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Improving reliability of the geotechnical model for Cenozoic cover sequence sediments in the Pilbara, Western Australia

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Abstract

This paper presents a case study of the ongoing development of the geotechnical model in Cenozoic cover sequence sediments for a large open pit operation located in the Pilbara region of Western Australia. Model development involves a novel approach that couples the resource geochemistry and downhole geophysics database with traditional geotechnical cored drilling methods. The objective is to manage uncertainty in pit design due to variability in the distribution of geotechnical units in the Cenozoic cover sequence sediments.

The operation comprises a series of open pits with an areal coverage of approximately 27 km by up to 8 km. The deposit is covered by a 100 m thick Cenozoic-aged sequence of sediments comprising mudstones, clays, and conglomerates, much of which is below the groundwater table. Challenges for developing the geotechnical model include:

- *Pits situated over a large area.*
- *The high degree of uncertainty in the existing Cenozoic geological model.*
- *Limited hydrogeological data for below watertable areas.*
- *The requirement to elevate the current understanding from conceptual to execution level.*

The modelling approach comprises comparing selected reverse circulation (RC) resource drill results against adjacent diamond core drilling with detailed geotechnical logging. The aim is to characterise the key geochemical and geophysical signatures for the major geotechnical units. These signatures are then applied to selected sections through the resources drilling database from which the geotechnical model is interpreted. Developing an understanding of the geological history and the spatial variability of the resulting Cenozoic cover sequence is important to the model development.

The resulting model is used to guide slope stability and hydrogeological analyses in areas identified as critical to slope performance. The outcome is optimising the slope design with steepening of inter-ramp angles in some areas and developing pit slope risk management strategies to be applied during mining.

Keywords: *Cenozoic sediments, geotechnical model, Pilbara, slope design*

1 Introduction

The Pilbara region of Western Australia is one of the world's most significant iron ore producing regions. Since the 1960s, iron ore has been extracted through open pit hard rock mining methods, primarily in the Archean Marra Mamba and Brockman iron formations (IF). In the past decade, efforts to unlock further resources have led to an increasing number of open pits excavated within the Cenozoic detrital sequences; these include channel iron deposits (CID) as well as mineralised Archean iron formations dipping shallowly below the wide, sediment infilled valleys between banded iron formation (BIF) ridges.

The large scale of these deposits and the spatial variability of the Cenozoic sediments makes the traditional method of geotechnical model development by extensive diamond core drilling, geotechnical logging, and geomechanical testing impractical and expensive. As a result, a method has been developed to enable the formulation of a robust geotechnical model based primarily on geochemical and geophysical analysis of the existing resource drillhole database.

This paper presents the methodology for model development and the update applied to an existing geotechnical model and discusses implications for slope design for a large operational mine. The update includes site-specific geochemical analysis, improved understanding of the geological history of Cenozoic deposition, and updated hydrogeological analysis methods, which have improved confidence in the geotechnical model and subsequent slope design.

2 Background and geological setting

2.1 Study background

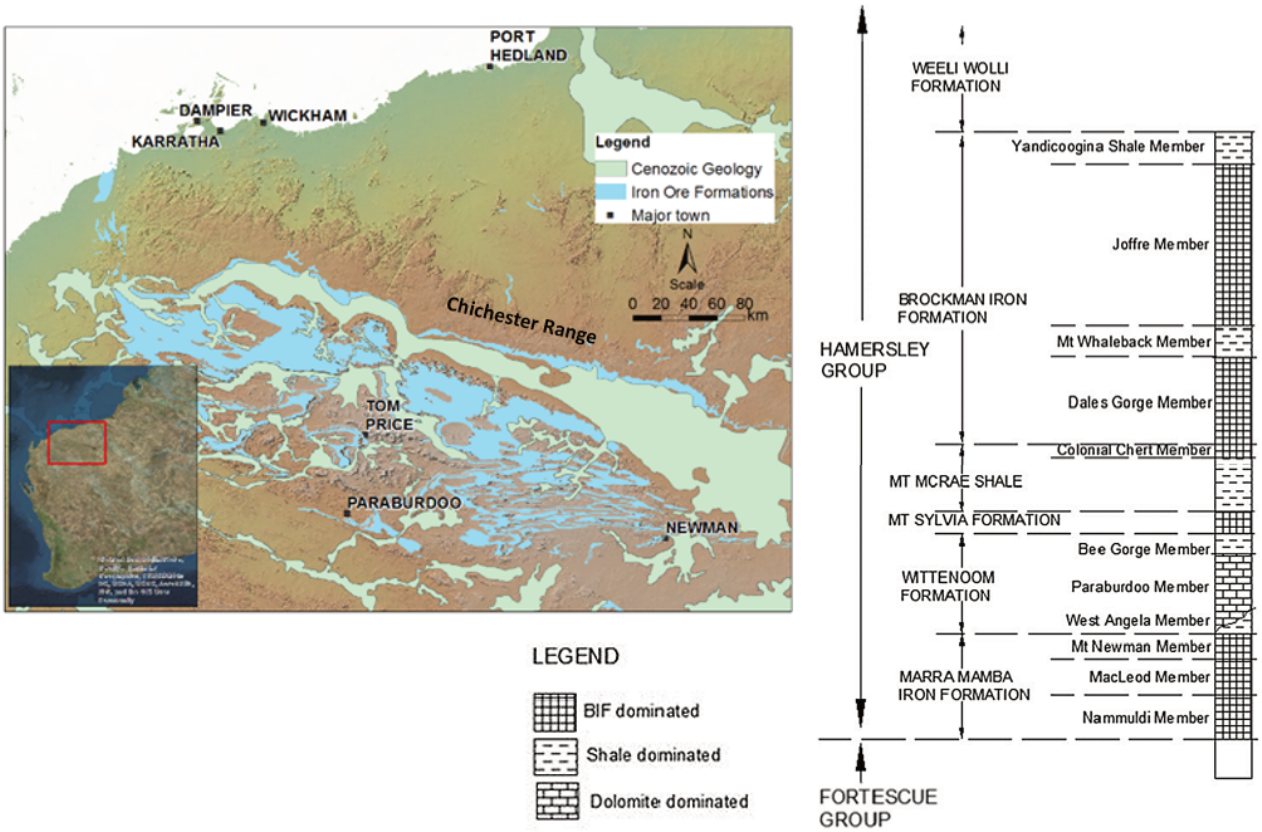
The method of using the resource borehole database to interpret the geological history of a deposit and develop a geotechnical model has been used previously in Pilbara slope design studies (Baxter 2016; Hemraj 2018; Hemraj & Eggers 2020). These studies have shown that the method can be used effectively to develop a slope design using very limited, carefully planned geotechnical boreholes in conjunction with existing data routinely collected during the project's exploration and resource definition stages. This study builds on Hemraj (2018) and Hemraj & Eggers (2020) to extend the existing geotechnical model and improve our understanding of the Cenozoic stratigraphic sequence and geological history within the Marra Mamba–Brockman Strike Valley in which the case study deposit is situated.

The study site is located on the lower slopes and alluvial plains at the foot of the Chichester Range in the East Pilbara region of Western Australia. Mineralisation is hosted within the shallowly dipping, Archean Nammuldi Member BIF, and the immediately overlying detrital CID. The mine consists of a series of pits, typically starting in the exposed Archean bedrock and progressing into the deep Cenozoic sediments as mining follows the mineralised units along the base of the valley paleochannel. An implementation level geotechnical slope design study was completed in the north of the deposit in 2017 using the methods described in this paper (Hemraj 2018; Hemraj & Eggers 2020). While mining is already underway in the northern pits, the southern mine area, consisting of a 12 km strike length, was only at a conceptual slope design study level, and the objective of this study was to elevate the model and design confidence to execution level.

2.2 Archean geology

The Archean geology of the Pilbara comprises granites overlain by late Archean to early Proterozoic (2.75–2.30 Ga) Hamersley Group BIF, shale, dolomite, and mudstones. Within the Hamersley Group, iron ore deposits are predominantly hosted within the Dales Gorge and Joffre Members of the Brockman IF and the Mt Newman and Nammuldi Members of the Marra Mamba IF. Situated stratigraphically between these IFs is the Wittenoom Formation, consisting of shales and dolomite. Figure 1 shows the distribution of IF and Cenozoic geology in the Pilbara and a stratigraphic column of the Hamersley Group.

Structurally, the Pilbara is characterised by numerous deformation events which have resulted in regional scale folding and thrust faulting. Subsequent deformation events have resulted in upright folds and dome and basin features.



(a) (b)

Figure 1 (a) Simplified geology of the Pilbara showing the distribution of Cenozoic geology and Archean iron formations (after Hemraj 2018. Source: Geological Society of Western Australia); (b) Stratigraphy of the Hamersley Group (after Thorne et al. 2008)

2.3 Cenozoic geology

Cenozoic sediments in the Pilbara typically comprise valley infill deposits, which are generally overlain by Quaternary alluvial and colluvial sediments. These deposits make up most of the surficial geology in the Pilbara.

Based on their geological and depositional character, the Cenozoic-aged sediments can be separated into three broad groups (Morris & Ramanaidou 2007; Baxter 2016; Hemraj 2018), youngest to oldest:

1. CzD3 comprises coarse-grained colluvium and alluvium. The sediments are typically sourced from adjacent Brockman IF and Marra Mamba IF exposures.
2. CzD2 comprises lacustrine clays, carbonaceous clays and iron-rich conglomerates with CID equivalent pisolitic units and may be overlain or overprinted by bands of calcrete cemented sediments.
3. CzD1 comprises hematitic, mixed, coarse, proximal fragments to distal, silty, red ochre detritals. Clasts may display BIF derived textures.

CzD1 and CzD2 sediments are typically present immediately above the Archean paleosurface and can be difficult to distinguish in core samples against the weathered rock below the paleosurface.

3 Data

The key advantage of the methods used in this study approach is that the geotechnical model can be developed over extensive areas with a relatively small and therefore, less expensive geotechnical site investigation. This is achieved by utilising the existing, extensive datasets typically available on most open cut mine sites. The critical datasets used in this study include:

1. Fifteen dedicated, cored geotechnical boreholes drilled in the early stages of the northern and southern deposit studies. Data collected during the site investigation phase includes geotechnical logging of rock mass and soil strengths, defect orientations and conditions, and soil properties. Core samples are also collected for geomechanical laboratory testing including consolidated undrained triaxial, unconfined compressive strength and direct shear strength testing of bedding defects in Archean units.
2. Historical cored boreholes (122) with core tray photographs of which 43 were cored through detrital materials. Because these boreholes were drilled primarily for metallurgical or hydrogeological investigations, many were pre-collared through the detrital sequence and did not include logging or photographs of the detrital units.
3. Geochemical assay data, which is routinely collected during the resource definition phase of a deposit. Assay data commonly includes a broad suite of major and minor elements, oxides and volatile mineral content. Assay samples are usually collected by percussion drilling methods with samples taken of each meter drilled or a composite sample of up to 10 m. 7,806 reverse circulation (RC) boreholes with assay data were available for this study.
4. Downhole geophysical data collected during resource definition drilling and the geotechnical site investigation. These typically include natural gamma, density and magnetic susceptibility. 75% of resource definition boreholes in this case study had some geophysical survey data.
5. Geological mapping data, typically collected in the early stages of exploration and resource development. Mapping data is usually limited to areas of outcropping Archean geology and includes structural measurements of bedding orientations.
6. Groundwater data, including piezometer or standpipe levels and data collected from nested vibrating wire piezometers (VWP) installed during the geotechnical site investigations.

4 Methodology

The methodology used to develop the geotechnical model follows that used by Baxter (2016), Hemraj (2018), and Hemraj & Eggers (2020) and consists of the following steps:

1. Geotechnical site investigation – the inclusion of a targeted geotechnical site investigation, consisting of cored boreholes drilled in key locations of the planned pit walls, adds valuable geotechnical data to the study, including field testing and logging, structural measurements, and the opportunity to conduct geomechanical laboratory testing of core samples. Each geotechnical borehole is designed to 'twin' an existing RC borehole with good geochemical data.
2. Interpretation of site-specific detrital stratigraphy and geotechnical rock mass units from the available geotechnical and existing cored boreholes as well as surface or in-pit mapping where available.
3. Comparison of interpreted units with our understanding of the stratigraphy and geological history of the detrital sequence in the Pilbara region.
4. Correlation of interpreted detrital geotechnical units with geochemical characteristics – using the existing assay and downhole geophysical survey database, geotechnical units identified throughout the sequence can be correlated with geochemical and geophysical datasets in adjacent resource definition boreholes. In this way, characteristic signatures can be developed for each identified detrital unit and the Archean bedded sequence. The result is a series of one-dimensional stratigraphic columns at the available cored borehole locations throughout the deposit and corresponding geochemical and geophysical 'signatures' for each geotechnical unit.

5. Confirmation of the unit boundaries by comparison with downhole geophysics.
6. Development of two-dimensional (2D) geotechnical models along key cross-section locations across the deposit by interrogating the relatively closely spaced resource definition borehole database. These representative cross-sections were located in areas of highest geotechnical risk. This includes where the highest pit slopes are to be developed in the detrital sequence or where low strength or low permeability geotechnical units, such as lacustrine clays, which are important for slope stability, are expected to be encountered. The cross-sectional models are also utilised in numerical modelling of groundwater depressurisation and slope stability.
7. Assessment of risk in areas outside of the 2D models and geotechnical site investigation – the development of 2D geotechnical models allows for broader interpretations of the site-wide stratigraphic sequence and the geological history of the valley. This, in turn, can aid in assessing risk to areas outside of the modelled sections through interpretation of geomorphic features, paleo-valley morphology and the spatial variability of units both across the valley and between cross-sections.

Three-dimensional models can be developed from the interpreted 2D sections, depending on the available section spacing and study requirements concerning model confidence.

5 Model development

5.1 Geotechnical site investigation

The geotechnical site investigation for this study of the southern deposit consisted of eight new geotechnical boreholes in addition to the seven boreholes drilled for the earlier 2017 study in the north of the project. The results of laboratory tests and geotechnical logging of soil and rock mass properties informed the selection of soil, rock mass, and defect shear strength parameters used in numerical stability analyses. Index testing such as particle size distribution and Atterberg limits were undertaken on fine sediments to assess clay content and plasticity, which aided in selecting intact shear strength properties for the stability analyses, and estimating hydraulic properties used in numerical hydrogeological analyses.

The site investigation also included installing up to four nested VWPs, grouted in place in several of the geotechnical boreholes. These instruments record piezometric pressure every 12 hours and are used to monitor pore pressure changes resulting from the passive and active pit dewatering as mining progresses towards the final wall positions. This data helps guide the groundwater assumptions for slope stability analyses.

5.2 Interpretation and characterisation of geotechnical units

Geotechnical units were interpreted from the geotechnical site investigation boreholes and a small number of existing cored boreholes throughout the deposit. Datasets consisting of geochemical assay data and downhole geophysics were collated from adjacent RC 'twin' boreholes for each geotechnical unit identified. These datasets were then interrogated to establish characteristic signatures for each unit, building on those identified in the 2017 study (Hemraj & Eggers 2020). The units encountered in the study are summarised in Table 1, including selected diagnostic characteristics.

The interpreted geotechnical units largely align with those identified in the 2017 study, however, two additional units were also identified: Calcareous Lacustrine clay, which occurs as geotechnically significant calcrete and silcrete overprinting of the lacustrine clay near the upper contact of the unit, and Cemented Detritals, an iron-rich, high strength, clastic unit that occurs immediately above the Archean paleosurface.

Table 1 Summary of interpreted geotechnical units and diagnostic characteristics

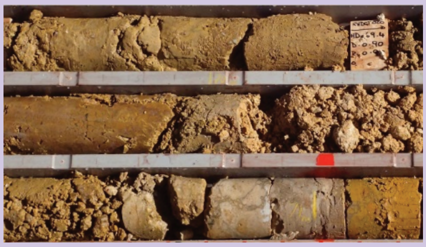
Geotechnical unit	Diagnostic characteristics	Example photograph
Quaternary Detritals A conglomerate of mixed ore, banded iron formation (BIF), and shale clasts. Variable in character from moderately well-consolidated conglomerate to loose gravel and silt.	Moderate Fe (<40%) and SiO_2 (>30%). High K_2O (0.2–1.2%) due to clay in the matrix	
Gravelly Siltstone (CzD3) Generally, moderately consolidated and matrix dominated with the gravels consisting of sub-rounded hematite with some sub-angular BIF gravels and pisolite rich zones. Relatively homogenous.	Moderate Fe (<40 %) and SiO_2 (20–50 %). Distinguished from Quaternary Detritals by high TiO (>1 %) and relatively low K_2O	
Calcareous Lacustrine Clay This unit consists of discontinuous lenses or gravels of rock strength calcrete and silcrete in lacustrine clay matrices.	Distinguished from the lacustrine clay by relatively low Al_2O_3, elevated CaO (<10%) and high SiO_2 due to incomplete calcrete and silcrete overprinting	
Lacustrine Clay (CzD2) Typically, grey to red-brown with white zones where calcrete has developed. Generally stiff to hard consistency.	High Al_2O_3 content (>15 %) and K_2O greater than 1% due to a high content of clay minerals	
Calcrete Pale white-grey, massive, and sometimes interbedded with calcrete clay. This unit was observed to overprint the extensive clay unit in the southwest of the project area	High CaO (>10 %) and loss on ignition (LOI) >10 %. Gamma is low due to the replacement K2O bearing clay minerals with carbonates	
Clayey Breccia Colluvium Variable in appearance from gravel dominated breccia to cobbles and boulders of canga interspersed with laterally discontinuous lenses of clays. Occurs within or below the lacustrine clay or immediately above the Archean bedrock	Variable Fe, SiO_2, Al_2O_3, TiO, and K_2O as the rock transitions between iron-rich and clay-rich compositions. Distinguished from the overlying clay by increased Fe	

Table 1 Summary of interpreted geotechnical units and diagnostic characteristics (cont.)

Geotechnical unit	Diagnostic characteristics	Example photograph
Hematite Conglomerate Consists of moderately to highly cemented, sub-angular, fine to coarse gravel clasts of hematite in a silty, sandy matrix	High Fe (>40 %) and moderate SiO_2 (<30 %) due to hematite/goethite rich clasts. Al_2O_3 is typically (<10 %). Magnetic susceptibility is highly variable over short intervals	
Cemented Detritals Gravelly, iron-rich, cemented and occasionally hydrated detritals. A pisolitic texture is preserved in places while elsewhere, the clastic texture is entirely overprinted, and the rock has a 'welded' appearance	Very similar to that of Hematite Conglomerate due to the presence of iron-rich gravels. Lower TiO_2 and K_2O, due to the absence of a clayey matrix, also distinguishes it from the Clayey Breccia Colluvium, which often occurs in close proximity	

In addition to the new geotechnical units identified in the southern deposit, some subtle differences in geochemical signatures were noted between the north and south project areas. These include:

- Generally higher Fe content, particularly in the Quaternary Detritals and Clayey Breccia Colluvium.
- Higher silica content in the coarse detrital units such as Quaternary Detritals, Gravelly Siltstone and Hematite Conglomerate.
- Higher alumina content in the Lacustrine Clay and Calcrete units.

Shear strengths formulated for the southern deposit were comparable to those developed in the northern study, but with higher confidence due to the additional logging and testing data available across the project.

5.3 Interpretation of geological history

To understand the spatial variability of the identified geotechnical units, the geological history was interpreted. This involved explaining each unit's origins, their relative ages, and their relationship to the surrounding geology and geomorphology.

The depositional history of the study area can be summarised in four main stages, as illustrated in Figure 2 and outlined as follows:

1. In Stage 1, the early river system erodes into the exposed Marra Mamba IF, forming the valley. The valley sides retreat as the river cuts down, and weathering of the surrounding bedrock surfaces produces a lateritic profile or ‘hard cap’.
2. In Stage 2, the valley sides have become over-steepened, and instability and erosion of the slopes results in broad alluvial fans and colluvial aprons extending into the valley floor. These deposits form the Hematite Conglomerate and Cemented Detrital units overlying the unconformity. The now wide alluvial plan is flooded, and lacustrine clays are deposited across the basin, including infilling the weathered hard cap and colluvial deposits to form the Clayey Breccia Colluvium.

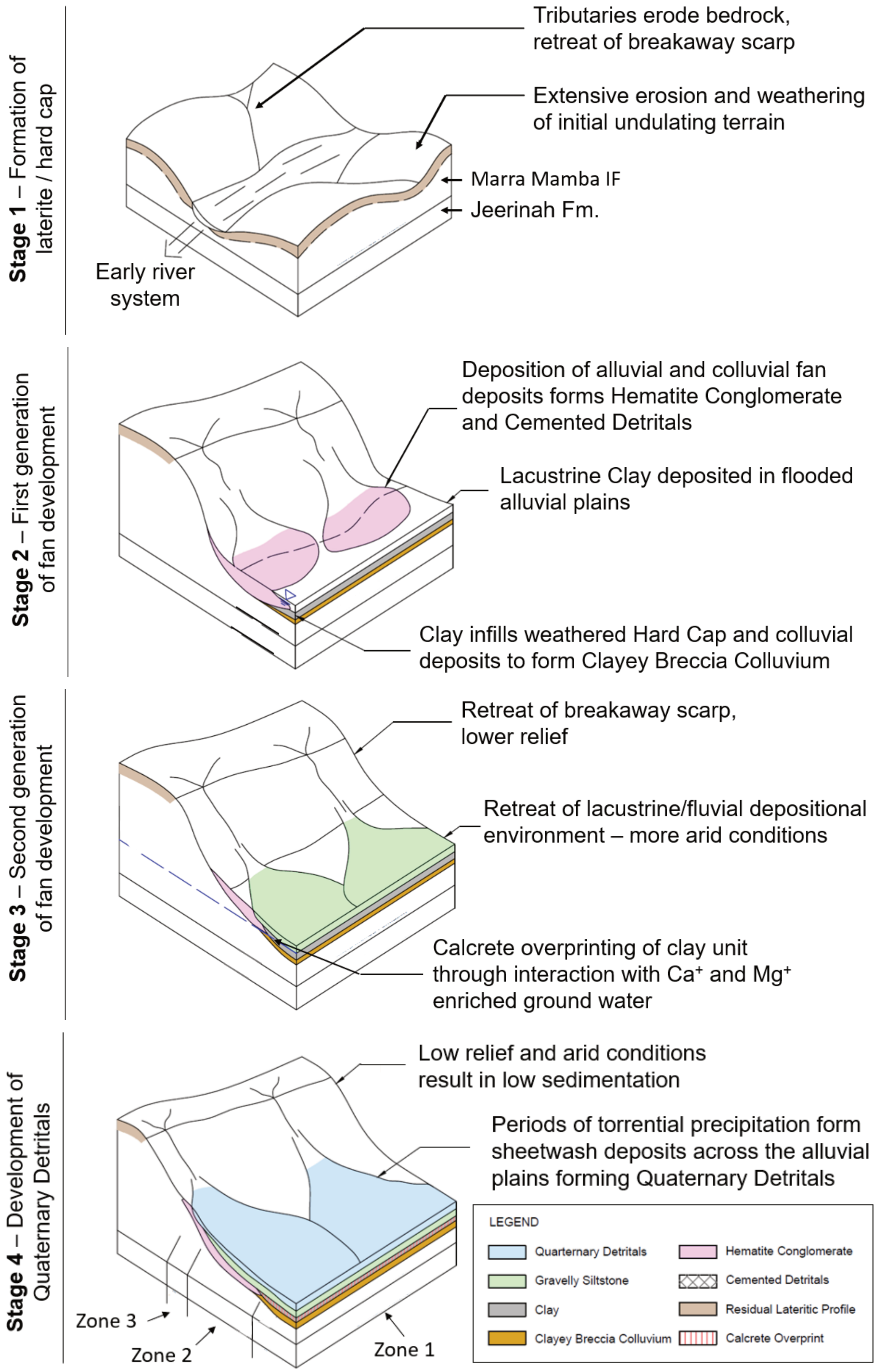


Figure 2 **Interpreted detrital deposition history within the study area paleo-valley**

In Stage 3, climatic conditions become more arid, and the lacustrine environment retreats from the valley. Erosion of the valley sides continues as the escarpments retreat and alluvial fans cover the valley floor, forming the Gravelly Siltstone. Groundwater enriched with Ca+ and Mg+ interacts with the clays resulting in the development of calcrete units. Partial calcification and silicification of the upper portion of the lacustrine clay forms the Calcareous Lacustrine Clay unit.

In Stage 4, the continuing erosion of the valley sides has resulted in low relief and low sedimentation rates in the valley. Periods of torrential precipitation form sheet flood deposits, which blanket the Cenozoic sequence across the width of the alluvial plain, resulting in the Quaternary Detritals.

The geological history presented above explains the formation of all the major geotechnical detrital units and aids in the development of the 2D cross-sections and further extrapolation of the geotechnical conditions across the deposit.

5.4 Spatial distribution of units

The geochemical and geophysical characterisation of detrital units allows for interpreting the detrital sequence along resource definition drill lines. Assay and borehole geophysical data were assessed on a hole-by-hole basis to extend geotechnical units between the cored boreholes on each section.

The units presented within the deposit vary with distance from the valley side, where Archean bedrock is outcropping. Schematic stratigraphic columns of three detrital zone sequences typical of the deposit are presented in Figure 3. The zonation can be broadly described as follows:

1. Zone 1 is the furthest zone from the valley side and comprises the thickest detrital sequence in the mine area of up to 100 m. Quaternary Detritals overlie the Cenozoic sequence of Gravelly Siltstone, calcrete, and lacustrine clay up to 30 m thick, with or without a basal Clayey Breccia Colluvium or Cemented Detrital unit immediately above the unconformity. Zone 1 is further divided into two sub-zones, with Zone 1B comprising the same geotechnical units as Zone 1A but with a significantly thinner clay unit, generally less than 15 m. Significant portions of the final highwall are within Zone 1.
2. Zone 2 runs through the middle of the deposit and comprises a detrital sequence up to approximately 60 m thickness. The zone is characterised by a lack of lacustrine clay and Clayey Breccia Colluvium and the introduction of the Hematite Conglomerate, which occurs at the bottom of the sequence. Zone 2 encompasses the remainder of the final highwall positions.
3. Zone 3 is proximal to the Archean bedrock at the valley side. The detrital units in this zone consist of Quaternary Detritals overlying Hematite Conglomerate, Cemented Detritals or Archean bedrock. Zone 3 was also found to include podiform Lacustrine Clays and Clayey Breccia Colluvium near the unconformity.

An exception to the zones is the Clayey Breccia Colluvium and thin lacustrine clay units identified within detrital Zones 2 and 3, which extend much closer to the valley sides than the main lacustrine clay. These units form narrow corridors trending towards the centre of a paleochannel, aligned with the major tributaries emerging from the Chichester range. The deposits are interpreted to have formed towards the end of Stage 2 and before the deposition of the Gravelly Siltstone in Stage 3. The clayey sediments were deposited within tributary channels which had eroded into the lower clastic sediments and were then flooded, allowing fine sediments to accumulate and infill the underlying colluvium before being buried and preserved beneath the growing alluvial and colluvial deposits during Stage 3. The distinct relationship between these deposits and the geomorphology of the Chichester Range allows for further interpretation of potential clayey channel deposits in areas outside of the 2D geotechnical sections. These interpretations may then be investigated further if they are considered critical to the design.

The result is a series of 2D geotechnical models across the deposit at key locations, with an example presented in Figure 4. The plan distribution of detrital zones interpreted for part of the deposit is shown in Figure 5, illustrating the geomorphic controls on zone location.

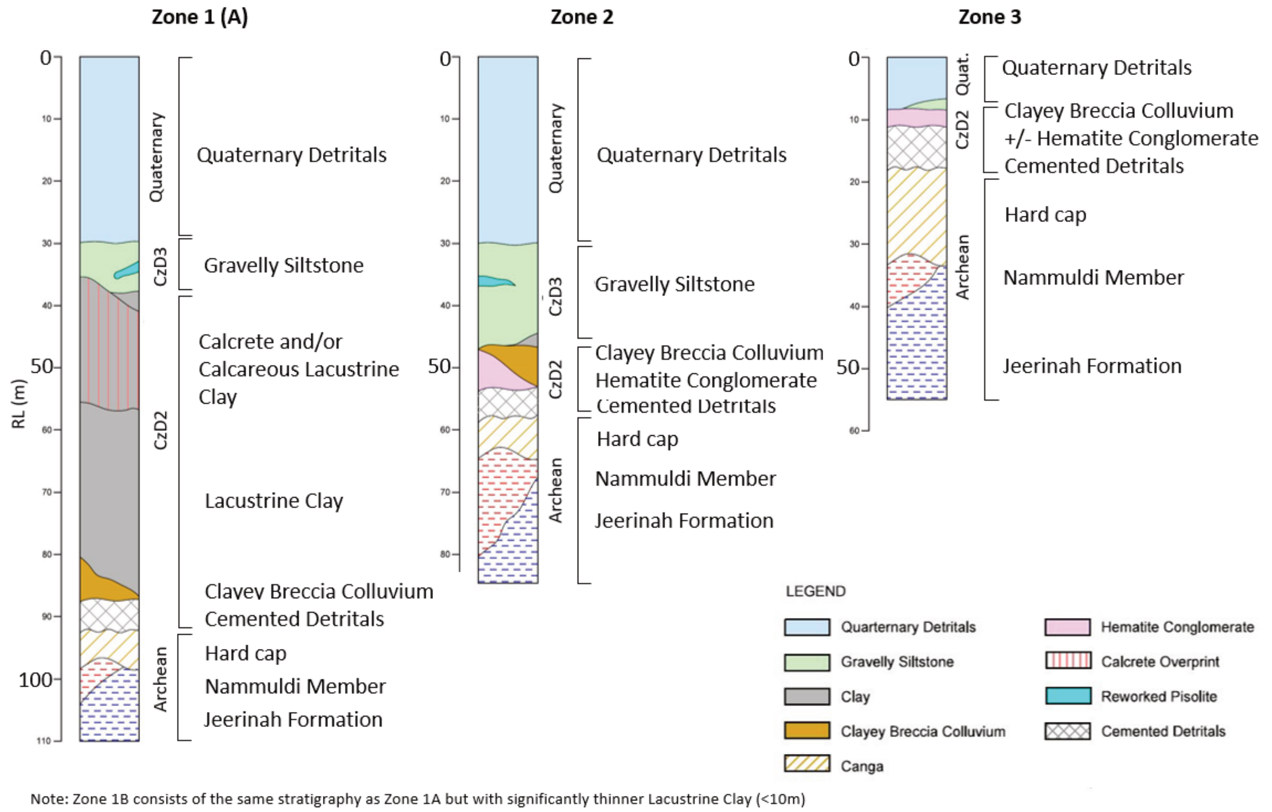


Figure 3 Schematic stratigraphic columns for three interpreted detrital zones

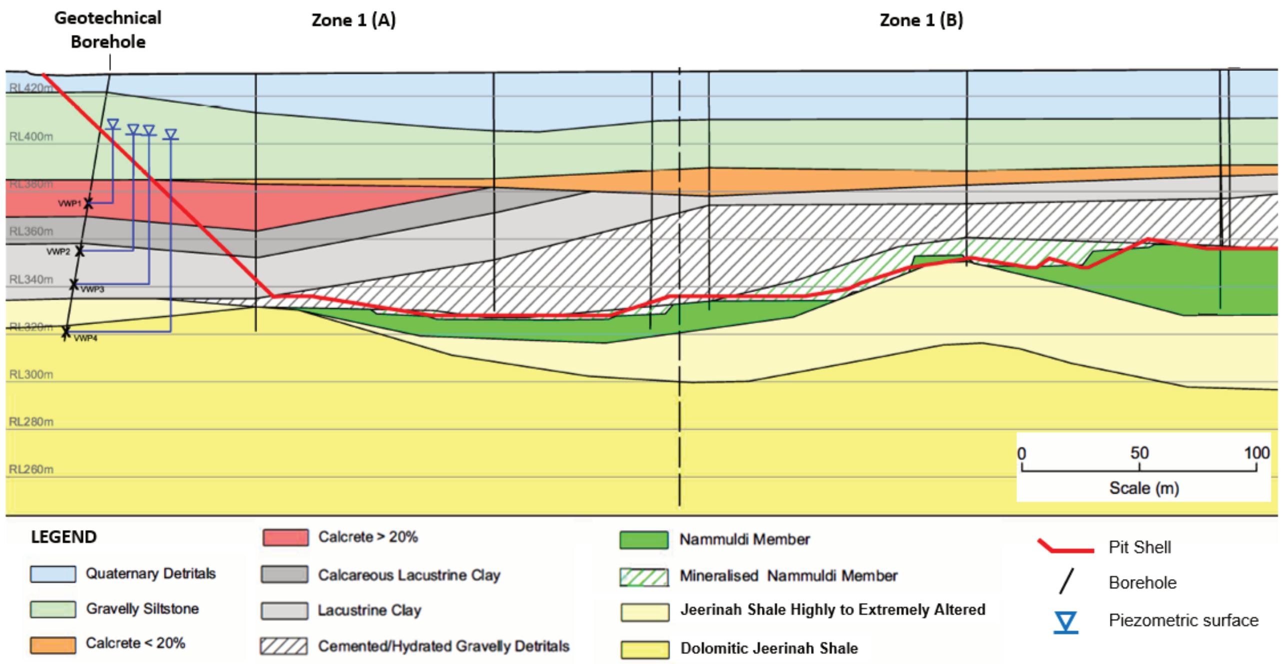


Figure 4 An example of a two-dimensional cross-section developed for this study

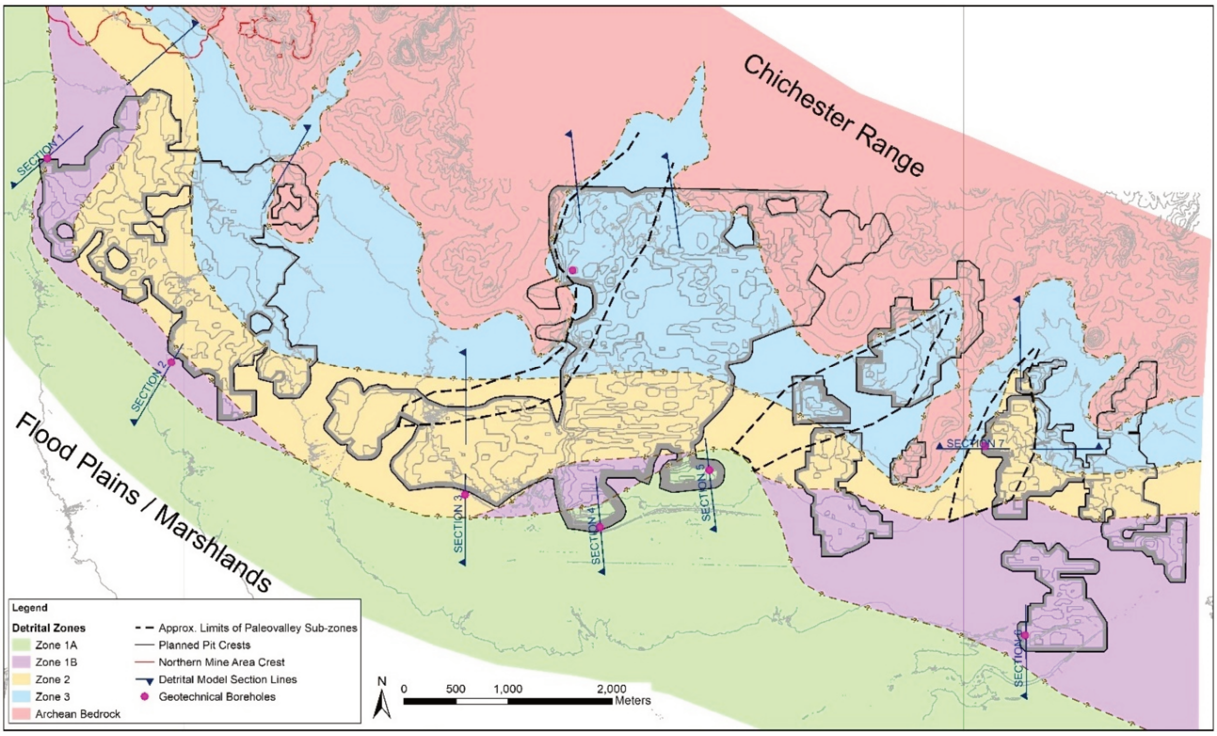


Figure 5 Geotechnical section locations and detrital zone interpretation

5.5 Hydrogeology

The development of a robust geotechnical model across the site improved our understanding of the hydrogeology of the deposit, which is an integral part of the pit slope stability analyses.

The geotechnical model was assessed as suitable for adaptation for hydrogeological modelling with hydrogeological characteristics being assessed from laboratory testing, engineering geological descriptions, VWP monitoring, and from past experience in similar materials.

The key outcomes of the modelling were:

- Identifying a low hydraulic conductivity layer comprising the lacustrine clay, which may result in high transient pore pressures in the slopes in Zone 1.
- The presence of high conductivity layers, including the Quaternary Detrital, Gravelly Siltstone, and Hematite Conglomerate may aid in depressurising the pit slopes.
- The complex distribution of the layers indicated numerical groundwater modelling would be necessary and useful to understand the pore pressure distribution in the proposed pit slopes. As a result, 2D transient groundwater modelling was undertaken to inform pore pressure assumptions for stability analyses.

6 Implications for analysis and design

6.1 Stability analyses

The utilisation of the resource drilling database improved the reliability and robustness of the geotechnical model. The implications of these improvements for engineering analyses include:

- More accurate prediction of engineering behaviour of the detrital sequence when exposed in a pit wall.
- Understanding of critical failure mechanisms and their potential spatial occurrence.
- Improved confidence in the model for hydrogeological analyses.

Detrital Zones 2 and 3 represent favourable conditions for pit slope stability, and the interpreted failure mechanisms are circular mass failure potentially with some component of basal sliding along bedding in the Archean geology. Zone 1 represents poor stability conditions primarily due to the presence of soil strength lacustrine clays which control pit slope stability. However, the presence and distribution of the clays is complex with some areas presenting thin non-continuous layers while others have thick continuous layers. Therefore, within Zone 1, the potential failure mechanism may vary. Ultimately, the geotechnical model and the division of the model into detrital zones has allowed for an understanding of different failure mechanisms and the potential geotechnical risks across the deposit.

The lacustrine clay is also likely to contain high pore pressures due to low hydraulic conductivity, which will impact the stability conditions. However, overlying and underlying materials with high hydraulic conductivities may assist in depressurising the clays. Due to the model's reliability, hydrogeological analyses were undertaken with reasonable confidence to understand the potential depressurisation of the pit slopes.

6.2 Slope design

The nature of the geotechnical model, along with the improved stability analyses, resulted in a number of implications to the slope design, including:

- Shallow slope angles in detrital Zone 1A, where thick clay units are present in the mid to lower slopes. These soil strength, low permeability units are present in final highwalls of over 100 m and present an inter-ramp to overall scale stability risk in the vicinity of sections 4 and 5, Figure 5. Inter-ramp angles (IRA) in these areas had to be significantly shallower than in the other detrital zones to meet the required design criteria.
- Reduced overall slope angles in the clay infilled paleochannels along major tributaries entering the valley from the Chichester Range. These clay units are present in the mid-slope and are typically underlain by relatively strong cemented clastic units. This results in a dual IRA design in these sectors with a steepened lower slope and shallower upper slope to reduce the risk of instability with sliding along the base of the clay units.
- Increased IRAs where no clays are present in the detrital sequence. This includes detrital Zones 2 and 3 and the Archean bedrock. These zones comprise the majority of interim and final pit slopes.
- Depressurisation is critical to the successful implementation of the slope design, particularly where low permeability lacustrine clay units are present. Furthermore, the depressurisation potential of these slopes will be dependent of the distribution and lateral extents of these clays for which a reliable and robust understanding has been developed. Additionally, the VWPs installed during the geotechnical site investigation will provide critical information about depressurisation rates in the detrital units, and Archean bedrock as mining progresses towards the final wall positions.

7 Conclusions

This case study of a major iron ore operation in the Pilbara region has shown how a robust geotechnical model can be developed over a large area of deep Cenozoic detrital sediments by utilising the geochemical and geophysical drillhole databases commonly available for large open cut mine developments.

The use of the resource drillhole database improved the model's reliability in areas where no dedicated geotechnical site investigation had been undertaken. This allowed for the development of geological depositional history and interpretation of the relationships between geology and geomorphology, leading to high confidence interpretations of geotechnical risks in areas distal to the geotechnical boreholes.

The robust geotechnical model was used to guide hydrogeological and slope stability analyses, resulting in an implementation level slope design optimisation that includes steepened inter-ramp angles over much of the deposit.

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