Geophysical investigation to support characterisation of structurally controlled groundwater flow into an open pit mine

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SUMMARY

Efficient dewatering operations depend on reliable predictions of expected inflow and likely water level behaviour. These predictions stem from the conceptual understanding of the hydrogeology of the area, which itself is derived from studies into the aquifer extents, hydraulic parameterisation and connectivity with adjacent aquifer units. Due to their isolated nature, structural controls on these inputs to the conceptual understanding are amongst the most challenging to determine.

An investigation was undertaken on structurally controlled flow into an open pit iron ore mine in the Pilbara region of Western Australia. Bore yields, groundwater salinity and water level behaviour of in-pit bores unmistakably indicated flows in excess of normal aquifer throughflow. Airborne magnetic data allowed regional identification of a potential lineament which was confirmed with high density grade control drilling results. These indicated the presence of a trough-like mineralised feature likely to enhance connection to a regional aquifer system down dip of the iron ore body, or with a fractured rock aquifer beneath the ore body. A detailed ground magnetic survey was conducted along strike from the interpreted lineament, drastically improving on the aeromagnetic data, further validating the conceptualisation of the structure and providing greater accuracy with which to target future hydrogeological works around the current pit. Subsequent quantitative magnetic modelling constrained with close spaced drilling information and downhole magnetic susceptibility logging, increased the understanding of the characteristic basement magnetic response, and encourages the use of the magnetic method for local hydrogeological studies.

Key words: Dewatering, hydrogeology, magnetics.

INTRODUCTION

Fortescue Metals Group (Fortescue) owns and operates three iron ore mines in the Pilbara Region of Western Australia. Each of these mines operates below water table, requiring dewatering of pit areas prior to mining taking place. In 2013, vertical advance at one pit in particular (Pit N) encountered groundwater saturated material and several point springs flowing onto the pit floor (Figure 1). The existing dewatering bore field for Pit N was not able to effectively lower water levels and an investigation commenced to determine the source of the unexpected groundwater and how to best manage inflow. Concurrently, mine operations staff drilled additional dewatering bores, one of which intercepted what was interpreted as a fault in the stratigraphic unit underlying the ore body.

The role of geological structure can be one of the most important aspects of characterising mine water control **(**Beale and Read, 2013). Although, in Fortescue's operational history, structure had not yet been identified as a major concern to dewatering operations. The Marra Mamba Iron Formation ore body serves as the primary aquifer for dewatering, with permeability in excess of 50 m/day along the majority of the Chichester Range strike length (Fortescue, 2013). This level of permeability and connectivity may have, in part, served to mask the impact of structure. However, the level and salinity of groundwater at Pit N, coupled with the uncommon drilling intersection, was significant enough to warrant further analysis of a likely structural control on water ingress to the pit.

A combination of geological, hydrogeological and geophysical data was reviewed in the process of the investigation. Geological information was collated from densely spaced grade control drilling with field lithological logging, geochemical assay results and stratigraphic interpretation. A summary of the Marra Mamba Iron Formation stratigraphy can be found in Hannon *et al* (2005). Hydrogeological data included drilling airlift yields, test pumping analysis and water quality information. These helped to establish a conceptual hydrogeological model for further assessment and highlighted the need to map the potential structure down dip in areas where future mining may take place. Several geophysical datasets were reviewed, including airborne radiometric, magnetic and electromagnetic data. Potential regional structural features were identified in the aeromagnetic (AMAG) data, and subsequent ground magnetic (GMAG) survey was carried out to increase resolution over what was considered to be the main structure in Pit N.

Additional three-dimensional magnetic inverse modelling and reconciliation with downhole magnetic susceptibility logging was undertaken to help understanding the various mapped responses. The preliminary conclusion to the investigation is that a workflow consisting of a. AMAG data review, b. geological and hydrogeological data analysis around identified structures and c. GMAG surveying along features of interest, could be a valuable approach to flag potential dewatering complications ahead of Fortescue's future open cut iron ore mining in the Pilbara.

Figure 1: Excess groundwater flow into Pit N.

METHOD AND RESULTS

Conceptual Hydrogeological Model

A conceptual hydrogeological model was created from data sources listed in Table 1. The model serves to combine available geological information with water level behaviour observed in in-pit dewatering bores. Figure 2 illustrates the perceived influence of a fault plane, interpreted from drilling intercepts and the presence of a tight, synclinal feature evident in the layering of the stratigraphic units within the Nammuldi Member of the Marra Mamba Iron Formation. Groundwater levels are marginally elevated in proximity to the fault plane's trace through the Nammuldi Member, with localised drawdown adjacent to the in-pit dewatering bore shown in the cross-section. Potential zones of locally increased permeability are indicated by the presence of higher grade mineralisation at the base of the ore body, overlain by a zone of increased shale content, evident from increased Al_2O_3 in assay data. The impact of the fault trace on iron ore grade and mineralisation style (e.g. hypogene versus supergene) was not explicitly investigated. However, local variations in permeability will influence the degree of connection between the fault trace and the surrounding ore body, as well as the performance of any existing or planned dewatering bores.

Data Source	*Description*	*Use*
Grade control drilling	Interpreted stratigraphy	Creating geological layers
	Assay results	Identifying areas of higher alteration (Fe%) or shale content (Al%)
Dewatering bores	Water levels	Establishing hydraulic gradients
	Lithology	Identification of fault intersects

Table 1: Summary of datasets used to create the Pit N conceptual hydrogeological model.

Airborne Magnetic Data Review

Following the aforementioned conceptualisation, potentially significant lineaments were sought from various available geophysical datasets. The most fruitful exercise was the undertaking of a simplified regional structural interpretation of available AMAG data, acquired in 2005 over a large part of Fortescue's mining tenure. The airborne survey was following a N0 line orientation along 200 m spaced flight lines with a nominal sensor height of 60 m. The AMAG data review revealed swarms of NNE and NE lineaments with an average frequency of approximately 1000 m cross-cutting the E-SE trending stratigraphy, and more particularly a zone of intensified structural complexity in the vicinity of Pit N (Figure 3). The delineation of this structurally complex corridor was consistent with the presence of anomalously fractured basement around Pit N, but also revealed the possibility of increased lateral permeability between production and injection bores located several kilometres south of Pit N. Although the interpretation was very informative on a regional scale, increased resolution was required to effectively pinpoint any follow up hydrogeological work at the mine scale.

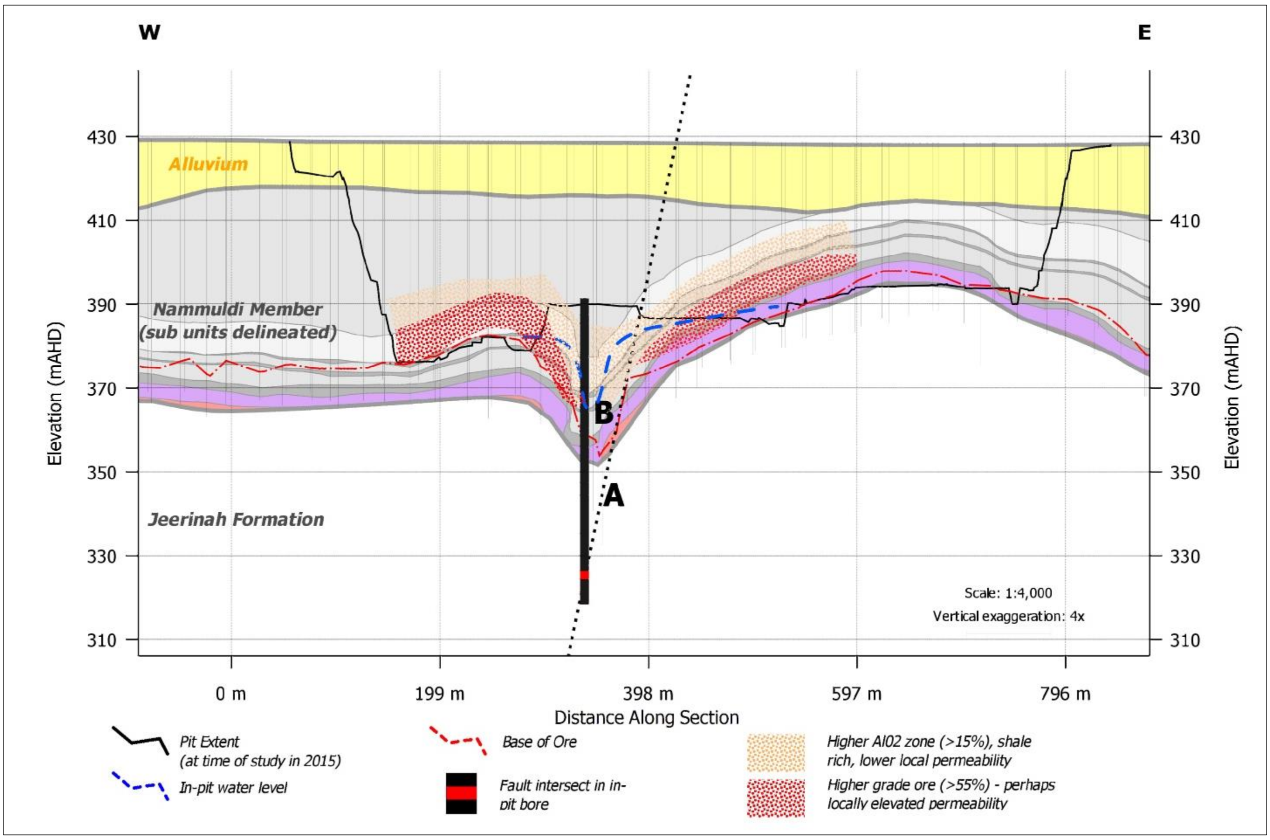

Figure 2: Conceptual cross-section through Pit N illustrating key features relevant to the observed hydrogeological conditions, including A) groundwater flow from depth along fault plane and along borehole conduits and B) diffuse groundwater flow through ore body; influenced by local heterogeneity in permeability.

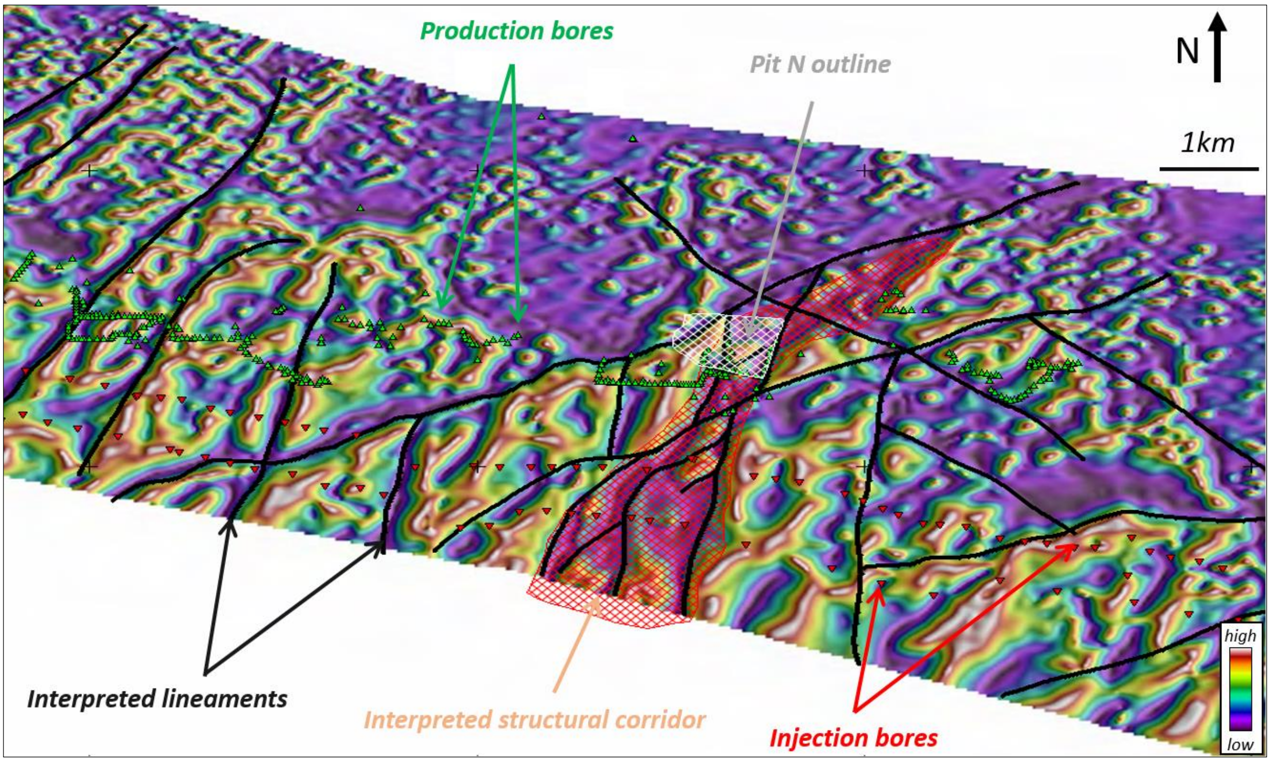

Figure 3: Interpreted lineaments around Pit N over AMAG data Reduced-To-the-Pole (RTP) tilt-angle filter image.

Ground Magnetic Data Acquisition and Analysis

A small detailed GMAG survey was carried out on foot in April 2015 immediately south of Pit N to increase the definition of the feature running through Pit N. Surveying within Pit N was not possible due to active mining operations taking place where the pit floor was not submerged. An average line spacing of 25 m was maintained over an area approximately 750 m by 800 m comprising cleared E-W grade control drilling lines (Figure 4). Magnetic data acquired by the roving survey unit was corrected for diurnal variations concurrently measured by a stationary base station. Gentle low-pass filtering was subsequently applied to the data to remove high-frequency variations likely due to the presence of surficial magnetic material in soil and inevitable sensor swings during acquisition.

The higher resolution GMAG survey results were broadly consistent with the AMAG data interpretation, and successfully characterised a NNE trending linear and narrow (~700 nT) magnetic low anomaly along strike from the interpreted fault in Pit N (Figure 4). The mapped magnetic low proved to accurately delineate a V-shaped synclinal feature identified from downhole assay data and stratigraphic interpretation. It is worth noting that part of the magnetic low present in the GMAG data shows a sharper gradient to the west, which is consistent with the asymmetric geometry of the buried tight synclinal feature (see Figure 2).

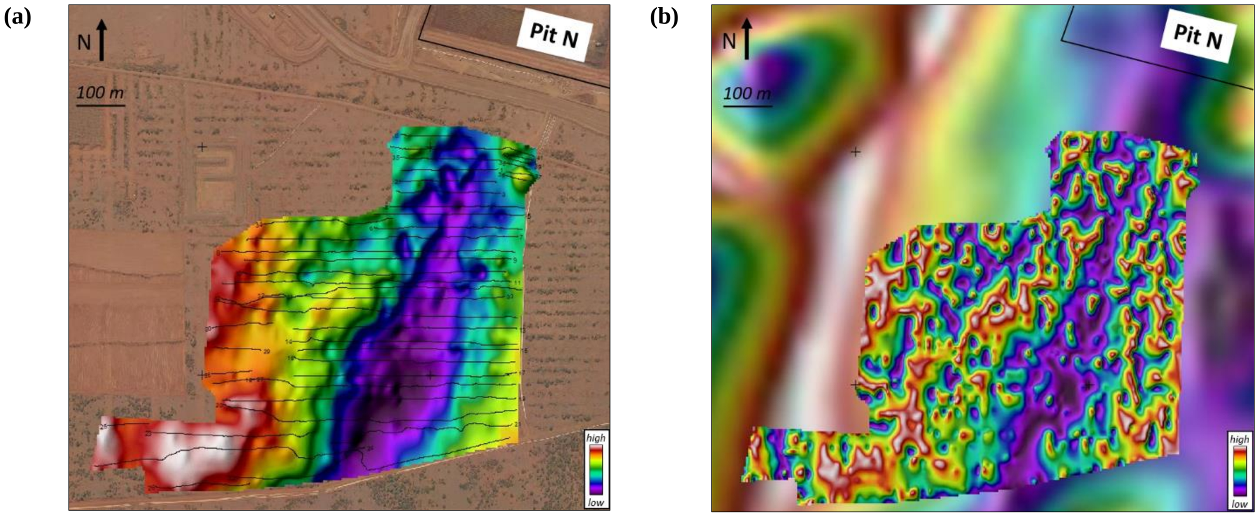

Figure 4: GMAG survey results (a) survey lines over GMAG data RTP image and aerial photography, (b) GMAG data tilt-angle filter over AMAG data RTP tilt-angle filter image.

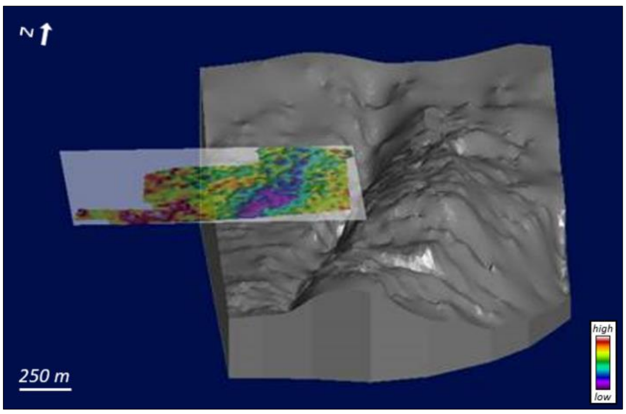

Figure 5: 3D perspective north-looking view of the bottom of U5 sub-unit (as per Hannon *et al*, 2005) defined by close-spaced drilling with GMAG RTP image projected onto ground surface.

Quantitative and geologically constrained three-dimensional inverse magnetic modelling was undertaken to understand the cause of the refined lower magnetic response in the GMAG data (Figure 5). Preliminary results demonstrated that the trough in magnetic basement alone was not sufficient to explain the magnetic low. Instead, a localised decrease in basement magnetic susceptibility near the trough was also necessary to adequately simulate the measured magnetic data. This approach was corroborated by a compilation of over 33,000 downhole magnetic susceptibility measurements of Nammuldi Member stratigraphy across the region (there was no data available from Pit N or surrounding projects), which shows that even though a median magnetic susceptibility of 125 x 10^{-5} SI is consistent throughout the Nammuldi Member, some sub-units display significantly lower magnetic characteristics when altered (Figure 6).

It was therefore concluded that the lineaments interpreted from magnetic data around Pit N are a result of the contribution from detectable vertical displacements within the magnetic basement in addition to localised decreased magnetic susceptibility caused by structurally controlled alteration.

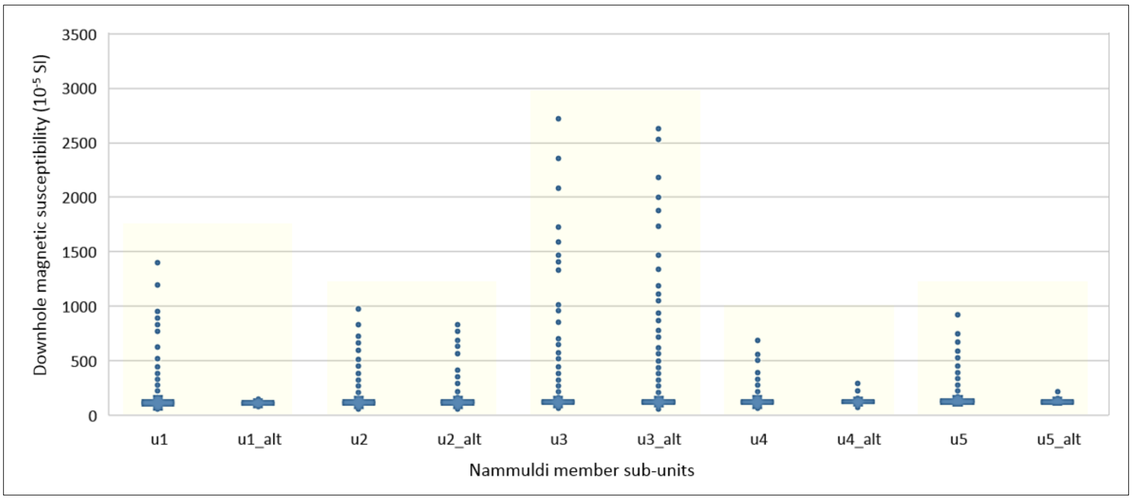

Figure 6: Compilation of downhole magnetic susceptibility measurements of Nammuldi stratigraphy demonstrating that some sub-units (namely U1, U4 and U5, as per Hannon *et al*, 2005) display a significant difference in magnetic susceptibility between fresh and altered states (e.g. fresh 'U1' returned values up to 1500 x 10^{-5} SI whereas the maximum recorded value for altered 'U1_alt' is 150 x 10^{-5} SI).

Application to Dewatering Investigations

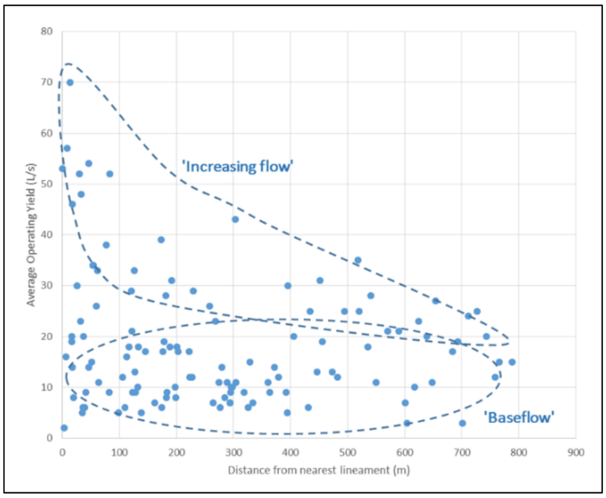

Figure 7: Cross plot of borehole groundwater yield versus distance from bore collar to the nearest interpreted fault plane (adapted from Reid, 2015), showing the interpreted 'baseflow' and potentially structurally controlled 'increasing flow' groupings.

In an attempt to assess the suitability of predicting dewatering requirements, average bore yield information from 122 existing production bores were compared by their proximity to an interpreted structure around Pit N. This approach is hindered by the difficulty to quantify the impact of varying bore construction, bore age (one to seven years old), bore depth (and hence intercepted geology), bore diameter, installed pump capacity and operational status. But for this assessment, it is proposed that a simple plot of average bore yield versus distance from the nearest interpreted lineament may nevertheless identify any spatial pattern in the data. Figure 7 is a scatter graph of bore yield versus distance to the nearest lineament interpreted from the AMAG data. Although no obvious correlation can be extracted from the graph, data points seem to display two broad groupings. In general, the bore field is dominated by a 'baseflow' of bores abstracting between 10 and 30 L/s, irrespective of distance from a lineament. The flow to these bores is likely dominated by permeability in the ore body, which although variable, is elevated throughout the strike length of the deposit. The second group has tentatively been identified as bores with a trend of 'increasing flow' when the distance to an interpreted lineament is less than approximately 100 m. As discussed above, further detailed analysis is restricted by the many variables associated with using operational yield values as well as the inherent approximation resulting from geophysical data interpretation. However, the identified pattern are deemed encouraging enough to postulate that increased permeability may be preferentially located around these interpreted magnetic lineaments, hence justifying further use of readily available AMAG data to target areas of interest for detailed hydrogeological investigations.

CONCLUSIONS

This case study suggests that magnetic surveying (both airborne and on the ground) can resolve lineaments of interest within the geological environment at Fortescue's Pilbara mining operations. Furthermore, supporting data from Pit N demonstrate these lineaments can represent large scale structures creating hydrogeological complexity that increases the dewatering effort required to manage inflow to a pit. A review of local basement physical properties and limited three-dimensional inverse magnetic modelling postulate that rapid changes in basement geometry and localised alteration may be the main sources for the mapped magnetic lineaments.

The collection of AMAG data should therefore be considered early in the mine planning stage to predict areas of possible intensified structural complexity and to identify areas where additional investigative drilling may be warranted. Further refinement of the lineament location can then be achieved with detailed GMAG surveying should more explicit bore targets be required.

Advances in drone-based technology are anticipated to allow for detailed in-pit magnetic surveying where ground access if often restricted due to active mining operations or, as it is the case here, submerged pit floor. Trial drone-based magnetic surveying within Pit N is scheduled for early 2018.

The detailed identification of magnetic lineaments associated with potential increased groundwater flow is a strategy which has since been applied successfully by Fortescue to delineate new water supplies throughout the region.

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