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Engineering geological modelling of the Archean – Cenozoic unconformity in the Pilbara and implications to open pit slope design

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ABSTRACT: Engineering geological modelling of the Archean – Cenozoic unconformity is becoming increasingly important to open pit slope designs for iron ore mines in the Pilbara. This is because Cenozoic sediments have significantly different geotechnical properties to the Archean geology. Therefore the location, shape and condition of the Archean - Cenozoic unconformity is important. The unconformity is difficult to model due to a number of factors including complex geomorphic settings on the unconformity surface, limitations in geological modelling techniques and limitations in drilling data. A wide range of geomorphological processes shaped the paleo-surface that represents the unconformity, ranging from lateritic weathering to high energy fluvial and colluvial processes. This paper outlines the geological and geomorphological setting of unconformities, describes engineering characteristic based on two iron ore deposit and outlines challenges associated with modelling unconformities and implications to slope design. Two simple engineering geological models are also presented to help visualise the geomorphological features

1 INTRODUCTION

Open pit mining for iron ore has been operating in the Pilbara region of Western Australia since 1966 and today represents an important and strategic resource to the Australian economy. For the first 30 years mining took place on ridges and slopes largely above water table in Archean-aged hard rock where mineralisation was virtually sub-cropping. While this style of deposit remains the focus of some operations, in more recent years mining is targeting deposits that dip below valley floor level. As such pit walls are now being developed across the unconformity which separates the Archean aged rocks and Cenozoic aged valley infill sediments.

The Cenozoic aged sediments have significantly different geotechnical properties to the underlying Archean aged rock. Therefore the location, shape and condition of the Cenozoic-Archean unconformity are important for geotechnical slope design. The identification of the unconformity is challenging due to:

- Complex geomorphological settings which formed the palaeo-surface that represents the unconformity,
- Similarities in the geological conditions and their geochemical/geophysical signatures across the unconformity due to the deep weathering profile, and
- Limited drill information targeting this zone of the deposit.

This paper outlines the geological and geomorphological setting of unconformities, describes engineering characteristic based on two iron ore deposit and outlines challenges associated with modelling unconformities and implications to slope design.

2 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

2.1 *Archean aged geology*

The Pilbara bedrock is comprised of Archean aged granites which are overlain by late Archean – to early Proterozoic (2750 – 2300 Ma) Hamersley Group (Tyler 1991) The Hamersley Group comprises banded iron formation, shale, dolomite and mudstones. Figure 1 presents a simplified geology map of the Pilbara showing the iron formations and Cenozoic deposits.

The iron ore deposits are predominantly hosted in the Hamersley Group within the Dales Gorge Member of the Brockman Iron Formation (IF) and the Mt Newman Member within the Marra Mamba IF though Joffre and Nammuldi Members also host ore. A stratigraphic column of the Hammersley Group is presented in Figure 2. Situated stratigraphically between the Brockman IF and Marra Mamba IF, is the

West Angela Shale Member and Paraburdoo Dolomite.

The structural geology of the region is characterised by numerous deformation events. These events formed large recumbent and overturned folds as well as thrust faulting. Later deformation events are likely to have created large scale upright folding along with dome and basin features.

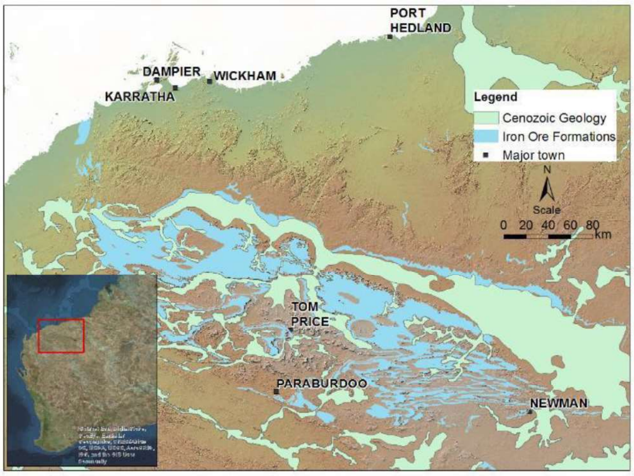

Figure 1. Simplified geology map of the Pilbara showing iron ore formations and Cenozoic geology locations (Source: GSWA)

2.2 *Cenozoic aged sediments*

Cenozoic-aged sediments are typically in fill valley deposits (Figure 1) and along with Quaternary-aged sediments comprise the majority of the surficial geology of the Pilbara.

The Cenozoic-aged sediments are separated into three broad groups based on their geological and depositional character (Morris and Ramanaidou 2007, Baxter 2016):

- CzD3 is comprised of coarse grained colluvium and alluvium. The sediments are typically sourced from adjacent Brockman IF and Marra Mamba IF exposures.
- CzD2 is composed of lacustrine clays, carbonaceous clays and iron rich conglomerates with CID equivalent pisolitic units. May be overlain by depositional calcrete sediments
- CzD1 is comprised of hematitic mixed coarse proximal fragments to distal silty red ochre detritals BIF derived textures.

Typically the CzD1 or CzD2 sediments are present adjacent to the unconformity. In many cases it is difficult to distinguish whether the basal units are CzD1 or CzD2 sediments.

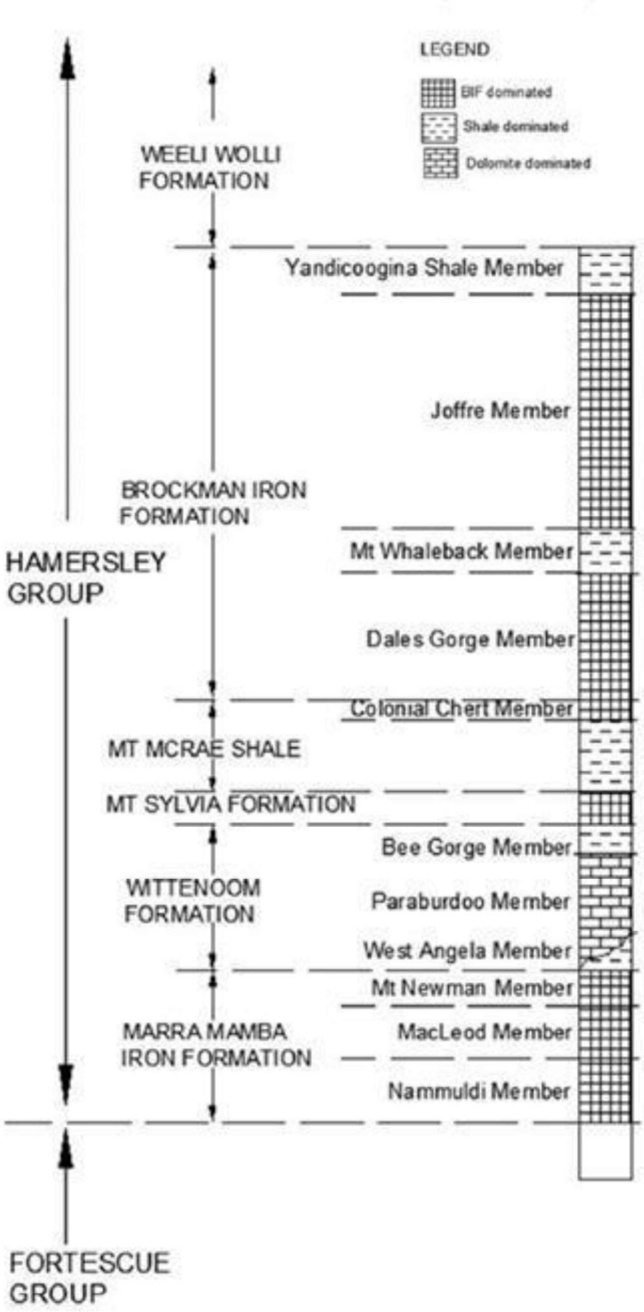

Figure 2. Stratigraphic column of the Hamersley Group (after Thorne *et al 2008)*

3 SITE DESCRIPTIONS

The engineering characteristics of unconformities are described for two iron ore deposits termed Site 1 and 2. Site 1 is located 90km west north west of Newman and where the ore is hosted in the Mt Newman Member of the Marra Mamba formation. The footwall is located in Archean aged geology and the hanging wall interacts with Cenozoic sediments and weathered Archean rock. The Archean structural geology is characterized by moderate dipping beds with recumbent folding and thrust faults. The Cenozoic sediments contains the three sediment groups and are formed in the palaeo-valley that is up to 200m deep.

Site 2 is located 115 km north of Newman along the northern flanks of the Fortescue Valley. The ore is hosted in the Nammuldi Member. The footwall interacts with the Archean geology. The hanging wall interacts with Cenozoic sediments and weathered Archean geology. The Archean structural geology is characterized by shallow dipping beds and gentle upright folding. The Cenozoic sediments comprise the upper two groups and are formed in a palaeo-valley up to 150m deep at the site. However to the southwest the palaeo-valley infill thickness is expected to be substantially thicker.

4 GEOMORPHOLOGICAL SETTING

4.1 *Palaeo-geomorphology*

Kneeshaw and Morris (2014) subdivide the geomorphological environments in the Pilbara into two significantly different detrital iron depositary types:

- Marra Mamba to Brockman Iron Formation Strike Valley (MBSV),
- Brockman Plateau Valley (BPV).

The two sites discussed in this paper are located in a MSBV setting.

MBSV typically form the deepest palaeo-valleys and are formed by erosion of the West Angela and Paraburdoo Members. The Marra Mamba and Brockman IFs typically form the ridges either side of the valley (Figure 3). The underlying Archean geology is typically shallow to steeply dipping. These valleys comprise the full sequence of CzD1 to CzD3 sediments.

Site one is located in a classic MSBV setting where mining takes place in ridges comprised of Brockman IF and Marra Mamba IF with the hanging wall interacting with detritals and the unconformity.

Site 2 is located on the edge of the broad Fortescue valley with a single flank of Marra Mamba IF. This valley is interpreted as a MSBV setting as the southern flank of the valley (outside the mine site) is comprised of Brockman IF.

4.2 *Palaeo-climate*

The Pilbara region is currently a semi-arid environment however the palaeo-climate of the Pilbara has been vastly different over its recent geological history. Anand (2005) and Morris & Ramanaidou (2007) provide a comprehensive summary of the palaeo-climate during the Cretaceous and Cenozoic periods. In summary, the palaeo-climate of Pilbara comprised:

- Cretaceous – very warm and humid period
- Cenozoic :
  - Paleocene – warming period
  - Eocene – cooling transitioning to a warming period
  - Oligocene – cooling period
  - Miocene - warming period

The various warming periods resulted in the development of deeps weathering profiles (Morris 2007) whereas erosion of the palaeo-valleys occurred in the cooling periods. Of particular interest for the formation of the deep valleys is the warming period followed by the cooling period in the late Paleocene and early Eocene.

4.3 *Processes*

A wide range of geomorphological processes have shaped the palaeo-valley surfaces and influence its engineering geological characteristics, including:

- Weathering,
- Fluvial processes
- Colluvial processes
- Slope processes
- Chemical weathering of karst landscapes

It is important to understand these processes as they form geomorphological features that are useful markers for modelling and understanding the potential engineering characteristic of the unconformity.

The weathering processes formed deep duricrust and saprolite profiles on the exposed palaeo-valley surfaces. Typically the duricrust (also known as canga or hydrated hardcap) formed over band iron formation rocks while the saprolite profiles developed over shale and dolomite units. In some cases

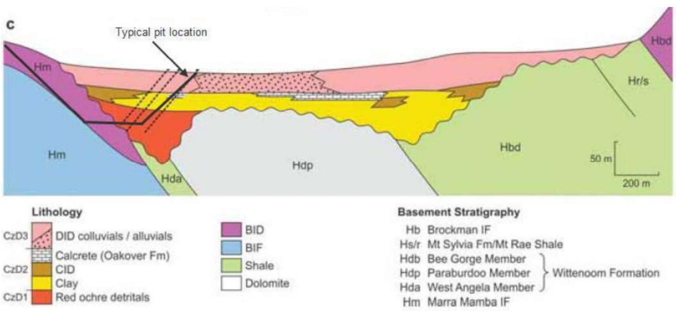

Figure 3. Cross section of a MSVB environment, looking west (Kneeshaw & Morris 2014)

weathering can reach depths of over 100m and can completely overprint the original bedrock textures.

The morphology of palaeo-valleys are dependent on the inclination (or structure) of the underlying Archean stratigraphy. Generally the steeper the bedding dip, the narrower and possibly the deeper the valley which was formed. Additionally, the dip of the Archean stratigraphy can also influence the geomorphological processes on the unconformity surface. For broader valleys with shallow Archean geology dips, the unconformity is exposed to lower energy processes and as a result the weathering profile is likely to be more intact and deeper, whereas steeper and narrow valleys have a high energy environment with mass movement deposits and a thinner remnant weathering profile.

5 ENGINEERING GEOLOGICAL CHARACTERISATION OF CENZOIC – ARCHEAN UNCONFORMITIES

This section outlines the engineering geological characteristics of Cenozoic sediments and Archean rocks adjacent to the unconformity separating them with particular reference to impacts on pit slope design. The purpose is to highlight typical engineering conditions around the unconformity and how they are related to their geological and geomorphological histories. Visual similarities are also shown, to highlight some of the difficulties in differentiating the location of the unconformity. The engineering geological characteristics can be separated into two broad groups:

– Cenozoic sediments are categorised by transportation processes such fluvial, colluvial processes and have isotropic strengths
– Archean geology are characterised by weathering processes, structure and lithology with anisotropic strengths

The characteristics described are based on the two sites described earlier. While these two sites are not likely to cover the full spectrum of materials across the Pilbara, it is hoped that this will provide a reasonable range to assist in recognising the engineering geological units associated with the unconformity. Strength codes are based on CANMET (1977).

5.1 *Cenozoic sediments*

The engineering characteristics are typically dependent on the geomorphological environmental setting. MSBV geomorphic environments typically contain CzD1 or CzD2 sediments above the unconformity which are typically comprised of hematitic polymictic conglomerates or red ochre detritals with a *terra rosa* silt/clay matrix.

Site 1 contains primarily hematitic conglomerate (possibly Red ochre detritals (ROD)) with varying degree of cementation as shown in Figures 4 and 5.

Site 2 contains hematitic conglomerate (or ROD) with a cemented matric (Figure 4) and a duricrust (or canga/hardcap) unit likely of Archean age with Cenozoic aged clay infill (Figure 6). This unit is interpreted as the remnants of the ancient Hamersley surface that has been inundated and vughs/cavities filled with an alluvial clay deposit. This unit should not be confused with an iron breccia and clay mix unit which is interpreted as a landslide deposit (Baxter, 2016).

5.2 *Archean geology*

The engineering geological units typically encountered below the unconformity can be broadly separated into three categories:

1. BIF dominant units such as Mt Newman, Nammuldi and Dales Gorge Members (Figure 7)
2. Shale dominant units including West Angela Shale (Figures 8 and 9)
3. Dolomite dominant units such as Paraburdoo Dolomite (Figure 10)

The dominant process influencing the engineering properties of the underlying Archean bedrock is weathering. Furthermore the depth of weathering is likely to be a function of the palaeo-valley morphology. High energy environments can be expected to strip away much of the weathered material particularly in the shale dominant units, while low energy environments may preserve much of the weathered material. The presence of ferricrete capped surfaces in a rapid depositional setting also form a protective surface which can also preserve deep weathering

Figure 4. Hematitic conglomerate with cemented matrix.

Figure 5 Hematitic conglomerate with poorly cemented matrix.

Figure 6. Duricrust or Canga/Hardcap with Clay Infill

profiles.

In general, BIF dominant units typically comprise a ferricrete surface (Figure 7). The ferricrete surface can also form over shale dominant units within local BIF layers which is underlain by weathered shale. The shale units typically are characterised by a saprolitic weathering profile (Figures 8 and 9) where the original fabric or largely overprinted though relic fabric still exists. The dolomitic units may contain karst profiles characterised by weathered dolomite and cavities infilled with clay (Figure 9).Site 1 contained all three categories while Site 2 contained categories 1 and 2.

Figure 7. Ferricrete or hardcap over BIF.

Figure 8. Extremely to highly weathered West Angela Shale (bedding mostly overprinted).

Figure 9. West Angela Shale – Brecciated/Sheared.

Figure 10. Extremely to highly weathered Paraburdoo Dolomite

6 SIMPLE ENGINEERING GEOLOGICAL MODELS

Two schematic engineering geological block models have been developed for Sites 1 and 2 to visualise the geomorphological features present in the Cenozoic-Archean unconformities. The Site 1 model (Figure 11) represents where strata dips moderate to steep, 30 to 60°. The Site 2 model (Figure 12) replicates conditions where the strata dips shallow at approximately 30° or less.

The Site 1 model (Figure 12) represents a geomorphic environment interpreted to comprise:

- Ferricrete surface over the BIF dominant units such at Mt Newman Member
- Sheared/deformed rock mass in the mid slope region caused by large scale creep and / or landslide processes
- Talus/colluvial slope deposits on the flanks of the valley forming the hematitic conglomerate.
- Deep saprolite weathering profile in the shale dominant units at the base of the valley. Some zones of ferricrete may be present within BIF layers.
- Karst landscape over the dolomitic units which are expected to range between youthful and complex based on the Waltham and Fookes (2003) engineering classification of karst environments.

Site 2 model (Figure 11) represents a geomorphic environment interpreted to comprise:

- A ferricrete surface over the BIF dominant units,
- Away from the palaeo-valley flank the ferricrete surface contains vughs and cavities infilled with clay
- Weathered saprolite profile in shale units underlying the ferricrete or formerly exposed in the palaeo-valley.
- Colluvial/scree deposits likely to form hematitic conglomerate.

7 MODELLING OF CENOZOIC – ARCHEAN UNCONFORMITY

As discussed in Section 4, the materials across the unconformity often appear to be very similar in physical character. This similarity extends to geophysical and geochemical parameters used to distinguish between Archean and Cenozoic geology.

Geophysical data of Cenozoic deposits are typically characterised by 'noisy' patterns whereas Archean geology has well established, clearer patterns. However, weathering processes can distort the patterns in the Archean geology complicating interpretations.

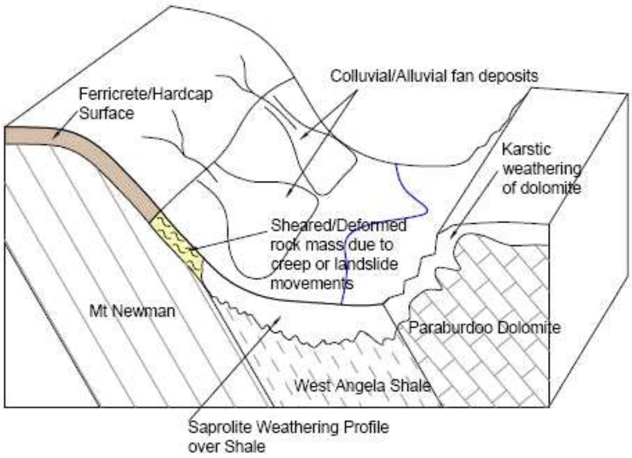

Figure 11 Site 1 model where Archean stratigraphy is moderately dipping

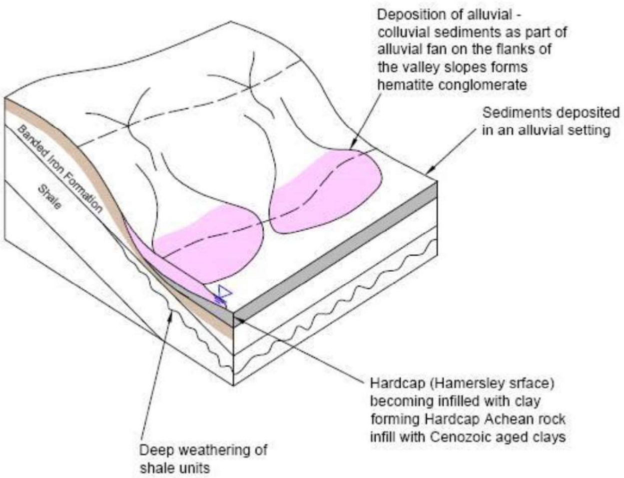

Figure 12 Site 2 model where Archean stratigraphy is shallowly dipping

Geochemical signatures of the Archean geology are well-established whereas Cenozoic sediments signatures are less recognized. The complicating factor is the Cenozoic sediments and Archean geology often has similar geochemical signatures.

Geological borehole logging data can be from RC drilling chips or diamond core. Core is more reliable for assessing the unconformity however this dataset is often limited. Distinguishing between Cenozoic sediments and weathered Archean geology in RC chip logging is less reliable.

Mapping of exposures or pit walls is the most dependable method for assessing the unconformity however mapping exposures are not often available for many sites. Mapping can be used to verify the unconformity during mining or to aid in the modelling for adjacent pits.

As a result of these similarities and challenges the location of the Cenozoic – Archean unconformity is often poorly understood. For Site 1 and 2, the Cenozoic and Archean models were developed separately and both modelled an unconformity. The discrepancies between the unconformities were up to 50m in vertical depth.

Based on a review of the modelling, for both Sites 1 and 2, the weathered Archean geology was incorrectly interpreted as Cenozoic aged sediments resulting in the unconformity modelled lower than the actual position. The review involved assessing geological borehole data (esp. core photos) and pit wall mapping as the unconformity was exposed.

Based on this review it was established that the Archean models were based primarily on geochemical and geophysical data, therefore weathered Archean geology could not be adequately separated from Cenozoic sediments in the geological model for geotechnical and hydrogeological studies.

8 IMPLICATIONS TO PIT SLOPE DESIGN

The implications to pit slope design are dependent of the relative material strength differences across the unconformity and structure on the Archean geology.

Across the unconformity, four engineering geological scenarios can occur:

1. Competent isotropic Cenozoic sediments overlying competent ferricrete weakly to strongly anisotropic Archean BIF/ferricrete units.
2. Competent isotropic Cenozoic sediment overlying weak anisotropic weathered shale/dolomite
3. Weak Cenozoic sediments overlying weak anisotropic weathered shale/dolomite.
4. Weak Cenozoic sediments overlying competent weakly to strongly anisotropic Archean BIF/ferricrete units

Scenario 1 has relatively low impact to stability modelling and design if the failure mechanism is a rock mass controlled. However where the Archean geology is dipping unfavourably out of the slope the implications to the slope design can be significant as the failure mechanism is controlled by the anisotropic strengths of the Archean units

Scenarios 2 and 3 have the most significant implications to slope design as the strength conditions and the failure mechanism changes depending on the unconformity location.

The failure mechanism in Scenario 2 is highly dependent on the unconformity location relative the pit wall. An unconformity location in the upper portion of the pit wall will have a failure mechanism govern by the anisotropy in the weak Archean geology. Whereas the slope design where unconformity interacts with the lower portion of the slope will have greater influence from the isotropic Cenozoic sediments

The unconformity location is important in Scenario 3 as the failure mechanism is highly dependent on it location. The unconformity location will define if the failure mechanism is a circular failure mechanism or a composite rock mass and structural sliding failure mechanism.

Scenario 4 occurs less commonly than the previous three scenarios and typically occurs on the flanks of the palaeo-valley. The impact to slope design of the unconformity is the critical failure mechanism is likely to be confined to the weaker Cenozoic sediments. The exception may occur if the Archean geology dips unfavourably.

In addition to the above, hydrogeological conditions can vary across the unconformity. This contrast has important implications to mine dewatering and depressurisation. The Cenozoic sediments above the unconformity are likely to have relatively higher, isotropic hydraulic conductivity. The Archean geology on the other hand, has highly variable conditions depending on lithology, degree of alteration and fracturing etc.

Scenario 1 is likely to have the lowest impact on hydrogeological conditions except that the Cenozoic sediments are isotropic and Archean geology is anisotropic.

Scenario 2 represents a significant contrast in hydrogeological conditions across the unconformity, with isotopic high hydraulic conductivity Cenozoic sediment overlying an anisotropic, low hydraulic conductivity unit. The unconformity location will be important to understand the pore pressures for slope stability purposes and flow paths for dewater-ing purposes.

Scenario 3 is similar to Scenario 2 except the hydraulic conductivity contrast across the unconformity will be less however still significant.

Scenario 4 represents conditions where the hydrogeological contrast can be variable depending on the hydraulics of the Archean geology, which is dependent on degree of alteration, weathering and fracturing.

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REFERENCES

Anand, R.R. 2005. Weathering history, landscape evolution and implications for exploration. In: Butt, C.R.M.; Robertson, I.D.M.; Scott, K.M.; Cornelius, M. Ed. *Regolith expression of Australian ore systems: a compilation of exploration case histories with conceptual dispersion, process and exploration models.* Perth, W.A.: CRC LEME; 2005. 15-45.

Baxter H. 2016. Geophysics, geochemistry and engineering geology: how disciplines combine to improve mine slope design in the Pilbara detrital valleys of Western Australia. In Eggers M.J *et al* (ed.) *Developments in Engineering Geology.* Geological Society, London. Engineering Geology Special Publication, 27. 81-92

CANMET (1977). *Pit Slope Manual*. Project of the Mining Research Laboratories, Canada Centre for Miner and Energy Technology (CANMET), Ottawa, Ontario: Department of Energy, Mines and Research.

Kneeshaw, M. & Morris, R.C. 2014. The Cenozoic detrital iron deposits of the Hamersley Province, Western Australia. *Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia*, 61:4, 513-586.

Morris R.C & Ramanaidou E.R. 2007. Genesis of the channel iron deposits (CID) of the Pilbara region, Western Australia. *Australian Journal of Earth Sciences*. 54. 733-756.

Thorne W, Haremann S, WebbA & Clout J. 2008. Banded iron formation-related iron ore deposits of the Hamersley Province, Western Australia. *Reviews in Economic Geology*. 15. 197-221.

Tyler, I.M, Hunter, W.M. & Williams, I.R. 1991. *Geological Survey of Western Australia*. Newman, Western Australia. 1:250000 Geological Series – Explanatory Notes.

Waltham A.C. & Fookes P.G. 2003. Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology and Hydrogeology*. 36. 101-108.