INTERPRETATION OF AIRBORNE ELECTROMAGNETIC, MAGNETIC AND FALCON™ GRAVITY GRADIOMETER DATA

PILBARA COAST
WESTERN AUSTRALIA

SUMMARY REPORT

PREPARED FOR
DEPARTMENT OF WATER
GOVERNMENT OF WESTERN AUSTRALIA

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EXECUTIVE SUMMARY

TEMPEST airborne electromagnetic (AEM) and magnetic data were acquired at 2000 m line spacing over four survey areas (De Grey River, Yule River, Fortescue River and Robe River) in the Pilbara Region of Western Australia. In addition, FALCON™ airborne gravity gradiometry (AGG) was flown over the De Grey and Yule survey areas at a line spacing of 4000 m. This study aims to expand the understanding of aquifer geometries and groundwater salinity distribution within the region. The information will be primarily used to support the development of a regional groundwater model along the Pilbara Coast.

In addition to the acquired survey data (airborne electromagnetics, magnetics, gravity and DTM) the client supplied borehole logs which covered the survey areas and surroundings. Publicly available datasets (regional magnetics and radiometrics, Landsat 7ETM+, SRTM and geological maps) were incorporated into this study. All available data were integrated to provide a regional overview of the hydrogeology.

The survey accomplished the following objectives:

- Provided an updated interpretation of the basement geology, focussing on structures that control hydrogeology in regolith aquifers
- Developed interpreted relative porosity maps showing the vertical and horizontal extent of various units identified from changes in conductivity
- Defined the basement surface (base of the regolith groundwater system) in areas where there are no borehole logs
- Mapped the extents of alluvial and sedimentary aquifers
- Identified the onshore seawater interface (seawater intrusion)

It is anticipated that this information will provide invaluable information for any future groundwater model.
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1 INTRODUCTION

This report documents the interpretation of the TEMPEST airborne electromagnetic data, FALCON™ airborne gravity gradiometry (AGG) data and magnetic data acquired by Fugro Airborne Surveys (FAS) over the De Grey, Yule, Fortescue and Robe areas on the Pilbara coast during May, 2009 for the Department of Water, Government of Western Australia (Figure 1.1).

The four study areas all lie between the Carnarvon Basin and the western edge of the Canning Basin. The survey areas cover 4,635 km² and consist of 2,556 line km of time domain AEM and magnetic data with a line spacing of 2000 m and an average elevation clearance of 120 m for the transmitter and 80 m for the receiver. 1,264 line km of FALCON™ AGG was collected over the De Grey and Yule areas with a line spacing of 4,000 m and a nominal flying height of 80 m.

1.1 Scope of Service and Interpretation Products

The primary aims of the surveys were to expand the understanding of the aquifer geometries and groundwater salinity distribution beyond the current borefield drilling information.

The survey accomplished the following objectives:

- Provided an updated interpretation of the basement geology, focusing on structures that control hydrogeology in regolith aquifers
- Developed interpreted relative porosity maps showing the vertical and horizontal extent of various units identified from changes in conductivity
- Defined the basement surface (base of the regolith groundwater system) in areas where there are no borehole logs
- Mapped the extents of alluvial and sedimentary aquifers
- Identified the onshore seawater interface (seawater intrusion)

1.1.1 Interpretation Products

- Regional basement geology map in ArcGIS™ format
- Relative porosity maps in ArcGIS™ format
- Surfaces representing the top of weathered basement and top of fresh basement interpreted from the conductivity data in both ERS grid and ASCII formats
- Vertical and lateral extent of the seawater intrusion and aquifers in 3D DXF format
• ArcGIS 9.3 project containing all geophysical images used in the interpretation including data images, located boreholes (provided by the client), digital terrain model (DTM) and shape files of other interpretation products.

Figure 1.1: Location map for the De Grey, Yule, Fortescue and Robe River survey areas. The survey areas appear as red outlines. The inset (top left) indicates the location within Western Australia.
2 PREVIOUS INVESTIGATIONS

The survey areas have been subject to considerable previous investigations into the nature and distribution of the groundwater as well as the regional geology. Both the Department of Water, Government of Western Australia and the Geological Survey of Western Australia have contributed to the wealth of available information. This study did not entail a detailed account of the previous investigations into the Pilbara coast and therefore only the background necessary for the interpretation has been included. Further detail should be sought in the reports mentioned below.

The Department of Water provided FAS with detailed borehole logs in Excel format for all survey areas as seen in Figure 2.1. Discrepancies in the borehole logs have been noticed between the information provided by the Department of Water and the interpretation by Commander (1994b). Figure 2.2 is an example between the two sources for the same borehole (18A). The main difference is noticed when Haig (2009) makes inferences as to the formation names of particular lithologies as well as the presence of calcrete and lack of clay recorded by the Department of Water. Although the differences are not drastic, they are noticeable and could affect the results of the interpretation where the data is used.

In addition to the borehole logs, the Department of Water have published two recent reports on the water supply of the Pilbara Coast (Haig, 2009; MWH Global Inc., 2009) which provide a detailed summary of the current groundwater conditions facing the northern coast of Western Australia.

The Geological Survey of Western Australia (GSWA) has published several reports starting from as far back as the 1960’s covering all aspects of the geology and hydrogeology within the study areas. The main reports used in this study can be divided into; geology reports (Hickman and Gibson, 1982; Ryan, 1966; various geological maps) and hydrogeological reports (Allen, 1997; Commander, 1994a; Commander, 1994b; Barnett and Commander, 1986; Davidson, 1976; Davidson, 1975; Forth, 1972; Whincup, 1967).

Although many more reports are available on the geology and hydrogeology of the Pilbara coast, only the information in the reports mentioned above were used for this study as to provide a background context for the interpretation.
Figure 2.1: Borehole field within and surrounding the survey area. The year the borehole was drilled has been indicated.
Figure 2.2: Comparison figure of borehole 18A within the Robe survey area. The left is from Commander (1994b), whereas the right has been generated from the borehole logs provided by the Department of Water.
3 GEOLOGICAL AND HYDROGEOLOGICAL BACKGROUND

This summary is largely based on the Hydrogeological record series No. HG34, *The Pilbara coast water study*, Western Australia, February 2009 by T. Haig.

3.1 Geology

A sound understanding of the geology within the survey areas will aid in the interpretation of the gravity, magnetic, electromagnetic and remotely sensed data. From the integration of the currently known geology with these datasets it is possible to understand how the geology is influencing the groundwater and consequently any future groundwater model.

The basement rocks of the Pilbara coast can divided into; Archaean mafic to ultramafic volcanic and intrusive rock, Archaean granitic intrusives of the Pilbara Craton, and Archaean meta-volcanic/meta-sedimentary rocks, refer to Figure 3.1 (Western Australia Geological Survey, 1998).

The Archaean granitic intrusives of the Pilbara Craton consist of batholithic domes ranging in composition from alkali feldspar granite to tonalite and diorite, but most commonly biotite adamellite (Hickman and Gibson, 1982). The sheared and folded volcanic and sedimentary rocks separate the batholiths by synclinoria. This combination of meta-volcanics, meta-sediments and felsic to ultramafic sills and are generally referred to as greenstone within the Pilbara (Hickman and Gibson, 1982).

The Lower Proterozoic volcanics and sediments unconformably overlie the Archaean basement rocks. Further up the stratigraphic sequence are Cenozoic and Quaternary sediments of the Hamersley and Canning Basins. Recent unconsolidated sediments consist of Quaternary alluvium, which account for the majority of the surface cover. See Figure 3.2, Figure 3.3 and Figure 3.4 for the simplified surficial geology of the De Grey, Yule, and Robe/Fortescue survey areas respectively. The geology and major structural features are from the Geological Map of Western Australia, 1:2,500,000 (Western Australia Geological Survey, 1998) with drainage mapped from Landsat 7ETM+ and publicly available digital terrain models.
Figure 3.1: Simplified geology map of northern Western Australia (Western Australia Geological Survey, 1998).
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Figure 3.3: Simplified surficial geology map of the Yule River survey area and surrounding area (Western Australia Geological Survey, 1998).
Figure 3.4: Simplified surficial geology map of the Robe River and Fortescue River survey areas and surrounding area (Western Australia Geological Survey, 1998).
Across the survey areas there is a weathered profile at the top of the Archaean basement which is recorded in many of the deeper boreholes (Whincup, 1967; Davidson, 1976). Both authors report occasional occurrences of calcrete within this weathered profile. This calcrete layer above the basement could potentially act to confine the groundwater within the fractured basement.

The Tertiary and Quaternary alluvium profile consists of layers of alluvial sand, gravel, silt and clay with variable calcrete (Haig, 2009). Figure 3.5 shows the alluvium profile across the Fortescue River and is also representative of the profile across the Robe River survey area.

Figure 3.6 shows a cross-section across the Yule River which is representative of the overall alluvium profile across both the Yule River and De Grey River survey areas. The main differences between the two sediment profiles are the relative increase in the amount of gravel in the upper profile and the presence of a limestone bed towards the bottom of the profile of the Fortescue River. In contrast the upper profile of the Yule River appears to be dominated by finer sands and clays with minor gravel lower down in the sequence.
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Figure 3.6: Cross-section (A - B) across the Yule River (after Haig, 2009).
3.2 Hydrogeology

The groundwater system for the survey areas can be best summarised in Figure 3.7. The main region of interest for this study is within the sedimentary basin where both confined and unconfined aquifers are recorded (Haig, 2009). Fractured rock aquifers are also present within the survey areas but at depth below the sedimentary basin.

Groundwater originates either directly from rainfall infiltration or indirectly from riverbed leakage. The average rainfall across the region varies from approximately 290 mm to 356 mm and mainly falls during heavy storms and cyclones between December and April (Davidson, 1976; Barnett and Commander, 1986; Commander, 1994a).

![Figure 3.7: Groundwater model (after Allen, 1997)](image)

The main contributing factors when considering usable groundwater availability are salinity, aquifer type and recharge. Included below is a general overview of all three but this study focuses on the interpretation of the salinity influence by the seawater intrusion.

3.2.1 Aquifers

Haig (2009) and Allen (1997) have divided the aquifer types into three main divisions, unconsolidated sedimentary aquifers, consolidated aquifers and fractured rock aquifers. A summary of each main division as well as the various sub-divisions is as follows:
Unconsolidated Sedimentary Aquifers

Coastal alluvial aquifers

- Occur across the coastal plains
- Groundwater generally contained in Quaternary sediments
- Generally unconfined conditions
- Within the coastal plains between the De Grey to Yule survey areas the aquifer is in hydraulic connection with underlying weathered fractured rock aquifers
- Within the Fortescue to Robe survey areas the coastal aquifer is in hydraulic connection with the confined aquifers of the Mesozoic to Cenozoic sedimentary rock.
- Recharge occurs mostly from riverbed leakage

Valley fill aquifers

- Present within the Fortescue River Valley
- Typically consists of alluvium and colluvium, overlying pisolitic limonite and calcrete
- Generally unconfined
- Recharge is dominated by riverbed leakage, with a minor component from rainfall infiltration

Calcrete aquifers

- Commonly occur in Miocene sediments and typically overlie pisolite
- Calcrete can reach thicknesses of 46 m with an average of 10 m
- Concretionous calcrete occurs within the zone of watertable fluctuation but are unlikely to form significant aquifers due to low permeability
- Pedogenic calcrete occurs as soil develops over basic rocks. This type of aquifer has been recorded around the Yule and De Grey rivers
- Recharge is dominated by riverbed leakage from surface watercourses as well as directly by rainfall infiltration

Pisolitic limonite aquifer

- Potentially significant aquifers where located in close proximity to current drainage
• Usually only forms an aquifer if deposited in channels cut into basement rocks by early drainage
• Recharge is often through direct infiltration from overlying alluvium

**Consolidated Rock Aquifers**

**Sandstone aquifer**
• Main aquifers in the West Canning Basin (Broome Sandstone and Wallal Sandstone)
• The Broome Sandstone is unconfined with recharge directly from rainfall infiltration
• The Wallal Sandstone is largely confined by the Jarlemai Siltstone
• Recharge into the Wallal Sandstone aquifer varies from direct rainfall infiltration where unconfined, or leakage from the overlying Broome Sandstone where the Jarlemai Siltstone is not present

**Trealla Limestone aquifer**
• Occurs proximal to Robe and Fortescue rivers
• Recharge is from leakage from overlying alluvium
• Forms a confining bed over the Yarraloola Conglomerate

**Yarraloola Conglomerate aquifer**
• Confined by shale and/or limestone
• Potential aquifer within the upper Robe River, if salinity is not too high, and to a lesser extent along the Fortescue River due to its limited occurrence
• Recharge is by leakage from overlying alluvial aquifers

**Fractures-rock aquifers (granites and greenstones)**
• Exist within a variety of basement formations within the region
• Secondary porosity develops in fractured and weathered zones or along bedding planes and joints
• Recharge can occur from various sources, primarily from direct infiltration from rivers in topographically elevated areas
• Groundwater flow is largely controlled by local geology and weathering
3.2.2 Seawater Intrusion

Despite the increasing problems associated with the effects of seawater intrusions there is little published material available covering investigations across the Pilbara region and, more widely, Western Australia.

Allen (1997) identified a number of unconfined and confined aquifers located around Western Australia where seawater intrusion is known to occur. Additionally, numerous groundwater bores and wells are recorded as becoming saline as a result of upconing of underlying seawater. Allen (1997) concluded that most of the known occurrences of seawater intrusion are minor and it does not represent a significant problem to the current stage of groundwater development in Western Australia. However, there is the possibility that with time the problem may become serious.

Within the Fortescue survey area Commander (1994a) reports the presence of a saltwater interface located close to tidal flats around boreholes FCP 25 – 29 inclusive. Here the saline interface occurs at a depth of between 4 – 8 m below the watertable. Measured salinities at the water table in these boreholes ranges from 1,850 mg/L to 18, 500 mg/L, increasing to 18,000 mg/L to 75,000 mg/L within the saline groundwater. Although not mentioned directly in the report, the close proximity of these boreholes to the tidal flats (generally within 2 km) suggests some influence from seawater incursion.

3.2.3 Salinity

Typically, groundwater salinity increases away from the freshwater source in both horizontal and vertical directions. Haig (2009) compiled multiple groundwater salinity maps from across the Pilbara region to generate regional groundwater maps for both the Port Hedland Plain (Figure 3.8) and the Ashburton Coastal Plain (Figure 3.9).

The increase in salinity away from the primary drainage in the horizontal direction is observed within all the survey areas. Vertical salinity variations across the De Grey River survey area have been reported to increases with depth within the alluvial aquifer, with highest salinity values recorded in the vicinity of the weathered bedrock aquifer (Haig, 2009). The opposite has been observed by Davidson (1976) within the Yule River area. In some cases the salinity in the alluvial aquifer’s upper portion was found to be higher than the salinity at depth. The higher salinity values in the upper portion of the aquifer were reported to be a potential effect of evapotranspiration (Commander, 1994b). As for the Robe River area, Commander (1994b) discovered higher salinity readings after river flooding when water levels were at their highest.
As the water level decreased the salinity levels were also recorded to decrease, although no suggestion has been made to the cause of the phenomenon.

Figure 3.8: Groundwater salinity across the Port Hedland Plain with De Grey River and Yule River survey outlines (modified after Haig, 2009).
Figure 3.9: Groundwater salinity within the Ashburton Coastal Plain with Robe River and Fortescue River survey outlines (modified after Haig, 2009).
4  INTERPRETATION

An integrated geological interpretation is an iterative process, whereby all available data sets are analysed and correlated to define and map structural and lithological features. Dickson and Scott (1997), Isles et al. (1997), Minty (1997), Nash (1997) and Wilford et al. (1992) all describe theory, procedures and methods for interpreting airborne geophysical data and remote sensing imagery. These techniques are used extensively in the qualitative FAS interpretation procedure, as well as specialised techniques developed in house. Typical datasets used include; electromagnetic, magnetic, radiometric, Landsat 7ETM+, DTM and any geological, geophysical and topographical data available.

The following datasets, in addition to the borehole data provided by the client, were generated to assist with the interpretation procedure. A selection of images is presented in Appendix A:

- Conductivity - elevation grids
- Conductivity depth images (CDIs)
- Magnetic images merged into regional datasets
- FALCON™ AGG grids and profile grids
- Onboard Digital Terrain Model (DTM) merged with the regional Shuttle Radar Topography Mission (SRTM) dataset (www.csi.cgiar.org)
- Landsat 7ETM+ images
- Ternary radiometric image

4.1  Basement Geology

Magnetic data collected during the airborne surveys were merged with publically available data available from Geoscience Australia to produce a regional magnetic dataset (http://www.geoscience.gov.au/bin/mapserv36?map=/public/http/www/geoportal/gadds/gadds.map). These regional datasets extend beyond the boundaries of the AEM survey allowing for a comprehensive interpretation of the regional basement geology to be undertaken. The publicly available data was typically acquired at 400 m line spacing compared to the 2000m line spacing of the AEM survey. The interpretation of the magnetic data allows for the subdivision of lithologies based on their magnetic character. Within the survey areas and surrounds the basement geology has been divided into various granite (early, late, magnetic, non-magnetic), volcanic (highly magnetic, moderately magnetic), metasedimentary (highly magnetic, weakly magnetic) and meta-volcanosedimentary units (various magnetic intensities).
In conjunction with the magnetic data, FALCON™ AGG data and AEM data were compared to the final magnetic interpretation in order to provide confirmation, where possible, of identifiable features. Additionally, any geological features present in the two complimentary datasets that were absent in the magnetic data were included in the interpretation.

4.1.1 De Grey and Yule Rivers

The interpreted basement geology surrounding the De Grey River and Yule River survey areas is presented in Figure 4.1 and Figure 4.2 respectively.

Basement geology of the De Grey and Yule areas consists of highly deformed volcanics which have been faulted/sheared along northeast and east-northeast trends. Also deformed, but largely to a lesser extent, are the meta-sediments and meta-volcanosediments. The De Grey area contains highly magnetic ferruginous sediments, possibly representing the banded iron-formation (BIF) of the George Creek Group. The possible BIF has been interpreted to be intensely deformed with the volcanics trending northeast. Subsequently, everything has been intruded by a series of granitoids which vary in relative age.

All basement units display late east-northeast and west-northwest faulting along with minor west-northwest dykes which cross-cut all lithologies.
Interpretation of Airborne Electromagnetic, Magnetic and FALCON™ Gravity Gradiometer Data - Pilbara Coast, Western Australia

Figure 4.1: Interpreted basement geology covering the De Grey River survey area. Magnetic data acquired during this survey was integrated with data publicly available from Geoscience Australia.
Interpretation of Airborne Electromagnetic, Magnetic and FALCON\textsuperscript{TM} Gravity Gradiometer Data - Pilbara Coast, Western Australia

Figure 4.2: Interpreted basement geology covering the Yule River survey area. Magnetic data acquired during this survey was integrated with data publicly available from Geoscience Australia.
Assessment of the FALCON™ AGG gridded data collected over the De Grey River survey area (see Figure 6.8) confirmed the general distribution of the major geological units. The interpreted banded iron formation meta-sediments (MS1) and surrounding volcanic units (VS1 and VS2) appear as high amplitude gravity responses in the vertical gravity component (gD) surrounded by low amplitude responses associated with lower density granites. The very high amplitude gravity response located towards the western boundary of the survey area coincident with the very high first vertical derivative response overlies the Pardoo Operation of Atlas Iron Limited as well BHP Billiton’s Ridley and Ord Iron Deposits and the Sunbeam gold prospect.

It is clear from looking at the gridded data that the 4,000 m line spacing utilised for this survey has negated the advantages of utilising high resolution FALCON™ AGG. To generate the grid images it is necessary to use a grid cell size of 1,000 m meaning higher frequency gravity signals are suppressed during the gridding process. There is little additional information that can be gained from the AGG data in comparison with the regional magnetic data available over the survey area when using such a data display.

In order to extract further information from the FALCON™ AGG data profile grids were generated utilising a much smaller grid cell size of 300 m (see Figure 6.8), which represents a compromise between the system resolution, the noise content of the data and the low-pass filter applied during data processing. The correlation of the Curvature Gradient Amplitude (Gc) profile grids with both the First Vertical Derivative of the Total Magnetic Intensity, Differentially Reduced to Pole data (TMI_DRTP_1VD) and the De Grey River basement geology interpretation is presented in Figure 4.3.

The presentation of the profile grids provides some indication of the high resolution information that can be obtained from the FALCON™ AGG system. The comparison of the Gc profile grids with the TMI_DRTP_1VD grid shows the AGG data highlighting contacts visible within the magnetic data, particularly the contacts between the high density meta-sediments (MS1) and volcanics and the lower density granites. There is also some indication of layering within the metasediments, however the wide line spacing means it is not possible to makes cross-line correlations.
Figure 4.3: Comparison between the Curvature Gradient Amplitude (Gc) from FALCON™ AGG data and; (A) First Vertical Derivative of the Total Magnetic Intensity, Differentially Reduced to Pole for the De Grey River survey area and (B) and De Grey River basement geology interpretation.
As with the FALCON™ AGG gridded data collected over the De Grey River survey area the Yule River AGG data (see Figure 6.9) provides confirmation of the general distribution of the major geological units. The broad, sweeping band of highly magnetic volcanics (VS1) appears as a gravity high, indicating the unit has an elevated density in comparison to the surrounding units. There is some indication of a decrease in amplitude of the volcanics’ AGG response to the south of the major west-northwest trending dyke that extends through the whole survey area (most likely a dyke intruded along a previous fault plane), providing some evidence for some downthrow to the south of the dyke.

To the northwest and southeast of the volcanic belt the gravity response is suppressed in amplitude, indicating the undifferentiated meta-sediments (MS2) which dominate in these areas have a lower density than the highly magnetic volcanics (VS1). There is some indication of variability in the density distribution to the northwest of the volcanics, however the broad line spacing of the survey (4,000 m) means any possible high resolution information in this area is suppressed during gridding.

Like the De Grey River FALCON™ AGG data, profile grids were generated from the Yule River dataset (see Figure 6.8). The correlation of the Curvature Gradient Amplitude (Gc) profile grids with both the First Vertical Derivative of the Total Magnetic Intensity, Differentially Reduced to Pole data (TMI_DRTP_1VD) and the Yule River basement geology interpretation is presented in Figure 4.4.

Comparison of the Gc profile grids with the TMI_DRTP_1VD grid shows the AGG data highlighting contacts visible within the magnetic data, particularly the contacts between the high density volcanic belt and the surrounding meta-sediments. To the northwest of the main volcanic belt the profile grids also show the smaller scale volcanics (VS1 and VS2) seen in the magnetic data. These units appear as moderate amplitude anomalies in the AGG profile grids, though their full extent cannot be mapped due to the broad line spacing of the AGG survey. It is also noticeable that there are variable amplitude responses present in the Gc data coincident with the volcanic belt suggesting the presence of density layering within the volcanics.
Figure 4.4: Comparison between the Curvature Gradient Amplitude (Gc) from FALCON™ AGG data and; (A) First Vertical Derivative of the Total Magnetic Intensity, Differentially Reduced to Pole for the De Grey River survey area and (B) its basement geology interpretation.
Comparison of the basement interpretation against the AEM conductivity data provided little additional geological information, but was able to identify the seawater influence and a number of the controlling structures (Figure 4.5 and Figure 4.6). There was moderate correlation with the current drainage within the Yule survey whereas no strong correlation with the current drainage was noticed in the De Grey survey. Further interpretation of the AEM data with respect to the basement geology is covered where appropriate in Section 4.4.
Figure 4.5: Comparison between the De Grey basement geology interpretation (A) and AEM conductivity (sunshade from north east) at an elevation of 0 m (B). Current drainage and seawater influence have been indicated.
Figure 4.6: Comparison between the Yule River basement interpretation (A) and AEM conductivity graph (shaded from north east) at an elevation of 0 m (B). Current drainage and seawater influence have been indicated.

Legend
- GR: Granite: Relatively late undifferentiated granitoid complex
- GMR: Granite: Relatively early undifferentiated granitoid complex
- GRN: Granite: Relatively late undifferentiated non-magnetic granitoid complex
- VM: Volcanics: Highly magnetic
- VMW: Volcanics: Moderately magnetic
- MS: Meta-sediments: Possible BIF and/or other ferruginous sediments
- MSU: Meta-sediments: Undifferentiated, subordinate meta-volcanics
- MW: Meta-volcanosediments: undifferentiated, moderate to highly magnetic
- MWK: Meta-volcanosediments: undifferentiated, moderate to weakly magnetic
- Major fault - confident
- Major fault - inferred
- Late fault
- Dyke
- Geological boundary - basement
- Magnetic trends
- Drainage
- Coastline
- Survey Area

Fault possibly controlling sea water influence
4.1.2 Robe and Fortescue Rivers

The interpreted basement geology surrounding the Robe and Fortescue survey areas is presented in Figure 4.7.

Basement geology of the Robe and Fortescue areas consist of similar lithologies to the De Grey and Yule areas, with the addition of ferruginous sediments of various ages and undifferentiated deep intrusives. Structurally, the Robe and Fortescue areas are quite different to the other survey areas to the east. Within this area the structural trends are dominated by north striking faults as well as late north trending dykes and minor east striking dykes. The normal component on the north striking faults has been inferred from the magnetic data and does not reflect the previously mapped geology by the GSWA.

The magnetic response of the ferruginous sediment in the central part of the survey area shows a sudden change from a high frequency to a lower frequency from east to west suggesting an increase in depth to magnetic sources (see Figure 6.7). In addition to this deepening of the sediments, the unit also appears to be indicating a change in dip from horizontal in the east to more vertical in the west. This is indicated by a magnetic texture change from mottled (flat lying), sub-linear (inclined) and linear (near vertical).

The deep intrusives have been identified as part of this comprehensive interpretation but appear to have very little significance with respect to the hydrogeology due to their deep seated nature.

The comparison between the basement interpretation and the AEM data provided similar results as to the Yule and De Grey comparison. The presence of seawater and its possible structural controls were identified and have been shown in Figure 4.8. Although no new geological information was identified in the AEM data, a minor correlation between the basement geology is present.
Figure 4.7: Interpreted basement geology covering the Robe River and Fortescue River survey areas. Magnetic data acquired during this survey was integrated with data publicly available from Geoscience Australia.
Figure 4.8: Comparison between the Robe River and Fortescue River basement interpretations (A) and AEM conductivity (sunshade from north east) at an elevation of 0 m (B). Current drainage and seawater influence have been indicated.
4.2 Relative Porosity

Measurements of the electrical resistivity of the earth have been used for many years for groundwater exploration. Originally measurements were made using grounded electrodes in a variety of resistivity arrays (Wenner, dipole–dipole, Schlumberger, etc) to ‘inject’ current into the ground and measure the resulting potential difference (Reynolds, 1997). Inductive electromagnetic techniques, which measure conductivity, provide better resolution in areas of high conductivity where resistivity techniques can be less effective. Additionally, inductive techniques provide better spatial resolution due to short intercoil spacing and have an advantage of not requiring direct contact with the ground.

AEM surveys have been used extensively to assist with groundwater and land management applications related to aquifer mapping, hydrogeologic investigations and salinisation studies (Street, 1992; Lane et al., 2000; Wynn et al., 2000; Humphreys et al., 2002; Paine and Collins, 2003; Sattel and Kgotlhang, 2004; Baldridge et al., 2007). Within Australia the National Airborne Geophysics Projects (NAGP) was aimed at identifying the benefits to be gained by using airborne geophysics for the management of dryland salinity (Coppa et al., 1998). Results indicated that AEM, whilst not answering all questions, provides invaluable information on the hydrogeology, spatial distribution of salt and geological structure controlling groundwater.

In rocks and minerals with an absence of pores or pore fluids electricity is conducted by electrons. However, except for metallic sulphides, graphite and native metals, most rock forming minerals are very resistive. In contrast, within regolith or highly permeable rocks and soils with intergranular pore fluids the electrical conductivity is principally electrolytic through the movement of ions in the pore fluid. The rock matrix can be assumed to be an insulator. The electrical conductivity of soils and porous rocks is influenced by:

- Soil structure or porosity and shape of pore spaces
- Moisture content or degree of saturation
- Salt content of the soil moisture
- Clay mineralogy or the presence of clays with cation exchange capacity
- Temperature

Further discussions of these relationships are presented by McNeill (1980), McNeill (1990), Palacky, (1987) and Emerson, (1997).
In a saturated medium Archie’s Law (Archie, 1942) describes the influence of soil structure and salt content as on bulk conductivity;

\[ \sigma_a = \sigma_w \phi^m \]

Where

- \( \sigma_a \) = bulk conductivity of the soil
- \( \sigma_w \) = conductivity of the soil water
- \( \phi \) = soil porosity
- \( m \) = numerical factor between 1.2 and 1.9 dependent on particle shape.

Below a certain moisture level, material can not conduct electricity as there is no continuous water path for conduction to occur through (Emerson, 1997). The critical water level where conduction will occur differs for different materials. Soil and regolith are primarily a combination of clays, sands and weathered rock with typical clays consisting of kaolinite, illite or smectite groups.

Emerson (1997) presented results showing the desaturation behaviour is different for sands and kaolinite. A slower decrease in conductivity occurs as water content decreases in kaolinite as compared to sands (Emerson, 1997). To obtain reasonable measures of conductivity of clays they should be 10% saturated whereas sands should be approximately 20% saturated (Street et al., 1998).

When soil is partially saturated conductivity varies approximately as (Keller and Frischknecht, 1970);

\[ \sigma_d = \sigma_a S^k \]

Where

- \( \sigma_a \) = bulk conductivity of the soil
- \( \sigma_d \) = conductivity of partially saturated soil
- \( S \) = fraction of total soil volume filled with electrolyte
- \( k \) = a factor experimentally determined to be approximately two.

Field investigations have shown that below a surficial zone, which is subject to seasonal variations in moisture content, the degree of water saturation in the regolith is sufficient to make the salt conductive (Palacky and Kadekaru, 1974). De Jong (1976) showed that for a heavy
clay soil in Canada moisture content below 1 m was relatively uniform throughout the year whereas the top 75 cm showed seasonal variations and the top 30 cm showed shorter term responses to precipitation. From these results it can be assumed seasonal moisture variations will affect conductivity measurements in the near surface but the variations will generally be restricted to the top 1 or 2 metres. Due to the transmitter frequencies used and the positioning of the recorded time gates, AEM systems are unable to resolve the layer affective by seasonal moisture variations.

An additional component of electrical conductivity to be considered is Cation Exchange Capacity (CEC) resulting from the presence of clays. Cations present within the clay lattice allow for electrical conduction (McNeill, 1990), an effect that is independent of the electrolytic component of conduction. Taking CEC into effect Archie’s Law becomes

\[ \sigma_a = \sigma_w \phi^m + \sigma_{clay} \]

The CEC component of electrical conductivity has the largest contribution to the bulk conductivity when the concentration of electrolytic conductors is low, such as in areas of low groundwater salinity and/or salt storage. At high ionic concentrations it becomes negligible, especially for clays with low to moderate CEC (McNeill, 1990).

Lateritic weathering of much of Australia’s inland areas has resulted in a regolith dominated by kaolinite clays (Butt, 1983). This occurs either by the direct weathering of granitic or more acid rocks to produce saprolitic clays composed mostly of kaolinite or by the weathering of more basic rocks to a saprolite of montmorillonite (smectite) which is enriched in kaolinite and halloysite on further weathering (Loughnan, 1969). The resulting kaolinite clays have a very low CEC (Keller and Frischknecht, 1970).

As the survey was flown towards the end of the rainy season in northern Australia it is considered that the regolith would still be moist though unsaturated. It is possible that the top one to two metres was dry but this would be beyond the resolution of the AEM system.

Assuming that the majority of the clays underlying the survey area were kaolinite (much of the survey area overlies undifferentiated granitoids) then the contribution of the CEC component to the bulk ground conductivity can be considered to be minimal. As such, it is most likely that the conductivity is dependent on the conductivity of the soil water and the porosity of the soil.

However, due to the lack of up-to-date salinity maps, and the relatively thin sediment units from the geology logs, it is uncertain which of these parameters (salinity or porosity) is the primary controller on the conductivities within the sedimentary package. This means it is not possible to distinguish between a gravel unit saturated with fresh water and a partially saturated sand unit.
Conversely, a gravel unit saturated with brackish water may well display conductivities similar to a saturated clay unit.

The inability of the electromagnetic technique to make these distinctions means it is not possible to produce a ‘true’ map showing how units of differing porosity are distributed across the survey areas. Instead relative porosity maps were generated for each of the conductivity – elevations by selecting different conductivity bands to represent porosity. Ranges for each of the conductivity bands were determined by examination of the various electromagnetic datasets and comparison with the known and anticipated distribution of different lithologies. It was assumed that any groundwater present would be fresh and not brackish. The different conductivity bands and their interpreted relative porosity are presented in Table 4.1.

Table 4.1: Conductivity bands and interpreted relative porosity.

<table>
<thead>
<tr>
<th>Conductivity (mS/m)</th>
<th>Relative Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;15</td>
<td>Bedrock, very low porosity except in fractures and faults that may not be interconnected</td>
</tr>
<tr>
<td>15 - 25</td>
<td>Weathered bedrock, low porosity</td>
</tr>
<tr>
<td>25 - 35</td>
<td>High porosity, possibly gravels or coarse sands, fresh water may be present</td>
</tr>
<tr>
<td>35 - 50</td>
<td>Moderately high porosity, possibly gravels or sands with some clay, low possibility of fresh water</td>
</tr>
<tr>
<td>50 - 65</td>
<td>Moderate porosity, possibly sands with clay, low possibility of fresh water</td>
</tr>
<tr>
<td>65 - 90</td>
<td>Moderately low porosity, possibly clays with some sand or gravel, low possibility of fresh water</td>
</tr>
<tr>
<td>90 - 300</td>
<td>Low porosity, possibly clays or silts, low possibility of fresh water</td>
</tr>
<tr>
<td>&gt; 300</td>
<td>High probability of seawater intrusion</td>
</tr>
</tbody>
</table>

A selection of relative porosity – elevation grids for each survey area are presented in Figure 4.9 (De Grey), Figure 4.10 (Yule), Figure 4.11 (Fortescue) and Figure 4.12 (Robe).
Figure 4.9: Relative porosity maps for the De Grey River survey area generated from conductivity – elevation grids for indicated elevations (all elevations are relative to datum).
Figure 4.10: Relative porosity maps for the Yule River survey area generated from conductivity – elevation grids for indicated elevations (all elevations are relative to datum).
Figure 4.11: Relative porosity maps for the Fortescue River survey area generated from conductivity – elevation grids for indicated elevations (all elevations are relative to datum).
Figure 4.12: Relative porosity maps for the Robe River survey area generated from conductivity – elevation grids for indicated elevations (all elevations are relative to datum).
4.3 Bedrock Contacts

Determination of the depths to both weathered and unweathered bedrock was possible by assigning conductivity values for each layer. The significant contrast between the unconsolidated sediments and the bedrock allows for the identification of the upper contact of the weathered bedrock. In addition, the availability of borehole data from holes that penetrated bedrock assisted in determining this contact. A limited range of conductivity values generated surfaces that approached a close fit with the interpreted upper weathered bedrock contact. These surfaces were compared with available borehole data to assist in determining the most appropriate conductivity value to represent the top of weathered bedrock. Using this best-fit approach it was determined that a conductivity value of 25 mS/m provided the best results.

Although there is borehole control, this surface should be considered approximate. This is due to the variability in borehole logging styles between 1965 and 1985, the variation in weathering of the basement contact, as well as the different conductivities of the various basement lithologies (Figure 4.13).

![Figure 4.13](image-url)
Borehole control was not available to assist in the determination of the upper unweathered bedrock contact. In order to determine the most appropriate conductivity to assign to this boundary both the 3D voxel model and CDI’s were examined to identify zones of high conductivity gradient. These zones are indicative of lithological contacts that gridding processes are unable to reproduce as sharp boundaries. A conductivity value of 15 mS/m was decided to represent the weathered/unweathered bedrock contact.

4.3.1 De Grey River

Figure 4.14 displays both the weathered and unweathered basement surface within the De Grey with a minimum elevation of -175 m for the weathered basement to -200 m for unweathered basement. Within the south of the survey area the basement is outcropping or near outcropping, with a prominent basement high where the BIF has been mapped (Figure 4.15). A significant late fault was interpreted in both the magnetic and AEM conductivity data in the north east of the survey area. This feature appears to be acting as a barrier to the seawater influence from the coast, as well as possibly directing the groundwater flow from the south of the structure in a more east-west direction.

A palaeochannel trough within the basement surface was evident within the weathered and unweathered basement surface grids. This trough is consistent with the results of Davidson (1974) who indicates the trough is infilled with alluvial deposits and represents the most prospective aquifer in the De Grey River area. The location of the palaeochannel, which appears to have no correlation with any basement structures, is presented in Figure 4.15.
Figure 4.14: Weathered (A) and unweathered (B) basement surfaces for the De Grey River survey area.
Figure 4.15: Unweathered basement surface overlaid by basement structural interpretation, current drainage and the extent of possible palaeochannel within the De Grey River survey area. Elevation range is indicated in Figure 4.14B.

4.3.2 Yule River

Figure 4.16 displays both the weathered and unweathered basement surface within the Yule survey area. The elevation ranges from a minimum of -130 m for the weathered basement to -135 m for unweathered basement. No outcrop has been interpreted in the basement surfaces, which correlates with the Landsat 7ETM+ data as well as previous mapping by the GSWA.

Within the Yule area many drainage features have been interpreted from the remotely sensed data and has been overlayed in Figure 4.17. It would appear that the main river channels have exploited late NNW trending faults in the volcanic belt. Previous work to the south of the Yule
River survey area by Fugro Airborne Surveys (2009) suggests that this faulting has had a major influence on the course of the Yule River over time.

Figure 4.16: Weathered (A) and unweathered (B) basement surfaces for the Yule River survey area.
Figure 4.17: Unweathered basement surface overlaid by basement structural interpretation and current drainage within the Yule River survey area. Elevation range is from high to low represented by white to blue respectively.

4.3.3 Fortescue River

Figure 4.18 displays both the weathered and unweathered basement surface within the Fortescue survey area. The elevation ranges from a minimum of -150 m for the weathered basement to -175 m for unweathered basement. Within the south east corner of the survey area the weathered basement surface crops out (Figure 4.19). This outcrop roughly correlates to outcrop seen in the Landsat 7ETM+ data. Further identified from the remote sensing data was the current drainage, which in the Fortescue survey area is concentrated in the east where the Fortescue River is the main channel.
A possible erosional feature in the meta-sediments has been highlighted in Figure 4.19. This depression could be related to the inferred normal fault interpreted to the east. Further investigative borehole drilling would be required to confirm this feature.

Figure 4.18: Weathered (A) and unweathered (B) basement surfaces for the Fortescue River survey area.
4.3.4 Robe River

Figure 4.20 displays the depth to both the weathered and unweathered basement surface within the Robe survey area. The elevation ranges from a maximum depth of -190 m for the weathered basement to -225 m for unweathered basement.

Comparison of the basement surface to structural interpretation and surface drainage indicates no obvious correlation (Figure 4.21). A possible contact between the ferruginous sediments (MS1b) from the AEM data further to the west of the contact interpreted from the magnetic data would suggest the AEM data is identifying a deeper contact of the sediments. Further investigation would be required to confirm this interpretation.
Figure 4.20: Weathered (A) and unweathered (B) basement surfaces for the Robe River survey area.
Figure 4.21: Unweathered basement surface overlaid by basement structural interpretation and current drainage within the Robe River survey area. Elevation range is from high to low represented by white to blue respectively.
4.4 Aquifer Geometry

The principal aquifer type within each survey area is the alluvial deposits, though in the eastern half of the De Grey River survey area the Broome and Wallal Sandstone aquifers, that are associated with the West Canning Basin, are also present (Haig, 2009). Within both the De Grey River and Yule River survey areas the recorded thicknesses of the alluvial aquifers is quite significant, reaching a maximum thickness of 75 m within the basement palaeochannel of the De Grey River and 70 m adjacent to the Yule River (Haig, 2009). Within the De Grey River survey area alluvial aquifers are reported to be associated with the Strelley and Shaw Rivers (Haig, 2009) though they are less extensive than the De Grey River aquifer (Davidson, 1974). These three rivers (De Grey, Strelley and Shaw) are the main source of recharge for the alluvial aquifer in the De Grey area. Across the Fortescue River and Robe River the alluvial aquifers are much thinner, locally reaching a maximum thickness of 15 m adjacent to the Fortescue River (Commander, 1994a) and 10 m adjacent to the Robe River (Commander, 1994b). These rivers are the main source of recharge for the alluvial aquifer in each area.

Determination of the aquifer geometries from the conductivity data alone has proved to be inconclusive. Generally it is not possible to identify the saturated alluvial aquifer from the alluvial floodplain material as both display similar conductivity values.

In the thicker aquifers of the De Grey and Yule Rivers the conductivity values appear to be dominated by clay material resulting in elevated conductivities. It is possible that in a small number of locations the presence of freshwater results in a reduction in the observed conductivities, though a reduction in the clay content could result in a similar effect. As can be seen from Figure 4.24 and Figure 4.27, as distance from the main river channels increases there is little variation in the observed conductivity values of the alluvium.

The principal issue with attempting to define the Fortescue River and Robe River alluvial aquifers is the thickness of the alluvial material present. Both aquifers are relatively thin, with maximum thicknesses of 15 m and 10 m respectively. As the units are at the very limits of detection for the TEMPEST system, especially when they are located at, or very close to, ground surface, it is not possible to identify them with any level of confidence.

Although numerous FALCON™ AGG surveys have been flown targeting deposits related to palaeochannels there are few publications on the use of the technique for groundwater investigations, most likely as a result of the proprietary nature of the data. Isles and Moody (2004) present the results of a FALCON™ AGG survey at Ellendale on the fringes of the Kimberley Basin that identifies palaeochannels that drilling results indicate may be as thin as 20
m in average depth extent. Similarly, a FALCON™ AGG survey flown for Tawana Resources over their Tawana Alluvial Project clearly delineates the boundaries of a broad, diamondiferous palaeochannel. From 69 holes drilled the average depth to bedrock over the channel was calculated as being 21 m (Marx, 2007). FALCON™ data was also used in identifying ‘roll-front’ prospective palaeochannels over Stellar Resources’ Tarcoola Region licences in the Gawler Craton (http://www.stellarresources.com.au/user/files//Projects/Uranium\%20Overview.pdf).

The AGG data flown over both the De Grey River and Yule River survey areas were examined in an attempt to derive any possible information relating to palaeochannels. Due to the large cell size of the gridded products (Figure 6.8 and Figure 6.9) there was little information to be obtained. The mapped drainage was compared to the gridded profile data and profile plots of the Curvature Gradient Amplitude (Gc) (Figure 4.22 and Figure 4.23) to see whether there might be some correlation, but with little success. For example, it would be expected that the basement trough present within the De Grey River survey area would be imaged as a gravity low. However, there is no discernable response from this feature. The high frequency nature of the data does not allow correlation across such large line spacing. Therefore, if any useful information is present within the survey areas it could not be identified from the profiles.
Figure 4.22: FALCON™ AGG data over the De Grey River survey area compared with mapped drainage. (A) Profile grids of Curvature Gradient Amplitude (Gc); (B) profiles of Curvature Gradient Amplitude (Gc).
Figure 4.23: FALCON™ AGG data over the Yule River survey area compared with mapped drainage. (A) Profile grids of Curvature Gradient Amplitude (Gc); (B) profiles of Curvature Gradient Amplitude (Gc).
4.4.1 De Grey River

Three palaeochannels have been identified in the conductivity data, one of which has been mapped with a high degree of confidence and appears to extend to the basement surface (Figure 4.24A). This feature doesn’t appear to correlate with any basement structures and is interpreted to be an erosional channel in the basement which has been infilled with alluvium. The extents of the alluvial aquifer previously discussed by Davidson (1974) and mapped by Haig (2009) has also been indicated in Figure 4.24A. The mapped aquifer extents closely match the interpreted deep palaeochannel but are limited in the western extent, possibly due to a lack of data. The extensive coverage of the AEM survey in this area has allowed for this palaeochannel to be extended past its previous limits. Flooding of the surrounding rivers (De Grey River, Shaw River and the West Strelley River) are the main source of recharge for this aquifer (Haig, 2009).

The second and third palaeochannels have only been inferred and display a moderate to shallow depth extent in the conductivity data. As seen in Figure 4.24A the two channels cross which would indicate a change in drainage conditions with time. The moderate depth channel lies to the east of the Pardoo Creek and could represent a previous channel. It is worth considering investigating this feature as a potential alluvial aquifer, though from the comments of Leech (1979) the anticipated recharge from Pardoo Creek would be very small.

In an additional attempt to identify the aquifers and their geometries the AEM profile data was investigated and interpreted. To aid in the interpretation the AEM profile data was compared to geological cross-sections by Haig (2009). Using the previous borehole derived geological cross-section as a guide to the stratigraphy it was possible to interpret the CDIs in terms of the anticipated geology (Figure 4.24C). The recent alluvium, Broome Sandstone, Jarlemai Siltstone and the weathered and unweathered basement units were interpreted with the highest confidence whilst the interpretation of the Wallal Sandstone and the palaeochannel/old alluvium is less confident.
Figure 4.24: Interpretation of aquifer geometry within the De Grey River survey area. (A) Correlation between surficial geology from the Western Australia Geological Survey digital geological map with interpreted palaeochannels; (B) basement interpretation from magnetic data; (C) AEM CDI for flight line 1001602 with interpreted geology; (D) geological cross-section from Haig (2009).
The conductivity of the recent alluvium was significantly higher than might be expected for sand, silt, gravel and clay. The high conductivity values could be a result of either elevated salinity or clay concentrations, or a combination of the two. From the available information it is not possible to determine the exact cause.

The CDI section displayed in Figure 4.24 clearly demonstrates how it is not possible to accurately determine the extents of the alluvial aquifer based solely on conductivity data. As discussed above, the recent alluvium displays higher than anticipated conductivity values with little lateral variation except for localised conductivity lows close to the main river channels. It was anticipated that the freshwater contained within the De Grey River aquifer would result in a suppressed conductivity response, however this does not appear to be the case.

Due to the difficulties in determining the extents of the alluvial aquifer from conductivity data alone it was necessary to use the mapped aquifer extents of Haig (2009) as an initial guide to the aquifer boundaries. Comparison of the mapped aquifer extents and base of alluvium contours with the CDIs across the De Grey River survey area allowed the lateral extents to be refined and the depth extent to be interpreted from the conductivity data. The mapped extents of the alluvial aquifer are presented in Figure 4.25.
The ability to identify the Broome Sandstone/Jarlemai Siltstone/Wallal Sandstone sequence in the CDIs over the eastern half of the De Grey survey area has enabled the mapping of the sandstone aquifers along flight lines not inundated with seawater. A 3D representation of the mapped extents of these aquifers is presented in Figure 4.26.

Figure 4.26: 3D view of interpreted Broome Sandstone (left) and Wallal Sandstone (right) aquifers within De Grey River survey area. Displayed CDIs are 1002601, 1002101, 1001602 and 1001103 (from south to north). View is to south east.

4.4.2 Yule River

Figure 4.27 shows a comparison of the geological cross-sections by Haig (2009) with a CDI from the AEM data. The relatively simple geology of alluvial gravels, sand, clay and silt overlying Archaean basement is well defined by the AEM data. Lateral conductivity variations are visible within the alluvial deposits resulting from either lithological or salinity variations though it is clear that, as with the De Grey River survey area, there is no noticeable conductivity variation that can be confidently attributed to the presence of freshwater in the alluvial aquifer.
Figure 4.27: Interpretation of aquifer geometry within the Yule River survey area. (A) Correlation between surficial geology from the Western Australia Geological Survey digital geological map with mapped alluvial aquifer extents from Haig (2009); (B) basement interpretation from magnetic data; (C) AEM CDI for flight line 4001001 with interpreted geology; (D) geological cross-section from Haig (2009).
To map the extents of the alluvial aquifer within the Yule River survey area a similar approach was taken as for the De Grey River survey area. The mapped aquifer extents of Haig (2009) were used as an initial guide to the aquifer boundaries with the comparison of the mapped aquifer extents and base of alluvium contours with the CDIs allowed for the lateral extents to be refined and the depth extent to be interpreted from the conductivity data. The mapped extents of the alluvial aquifer are presented in Figure 4.28.

Figure 4.28: 3D view of interpreted alluvial aquifer (red sections) within Yule River survey area. Displayed CDIs are 4001001 and 4000501 (from south to north). View is to north west.

4.4.3 Fortescue River

A possible erosional trench in the meta-sediments has been highlighted in Figure 4.19. This depression could act as a pisolithic limonite aquifer, which have been recorded in the region (Haig, 2009), although Commander (1994a) reported that potential yields from pisolites in the lower Fortescue River might be less than 100 m³/d. This potential low flow and the close proximity to the seawater wedge make this an unlikely freshwater source.

Shown in Figure 4.29A is the approximate extent of the Yarraloola Conglomerate and the upper alluvial gravel as determined by Haig (2009). The Yarraloola Conglomerate has been recorded as a confined aquifer and forms within erosional features in the basement rocks (Haig, 2009). As with the Yule River and De Grey River survey areas, the Fortescue River was interpreted along the AEM profile data in an attempt to correlate the geology by Williams (1968), as well as
the borehole data, with the extent of the current aquifers (upper alluvial gravel and Yarraloola Conglomerate) (Figure 4.29). As discussed previously in this report, the relatively thin upper alluvial gravel within the Fortescue area is too thin for the AEM system to resolve accurately. The Yarraloola Conglomerate was thick enough to map using the conductivity data but with very low confidence due to a lack of borehole interception of the basal gravel.

4.4.4 Robe River

When the basement interpretation is compared with the profile data and geological cross-section derived by Haig (2009) a reasonable correlation can be drawn (Figure 4.30C). The location of the Trealla Limestone and the pisolithic unit was difficult to determine from the AEM data due to the influence of the highly conductive gravel/calcrete unit lying above, therefore the position of the lower units were mainly derived from borehole data.

As discussed earlier in this report, the identification of the alluvial aquifer was not possible due to its relatively thin depth extent. Instead the upper gravel/silt/clay sequence was mapped which includes this alluvial aquifer. The Trealla Limestone and underlying units have been interpreted with less confidence. Although the Trealla Limestone represents a possible aquifer elsewhere in the region it is locally considered to be too impermeable to offer reasonable groundwater storage whilst the Toolonga Calcilutite, Windalia Radiolarite and Muderong Shale are also impermeable, preventing any significant downward leakage to the Yarraloola Conglomerate.
Figure 4.29: Interpretation of aquifer geometry within the Fortescue River survey area. (A) Correlation between surficial geology from Williams et al. (1968) with mapped extents of alluvial gravel and possible extents of Yarraloola Conglomerate from Haig (2009); (B) basement interpretation from magnetic data; (C) AEM CDI for flight line 2000701 with interpreted geology; (D) geological cross-section from Haig (2009).
Figure 4.30: Interpretation of aquifer geometry within the Robe River survey area. (A) Correlation between surficial geology from Williams et al. (1968) with mapped extents of alluvial gravel from Haig (2009); (B) basement interpretation from magnetic data; (C) AEM CDI for flight line 3001201 with interpreted geology; (D) geological cross-section from Commander (1994b).
4.5 Seawater Intrusion

As with groundwater exploration, measurements of the electrical resistivity of the earth can be effectively used to identify and map the regional extents of seawater intrusion within coastal aquifers. Due to the large electrical conductivity contrast between seawater (5,000 mS/m; Fitterman and Deszcz-Pan, 2001) and freshwater (5 – 50 mS/m; Fitterman and Deszcz-Pan, 2001), electromagnetic methods are advantageous when looking to map the seawater intrusion.

Figure 4.31 shows unconfined and confined freshwater aquifer models, with the invading denser seawater being overridden by less dense freshwater which was used by Fitterman and Stewart (1986) to generate forward time domain sounding models. Results indicated that electromagnetic methods, and sounding techniques in particular, are excellent for mapping conductive targets, such as that provided by a seawater layer, even when overlain by thick, conductive clays. However, in contrast it is difficult to detect the higher resistivity fresh water within a confined aquifer unless present in significant thickness.

For small scale investigations surficial techniques are widely used (Massoud et al., 2009; Farrell et al., 2004; Bates and Robinson, 2000; Fitterman et al., 1999). However, the use of airborne techniques to map seawater intrusions is not as prevalent as for groundwater exploration and land management applications. Fitterman and Deszcz-Pan (2001) present the results of an airborne frequency domain electromagnetic survey over the Everglades National Park that was correlated with previous hydrologic work and borehole geophysical measurements. Siemon et al. (2007) utilised airborne frequency domain electromagnetic data to map shallow coastal saltwater occurrences, deep saltwater occurrences and potential freshwater resources in the Aceh Province of northern Sumatra, Indonesia following the Boxing Day tsunami of 2004.
In order to map the seawater intrusion a similar approach was taken to that of determining the weathered and unweathered bedrock surfaces in that a conductivity value was assigned that defined the leading edge of the seawater intrusion. However, without any borehole control determination of a suitable conductivity value is complex. Published values for the conductivity of seawater saturated lithologies are highly variable, ranging from relatively low conductivities in the range of 100 – 200 mS/m (Massoud et al., 2009; Fitterman et al., 1999; Fitterman and Stewart, 1986), through moderate conductivities in the range of 300 – 400 mS/m (Siemon et al., 2007) to much higher conductivities of greater than 500 mS/m (Bates and Robinson, 2000).

Using Archie’s Law (Section 4.2) it is theoretically possible to determine the bulk conductivity of lithologies affected by seawater intrusion. However, numerous unknowns that affect the calculation remain that leaves the range of values highly variable. For example, although published values for porosity are available (for example McWorter and Sunada, 1977) the range is quite large, whilst the empirical factor $m$ is undetermined and variable depending on lithology.
Additionally, the pore fluid conductivity and fraction of pores filled with conducting fluid are further unknowns.

As with determining the conductivity value to represent the unweathered basement, both the 3-D voxel model and CDI’s were examined to identify zones of high conductivity gradient that could represent the boundaries of the seawater intrusion. A number of high conductivity gradients were identified within the data focussed around conductivity values of approximately 300 mS/m, 600 mS/m and 750 mS/m. Comparison of these values with published conductivities for seawater saturated zones suggests a conductivity value of 300 mS/m represents the boundary of seawater intrusion whilst the higher conductivities are representative of variations within the zone influenced by the seawater intrusion. Utilising a conductivity value of 300 mS/m isosurfaces were generated for each of the survey areas to represent the extent of the seawater intrusion.

4.5.1 De Grey

Figure 4.32 shows a 3D representation of the interpreted extents of the seawater intrusion underlying the De Grey survey area. The Western Australia Geological Survey digital geological map is also presented draped over topography for reference.

It can be clearly seen from the image that the interpreted seawater intrusion extends a significant distance onshore beneath the survey area, especially in the western portion. The surficial influence of the seawater correlates very well with the mapped tidal flats from the geological map (pale green units bordering the coastline in the geological map).

In the extreme west of the survey area the interpreted outcropping metasediments and BIF present an impenetrable barrier to the seawater intrusion which partially wraps around the units to the south.

To the north east of this outcrop the southern extent of the seawater intrusion appears to be restricted around the main channel of the De Grey River. This may be a result of fresh water recharge from the river into the shallow alluvium reducing the salinity of the pore fluids present. In contrast, there appears to be a lobe of seawater intrusion underlying the course of Pardoo Creek. This seawater invasion could be infiltrating the interpreted palaeochannel described in section 4.4.1.

Utilising the conceptual models to classify coastal waterways presented by Ryan et al. (2003), the De Grey River is a tide-dominated estuary whilst Pardoo Creek is classified as a tidal creek. Two main differences between the two waterways are:
there is a much greater flow of water through a tide-dominated estuary in comparison to a tidal creek (Ryan et al., 2003)

tide-dominated estuaries tend to have extensive areas of intertidal flats and salt flats around the margins of the estuary which are lacking in tidal creeks due to their relatively small size and low freshwater input (Ryan et al., 2003).

It would appear that these two main differences are manifested in the conductivity data by the differing extent and shape of the seawater intrusion in close proximity to the river channels. The higher water flow and extensive intertidal flats and salt flats of the De Grey River are characterised by an extensive zone of landward seawater intrusion which is restricted in extent around the river channel where the fresh water flow flushes away the more saline fluid. In contrast, the low water flow along the Pardoo Creek, which prevents extensive areas of intertidal flats and salt flats from developing, results in the seawater have limited landward extents except along the river course where there is no flushing effect from fresh water.

Figure 4.32: 3D view of interpreted seawater intrusion within the De Grey survey area. Also shown are a number of CDIs along tie-lines and Western Australia Geological Survey digital geological map draped over topography. View is to northeast.
4.5.2 Yule River

Figure 4.33 shows a 3D representation of the interpreted extents of the seawater intrusion underlying the Yule survey area. The Western Australia Geological Survey digital geological map is also presented draped over topography for reference.

As with the De Grey survey area, the interpreted extent of the seawater intrusion is considered to be significant. The surficial influence of the seawater correlates very well with the mapped tidal flats from the geological map (pale green units bordering the coastline in the geological map). However, in contrast to the De Grey Survey area the landward extent is much less variable and tends to be located parallel to the coastline with a slight reduction in the southwards extent around the main channels of the Yule River, probably resulting from fresh water recharge from the river into the shallow alluvium reducing the salinity of the pore fluids present.

![Figure 4.33](image_url)

*Figure 4.33: 3D view of interpreted seawater intrusion within the Yule survey area. Also shown are CDIs along tie-lines and Western Australia Geological Survey digital geological map draped over topography. View is to northeast.*
Ryan et al. (2003) classify the Yule River as a tidal creek using their conceptual models of classifying coastal waterways suggesting low fresh water throughflow. However, data on river flow and aquifer recharge presented by Haig (2009) does not support this classification as the lower Yule River receives significant recharge approximately once every three years, though recharge is considered to be very low once every three years. The amount of flow along the Yule River is high enough to allow the development of limited intertidal flats and salt flats and extensive alluvial deposits further inland.

4.5.3 Fortescue River

Figure 4.34 shows a 3D representation of the interpreted extents of the seawater intrusion underlying the Fortescue survey area. The Yarraloola geological map sheet (Williams et al., 1968) is also presented draped over topography for reference.

The interpreted seawater intrusion displays considerable landward extent beneath the Fortescue survey area with the distance of the leading edge of the intrusion from the coastline increasing towards the west. This may be related to the fresh water recharge from the river into the shallow alluvium or changes in the shallow geology. It is noticeable that in the extreme northeast of the survey area the landward extension of the seawater intrusion appears to be partially restricted by the outcropping Yarraloola Conglomerate. Similarly, the Proterozoic basement that shallowly underlies the Yarraloola Conglomerate would also act as a barrier to seawater intrusion. These units gently dip to the northwest (Haig, 2009) which is consistent with the seawater intrusion which thickens to the northwest and which displays a northeast trending leading edge.

The surficial influence of the seawater intrusion appears to be much greater than within the De Grey and Yule survey areas and does not correlate well with the mapped extents of coastal mud flats, extending much further inland. However, the tendency for the surficial influence of the seawater intrusion to extend further inland towards the west of the survey area is consistent with the geology map. The map shows an increasing landward extent of the high seawater area towards the west with a significant area of coastal mud flats identified as extending inland along the western survey boundary (Williams et al., 1968). It is probable that tidal and salt flats, mangrove swamps, sand shoals, and sand dunes will be present along the coast (Williams, 1968) even though they do not appear on the Yarraloola map sheet.

Ryan et al. (2003) classify the Fortescue River as a tide-dominated delta. This model type represents a more mature form of a tide-dominated estuary which will have been largely infilled by terrigenous and marine sediments. There is little difference in the distribution of intertidal
flats, mangroves and saltmarshes in comparison to tide-dominated estuaries, though there are usually tidal sand banks formed to the seaward side of the river mouth.

Figure 4.34: 3D view of interpreted seawater intrusion within the Fortescue survey area. Also shown are CDIs along tie-lines and the Yarraloola geological map sheet (Williams et al., 1968) draped over topography. View is to west.

4.5.4 Robe River

Figure 4.35 shows a 3D representation of the interpreted extents of the seawater intrusion underlying the Robe survey area. The Yarraloola geological map sheet (Williams et al., 1968) is also presented draped over topography for reference.

The interpreted extent of the seawater intrusion displayed in Figure 4.35 shows considerable inland extent, in some areas beyond the southern boundary of the survey area where the apparent intrusion approaches surface. It is clear that the displayed extents do not map the true extents of the seawater intrusion.

Examination of the model generated shows that towards the coast there appears to be two distinct layers of material displaying conductivities greater than 300 mS/m, with the southernmost layer appearing to dip towards the northwest and beneath the second layer.
Comparison of the available borehole data within the Robe survey area with the conductivity data shows the dipping, southern layer is coincident with thick alluvial clay layers encountered in the boreholes. The presence of this highly conductive clay layer adds complexity to the interpretation of the seawater intrusion within the Robe survey area.

In order to better define the extent of the seawater intrusion the CDI data were re-examined. Manual interpretation of the conductivity data was undertaken and interpreted boundaries of the seawater intrusion were digitised from the CDI sections. The results of this manual interpretation are presented in Figure 4.36 along with the preliminary interpretation presented in Figure 4.35.

From the manual interpretation it is clear that the seawater intrusion is restricted to a much smaller zone concentrated towards the coastline, though there is still a significant landward ingress along the northern survey boundary. This increase in landward intrusion is coincident with a lobe of elevated groundwater salinity within the coastal plain alluvium identified by Commander (1994b) that is located between the Robe River and Peters Creek, which runs along the northern survey boundary.

To the southwest of this high salinity lobe the seawater intrusion is less extensive. Comparison of the mapped extents along the central tie-line with the geology map shows that the leading
edge of the seawater intrusion appears to terminate close to Multhuwarra Pool. Commander (1994b) identified the presence of a salt seep in the pool.

As with the Fortescue River, Ryan et al. (2003) classify the Robe River as a tide-dominated delta. The distribution of the high seawater area and coastal mud flats appears to be relatively uniform along the coastline with a slight increase in the landward extents along the northern survey boundary, coincident with the zone of significant landward ingress of the seawater intrusion.
5 CONCLUSIONS AND RECOMMENDATIONS

Interpretation of the geophysical data has provided a basement geology map derived from the magnetic data, relative porosity maps of all survey areas, approximate weathered and unweathered bedrock surfaces as well as the approximate geometry of the seawater intrusion within all survey areas. It was also possible to map the interpreted extents of alluvial aquifers within the De Grey and Yule River survey areas as well as the Broome Sandstone and Wallal Sandstone aquifers within the De Grey survey area. It is anticipated that this information will provide invaluable information for any future groundwater model.

The basement geology interpretation provides an updated and more detailed overview of the solid geology underlying the survey areas. Significant structural features have been identified and in some cases these features directly affect the groundwater system. Correlation with both FALCON™ AGG and AEM data has provided further confidence in the interpretation process.

Due to the lack of up-to-date salinity maps and uncertainties in the parameters controlling the bulk conductivity, it is not possible to produce a ‘true’ distribution of differing porosity across the survey areas. However, by assigning different conductivity bands to different porosity classifications it was possible to build up relative porosity maps over different elevations for each survey area.

Mapping the weathered and unweathered basement surfaces along the CDI profiles has allowed the generation of surfaces representing both interfaces. Correlation with borehole information allowed the determination of suitable conductivity values to represent these surfaces. It should be noted that these surfaces are considered approximate due to variations in the weathering of the basement contacts and the conductivities of the various basement lithologies. It is anticipated that additional work currently being undertaken by CSIRO may help to further refine these surfaces and the results should be reviewed when these data become available.

Although it was not possible to identify alluvial aquifers based solely on the conductivity data it was possible to map their extents using previous information as a guide. The published alluvial aquifer extents for the De Grey River and Yule River were used as an initial guide to the aquifer boundaries allowing the extents to be refined and the depth extents interpreted from the conductivity data.

Reviewing the CDIs from the De Grey River survey area with the borehole data and geological cross sections has enabled the identification of both the Broome Sandstone and Wallal Sandstone aquifers over the eastern half of the survey area. The presence of the conductive
Jarlemai Siltstone overlying the Wallal Sandstone means the confidence in the interpretation of the depth to the contact between the two units is not great. As with the basement surfaces, additional work currently being undertaken by CSIRO may help to further refine this contact.

It has not been possible to map the extents of the alluvial aquifers within the Fortescue River and Yule River survey areas due to the limited depth extent of the aquifers and their proximity to the ground surface. It is recommended that in order to map such targets in future a more appropriate geophysical system with superior near-surface resolution, such as Fugro’s RESOLVE system, is considered.

The high conductivity values resulting from the seawater intrusion results in a high contrast with the lithologies within the survey areas. Despite the numerous uncertainties with the use of using Archie’s Law to calculate an anticipated conductivity for the seawater intrusion, assessment of previous studies and the survey data allowed for an interpreted seawater intrusion to be mapped. The landward extents of the intrusions for each survey area are greater than might have been previously expected.

It was found that the FALCON™ AGG data was of limited use, apart from confirming certain features of the basement geology interpretation. Utilising such a system with a wide line spacing of 4,000 m nullifies any advantages that can be gained from the high resolution data. Although it is possible features of interest are present in the gravity data it is not possible to interpolate across the line spacing with any confidence. FALCON™ AGG has been used successfully to map palaeochannels for diamond and uranium exploration. If this technique is considered for future groundwater work then a more suitable survey design would be recommended.
6 APPENDIX A

6.1 AEM Datasets

Figure 6.1: AEM conductivity elevation grids for the De Grey River survey area. Elevations of (A) 10m, (B) 0m, (C) -10m, (D) -30m, (E) -50m, (F) -70m, (G) -90m and (H)-100m (All elevations are relative to datum). Conductivity values range from red (high) to blue (low).
Figure 6.2: AEM conductivity elevation grids for the Yule River survey area. Elevations of (A) 10m, (B) 0m, (C) -10m, (D) -30m, (E) -50m, (F) -70m, (G) -90m and (H) -110m (All elevations are relative to datum). Conductivity values range from red (high) to blue (low).
Figure 6.3: AEM conductivity elevation grids for the Fortescue River survey area. Elevations of (A) 0m, (B) -20m, (C) -40m, (D) -60m, (E) -80m, (F) -100m, (G) -120m and (H) -150m (All elevations are relative to datum). Conductivity values range from red (high) to blue (low).
Figure 6.4: AEM conductivity elevation grids for the Robe River survey area. Elevations of (A) 10m, (B) -10m, (C) -30m, (D) -50m, (E) -70m, (F) -90m, (G) -110m, (H) -130m and (I) -150m (All elevations are relative to datum). Conductivity values range from red (high) to blue (low).
6.2 Magnetic Datasets

Figure 6.5: Magnetic images for the De Grey River survey area. (A) Sunshaded Total Magnetic Intensity Differentially Reduced to Pole (TMI_DRTP), (B) TMI_DRTP - Horizontal Gradient (HG), (C) TMI_DRTP – 1st Vertical Derivative (1VD) and (D) TMI_RTP – Tilt Derivative (TD). Red outline indicates limit of AEM and FALCON™ AGG surveys, blue outline indicates the extent of the regional magnetic/gravity interpretation.
Figure 6.6: Magnetic images for the Yule River survey area. (A) Sunshaded Total Magnetic Intensity Differentially Reduced to Pole (TMI_DRTP), (B) TMI_DRTP - Horizontal Gradient (HG), (C) TMI_DRTP – 1st Vertical Derivative (1VD) and (D) TMI_RTP – Tilt Derivative (TD). Red outline indicates limit of AEM and FALCON™ AGG surveys, blue outline indicates the extent of the regional magnetic/gravity interpretation.
Figure 6.7: Magnetic images for the Robe River and Fortescue River survey areas. (A) Sunshaded Total Magnetic Intensity Differentially Reduced to Pole (TMI_DRTP), (B) TMI_DRTP - Horizontal Gradient (HG), (C) TMI_DRTP – 1st Vertical Derivative (1VD) and (D) TMI_RTP – Tilt Derivative (TD). Red outline indicates limit of AEM and FALCON™ AGG surveys, blue outline indicates the extent of the regional magnetic/gravity interpretation.
6.3 FALCON™ AGG Datasets

Figure 6.8: FALCON™ AGG images for the De Grey River survey area. (A) Vertical Gravity Component (gD) from Equivalent Source Processing, (B) Vertical Gravity Component (gD) from Equivalent Source Processing merged with regional data set, (C) Vertical Gravity Gradient (GDD) from Equivalent Source Processing, (D) Profile grids of Vertical Gravity Component (gD) from Equivalent Source Processing, (E) Profile grids of Vertical Gravity Gradient (GDD) from Equivalent Source Processing and (F) Profile grids of Curvature Gradient Amplitude (Gc).
Figure 6.9: FALCON™ AGG images for the Yule River survey area. (A) Vertical Gravity Component (gD) from Equivalent Source Processing, (B) Vertical Gravity Component (gD) from Equivalent Source Processing merged with regional data set, (C) Vertical Gravity Gradient (GDD) from Equivalent Source Processing, (D) Profile grids of Vertical Gravity Component (gD) from Equivalent Source Processing, (E) Profile grids of Vertical Gravity Gradient (GDD) from Equivalent Source Processing and (F) Profile grids of Curvature Gradient Amplitude (Gc).
6.4 Remote Sensed Datasets

Figure 6.10: Remotely sensed data for the De Grey River survey area. (A) Digital Elevation Model with brown/white as high elevation and blue as low, (B) Landsat 7ETM+ images representing bands 3, 2, 1 as red, green, blue respectively, (C) Landsat 7ETM+ images representing bands 7, 4, 1 as red, green, blue respectively and (D) Ternary radiometric image obtained from the Geological Survey of Australia, with potassium, thorium and uranium displayed as red, green and blue respectively. Red outline indicates limit of AEM and FALCON™ AGG surveys.
Figure 6.11: Remotely sensed data for the Yule River survey area. (A) Digital Elevation Model with brown/white as high elevation and blue as low, (B) Landsat 7ETM+ images representing bands 3, 2, 1 as red, green, blue respectively, (C) Landsat 7ETM+ images representing bands 7, 4, 1 as red, green, blue respectively and (D) Ternary radiometric image obtained from the Geological Survey of Australia, with potassium, thorium and uranium displayed as red, green and blue respectively. Red outline indicates limit of AEM and FALCON™ AGG surveys.
Figure 6.12: Remotely sensed data from the Robe River and Fortescue River survey area. (A) Digital Elevation Model with brown/white as high elevation and blue as low, (B) Landsat 7ETM+ images representing bands 3, 2, 1 as red, green, blue respectively, (C) Landsat 7ETM+ images representing bands 7, 4, 1 as red, green, blue respectively and (D) Ternary radiometric image obtained from the Geological Survey of Australia, with potassium, thorium and uranium displayed as red, green and blue respectively. Red outline indicates limit of AEM and FALCON™ AGG surveys.
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