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Realtime analysis and well planning using wireline logs in a hydrogeological context

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SUMMARY

During the drilling process, numerous decisions must be made, often with limited information. In a known area prior knowledge often guides these decisions. In a recent drilling program in the Northern Perth Basin, as part of a research project to monitor the use of aquifers, petrophysical logs were used to help inform some critical decisions. Further analysis of the data collected from the borehole was going to be used to monitor quality, extent and connectivity of the numerous aquifers that make up the Northern Perth Basin. As an aquifer monitoring program, it is critical to ensure that the bore is accessing the aquifer in question. Therefore, accurate knowledge of depth and quality of formation is key. This paper shows how to use a simple set of petrophysical logs including natural gamma, resistivity and borehole magnetic resonance logs can be used to make informed decisions. For example, using a composite log, decisions were able to be made on screen placement prior to running, and also helped decide if extra bores on the same drilling pad were required. Finally, we were able to determine the salinity of ground water from wireline logs. The ability to make these decisions with accurate information not only ensures successful well completion but also maximises resource use.

Key words: Hydrogeology, Borehole Magnetic Resonance, Salinity.

INTRODUCTION

The Northern Perth Basin is a well-known and utilised water resource and is made up of nine main aquifers. Recent increases in agricultural and horticultural industries in the area, has placed an ever-increasing demand on groundwater resources. As the demand increases for access to water supplies, the more information / data that is required to better manage the limited resource. Data on aquifers can come from several surface sources and existing bores, however information acquired from a borehole is invaluable. The data can not only answer immediate questions about well completion and water quality, it can be used in larger studies / models to help guide the management and regulation of the basin. To better help understand the long-term health of an aquifer, several bores were drilled in to the basin to monitor and determine; water quality, extent of aquifers and aquifer communication. To ensure the project success it is critical that bore completion is correct.

The drilling of bores is an expensive and time-consuming process. It can be also quite risky when drilling in to a new formation. The overall need for information however justifies this drilling expense. To minimise the risk, accurate data that provides relevant decision-making information, is required at the rig in near real-time.

When drilling a bore, there are several key questions that need to me made within a few hours from reaching the planned total depth and before completion starts.

1. Where to set screens to optimise aquifer monitoring?
2. What is the formation water salinity?
3. Are there any other aquifers of interest that should be monitored? Does this require another bore?

Historically these questions have been answered on previous experience in the area, chip descriptions, and occasionally basic wireline logs due to concerns about price, radiation, and fit for purpose. Recently more advanced logging tools typically seen in the oil and gas industry has made their way in to the slim hole market making them more readily accessible to the hydrogeology market. The BMR, Borehole magnetic resonance (BMR), is one such tool that provides a measurement sensitive to both porosity and pore size distribution allowing for the hydraulic characterisation of the formation. We show how one of these tools has had on the above decision-making process to great success.

METHOD AND RESULTS

A series of bores were drilled in to the Northern Perth Basin for the purpose of research and monitoring. The aim of the research is to investigate different aquifer systems, determine the quality of water, lateral and vertical extension, and connectivity. To ensure success of the research project it was decided that accurate downhole information is required, and wireline logs can supply the necessary information. The data can be supplied within hours of the tool returning to surface as well as being used as inputs for a petrophysical analysis to determine critical hydrogeological properties. The quick processing and turnaround of data is essential. For a monitoring program where specific formations are being targeted, it is critical to get the placement of screens correct. Zonal isolation is also very important in these cases to avoid between aquifer communications. To optimise screen location, the exact depth of the interval of interest is required and obtained from downhole wireline logging.

Wireline logging measurements range from the very basic to advanced. For example, natural gamma ray is very good for bed picking, however the notion that low gamma indicates clean sands, fails in locations where there are naturally occurring radioactive minerals. Resistivity tools can range from the very simple to very complicated and can use two different methods (induction and laterolog). The difference in quality between the basic and advanced tools is significant. Added to the complication of an accurate measurement is that the formation and drilling method plays a critical role in which method to use. Both Gamma ray and resistivity have been the mainstay of hydrogeology logging, with density often not used due to concerns about lost or damaged radioactive sources. To gain a better understanding of the hydraulic properties a nuclear magnetic resonance tool can be used to get a lithology independent porosity and permeability profile.

Nuclear magnetic resonance is a well-known measurement procedure and used in medical, chemical and oil and gas industries. The measurement is sensitive only to hydrogen in water and hydrocarbons and as such makes a great technique to measure fluids contained in pore spaces. For these reasons, the oil and gas industry has been using it since the 70s to quantify resources. The theory of nuclear magnetic resonance has been described elsewhere thoroughly (Kleinberg 2001, Neville and Hopper 2017). The use of borehole magnetic resonance in hydrogeological characterisation is increasing, as recently the tool size (length and diameter) has been significantly reduced in order to be run in water bores (Hopper Trofimczyk and Birt, 2017). Borehole magnetic resonance provides continuous measurements of hydrogeological properties at a scale intermediate between core and packer test data, providing a convenient framework for integration of all data. It also allows for the zoning of logs to get a more accurate value across the aquifer. Outputs of BMR are total porosity (lithology independent), specific yield, specific retention and permeability / hydraulic conductivities.

For a large drilling campaign, multiple open hole logs were conducted on the bores. The following logs were conducted:

- Resistivity (induction and laterolog)
- Natural Gamma
- Density
- Spectral Gamma
- Borehole magnetic resonance

After logging, a basic field print as shown in Figure 1 was delivered. Using this basic log, the drilling supervisor was able to make decisions on where to set screens, determine water salinity and make decisions on requirement for additional bores at the site.

SCREEN SETTING AND ADDITIONAL BORES

Direct access to the aquifer is through the screens, as such it is critical to get the depth correct. For single aquifers this setting is easy to predict using basic information like mud samples or gamma ray logs to find the location of the lithology change. In locations where there is significant local knowledge and simple lithology an educated guess can be made where the aquifer is before even drilling the bore. However, in more complex lithologies where we have multiple aquifers and varying water quality, a better understanding of the formation is required. Especially in cases where a blanket screening across multiple zones is not possible due to potential cross contamination of aquifers and the need for zonal isolation.

Figure 1 is an example of a typical composite log delivered less than 1 hour after logging. Track 1 details the natural gamma log and caliper, track 2 is the depth track, track 3 contains the spectral gamma logs, track 4 is the resistivity logs (shallow and deep), track 5 is the total porosity and compensated density log, track 6 is the BMR T2 distribution which is essentially a pore size distribution, track 7 is the water volumes based on the T2 distribution, and track 8 is the hydraulic conductivities calculated using two methods. The interpretation and processing of borehole magnetic resonance tool is complex with multiple parameters able to be adjusted. However, using previous research into clastic formations, the global standard for fluid cut-offs and hydraulic conductivity constants were used with excellent results.

Using only GR and resistivity logs the setting of screens can be difficult, especially in cases where resistivity measurements have been highly affected by borehole conditions. In one of the examples the resistivity failed. Often perceived as a simple measurement, resistivity tools rely of modelled responses of the conductivity changes in order to account for borehole and formation conductivity contrast, bedding and shoulder effects, borehole size, and tool standoff. Thus, the use of a more advanced resistivity tool is important when the aim is to calculate an accurate formation salinity.

Using the water volume track we can see break down between three main water classifications: bound water, capillary bound water and free water. This breakdown comes from the T2 distribution which gives us a pore size distribution function with larger grains indicating larger pores which implies free fluid. The grain size is also an indication of pore throat size which is the driving factor in permeability. When viewing the water volume track we see that there several zones that contain a large moveable water content and high hydraulic conductivity. These are the ideal location to set the screens, in this example two screens were set in sperate bores to access the aquifer at 313 m to 319 m. Based on the wireline logging results it was decided that a second bore was required to monitor a shallow aquifer 199 m to 205 m. In previous drilling campaigns this aquifer may not have been picked as there was insufficient data to quantify. Figure 2 shows a zoomed-out view of the borehole log. The orange sections show other possible locations that could be used for aquifer access.

SALINITY DETERMINATION

The ability to calculate groundwater salinity from the log is very essential for drilling operations. If salinity is greater than 1900 µS/sm (or ~1187 ppm) the drillers cannot discharge water on the ground during bore development and it must be contained. In case of high flow rate they have to be prepared to organise plastic containers to collect water and book special service to dispose water from the site. If prior knowledge of salinity levels is known before drilling is commenced resources can be booked accordingly at the site, either saving money by not requiring them or avoiding potential environmental harm. However, in exploration areas, this must be calculated at the wellsite using produced fluids via drillstem test or using wireline logs.

In a petrophysical interpretation, Archie's equation is used to calculate the water saturation in pores. The basic Archie's equation requires porosity (ϕ), water resistivity (R_w), and formation resistivity (R_t) (Archie, 1942). In a hydrogeological situation, water saturation is 1 and the equation can be simplified and rearranged to give formation water resistivity as below.

$$R_w = \frac{R_t \emptyset^m}{a}$$

Where a and m are constants and formation dependent. In shaly sands, as is the case in this lithology, 1.65 and 1.33 were used respectively. These can be calculated using cross plots as contained in the Schlumberger Log Interpretation Charts. There are several assumptions made in the determination:

- R_w should be calculated in the clean sand
- Thickness of the interval also should be not less 8-10 m to avoid shoulder effects on resistivity measurements (can be limited with focused resistivity tools)

Once water resistivity is known it can be simply converted to a salinity (ppm) using the following equation (Baker Hughes Inc, 2002). This equation is very similar to the one proposed by Sen, N. et al., (1992).

$$Salinity = 10^{3.562-LOG(R_w-0.0123)/0.955}$$

Alternatively, there are charts available for more manual conversions, for example the Schlumberger Gen-5 chart (Chart Gen-5, 2009).

Figure 3 is the results from two bores that had samples sent to the lab. All the results from geophysical logs are within the 5% uncertainty of the lab analysis. Previously it was required to wait on sample collection and lab analysis to determine downhole salinity. With the use of two logs of total porosity from a borehole magnetic resonance tool and a good deep resistivity, a water salinity can be calculated instantaneously. This knowledge allows for the better picking of screen locations and ensuring the waste disposal method during the drilling process is suitable for the water resistivity.

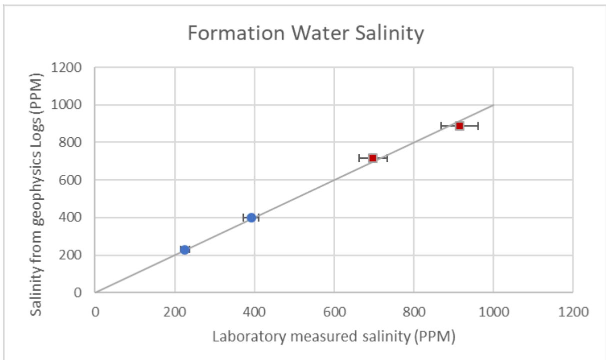

Figure 3. Cross plot of laboratory and petrophysical log salinity measurements. Data plots very close to the unity line showing great correlation between the data points.

CONCLUSIONS

The drilling process is very complicated and its success hinges on making informed decisions. These decisions will not only impact the direct quality of the bore but also impact the quality of research and questions that can be answered from the bore. As part of a research project investigating the Northern Perth Basin, a wireline logging program was included in the drilling program. The logging program was set to ensure that acquired data was able to be used both immediately and also in the ground water modelling. In the short term, decisions were made on which aquifers were to be accessed within the basin, and how many bores from the drilling pad were required for monitoring. Further to this the quality of water for water disposal during the drilling process determined in near real-time. Borehole magnetic resonance logs give a lithology independent total porosity and a pore size distribution which can be used to determine bound and moveable water volumes. The separation of the water volumes gives a clear indication of usable aquifers to aid in setting screen depths.

By combining all the logs and using petrophysical techniques water salinity can be determined. Water salinity not only directly influences whether the water can be used for humans, agriculture, livestock, or not at all. This salinity is also needed during the drilling operation to help decide on mud systems for swelling clay stabilisation. Saline water requires special waste disposal which can be costly and time consuming. This paper shows that with the correct design of a logging program the data can be used immediately to make informed decisions on the drilling program. These decisions can help save money and ensure monitoring and research program success.

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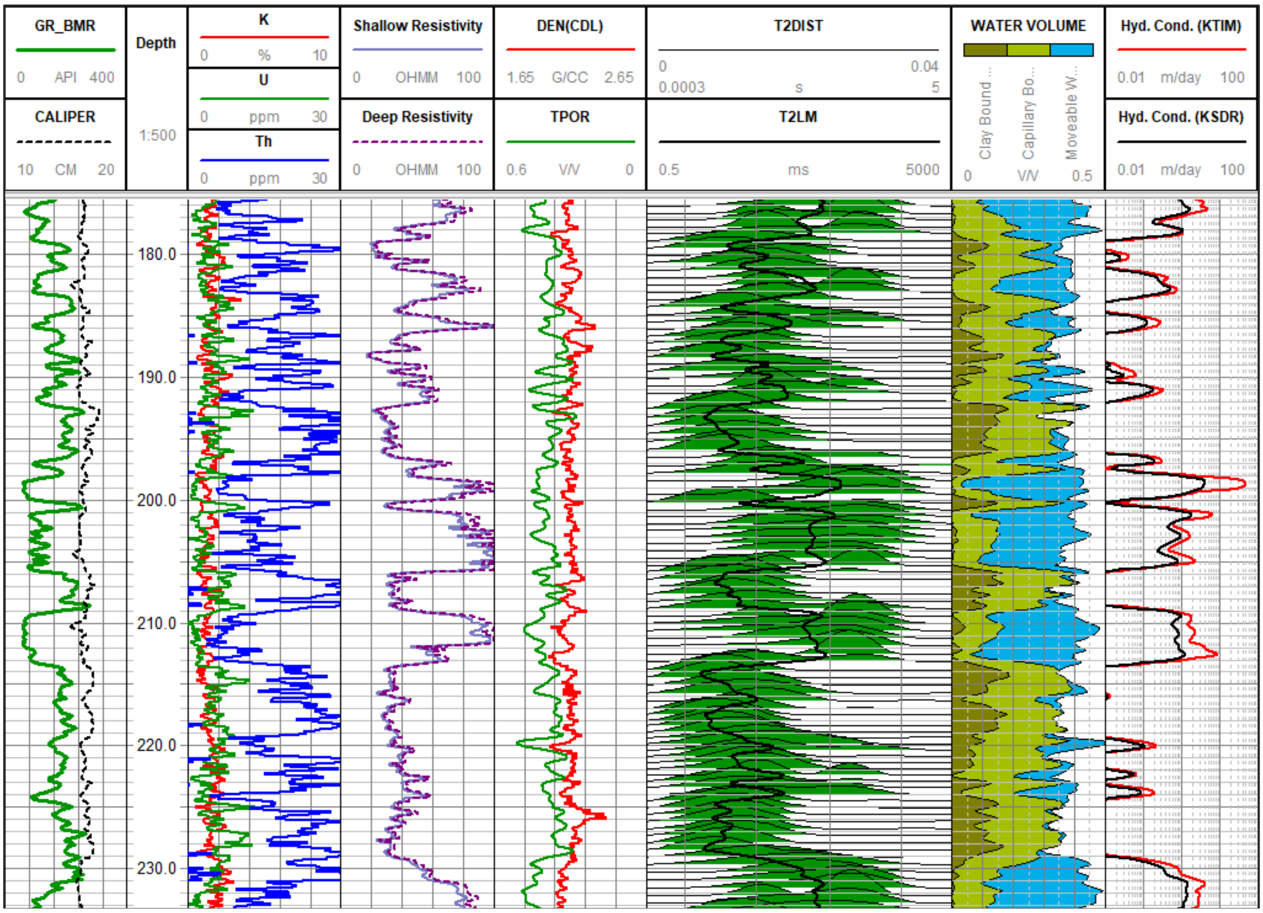

Figure 1. Example BMR log for a monitoring bore installation. Data includes spectral gamma ray, resistivity, density and borehole magnetic resonance. Combined gives both qualitative and quantitative analysis for both short term decisions and long term aquifer analysis

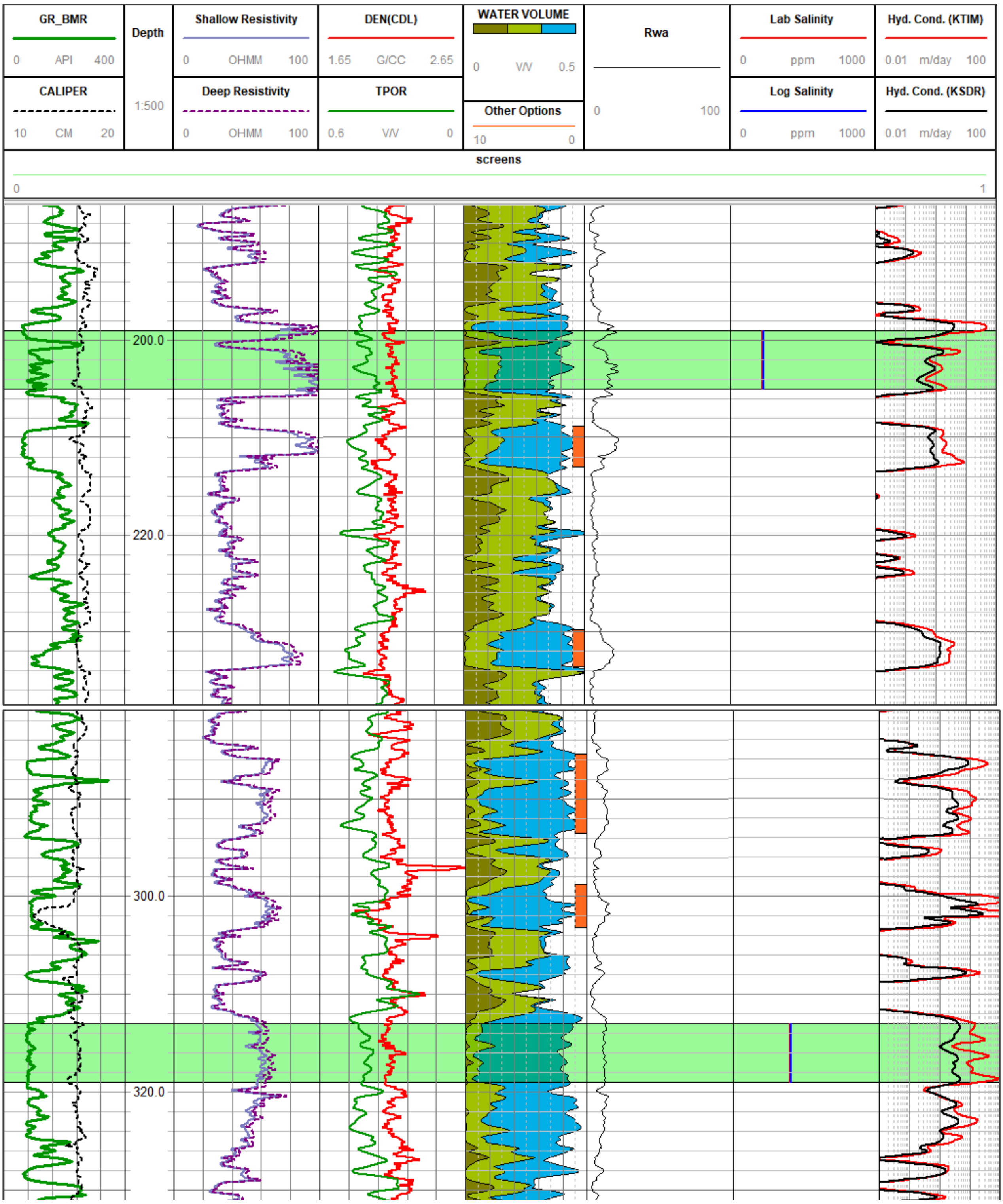

Figure 2. Screen placed over two different aquifers in two bores on the same pad. Other potential aquifers that could be monitored are highlighted with orange bars.