Using NMR T1-T2 Relaxation Times for Fluid Evaluation in Unconventional Resources

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Summary

Down-hole nuclear magnetic resonance (NMR) instrumentation generally fall into two catagories, referring to their magnetic field distribution: gradient tools and saddle point tools. Gradient tools are designed to evaluate fluid properties but face considerable challenges in unconventional reservoirs due to their long echo spacing, poor vertical resolution, and intollerance to low porosity and high salinity environments. Furthermore, diffusion, a key measurement from gradient tools, has little to no sensitivity to the short T2 relaxation times that are characteristic of unconventional reservoirs.

An alternative to T1-T2 vs. diffusion is T1 vs. T2. The contrast between T1 and T2 relaxation times increases at short T2 times, enabling differentiation of poro-fluid types. A continous measurement of T1-T2 coulpled with a short echo spacing, high vertical resolution, and tolerance to low porosity and high salinity are achieved with the saddle point tool design. Data analysis and interpretation of the T1-T2 data is conducted using data analytics.

Quantification of fluids using T1-T2 analysis vs. other log-based methods increases the confidence in the evaluation of hydrocarbon in place and fluids producibility. In gas reservoirs, T1-T2 analysis complements the NMR-based evaluation of total gas-in-place, providing gas-in-place estimates independent of Langmuir isotherms. Examples of formation evaluation using T1-T2 derived fluid volumes from both liquids and gas plays will be presented.

Introduction

NMR has long been used for the evaluation of formation pore fluids in conventional reservoirs. As opposed to resistivity-based methods, NMR does not require a priori knowledge of the myriad of parameters required for Archie's-type saturation equations, nor does it suffer from thin-beds or fresh formation water as can resistivity measurements. Instead, NMR capitalizes on its unique sensitivity to fluid properties to separate and quantify hydrocarbon from water. The fluid properties are chiefly described by the fluid's diffusion coefficient, T1, and T2 relaxation times.

In unconventional reservoirs, the evaluation is markedly more challenging than for conventional reservoirs. NMR is uniquely position for fluid evaluation because it is largely insensitive to matrix properties, which can be complex in unconventional reservoirs. Fluids may be hosted by inorganic and organic pore spaces and may consist of both light and viscous hydrocarbons. Relaxation times are typically much faster, requiring the shortest possible echo spacing during measurement, and are accompanied by a loss of sensitivity to diffusion. Fortunately, as sensitivity to diffusion decreases, the sensitivity contrast between T1 and T2 relaxation times increases. T1-T2 maps coupled with data analytics enable fluids evaluation in these very challenging formations.

Theory and/or Method

T2 transverse relaxation time is a fundamental measurement of NMR investigation. Subseqent analysis of the T2 distribution yields petrophysical parameters such as pore volume, free fluid vs bound fluid volumes, permeability, and pore size distribution. The saddle point design was engineered for an optimal evaluation of T2. The saddle point design provides a relatively short echo spacing (200 µs), high vertical resolution, and is robust in low porosity, high vsicosity and high salinity fluids and is thus ideally suited to the evaluation of unconventional reservoirs. However, fluid type information is often dificult if not impossible to quantify using T2 relaxation rates alone due to the superposition of fluid signals within the T2 distribution.

The NMR measurement can be modified to include an assessment of the T1 longitudinal relaxation time and diffusion coefficient of the fluids. The T1, T2, and diffusion coefficient vary for different fluid types and fluid viscocities thus providing sensitivity to poro-fluid compoenents. NMR measurements are typically made with gradient tools, at the expense of a longer echo spacing and realatively poor vertical resolution. A map of T1 or T2 vs. diffusion is most commonly used to quantify light hydrocarbon and water due to the relatively large contrast in diffusion coefficients, particularly for gas. T1 vs. diffusion is an effective means of quantifying fluid volumes within the pore space when the connected pore space is greater than the mean diffusion length of the hydrogen proton, as is commonly the case in conventional reservoirs.

When the mean diffusion length exceeds the connected pore space, as is commonly the case in unconventional reservoirs, the diffusion length is restricted and the diffusion coefficient is reduced. In T1-T2 vs. diffusion maps, the fluid signals become co-mingled and additional processing is required to separate the signals. Such processing may consist of restricted diffusion logic and implementation of the diffusion coefficient log mean to redistribute fluid signatures to fluid models. At very short T2 times, sensitivity to diffusion is lost altogether and the diffusion measurement becomes useless. However, at short T2 times the contrast between T1 and T2 relaxation rates increases, enabling an alternative method of fluid quantification.

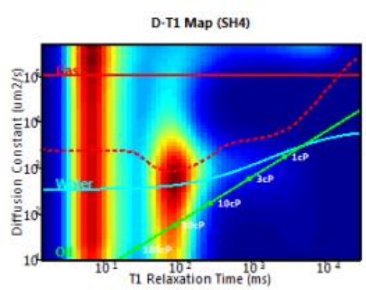
Thus, the preferred downhole NMR mesurement in an unconventional reservoir consists of a short echo spacing, high vertical resolution, tolerance to low porosity and high salinity, and a continuous T1-T2 measurement. These conditions are met by the current generation saddle point design NMR instrumentation. Analysis of the T1-T2 data map is non-trivial due to the complexity of the fluid distribution within the pore space and the inherrent noise of a down-hole NMR measurement. Modern data analytic techniques provide an effective means to anlyze this data. The application of non-negative matrix factorization is used to compute fluid volumes from the T1-T2 maps.

Results of NMR analysis are readily reconciled with other log and core data. The following examples are from various unconventional formations within North America. These examples include both liquids and gas resources.

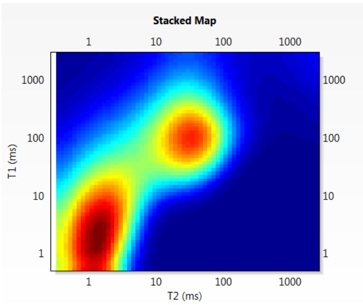
Examples

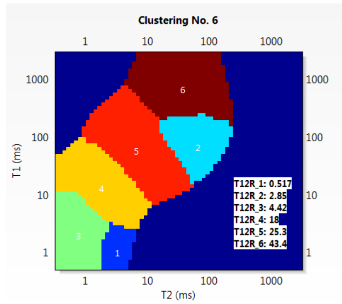
Meramec Formation, Oklahoma, USA

Both gradient and saddle point design NMR measurements were aquired across the Mississippian aged Meramec shale in Oklahoma. A T1 vs. diffusion map was generated using the gradient tool. T1 relaxation rates are about 200 ms or less. At these relaxation rates, the pore water and pore hydrocarbon signatures are co-mingled due to loss of sensitivity to diffusion. However, the two volumes can be reasonably resolved through use of a restricted diffusion model for water (cyane line) and the diffussion coefficient log mean computed at each value of T1 (red dashed line). What is not resolved is the fluid disribution



less than 20 ms that appears as a vertical bar due to complete loss of senstivity to diffusion. In a conventional reservoir, this signal may correctly be interpreted as clay bound water. In an unconventional reservoir, this signal may also consist of viscous hydrocarbons and/or light hydrocarbons in organic pores.

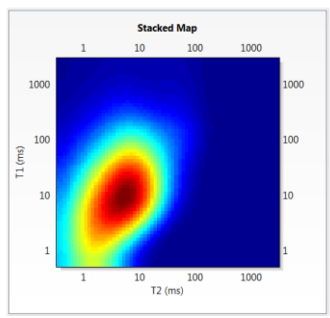


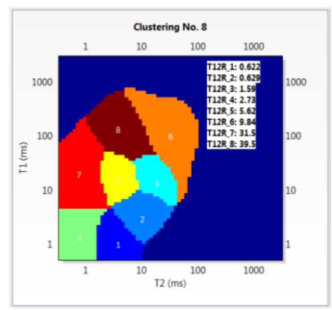


The T1-T2 map from the saddle point tool reveals mutlipe poro-fluid components that are less than 20 ms. The Meramec formation does not contain any signficant kerogen content, nor is bitumen expected, so these three components have been interpreted as various waters. Had keorgen or bitumen been present, the high T1-T2 ratio component would have been identified as bound hydrocarbon, increasing the bulk volume hydrocarbon over that of the T1-diffusion method, and resolving producible (greater than 8-10 ms in this example) vs. non-producible hydrocarbon and water volume fractions.

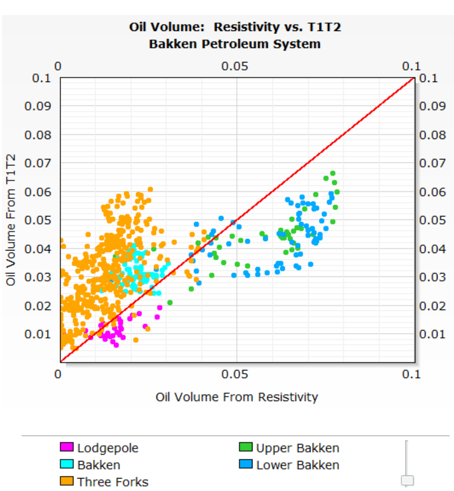
Bakken Petroleum System, USA

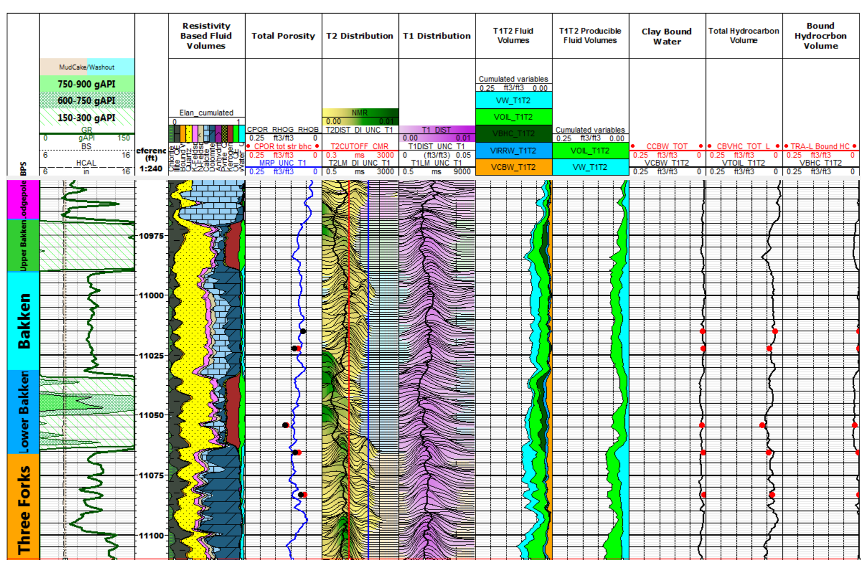
The Bakken petroleum system consists of both conventional and unconventional formations of late Devonian to early Mississipian in age. The Three Forks formation is thinly bedded, resulting in low resistivity. The Bakken shales have a high organic content, resulting in too high a density porosity if not properly accounted for. Across all of the constituent formations, values for Archie's parameters can be difficult to constrain.





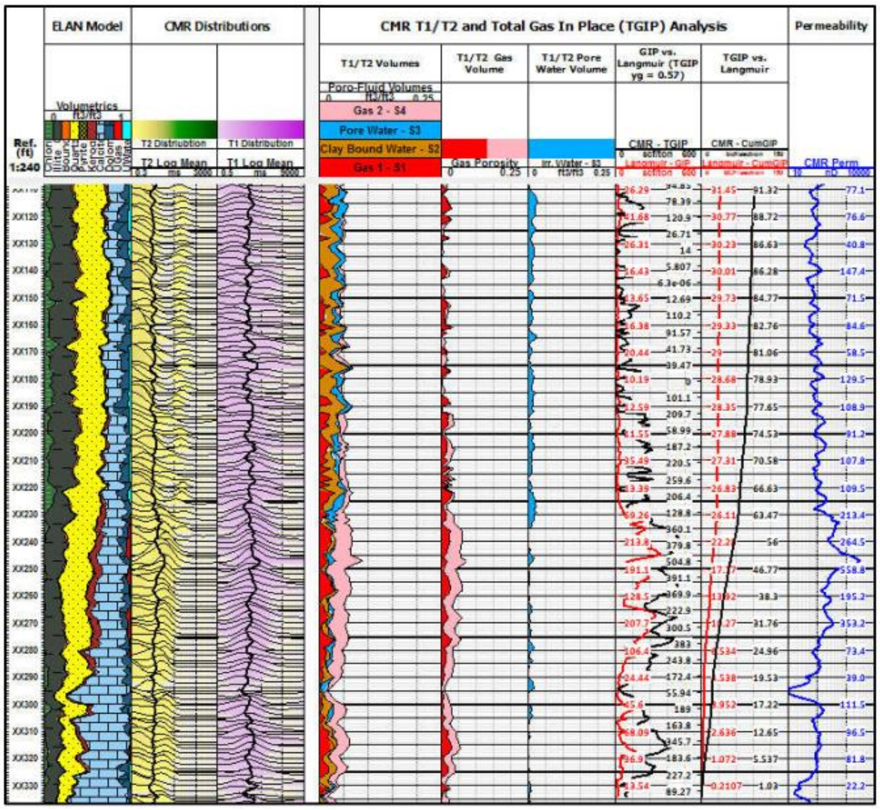
Continuous T1-T2 logging from NMR overcomes these limitiations, providing a robust evaluation of porosity and the poro-fluid components. 2D non-negative factorization of the stacked T1-T2 maps is used to define the individual poro-fluid clusters and their unique T1-T2 ratios. Fluid volumes are computed from the clusters and interpreted as to fluid type. A cross-plot of the oil volume from the resistivity model vs. that of the T1-T2 interpretation shows considerable differences between the two approaches. Not surprisingly, the resistivity method appears to underestimate the oil volume in the thin-beded Three Forks formation while overestimating the oil volume in the organic shales. The T1-T2 volumes show excellent agreement with the core analysis.





Utica Formation, West Virginia, USA

The Utica formation in West Virginia is a dry-gas shale of Middle Ordovician age. Although water production is minimal, quantification of both water and gas volumes is important for acurate reservoir volumetrics. A resitivity based approach is challenging due to the low water content and unconstrained Archie's parameters. In some cases, low resistivity has informally been attributed to over-mature organic matter. Continuous T1-T2 evaluation circumvents these issues and directly quantifies the water and gas pore volumes. Using the same NMR data, the water volume and total porosity from NMR are used in the TGIP analysis for total gas in place. In contrast to the resistivity based shale-gas analysis, in which a generalized Langmuir isotherm was used, the T1-T2 volumes and TGIP analysis added 60 bcf/section, significantly addting to the reserves estimate.



Conclusions

A high confidence evaluation of poro-fluids in unconventional reservoirs using NMR is achieved using T1-T2 maps coupled with data analytics. The measurements are made possible by leveraging the advantages of the saddle point NMR design, including a short echo spacing, high vertical resolution, and tolerance to low porosity and high salinity. In additon to resolving poro-fluid volumes, the interpretation can be used to help identify movable and non-movable fluids, be they water or hydrocarbon. T1-T2 analsys can also supply the inputs required for a stand-alone evaluation of total gas-in-place, independent of Langmuir isotherms.