Determination of formation specific NMR calibrations for water well evaluation in a semi-consolidated aquifer.

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SUMMARY

Downhole NMR data was collected through a fibreglass cased section of water well NG3A that intersected the semi-consolidated sediments of the Yaragadee Formation which is one of the main aquifers supplying domestic water for the city of Perth. The main purpose of this work was to empirically derive formation specific NMR processing parameters to match the hydraulic property estimates to a direct core measurements, to calibrate the system to deliver a more detailed log of porosity and permeability in the hole as well as other holes logged in a similar geologic environment.

Equations for NMR permeability estimation generally include lithology specific calibration coefficients. We show that application of "generic" calibration coefficients derived for unconsolidated aquifer materials overestimate permeability in the Yaragadee Formation when compared to core permeability measurements. This result is expected given that the Yaragadee formation is not unconsolidated but is partially consolidated/cemented. More appropriate site specific coefficients were derived by scaling the calibration coefficients to produce NMR permeability estimates that match the measurements derived from the core samples. The site specific coefficients determined for the Yaragadee are consistent with those derived in previous studies for partially consolidated aquifers in the United States.

The NMR T_2 distribution is very sensitive to pore size changes which often reflect subtle changes in the sedimentary geology of the formation. This can provide additional geological information which may not always be apparent in mud or core logging. Detailed knowledge of both the sedimentary geology as well as the hydraulic properties of the formation that can be obtained by NMR are likely to be useful in identifying the best place to place screens during the design of a production water well to generate the best possible yield.

Key words: Nuclear Magnetic Resonance, NMR, logging, well evaluation, water.

INTRODUCTION

Nuclear Magnetic Resonance (NMR) logging is a well-established technique in the oilfield for mapping water and hydrocarbons within the formation. NMR measurements directly respond to hydrogen atoms present in the pore space of the formation. The probe contains magnets that polarize the fluid hydrogen and uses radio-frequency coils to excite and measure the NMR response from the hydrogen. Processing of the NMR signal provides useful information about the hydrogeological properties of the measured material, including total porosity, relative pore size distribution and estimated hydraulic conductivity. Detailed discussions of the background theory behind NMR can be found in Dunn et al. (2002) and Coates et al. (1999).

Recent advances in the manufacturing of these tools has enabled the development of smaller diameter probes which are suitable for use in standard sized holes and wells commonly used by the mining and water industries (Walsh et al., 2013).

This paper examines the results of NMR logging in water production well NG3 which is managed and operated by the West Australia Department of Water. NG3A is located approximately 10km to the southwest of the town of Gingin, in the northern part of the Gnangara Mound of the Northern Perth Basin, Western Australia. The hole is cased with steel above 54m depth and has an assembly for extracting water, including metal screens below 220m depth. The remainder of the hole is cased with fibreglass at a diameter of 150mm which is surrounded by a further 25mm thick cement grout.

The majority of the interval of NG3A examined in this paper (57-217m depth) intersects fluvial sands and silts of the Late Jurassic Yarragadee Formation, which is one of the main aquifers that supplies the city of Perth with groundwater for domestic use. This is overlain (54-57m) by a thin marine clay, which is interpreted to be of Miocene or Pliocene age (Department of Water, 2009).

Independent measurements of the hydraulic conductivity of the rocks from laboratory testing of 41 core samples taken from this hole were made available by the Western Australia Department of Water using a predictive model based on the grain size distribution of sediment particles. These were used as the basis for calibrating the hydraulic permeability estimates from the NMR data.

One of the key reasons for selecting this hole for the study was the availability of core measurements that could be used to validate the permeability estimates derived from NMR logging, which was intended to be used to assess other water wells in a similar environment where core information was not available.

DATA ACQUISITION AND PROCESSING

NMR logging was completed by the Wireline Services Group (WSG) during June 2015 using the Vista-Clara Javelin system with a JP350 probe. This probe has an external diameter of 89mm, fitting easily into the well. The design of this tool provides a large diameter of investigation (380mm), which is critical for focussing the measurements within the undisturbed formation, well outside the fibreglass casing and grout which has a combined external diameter of 200mm.

The tool was run in a dual-frequency mode with data collected at 50cm spaced intervals. Each sounding acquired at a lower frequency of 245 kHz and a higher frequency of 290 kHz. Data were also collected using two separate wait times of 0.8s and 5s, allowing for better estimation of short relaxation time components of the NMR response. Data were processed using Vista-Clara's proprietary software which is designed for the Javelin system.

A basic description of NMR petrophysics can be found in Walsh et al. (2013) and Coates et al. (1999). The total porosity of the formation is directly proportional to the total amplitude of the NMR response. This parameter was calibrated in WSG's workshop before the commencement of the survey by measuring the response in a tank of water which is assumed to represent 100% porosity.

In addition to the amplitude of the response, the time that the NMR signal takes to decay, known as the T_2 relaxation time or T_2, gives an indication of the relative pore-size distribution, with short T2 values being associated with smaller pores and longer T_2 values being associated with larger sized pores. The pore water content of the rock may be further categorised by NMR as "free", "capillary" and "clay-bound" water. While the T_2 range cut-offs for these different classifications are best defined by laboratory NMR measurements on core samples representative of the study area, widely used cut-off values from the oilfield industry between clay-bound / capillary water and capillary / free water for sandstones are T_2 times of 3 and 33msec, respectively (Dunn et al. 2002).

The hydraulic conductivity of the formation is estimated from the NMR data during processing using two different empirical formulae that were originally developed in the petroleum industry (after Coates et al., 1999);

- The Schlumberger-Doll Research Equation K_{SDR} estimates hydraulic conductivity using a total porosity estimated from the NMR initial amplitude response, S_0, and the log of the average NMR decay time (T_{2ml}) identified from the amplitude vs. T2 Relaxation Time plot, where;

$$K_{SDR} = C\, T_{2ml}^2\, S_0^N \qquad \text{(Schlumberger-Doll equation)}$$

- The mean-of-echoes equation K_{SOE} estimates K as a function of the mean signal amplitude squared, thereby incorporating both signal amplitude and decay time, where;

$$K_{SOE} = C\, \overline{S(t)}^{\,2} \qquad \text{(Mean-of-echoes equation)}$$

Both of these equations include a calibration constant "C". The SDR relation also includes a power index variable "N". These parameters are best defined by a site-specific calibration against permeability measurements made on core, although default values from literature can be assigned if no samples are available.

A section of output from the NMR processing software is shown in Figure 1. Output parameters include;

- T2_distribution – A pseudocolour amplitude plot of the T_2 Relaxation Time.
- A cumulative histogram plot showing the relative fraction of water calculated to be stored in clay bound, capillary and mobile (free) fluid pore spaces.
- Calculations of apparent permeability K_{SDR} and K_{SOE} from the NMR data. These have been directly compared with laboratory measurements (K_{LAB}) of fluid conductivity made on core samples by the Department of Water.

RESULTS

The estimated total porosity estimated from the NMR data varies between about 30-40%. Unfortunately, no direct measurements of total porosity from the core samples were available for comparison. As expected the total percentage of free water drops off markedly in the marine marker bed at the top of the logged section.

Initial estimates of permeability were made using the mean-of echoes (K_{SOE}) and Schlumberger-Doll (K_{SDR}) relationships were calculated using the default calibration constants in Vista-Clara's processing software which are based on measurements of unconsolidated aquifer sediments (C_SOE = 4200, C_SDR = 8900, N_SDR = 1) from Knight et al. (2015). These calculations resulted in an overestimation of apparent permeability by more than order of magnitude relative to the laboratory core measurements (Figure 1). This overestimation is believed to reflect to the differences in the hydrogeological properties of the semi-consolidated sediments of the Yarragadee Formation compared with the unconsolidated sediments on which the default parameters are based.

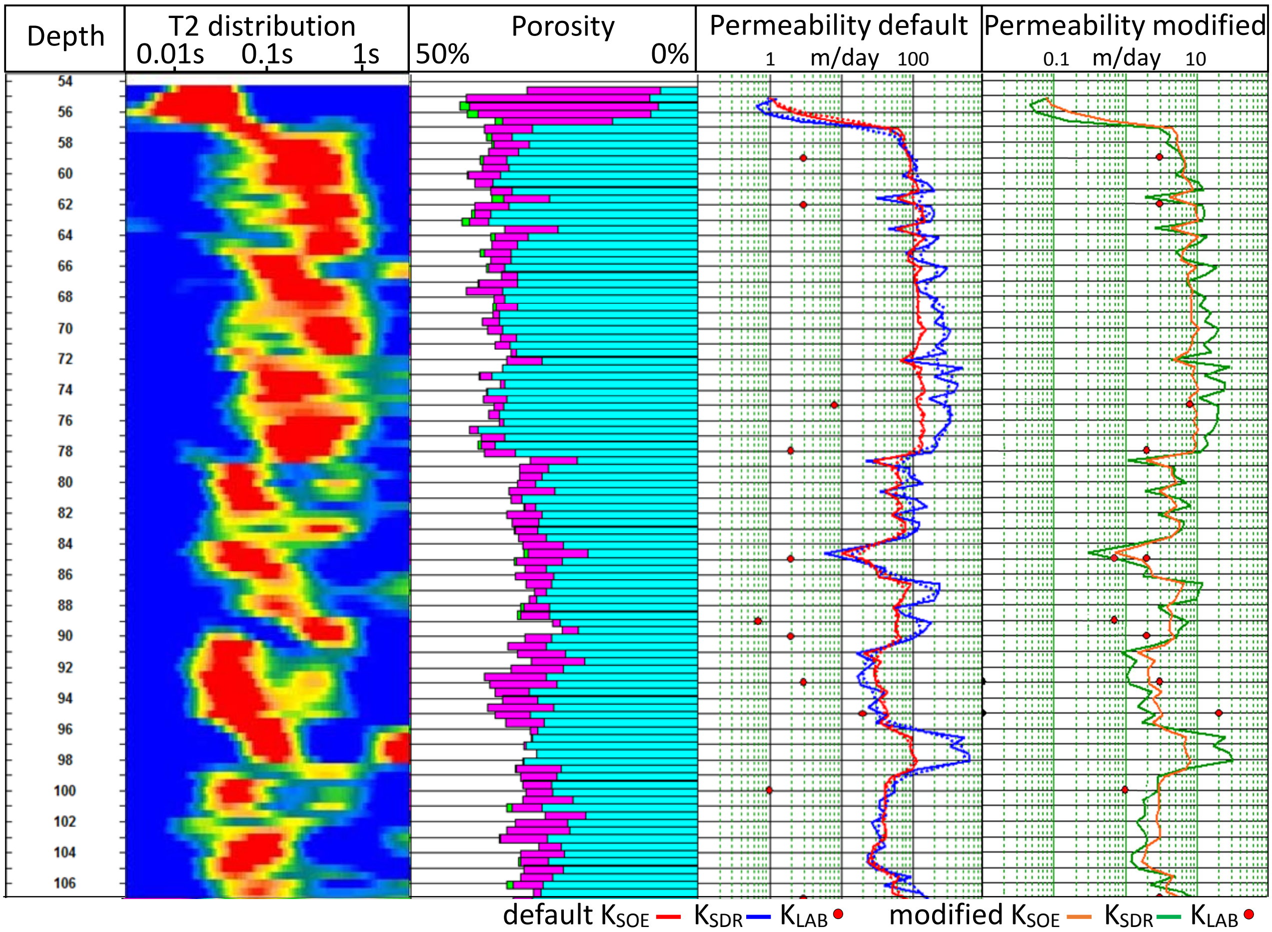

Figure 1: NMR logging results over a 50m section of NG3A showing (from left) T2 amplitude distribution; porosity estimates for the free (cyan), capillary (magenta) and bound (green) pore size fractions; comparison of laboratory and NMR derived permeability estimates using default processing parameters and modified parameters calibrated to this hole.

To allow for the difference in lithology, the data was reprocessed with empirically derived constants to better match the core measurements (C_SOE = 300, C_SDR = 1500, N_SDR = 2). These values are consistent with coefficients derived for partially consolidated/cemented aquifer materials in the central United States (Dlubac et al., 2013). The revised NMR permeability estimates calculated using these modified calibration parameters show a much closer agreement with the laboratory measurements (Figure 1, last column).

The NMR T_2 distribution is very sensitive to pore size changes which often reflect subtle changes in the sedimentary geology of the formation that cannot be easily identified from lithological logging of cuttings alone. While little differentiation could be seen in the sediment lithology interpreted from mud-logging (sand = yellow, silt/clay = green), even subtle changes in pore size can be readily identified in the NMR T_2 logs and the derived classification of bound / capilliary / free pore spaces. These, in turn, can be reasonably assumed to reflect changes in grain size of the sediments as shown in Figure 2.

The recorded T_2 response at the top of the hole shows the pattern of a series of cycles grading from long Relaxation Times at the base to shorter times above. This is suggestive of a series of upward fining sedimentary cycles which would be consistent with the braided stream sedimentary environment in which the Yarragadee Formation was deposited, with coarser clean sand representing the centre of a fast flowing channel leading to increasing finer sediments as the channel filled up. This pattern is repeated in the natural gamma and resistivity logs, thereby supporting our interpretation.

Of particular note are intervals of significantly more permeable sands (high_K sand) which are identified by a darker yellow colour in the WSG Litho log. These are primarily characterised by their high NMR hydraulic conductivity values (up to four times greater than other sands) and are assumed to represent intervals of clean sand which could potentially generate a high yield in a producing water well.

CONCLUSIONS

Production water well NG3A was successfully logged through fibreglass casing and 25mm of cement grout using the Javelin downhole NMR system with a JP350 probe to be able to map the hydraulic properties of the undisturbed formation. The large diameter of investigation of this probe is a key feature that allowed for successful logging in this borehole environment.

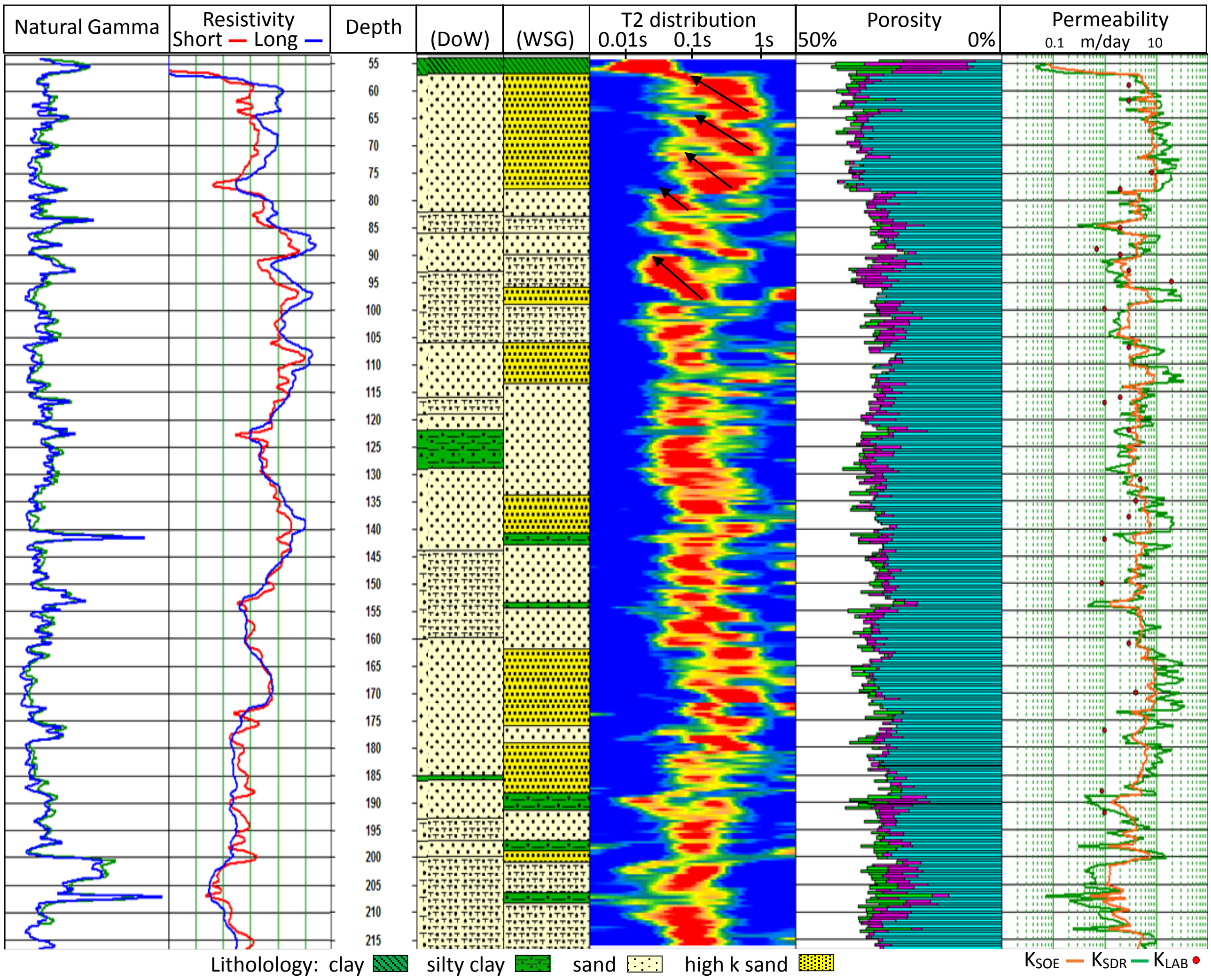

Figure 2: Compilation of wireline petrophysical logging and NMR results for NG3A. The lithology interpretation for the hole is has been revised using this additional information from the original mud-logging by Department of Water geologists. The geologist's mud-log is shown in the Litho (DoW) column, while an amended lithology interpretation based on NMR and geophysical logs are shown in Litho (WSG). Black arrows show likely upward fining sedimentary sequences interpreted from the T_2 distribution plot.

NMR offers a means of determining the porosity of the formation without the need for a nuclear source. It can also be used to determine other key aquifer parameters such as formation permeability which are expensive and time consuming to obtain by traditional methods such as laboratory measurements or pump testing on exploration water wells. However, it is important to consider differences in lithology, particularly the degree of consolidation and cementation, when determining the correct processing parameters for estimating the hydraulic conductivity from NMR data.

If laboratory measurements of hydraulic conductivity are available, formation specific calibrations for the estimation of permeability from the NMR response can be easily derived by curve matching to the core data. Formation specific calibrations are important where the lithology is significantly different to that used to define the "default" parameters used by the processing software as using the incorrect values can lead to errors in the permeability estimates of more than an order of magnitude.

Finally, plots of NMR T_2 Relation Time distribution can be used to identify relative subtle changes in sediment grainsize, and hence lithology which may not always be apparent in mud or core logging. These can, in turn, assist with interpretation of the sedimentary geology of the well.

This combination of information that can be derived from NMR logging can potentially assist in placing screens for a production water well to generate the best possible yield.

ACKNOWLEDGMENTS

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