BOREHOLE MAGNETIC RESONANCE IN COAL SEAMS

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Abstract

Borehole Magnetic Resonance (bMR) has been used routinely in the oil and gas industry for decades, but its application to the mining and water industries has been limited by the size of the logging tools and the cost of the service. This has recently changed with slim-hole bMR tools now available in a range of sizes. In addition to the standard porosity measurement and permeability estimate, NMR tools are also capable of differentiating water and hydrocarbons. This paper discusses the use of bMR for the standard hydrogeological uses as well as for resource evaluation of adsorbed gas. The ability to quantify the gas content, water content, and permeability through downhole measurements allows for detailed assessment of coal methane mining and the effect on aquifers.

Method

Conventional logs including GR, Density, Neutron, Resistivity, and Televiewer were acquired along with borehole Magnetic Resonance (bMR). The bMR tool was run at 1m/min throughout the entire well, to provide hydrogeological parameters needed in the modeling of water within the resource. The bMR tool was then logged using station measurements at the top and bottom of each coal seam. At these locations a diffusion measurement based on stimulated echoes was acquired. This technique was specifically developed for measuring adsorbed gas content. Adsorbed gas is a pseudo liquid membrane coating the coal faces and has a density of ~ 0.6-0.65 g/cc and hydrogen index of ~ 0.6-0.65. It has a low diffusion coefficient ~ 10^{-10} m/s^2 whilst still having a long T_2 (>500 ms). As a result of the low diffusion and long T_2 time, current bMR tools are not sensitive to the adsorbed gas and standard measurements such as T_1-T_2 and D-T_2 sequences have not been able to detect it.

The T_1/T_2 ratio is typically significantly greater than 1 for adsorbed gases and tightly bound surface fluid layers. In these cases it is advantageous to use a stimulated echo for encoding diffusion. Consider the following “diffusion editing” pulse sequence (M.D. Hurlimann, 2002).

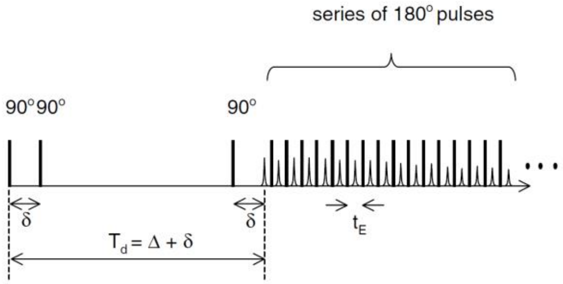

***Figure 1**: Diffusion editing pulse sequence.*

The sequence shown above consists of an initial diffusion encoding segment followed by a train of refocusing pulses. It can be viewed as a variant of the well-known Carr-Purcell-Meiboom-Gill (CPMG) sequence used to measure T_2 in which the normal 90° excitation pulse has been replaced by a composite excitation pulse with diffusion sensitivity. After an initial transient that typically lasts 2-3 echoes, the refocused echo amplitudes decay exponentially with a time constant T_{2eff} that is a weighted sum or T_1 and T_2. The amount of T_1 weighting depends on the B_0 and B_1 distributions but is typically no more than 10%.

The coherence pathway known as the "stimulated echo" stores longitudinal magnetization (aligned with B_0, i.e., the z-axis) during the delay of Δ-δ between the 2nd and 3rd 90° pulses. The magnetization decays exponentially with a time constant of T_1 during this interval, while it decays faster (with a time constant of $T_2 < T_1$) during the two inter-pulse intervals of length δ. The main advantage of the stimulated echo sequence is the fact that signal decay is relatively slow (T_1 relaxation) during the Δ-δ delay period, which improves measurement sensitivity for small diffusion constants. However, in the grossly inhomogeneous fields of bMR tools, a 16-part phase cycle is required to select the stimulated echo pathway. Phase cycled data should be collected for several values of δ while adjusting the value of Δ to keep $T_d = \delta+\Delta$ constant. The maximum value of δ is Δ, but in practice it is usually limited to $\Delta/2$ or less in order to minimize the amount of transverse signal decay (T_2 relaxation) during the diffusion encoding period.

After the end of the initial transient, the measured echo amplitudes as a function of echo number (k) and δ are given by;

$$A(kt_E,\delta)=\iiint dD\,dT_{2eff}\,dT_1\,f\left(D,T_{2eff},T_1\right)e^{-T_d/T_1}e^{-2\delta\left(1/T_2-1/T_1\right)}e^{-q^2D(\Delta-\delta/3)}e^{-kt_E/T_{2eff}}.$$

Here $q\equiv\gamma g\delta$ where γ is the gyromagnetic ratio of the nucleus and g is the static field gradient. In addition, $f\left(D,T_{2eff},T_1\right)$ is the three-dimensional (3D) relaxation-diffusion distribution function of the sample. However, it is difficult to invert this 3D integral equation to find $f\left(D,T_{2eff},T_1\right)$. Instead, we define the two-dimensional (2D) distribution function of spins that survive for time T_d as;

$$f_{T_d}\left(D,T_{2eff}\right)=\int dT_1\,f\left(D,T_{2eff},T_1\right)e^{-T_d/T_1}.$$

If we further assume that $\delta << T_d$, then $e^{-2\delta\left(1/T_2-1/T_1\right)}$ term is negligible compared to e^{-T_d/T_1}. The measured echo amplitudes are then given by;

$$A(kt_E,\delta)=\iint dD\,dT_{2eff}\,f_{T_d}\left(D,T_{2eff}\right)e^{-q^2D\left(T_d-4\delta/3\right)}e^{-kt_E/T_{2eff}}.$$

This 2D integral equation can be solved to find $f_{T_d}\left(D,T_{2eff}\right)$ by using the usual regularized 2D Laplace inversion methods.

The sensitivity of the diffusion editing sequence is affected by two quantities: *diffusion contrast* (defined as the ratio of change in initial signal amplitude to the maximum amplitude as a function of δ) and *signal-to-noise ratio* or SNR (in this case, defined as the sum of the echo amplitudes). Specifically, the product of these two quantities can be used as an approximate measure of sensitivity.

The bMR tool used for these experiments was the NMRSA QL69_NMR. Each measurement required 11 values of δ between 0 and 15 ms, i.e., 11 x 16 = 176 scans. The final SNR was improved by averaging each set of scans 4 times. This resulted in each station measurement requiring 176 x 4 = 704 pulse sequences. Processing of the data involved manually checking and removing data sets containing environmental noise spikes, because these can cause erroneous inversion results. The selected data was then inverted to find $f_{T_d}\left(D, T_{2eff}\right)$ and the results plotted as 2D maps to enable easy separation of various fluid types. The fluid volume of the adsorbed gas can then be calculated and converted to gas volume per cubic tonne of coal (m^3/tonne). These were then compared with desorption experiments performed in a lab. Locations for testing the stationary adsorbed gas technique were chosen by the petrophysicist after reviewing the bMR and standard log data. Core plugs were analyzed using a CMS^{TM}-200 Automated Permeameter. Confining pressure was applied to the cores to ensure accuracy of results.

Results

Six wells were logged, of which two had core data that was sent to the lab for desorption testing. These consisted of a number of core plugs taken from the whole core and standard helium porosity, permeability, and grain density measurements taken by Core Laboratories. The bMR data was split into clay bound water, capillary bound water, and free water volumes. The calculated dry weight matrix density compares well with the laboratory grain density measurements, as does the helium porosity. Porosity values in these coals are typically low, with values ranging from 1-10%. By combining the bMR free fluid track with an image log, it becomes possible to determine if cleats or fractures are open or closed.

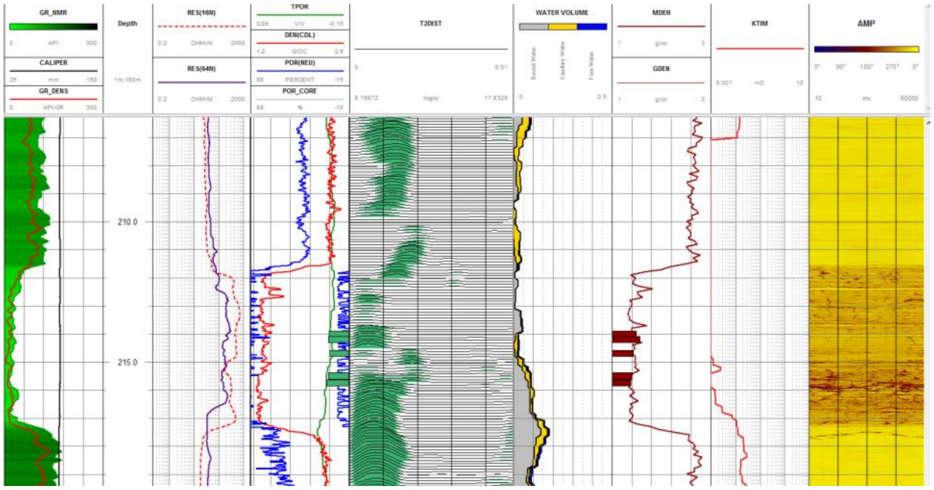

***Figure 2**: Typical log data over a coal seam with core data included.*

A typical $f_{T_d}\left(D, T_{2eff}\right)$ distribution (also known as a T2-StimD map) is shown as a 2D plot in the figure below. The adsorbed gas sits to the top left of the plot. Water sits on the vertical water line (25°C) and conventional liquid hydrocarbons on the diagonal line. Any free gas in the coal will appear in the top right. Note that without the separation caused by diffusion there is no way to distinguish free water and adsorbed gas.

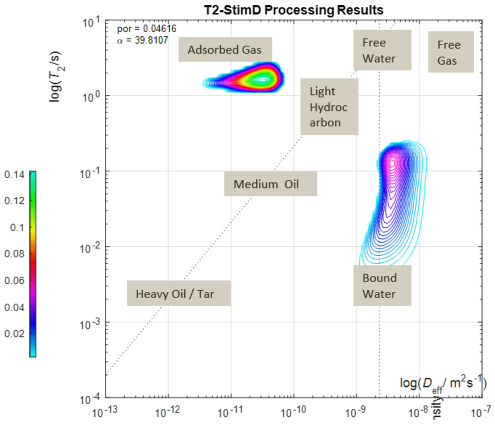

Figure 3*: Typical T2-StimD map. Data was taken from a station measurement in a coal seam.*

Unfortunately due to difficulties in the coring process only two sets of data could be compared (Table 1). There is excellent agreement between one of the station logs and poor agreement on the other. Some of this may be due to the loss of gas in the core sampling process as the core is retrieved to surface.

Station Log Depth	**bMR Adsorbed Gas (m^3/tonne)**	**Laboratory Adsorbed Gas (m^3/tonne)**
267 m	22.60	14.01
271 m	16.35	16.39

Table 1*: Adsorbed gas measurement results from field trials.*

Conclusions

Standard bMR logging is well-accepted in oil and gas fields, and results to date suggest that miniaturized bMR tools are also promising for mining and hydrology. Initial test results from a bMR tool used to measure adsorbed gas show great promise and potential for the mining industry. We still require significantly more data before this approach can be considered ready for commercial use as a replacement for laboratory testing of adsorbed gas content. However with future in-house tool development and improvements from the first round of testing, measurement of adsorbed gas is achievable with this tool. The downhole bMR technique offers a low-cost, fast method for obtaining conventional porosity and permeability. The downhole adsorbed gas content can now be added to this already impressive list of measurements. However, due to the nature of the measurement and physics constraints, a continuous log will be difficult to obtain. Nevertheless, the monetary savings obtained by acquiring all necessary information downhole are significant.

References

M.D. Hurlimann, L. V. (2002). Quantitative Measurement of Two Dimensional Distribution Functions of Diffusion and Relaxation in Grossly Inhomogeneous Fields. *J. Magn Reson*, 31-42.