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Mapping the hydrostratigraphy and groundwater salinity of the Ord Bonaparte plains from AEM and NMR data

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SUMMARY

This study is part of the groundwater investigations of the Ord Bonaparte plains in the East Kimberley region of Western Australia. A key project aim is to establish a spatial hydrostratigraphic framework to better understand the hydrogeology.

To achieve this, AEM data, inverted using 1D SELMA model, were produced as conductivity sections and elevation grids. Interpretation of the AEM data, in conjunction with lithostratigraphic information from three petroleum wells and seven project bores, aided the mapping of hydrostratigraphic units of the Devonian to Permian sequence of the Bonaparte Basin. Mapping results show that the Carboniferous Weaber and Kushill Groups are dipping to the east-northeast and contain laterally continuous stacked aquifers. Within the strata, resistive signatures are associated with sandstone aquifers, slight to moderate conductors are mapped as fine textured aquitard, or as interbedded fine to coarse textured sediment forming semi-confining layers.

A water table elevation map was constructed using surface NMR water content profile and machine learning approach to extrapolate across the study area. Using Archie's Law, groundwater conductivity was predicted from AEM conductivity and porosity derived from borehole NMR measurements.

Key words: AEM, NMR, hydrostratigraphy, Bonaparte, groundwater.

INTRODUCTION

This study forms part of the collaborative project between Geoscience Australia and Western Australia DPIRD to conduct a groundwater related investigation in the East Kimberley (Ord Bonaparte Plains) under the auspices of the WA Water for Food Program.

Prior to acquisition of new data, limited information was available on the hydrogeology of the study area. A single set of nested piezometers (13BP01) was installed in 2013 to provide a continuous standing water level record in a Carboniferous sandstone aquifer. A few shallow artesian privately owned bores are present along the edge of the sandy plain bordering the coastal mud flats. It was not known if the Devonian limestone aquifer is hydraulically connected to the Carboniferous aquifer; if the basin sedimentary rocks behave as a single aquifer or as multiple stacked aquifers, and the nature of the confining unit that gives rise to the artesian pressure observed in some bores.

As part of the groundwater investigation, an airborne EM survey using SkyTEM312 was flown in 2015. DAFWA drilled 7 pairs of monitoring bores ranging from 70 m to 110 m in depth into the shallow part of the Carboniferous aquifer. Geoscience Australia conducted a suite of geophysics surveys as well as soil and groundwater sampling campaigns in 2017 and 2018. The geophysics survey include borehole induction and natural gamma logs, borehole nuclear magnetic resonance (NMR) and surface NMR soundings.

The aims of this abstract are to present the technique and results of mapping the hydrostratigraphic units and water table and predicting the groundwater salinity by estimating its conductivity using AEM data and Archie's Law.

HYDROGEOLOGY

The study area is within the onshore part of the Petrel sub-Basin of the Bonaparte Basin, with rocks of Devonian to Permian age present. We use the stratigraphic terminology from Mory and Beere (1988) and Gorter et al. (2004, 2005). We infer the main units to be the Devonian Ningbing Group in the western part of the study area, the Late Carboniferous Weaber (Milligans and Tanmurra Formations) and Kulshill (Kuriyippi Formation) Groups, and the Permian Keep Inlet Formation in the northeast.

The main aquifers in the study area are the Tanmurra and Kuriyippi Formations. The Tanmurra Formation (Cut) consists of an interbedded calcareous and siliciclastic sequence deposited in a shallow shelf environment (Gorter et al., 2005). The Kuriyippi Formation (Cuk) was deposited in a fluvial environment with fining upward siliciclastic sequences typically 30 m to 90 m thick. The Keep Inlet Formation (Pk) consists of sandstone, shale and conglomerate deposited in shallow marine and glacio-marine environments (Mory and Beere, 1988) and is considered a semi-confined aquifer. The Milligans Formation (Clm) aquitard, composed of interbedded shale and siltstone, is present between the Devonian Ningbing Group (Dun) limestone aquifer and the Carboniferous aquifers. Prior to this study, it was not known if there is any hydraulic connectivity between the Devonian and Carboniferous aquifers.

MAPPING THE HYDROSTRATIGRAPHY

The hydrostratigraphic units were interpreted from AEM data, cross referenced with borehole litho-stratigraphic information, and electrical conductivity and natural gamma logs. The interpretation and hydrostratigraphic mapping were first carried out on a few representative AEM sections (Figure 7) across the survey area (labelled in Figure 1). This was followed by interpreting and mapping the hydrostratigraphy based on AEM elevation slice grids. The petroleum wells Bonaparte-1, Bonaparte-2 and Garimala, provided much needed lithological and stratigraphic information for interpreting the AEM at greater depths (> 150 m).

AEM Data

The SkyTEM312 AEM system was selected to provide semi-regional mapping of the groundwater system after a rigorous technology suitability assessment exercise. The AEM survey was flown in October/November 2015 with a total of 2,780 line kilometres of data acquired. The survey consisted of parallel lines flown with a spacing of 500 m over the main study area, with 2500 m and 5000 m spacing extending across the coastal plain, and individual traverses to the north and south-east of the survey area (Figures 1 and 2).

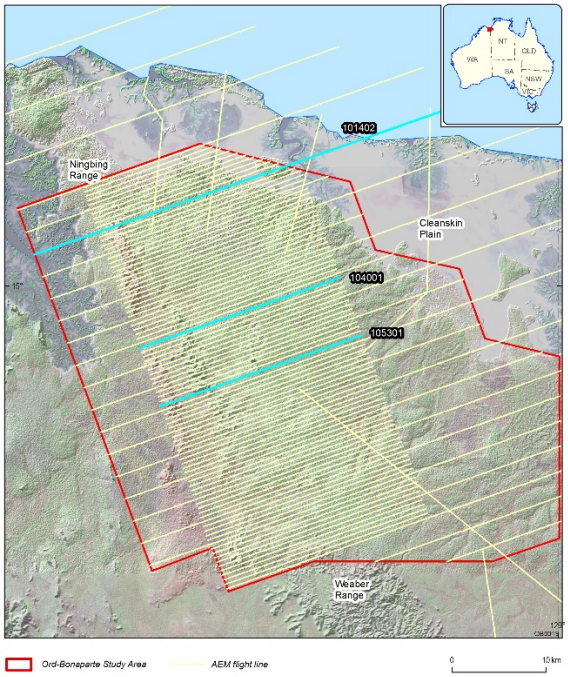

Figure 1. Bonaparte project area and AEM survey lines.

The AEM was first inverted with a 1D 30-layer Layer Constrained Inversions (LCIs) model (Auken et al., 2005) using the AarhusInv program (Auken et al., 2015). Following the availability of borehole induction conductivity logs, a borehole constrained inversion with few- and multi-layer models were produced using the SELMA 40 Inversion Procedure (Christensen, 2016).

The inverted AEM models were generated as flight line conductivity sections (Figure 2) and elevation grid slices from +160 m to -440 m. The thickness of each slice varies from 5 m to 50 m, with thickness increasing with depth (Table 1).

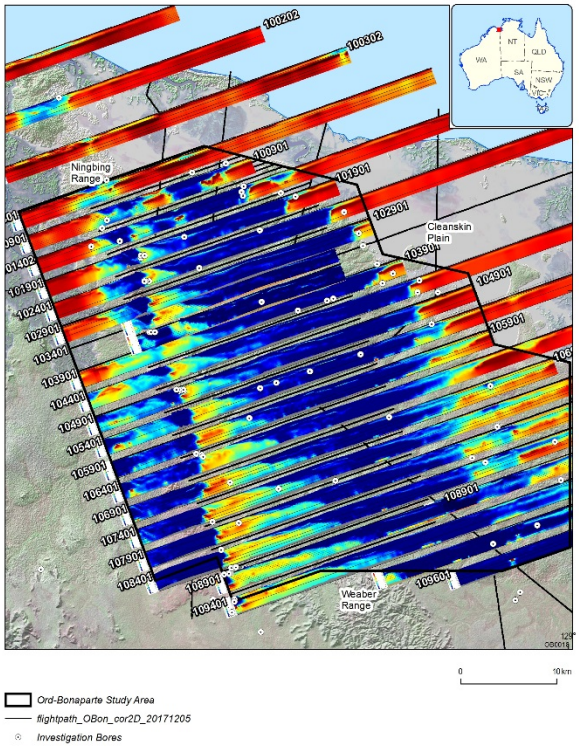

Figure 2. Representative AEM conductivity sections across the study area. Project bore locations are shown.

Table 1. AEM elevation slice intervals and thickness generated for hydrostratigraphic unit mapping.

From Depth (m AHD)	To Depth (m AHD)	Thickness (m)
160	-40	5
-40	-90	10
-90	-120	15
-120	-180	20
-180	-205	25
-205	-265	30
-265	-300	35
-300	-390	45
-390	-440	50

Mapped Hydrostratigraphy

From the conductivity patterns identified on AEM cross sections and elevation grids, the mid Devonian-Permian succession has been divided into nine electrical conductivity units which are correlated to the hydrostratigraphy. The principal near-surface aquifer underlying the proposed agricultural development area is termed the Kuriyippi Formation, which is divided into four units (Cuk1, Cuk2, and Cuk3 and its lateral equivalent Cuk3a). Cuk1 is a resistor, consisting of sandstone and include near surface vadose zone. Cuk2 is a weak conductor, and consists of thin beds of siltstone
and shale. Cuk3 is a resistor, which consists dominantly of sandstone interbedded with minor siltstone and shale. Cuk3a is a weak conductor, and comprises interbedded sandstone, siltstone and shale.

The Tanmurra Formation contains other principal aquifers in the study area, which are mapped as Cut1 and Cut2 based on

slight conductivity contrast. Cut1 has a lower conductivity than Cut2. Both Cut1 and Cut2 are dominantly sandstone with interbeds of limestone, siltstone and shale.

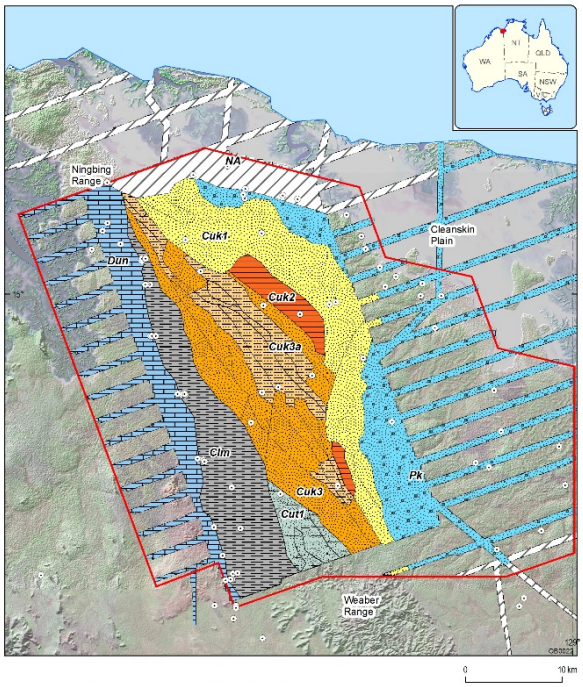

Figure 3. Mapped hydrostratigraphic units at elevation interval 0 to -5 m AHD. Refer to text for hydrostratigraphic codes.

An example of mapped hydrostratigraphic units for elevation grid 0 m to -5 m AHD is shown in Figure 3. The Carboniferous sequence, in general, has a northwest-southeast strike and dips towards northeast. The Milligans Formation is thick and laterally extensive, and separates the Devonian Ningbing Group limestone aquifers from the Carboniferous Tanmurra and Kuriyippi aquifers. However, the Milligans Formation becomes thin towards the north, and this may allow hydraulic connectivity between the Devonian and Carboniferous aquifers to occur. The Kuriyippi Formation aquifers are laterally extensive and separated in part by the confining aquitard layers (Cuk3a and Cuk2). The Permian Keep Inlet Formation overlies the Kuriyippi aquifer (Cuk1), where the latter becomes confined. Areas of high conductivity in the north mask the extent of the hydrostratigraphic units.

PREDICTING GROUNDWATER SALINITY

The conductivity of groundwater in the aquifers can be predicted by applying a function, derived from Archie's Law, to the AEM conductivity data from beneath the water table.

The relationships between *in situ* electrical conductivity of a sedimentary rock and its porosity, conductivity of the contained aqueous solution, and degree of saturation are illustrated in Archie's Law (Archie, 1950).

$$C_t = a^{-1} C_w \emptyset_m S_w^n \quad (1)$$

Where C_t is the bulk conductivity of the fluid saturated rock, C_w represents the electrical conductivity of the fluid, $\emptyset$ is the porosity, S_w is the fluid saturation, m is the cementation exponent of the rock, n is the saturation exponent and a is the tortuosity factor.

At full saturation where $S_w = 1$, Archie's Law can be written as equation (2). To determine the groundwater conductivity (C_w) of the aquifer, equation (2) was rewritten as equation (3).

$$\log C_t = \log C_w + \text{mlog}\,\emptyset \quad (2)$$
$$C_w = \text{Exp}_{10}(\log C_t - \text{mlog}\,\emptyset) \quad (3)$$

Aquifer Porosity

NMR data logs of six project boreholes were used to determine the total porosity of the aquifers using a Vista Clara JP350 sonde. Carr-Purcell-Meiboom-Gill sequence (CPMG) data were acquired at 0.5 m interval from the bottom of bore to 2 m above standing water level. The data were processed using Vista Clara custom software, with the capillary, bound and mobile water demarcated at < 3, 3 – 33 and > 33 milliseconds (ms) respectively. The 25th, 50th and 75th percentiles were calculated for the total water content as estimated by NMR. The averages for the six bores for these percentiles are 0.19, 0.21 and 0.24 respectively. The median value of 0.21 volume ratio is used to represent the porosity of the sandstone aquifers.

Mapping the Water Table

Standing water level measurements from 14 bores and 73 surface NMR data were acquired (Figure 4) to map the water table. These point measurements of water table depth were converted to water table elevation by intersecting with 1 m LiDAR digital elevation data (Figure 5). The modelling was done with a machine learning approach using the free spm package from the R project website (https://www.r-project.org/) (Lawrie et al., 2018).

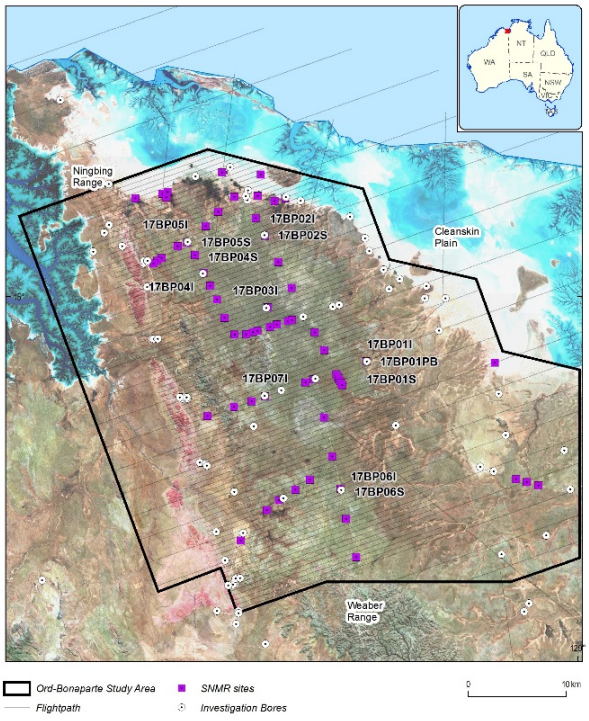

Figure 4. Location of project bores (labelled white dots) and surface NMR sites (purple square) overlain on LANDSAT imagery and AEM flight lines. Other white dots are pre-existing bores.

Surface NMR

Seventy-three sites were acquired with the surface NMR technique using a square transmission loop of 80 m to 100 m, an excitation pulse length of 60 ms and 80 ms, and with NMR frequency of 2041 Hz to 2044 Hz. The data were processed using Vista Clara customised interpretation software. The water content profile was modelled to 150 m depth with 60 m to 80 m depths of investigations.

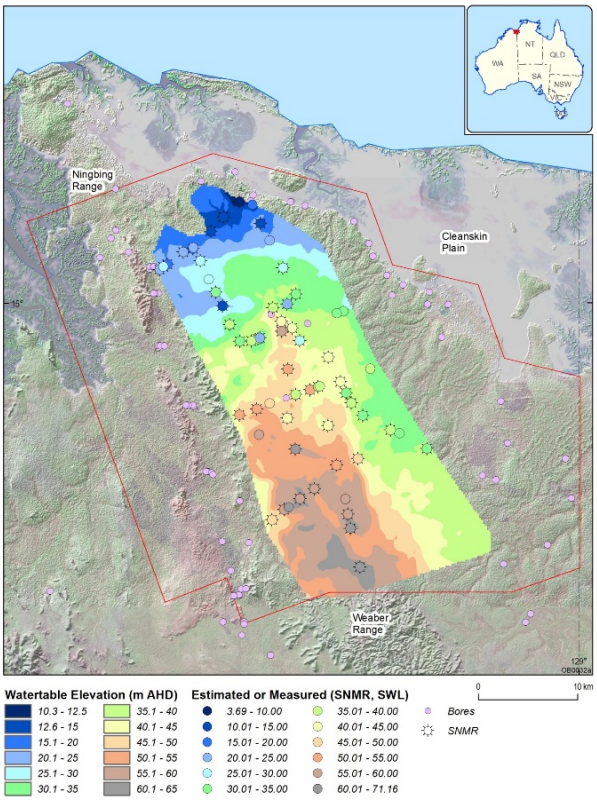

Figure 5. Predicted water table elevation map with surface NMR acquisition sites (dots).

Predicted Groundwater Conductivity Grids

Equation 3 was used to transform AEM conductivity below water table to pore water conductivity, the resulting grids are in µS.cm^{-1} for ease of interpretation. AEM conductivity in Siemens per metre (S.m^{-1}) is used as a proxy for C_t. The cementation exponent 'm' used is 1.8, with an averaged porosity of sandstone being 0.21 of the volume, which is derived from borehole NMR data. The mapped water table elevation was used to select the AEM elevation grid that represents the saturated condition. Surface NMR water content profiles were used to constrain the water table model.

Archie's Law assumes that the rock matrix is not electrically conductive and is valid for both clastic and non-clastic sedimentary rocks. If significant amount of phyllosilicates or sulphides are present in interbedded sandstone, siltstone and shale, equation 3 becomes invalid since the electrical conductivity is influenced by the solid matrix rather than, or in addition to, the conductivity of the solution in the rock pores.

Equation 3 is valid for predicting groundwater salinity using Archie's Law in the following aquifers: Cuk1 and Cuk3 (dominantly interbedded sandstones of varying textures, with minor siltstone, mudstone, and shale), Cut2 (mainly sandstone with interbedded limestone, calcareous sandstone and siltstone). Equation 3 should also be valid for Dun (mainly limestone with interbedded sandstone and siltstone). Archie's Law (and thus Equation 3) is not readily applicable to the Cuk3a or Pk due to abundant phyllosilicate minerals in interbedded siltstone, mudstone and shale.

An example of the estimated groundwater conductivity is shown in Figure 6. This map is generated from AEM elevation grids at 0 m to -5 m AHD, with extents of the hydrostratigraphic units shown. The salinity model shows that groundwater is mainly fresh (<800 µS.cm^{-1}) for Cuk1 Cuk3, and Cut2, with some areas of brackish groundwater (800-2000 µS.cm^{-1}). Groundwater in the Ningbing Group limestone (Dun) aquifer ranges from fresh to saline, and the western extent of Dun is not well defined from the AEM due to high electrical conductivity.

Groundwater conductivity may be overestimated for the semi-confined aquifers of Cuk3a and Pk due to the presence of clay in the interbedded units. The estimated conductivity is not applicable to the Milligans Formation (Clm), Cuk2, or coastal plain sediment due to the presence of abundant clay.

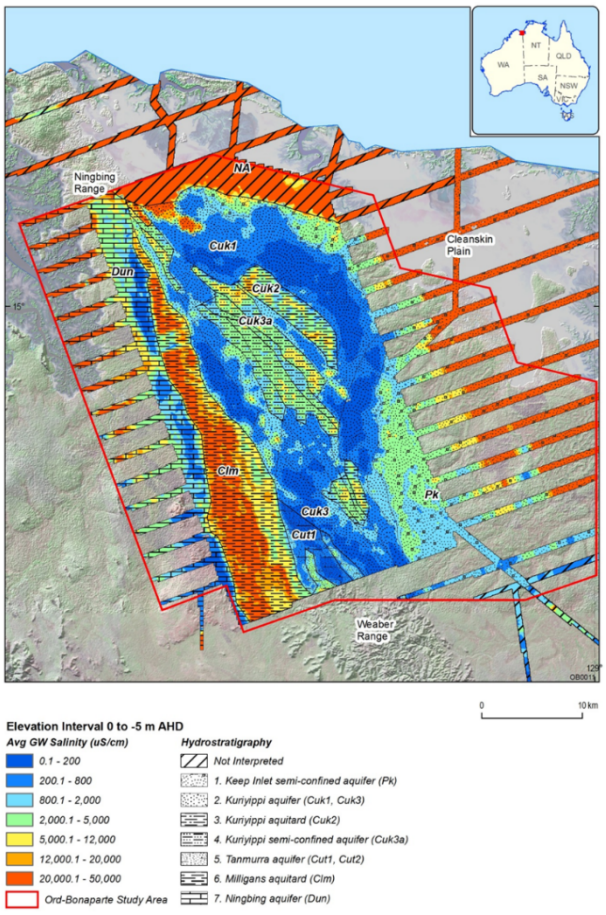

Figure 6. Predicted groundwater conductivity for the mapped hydrostratigraphic units for elevation interval 0 m to -5 m AHD. Refer to text for caveats.

CONCLUSIONS

The main Carboniferous aquifers of the Ord Bonaparte plains were interpreted and mapped using AEM data. Mapping results show that the Carboniferous Weaber and Kushill Groups are dipping to the east-northeast and contain laterally continuous stacked aquifers. Within the strata, resistive signatures are associated with sandstone aquifers, slight to moderate conductors are mapped as fine textured aquitard, or as interbedded fine to coarse textured sediment forming semi-confining layers.

Using Archie's Law, groundwater conductivity was predicted from AEM conductivity and porosity derived from borehole NMR measurements.

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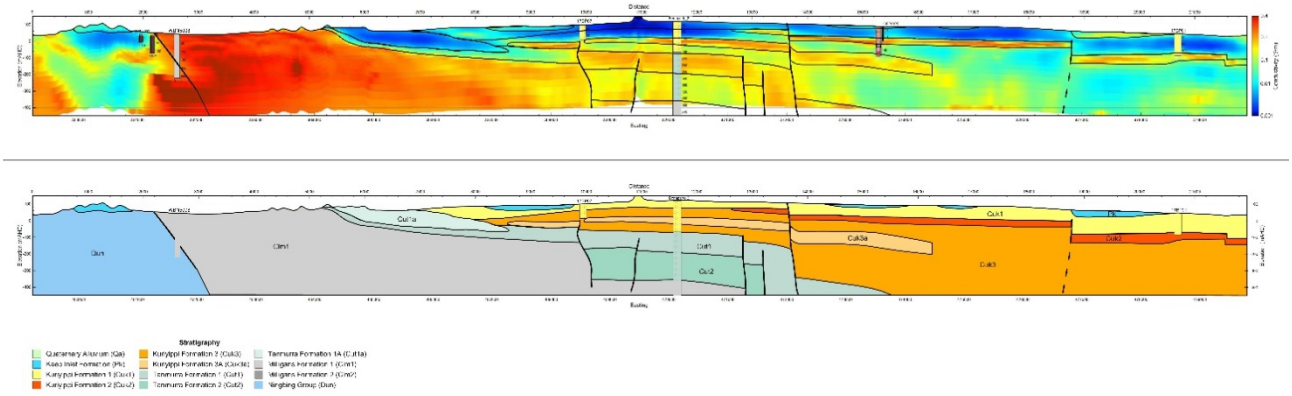

Figure 7. Interpreted hydrostratigraphy on an AEM conductivity section (survey line number 105301).