–southeast fold corridor in the field mapping and investigation that later summarised into the 2023 model provided opportunity to challenge previous designs and assumptions. This allowed our engineering teams to make several important changes to the geotechnical design domains and slope configurations in designs US727 and US827. The changes included but were not limited to sub domaining sectors that were previously structurally controlled by bedding anisotropy and dip angle to rock mass controlled domains, of note in Figure 7 where newly modelled folds were produced with support of additional data. Those rock mass controlled domains adopted more aggressive slope configurations leading to improvements in the overall slope angle (OSA) and final location of our ultimate pit crest. The relocation of the crest and the optimisation of the OSA of the design not only reduced the potential for waste mining and handling of uneconomic material but also reduced the impact the operation has on the land and removed the need to relocate critical infrastructure of an estimated AUD 100 million cost. Time and resources in a busy and large operation are also realised benefits from an optimised design.

Utilising 2D limit equilibrium analysis on critical geotechnical sections, optimisation of inter-ramp angle and batter face angle for the proposed cutback design was achieved. A 4˚ change (29–33°) in the inter-ramp as proposed by optimised ultimate design US827 would have an estimated volumetric saving of ~4.28×10^6 m^3 of material handling across 1 km of wall. This volumetric saving estimate can translate to a cost saving difference of ~ AUD 250 million in waste rehandling costs and further unlocks 60 million tonnes of high-grade ore.

Table 1 summarise the optimisation potential of the OSA along a single critical section in the recent analysis. The Factor of Safety (FoS) requirements were achieved while optimising the OSA by up to 5˚ in domains represented by cross-section (XS) 03 in the currently adopted design US727 and are but one example of an optimised geotechnical domain that has been completed due to the recent findings and modelling by the SG team at Rio Tinto Iron Ore. A summary of the achieved FoS and potentially optimised FoS in high confidence scenarios can be compared to their minimum required FoS for their respective sector (see Table 2).

Table 1 Overall slope angle (OSA) comparisons for differing pit scenarios and/or stages

Section line	Scenario/pit stage	Slope height (m)	Current geometry (OSA)	Optimised geometry (OSA)
XS03	As-built	144	38°	n/a
	US727	147 (inter-ramp upper)	29°	34°
		41 (inter-ramp lower)	34°	34°
	US827	180	29°	33°

Table 2 Factor of Safety (FoS) comparisons for differing pit scenarios and/or stages

Section line	Scenario/pit stage	Achieved FoS	Optimised FoS	Target FoS
XS03	As-built	1.44	n/a	1.2
	US727	1.35 (inter-ramp upper)	1.31	1.3
		2.28 (inter-ramp lower)	2.32	1.3
	US827	1.30	1.28	1.2

5 Conclusion

The SG model is critically important to developing reliable slope designs for Hamersley Basin strata bound iron ore deposits. Structural models need to include explicit interpretation of stratigraphic and structural geological boundaries as well as differentiating rock masses based on lithology, weathering and alteration state. Relatively minor changes in bedding dip angle can have major impacts on slope stability. Data-driven interpretations and realisation of certain limitations are also critical in avoiding unknown risks and unaccounted uncertainty.

A focused approach on the regional deformation history of this multibillion year old sedimentary deposit is key to translating and contextualising structures on a pit or prospect scale and improves the feasibility and certainty of an adopted structural model. Continuous design application with the use of SG for improved orebody knowledge is both economically and beneficial to operational safety as proven in conceptual design results for Pit A in the western Hamersley Basin.

Future works include improvements in UAV data collection methods and automation of structural data collection from the resulting photogrammetry product. Rapid updating of structural models with newly acquired structural data will improve overall confidence and facilitate superior geotechnical designs. Reduction in uncertainty and improved understanding of failure mechanisms present in these mineral systems are beneficial to the safe operation and execution of open pit mining in the Pilbara. The geotechnical engineering department which includes the SG team is applying this practice across our entire operation to reassess slope optimisation potential and unlocking potential value in both old and new open pits. The need to understand the structural deformation history of our strata bound deposits and their geotechnical implications will continue to be a core practice in the interpretation stage of 3D modelling and remain foundational to the products used in geotechnical design solutions for the lifetime of this large-scale mining operation.

Acknowledgement

Acknowledgements to the SG and geotechnical engineering design teams at Rio Tinto Iron Ore. Special thank you to Martin Nguyen and Akash Jani for their ongoing support as colleagues, mentors and collaborators during my iron ore career.

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