Here, we show how $T_1$-$T_2$ maps can be used to differentiate fluids with different viscosities. We demonstrate how water and bitumen can be discriminated with $T_1$-$T_2$ maps in representative shale formations. Further, we show how measuring $T_1$ and $T_2$ at different temperatures allows us to differentiate between components of varying viscosity.

**Method**

Initial inversion recovery CPMG $T_1$-$T_2$ measurements were obtained on six shale samples in the as received state. (Figure 1, left panel). The samples were then placed in brine under 2,000 psi of pressure for 48 hours to fully saturate the samples and the inversion recovery CPMG $T_1$-$T_2$ measurements were repeated. (Figure 1, center panel). All measurements were performed on an Oxford Instruments GeoSpec 2/75 2 MHz spectrometer with a 40 mm probe. The as received $T_1$-$T_2$ measurement was then subtracted from the fully saturated $T_1$-$T_2$ measurement to give the net $T_1$-$T_2$ measurement (Figure 1, right panel).

In recent years, lab based NMR core analysis researchers have begun to take advantage of enhanced signal-to-noise ratios (SNR) and shorter tau values to implement more data rich measurement techniques. In the past, extremely long acquisition times for $T_1$-$T_2$ maps, or correlation plots, made them next to impossible to obtain. Current SNR levels have eliminated this limitation and have allowed researchers to begin exploring what can be learned from these maps.

**Figure 1:** $T_1$-$T_2$ maps of shale core in various conditions

As received  Fully saturated  Net
Results

The T₁/T₂ ratio can be used to determine the origins of the signal in net T₁-T₂ maps [1]. In fluids with low viscosities, T₁ and T₂ are similar, but as viscosity increases T₁ and T₂ will deviate [2]. Higher ratios indicate more viscous materials such as bitumen while lower ratio contributions are likely due to water. In the T₁-T₂ maps of Figure 1, high signal intensity is red while low intensity is shown in blue. The white diagonal line represents a T₁/T₂ ratio of 1:1.

Temperature studies

Solid Wax

An initial measurement was taken on a solid wax sample at 35°C. Figure 2 shows T₁-T₂ maps of wax at different temperatures. The T₁-T₂ map shows signal at a high T₁/T₂ ratio indicating a highly viscous material. When the sample was heated to 45°C the signal spread to lower T₁/T₂ ratios. At a temperature of 70°C the sample was liquefied and the signal was present around the 2:1 line.

Figure 2: T₁-T₂ maps of wax at various temperatures.
Ozocerite

Figure 3 shows similar studies performed on ozocerite, a naturally occurring bitumen. At 35°C, signal appeared along the 20:1 line and at 70°C an extended signal area appeared near the 1:1 line. When the material becomes less viscous the $T_1/T_2$ ratio shifts to lower values.

Figure 3: $T_1$, $T_2$ maps of ozocerite at various temperatures.
Further temperature studies were performed on a group of eight shale samples. As with the previous studies, $T_1$-$T_2$ maps were acquired but in this study the temperatures were 35ºC, 65ºC, and 110ºC. Figure 4 shows a representative shale sample at these three temperatures. In the top panel, we see the results at 35ºC with the bitumen populations appearing in the 10:1 to 100:1 ratio range and the water peak nearer the 1:1 ratio line. In the middle panel, the results at 65ºC are shown. The two peaks begin to separate but show very little change. At 110ºC, (bottom panel) the water has begun to dissipate indicating drying. The bitumen peak also decreases, moving towards the 1:1 ratio line, indicating a change in viscosity.

References

[3] Ali Tinni, 2013, personal communication. Work was supported by the Unconventional Shale Gas Consortium at the Mewbourne School of Petroleum and Geological Engineering, the University of Oklahoma.