

Innovative Fluid Identification Method by Integrating Array Dielectric Measurements, Nuclear Magnetic Resonance and Spectroscopy Data: One Case Study in the Low Contrast Complex Oil Reservoir, Bohai Bay, China*

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Abstract

The Shahejie formation of the Bohai Bay is characterized by complex lithology with various minerals, low formation water salinity, high pore structure heterogeneity and flooding, which complicates the logging responses, especially the low contrast of resistivity. Traditional methods can hardly to quantify the complex minerals and evaluate the petrophysical parameters accurately; moreover, the fluid types are difficult to identify with the similar logging responses. In this study, the reservoir heterogeneity was investigated using spectroscopy data and nuclear magnetic resonance data, and then oil saturation was inverted using array dielectric data. By comparing the free fluid porosity from NMR with the oil-filled porosity from array dielectric measurements, a special reservoir evaluation and fluid identification method was established. The dielectric properties of water are very different from that of oil, and other formation components, making dielectric measurements particularly useful for saturation evaluation independent of resistivity. However, zones with the same water-filled porosity may produce different fluids due to heterogeneity in pore structure. Nuclear magnetic resonance data, spectroscopy data and borehole images can be used to analyze the properties related to reservoir heterogeneity, such as mineralogy, free fluid porosity, pore-size distribution and irreducible water-filled porosity. By comparing the oil-filled porosity from array dielectric measurements with the free fluid porosity from NMR, the relative ratio of oil in the free fluid porosity can be calculated, which has been proven as the driving factor of fluids types. This method can help to identify oil zones with high irreducible water saturation and water zones with residual oil saturation, which is not possible from resistivity measurements alone. This method has been applied in five wells, and all the sampling results agree well with our interpretation, which has demonstrated the effectiveness of the proposed method. Producing fluid identification has been improved by 30% using the new method. Identifying producing fluid from resistivity alone has been a challenge in these kinds of complex reservoirs. The combination of dielectric and nuclear magnetic resonance data overcame this difficulty by incorporating resistivity-independent saturation with reservoir heterogeneity information in an innovative way.

Objective/Scope

The Shahejie formation is one of the key targets for oil exploration in Bohai Bay, China. The lithology for the top and bottom section is mainly medium to fine grained sandstone of braided river delta, and the main mineral compositions are quartz (33.3%), feldspar (41.5%) and lithic (25.1%). The lithology in the middle section is carbonate mixed of calcite, dolomite, clay, quartz, and pyrite. For sandstone, the debris particles are not uniformly distributed and rock casting thin sections and scanning electron microscope show that the pore connectivity is not well developed. Pore types include intergranular pore, intergranular dissolved pore and dissolved small particle hole. These intergranular pores are filled by clay and some other minerals, most of which are illite/smectite mixed layers and carbonate minerals. Even though, the porosity of this formation is relatively high, 24% to 38.6%, the permeability varies more, 3.0mD minimum to 592.8mD maximum, which means the pore structure is more complicated than expected. For carbonate, the minerals and petrophysical properties are very difficult to quantify from conventional logs due to the complex mineralogy and pore structure, and the pay zones are difficult to identify ([Figure 1](#)).

In the traps controlled by structure, oil will normally migrate upward and water will migrate downward due to the density difference. The higher the height above the free water level, the higher the capillary pressure and then the higher, the corresponding oil saturation. If the trap height does not meet a certain height, which is the case for the reservoirs in this paper, the water in the small pores cannot be driven away, and the reservoir resistivity would be lower than that of a well-saturated reservoir. These reservoirs may produce oil, because the water in these small pores is difficult to flow out when the pressure drop is relatively low.

Because of reservoir sedimentation and the formation water activity during or after accumulation, the formation water salinity varies a lot vertically. The reservoir resistivity will increase, and may read higher than the resistivity of oil zone, if the low salinity formation water component increases in the reservoir. Complex lithology with various minerals, varied formation water salinity, high pore structure heterogeneity and low structure height complicate the logging responses, especially the low contrast of resistivity between water zone and oil zone ([Figure 1](#)). Traditional methods can hardly quantify the complex minerals and evaluate the petrophysical parameters accurately, and the fluid types are difficult to identify.

In this study, the reservoir heterogeneity was investigated using spectroscopy data and nuclear magnetic resonance data, and then oil saturation was inverted using array dielectric data. The most important step is comparing the free fluid porosity from NMR with the oil-filled porosity from array dielectric measurements, from which a special reservoir evaluation and fluid identification method was established.

Dielectric Measurements

The dielectric properties of water are very different from that of oil, and other formation components. This enables dielectric measurements particularly useful for saturation evaluation independent of resistivity. Dielectric logging was introduced to the oil and gas industry in the late 1970's (Calvert, et al., 1977). This methodology uses the fact that the dielectric constants of water and hydrocarbons are significantly different. [Table 1](#) provides the real and imaginary dielectric constants for several materials encountered in formation evaluation. Thus, measurements of the effective formation permittivity should be sensitive to the formation water content, and from the measurement of the effective formation permittivity, the water-filled porosity can be deduced. If a measurement of the total formation porosity is available, the water saturation can be

determined. A new generation array dielectric tool acquires dielectric measurements at four different frequencies with four transmitter-array spacings; these multi-frequency measurements allow estimation of water-filled porosity with better precision and accuracy than previous generation tools (Figure 2). The analysis of the multi-frequency dielectric measurements provides information about formation water saturation, water salinity, and rock texture (Hizem et al., 2008, Pirrone, et al., 2011, Marzooq, et al., 2014, Mosse, et al., 2009, Seleznev, et al., 2011).

Matrix Permittivity

Determination of the permittivity of rock matrix is often complicated by the rock porosity, heterogeneity and limited availability of rock material. A new high-definition source-less spectroscopy tool has the capability of providing more accurate and quantitative answers to both minerals and TOC compared with its old-generation tools (Radtke, et al., 2012). High neutron output, high count-rate capability and outstanding spectral resolution make the tool possible to log both capture and inelastic gamma ray spectroscopy at a high speed with high precision and accuracy. Enhanced suite of elements includes Al, Ba, C, Ca, Cl, Fe, Gd, K, Mg, Mn, Na, S, Si, Ti and metals such as Cu and Ni.

Compared with the old-generation spectroscopy tool, this new spectroscopy tool has greatly improved the measurement for many elements, and therefore can help to depict complex mineralogy more accurately (Adeyemo, et al. 2009). In the process of inversion from elements to minerals, Al is the key input for shaping the clay volume; K and Na helps to differentiate feldspars from quartz; and Mg is used to separate dolomite from calcite. The stand-alone TOC output is based on direct measurements solely by the tool of both the carbon elemental concentration and accurate quantification of the carbonate minerals in the formation, which determines the carbon content associated with those minerals. The difference between the two is the TOC, independent of the environment and the reservoir (Craddock, et al., 2013). The matrix permittivity can be calculated easily with the mineral quantification result from spectroscopy data (Figure 3).

Pore Structure Analysis

Zones with the same water-filled porosity may produce different fluids due to heterogeneity in pore structure. In fact, water-filled porosity provided by the array dielectric includes both bound and movable water. What determines the producible fluid type relies on not only the absolute values of water saturation but also the relative amount of bound and movable water. If the water saturation is high and most of the water is movable, the reservoir is most likely to produce water. However, if the water saturation is high but most of it is contributed by bound water, the reservoir is still possible to produce oil (Figure 4).

Nuclear magnetic resonance logging data has been proven as good data to analyze the properties related to reservoir heterogeneity, such as pore-size distribution, irreducible water-filled porosity, and free fluid porosity. Nuclear Magnetic Resonance (NMR) logging tool measures the rate of transverse relaxation, T₂, of hydrogen nuclei protons in formation liquids. The signal amplitude is proportional to the total amount of hydrogen, hence to porosity. The T₂ spectrum can be considered as a qualitative pore size distribution in the case of a single-phase fluid system and high bulk T₂ values. High-resolution processing of NMR acquisition delivers total porosity along with partitioning into micro-, meso-, and macro porosity and estimates of the bound and free fluid (Liu, et al., 2007). Especially in complex lithology, this information is critical for determining the irreducible water saturation and potential for water production.

The New Solution Workflow

What determines the producible fluid types relies on not only the absolute values of water saturation but also the relative amount of bound and movable water. Water in the micro- and mesopores are thought to be irreducible, the reservoir is most likely to produce pure oil if the oil occupies most of the large (or macro) pores. Or else, the reservoir will start to produce water if the oil cannot occupy the large pores, and free water fills the rest of it.

To evaluate this, 'Soil_Max' was proposed by dividing free fluid porosity (large pores) by total porosity, and compared with oil saturation from ADT.

To improve the conventional workflow, we added the pore structure analysis into the analysis and formed the new workflow:

- 1) Volumetric analysis of complex minerals is conducted
- 2) Matrix permittivity is calculated
- 3) Water-filled porosity and water saturation (S_{wxo_ADT}) are inverted from array dielectric tool
- 4) Free fluid saturation 'Soil_Max' is calculated
- 5) Compare 'Soil_Max' with oil saturation ($1 - S_{wxo_ADT}$)

This method has the advantage to identify oil zones with high irreducible water saturation, which is not possible from resistivity measurements alone.

Case Study

In China, several cases related to Array Dielectric Measurements have been published, including Changqing Oilfield low-porosity and low-permeability sandstone reservoirs (Cheng et al. 2012), the Longwangmiao complex carbonate reservoirs in Sichuan Basin (Lai et al. 2015), low contrast oil reservoir in Bohai Bay (Wang et al. 2016), Tight Conglomerate reservoir (Sun et al., 2017). Because of the successful application in JZ block, Bohai Bay, we propagate the same methodology to KL block in the same basin.

Figure 5 shows the petrophysical results of middle section for Well A8. The lithology for this interval is shaly carbonate with complex minerals including clay, quartz, feldspar, calcite, dolomite, ankerite, and pyrite. Besides, the TOC (Total Organic Carbon) content from spectroscopy tool ranges from 1.0% to 8%, which make the log responses more complicated. From the mineralogy result, we can see that the main mineral in zone 9 is quartz, there is little carbonate inside, while there are much more calcite or dolomite in zone 13,14,15,17 and 19. Total porosity from NMR tool is relatively constant, around 30%. However, the effective porosity (PME) and free porosity (PMF) vary a lot vertically, which is the biggest difference between oil zone (red) and poor oil zone (orange). The permittivity for oil zone is usually lower than that of water zone and the oil saturation ($1 - S_{W XO_ADT}$) is very close to the maximum fluid saturation (Soil_Max) from NMR. Take zone 17 for example, although the total oil saturation is only about 20%, the oil almost fills all the free pores in this zone and what is left is all irreducible water. Figure 6 is

the downhole fluid analysis data for depth 1265.0m from Modular Formation Dynamics Tester (MDT) Tool; oil content is more 90% after pumping for about 56 minutes, which agrees with our interpretation result very well.

Figure 7 shows the petrophysical results of bottom section for Well A8. The lithology for this interval is much different from that of the middle section. The spectroscopy mineralogy results show that the lithology of zone 27 is shaly sand with minerals including clay, quartz, feldspar, calcite, dolomite, while the lithology of zone 30 is volcanic. Free porosity (PMF) of zone 27 is 6%, total oil saturation from array dielectric tool is about 30%, close to Soil_Max, and this zone is thought to produce pure oil. The free porosity (PMF) of zone 30 is a little lower than that of Zone 27, however, and the oil saturation calculated from array dielectric tool is close to the Soil_Max, and no free water will be produced either. Both zones have been proven by the downhole fluid analysis from Modular Formation Dynamics Tester (MDT) Tool.

Conclusions

Identifying producible fluid type from resistivity alone has been a challenge in these kinds of oil reservoirs. The combination of dielectric and nuclear magnetic resonance data overcame this difficulty by incorporating resistivity-independent saturation with reservoir heterogeneity information from NMR. The method has been applied in five wells in this block in 2016, and all the sampling results agree well with our interpretation, which has demonstrated the effectiveness of the proposed method. Although the depth of investigation of dielectric measurements is limited to several inches, the hydrocarbon in the reservoir here is mainly heavy oil, and invasion is typically shallow. Oil saturation derived from dielectric measurements approximates the saturation of the undisturbed formation, which was cross-checked by the total organic carbon measurement from the new spectroscopy tool, which has a deeper depth of investigation. This method has also been applied to similar complex reservoirs in other oilfields, and fluid identification coincidence rate has been improved by 30%.

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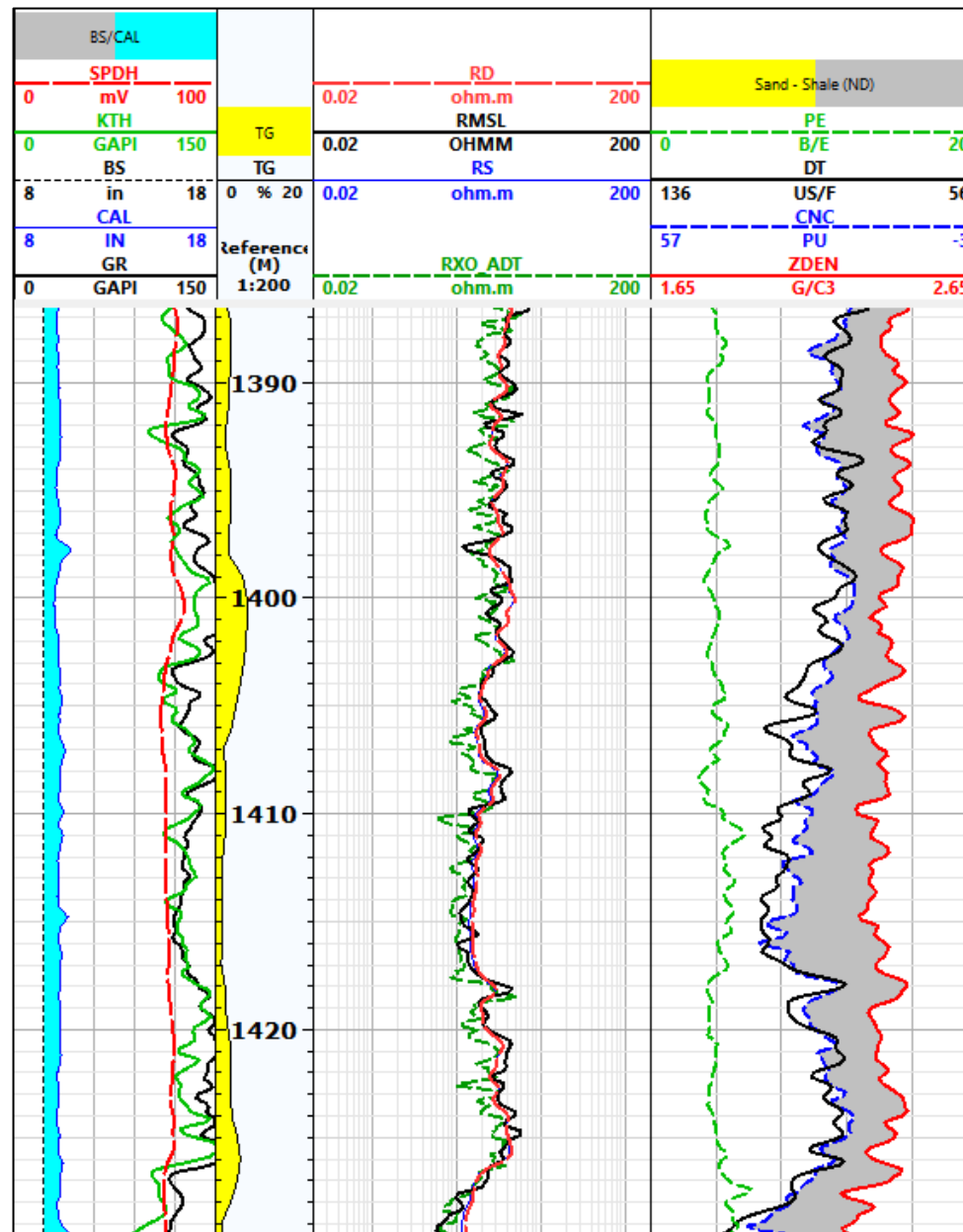


Figure 1. Log response of target reservoir. Due to complicated mineral components, it is difficult to identify the reservoir just from the conventional logs. In this circumstance, advanced logging technologies should be designed.

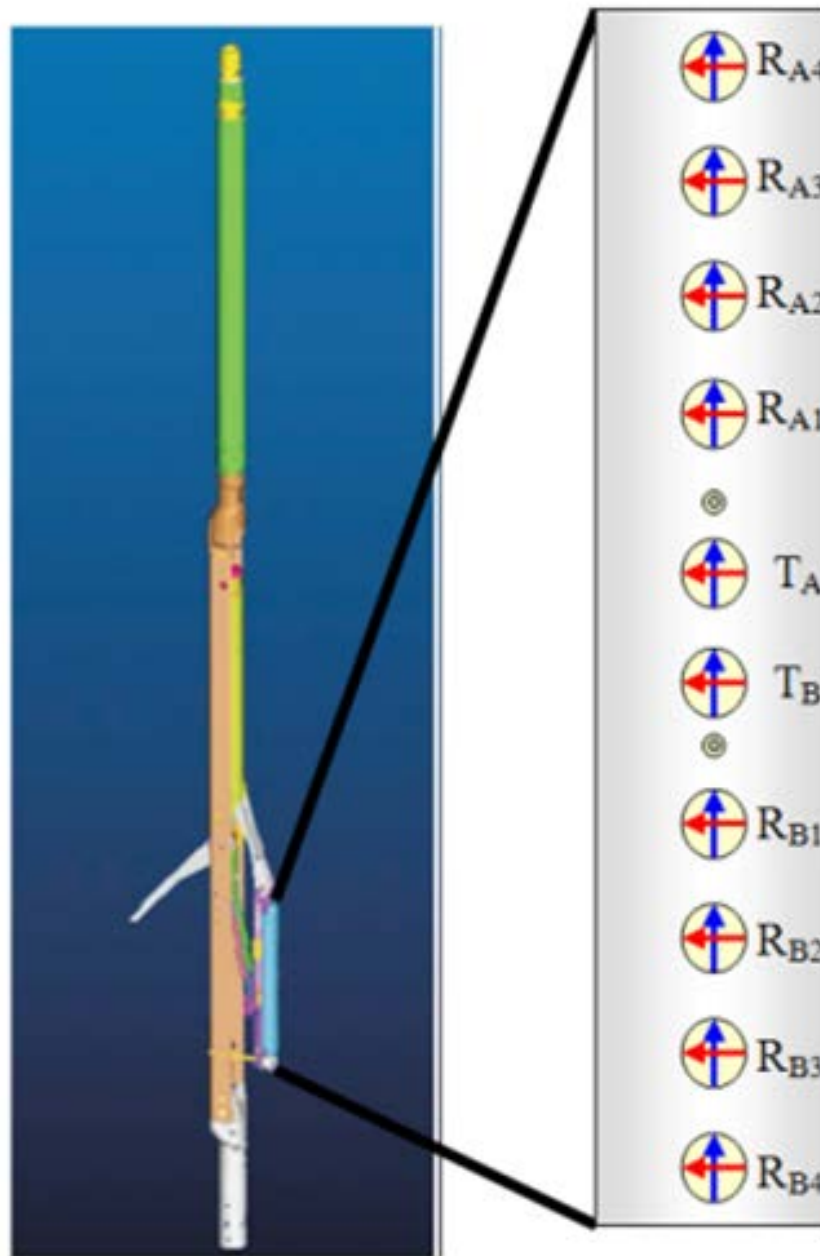


Figure 2. The array dielectric tool layout and pad antennas configuration.

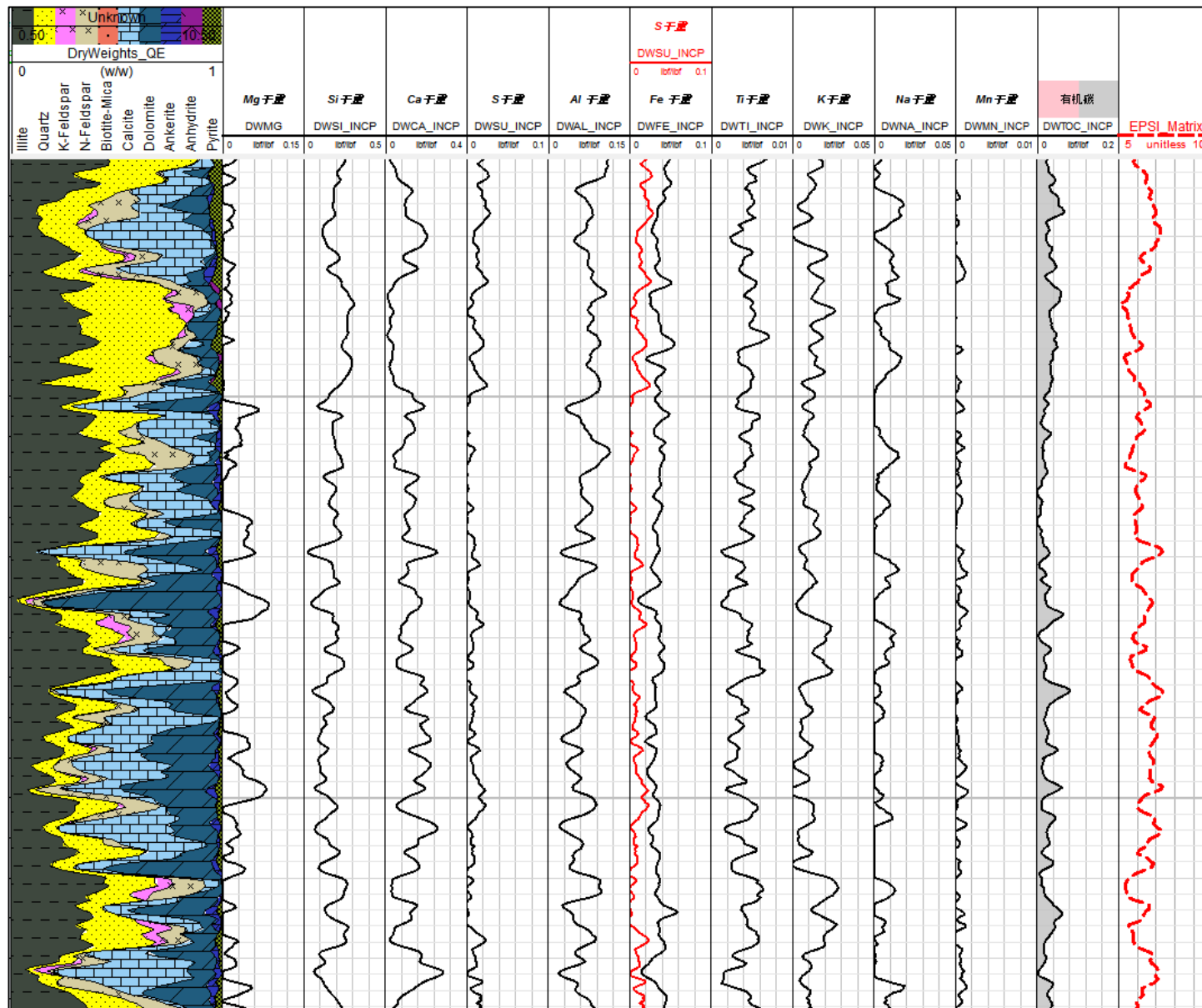


Figure 3. Mineralogy profile of S3 formation and the matrix permittivity from mineral quantification. From the elements measured by the spectroscopy tool, there is a lot of calcium, magnesium, aluminum and organic carbon in the formation. The matrix permittivity can be established by summing up all the minerals multiplied by the related volumes in the matrix.

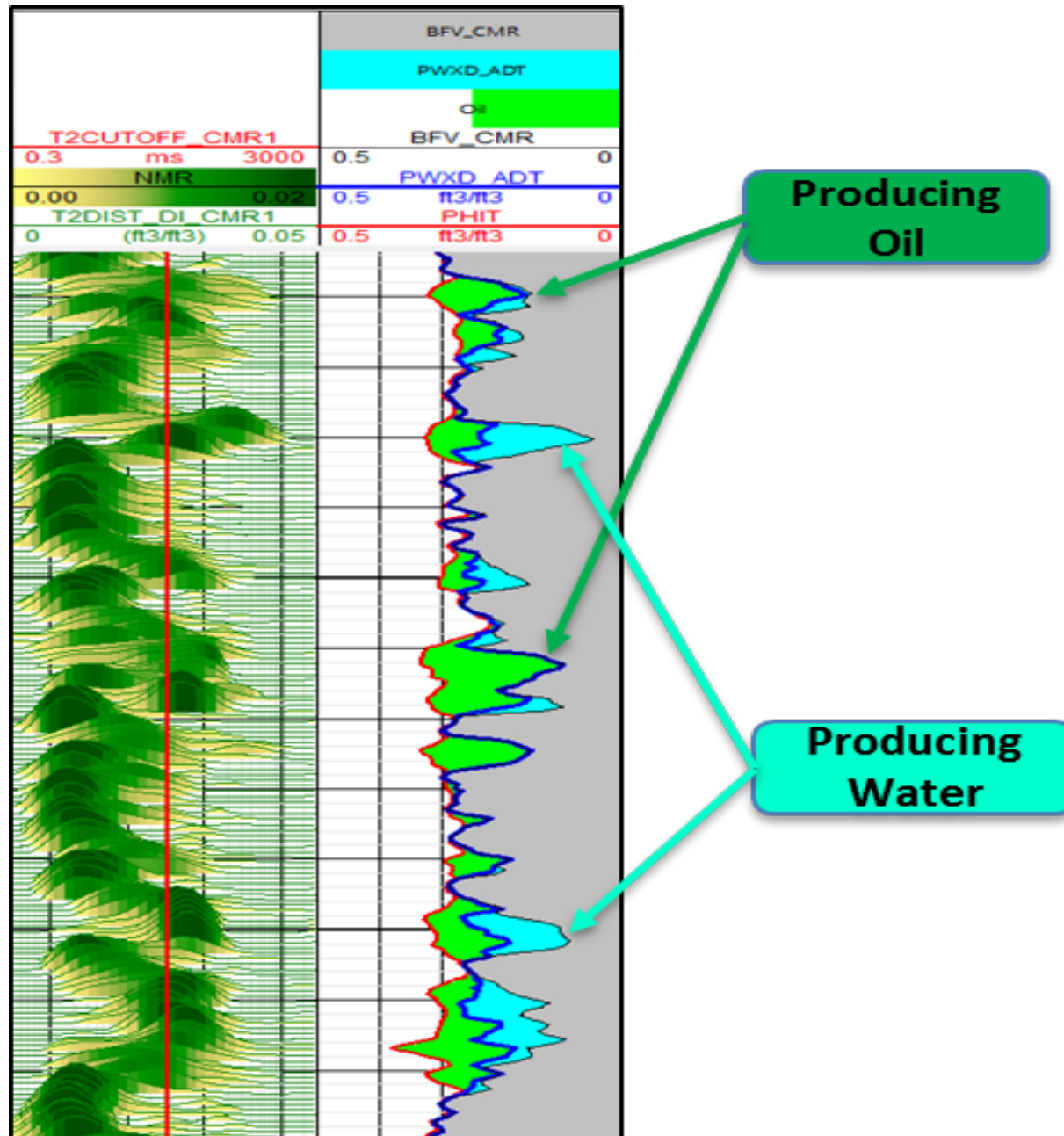


Figure 4. Fluid types related to the different volume of irreducible water.

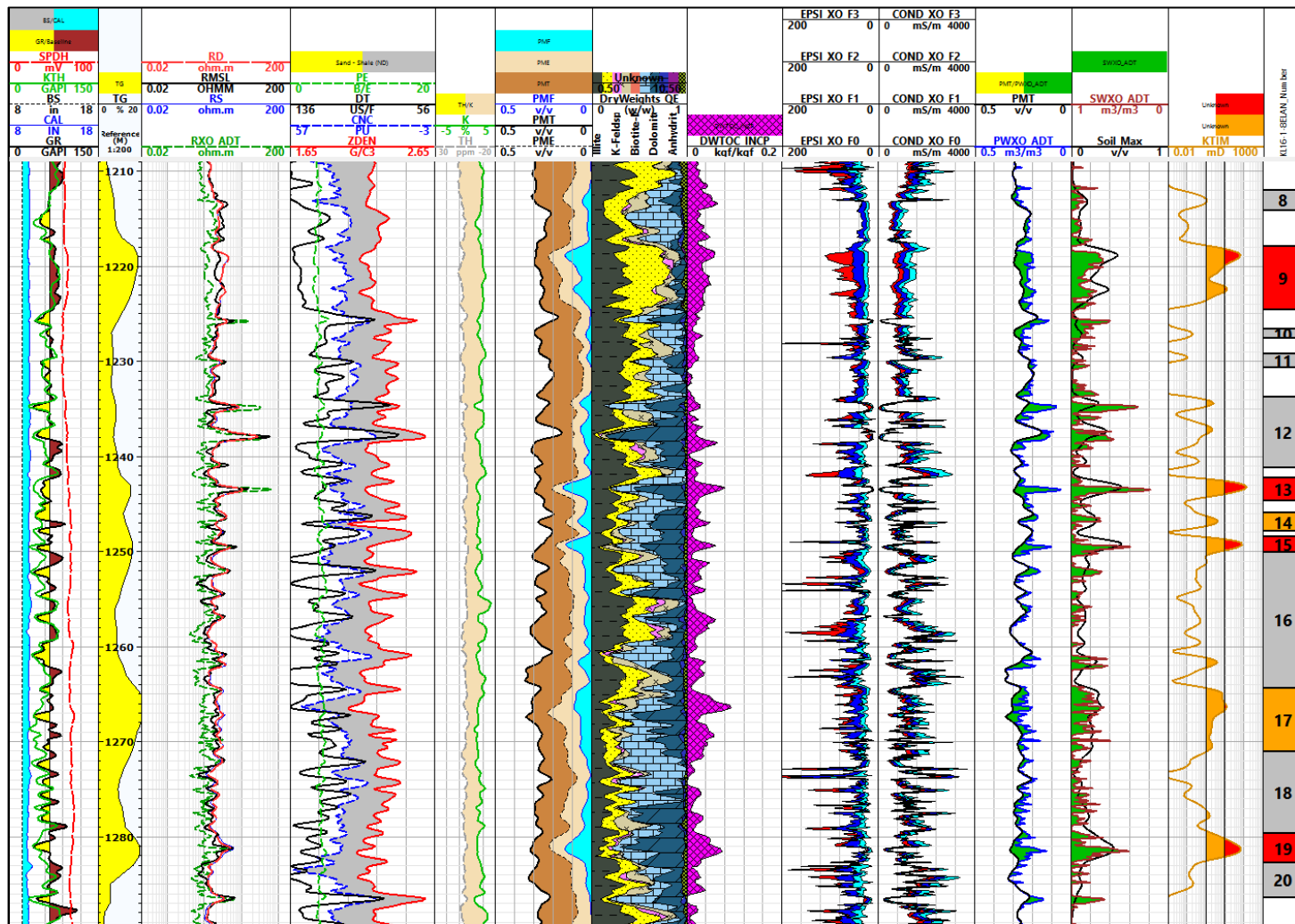


Figure 5. Petrophysical evaluation results of middle section for Well A8. Track 1: GR, SP, Caliper. Track 2: Depth and total gas. Track 3: Dual lateral logs, RXO inverted from array dielectric tool. Track 4: Neutron, density and compressional slowness. Track 5: Thorium and potassium. Track 6: Nuclear magnetic resonance porosities, including total porosity, capillary porosity and free fluid porosity. Track 7: Mineralogy profile from spectroscopy. Track 8: Total organic carbon. Track 9: Permittivities from array dielectric tool. Track 9: Conductivities from array dielectric tool. Track 10: NMR total porosity vs. water filled porosity from the array dielectric tool. Track 11: oil saturation from the array dielectric tool vs. maximum oil saturation from free water porosity by total porosity. Track 12: permeability from NMR. Track 13: interpretation result, red stands for oil zone, orange stands for poor oil, grey stand for dry zone.

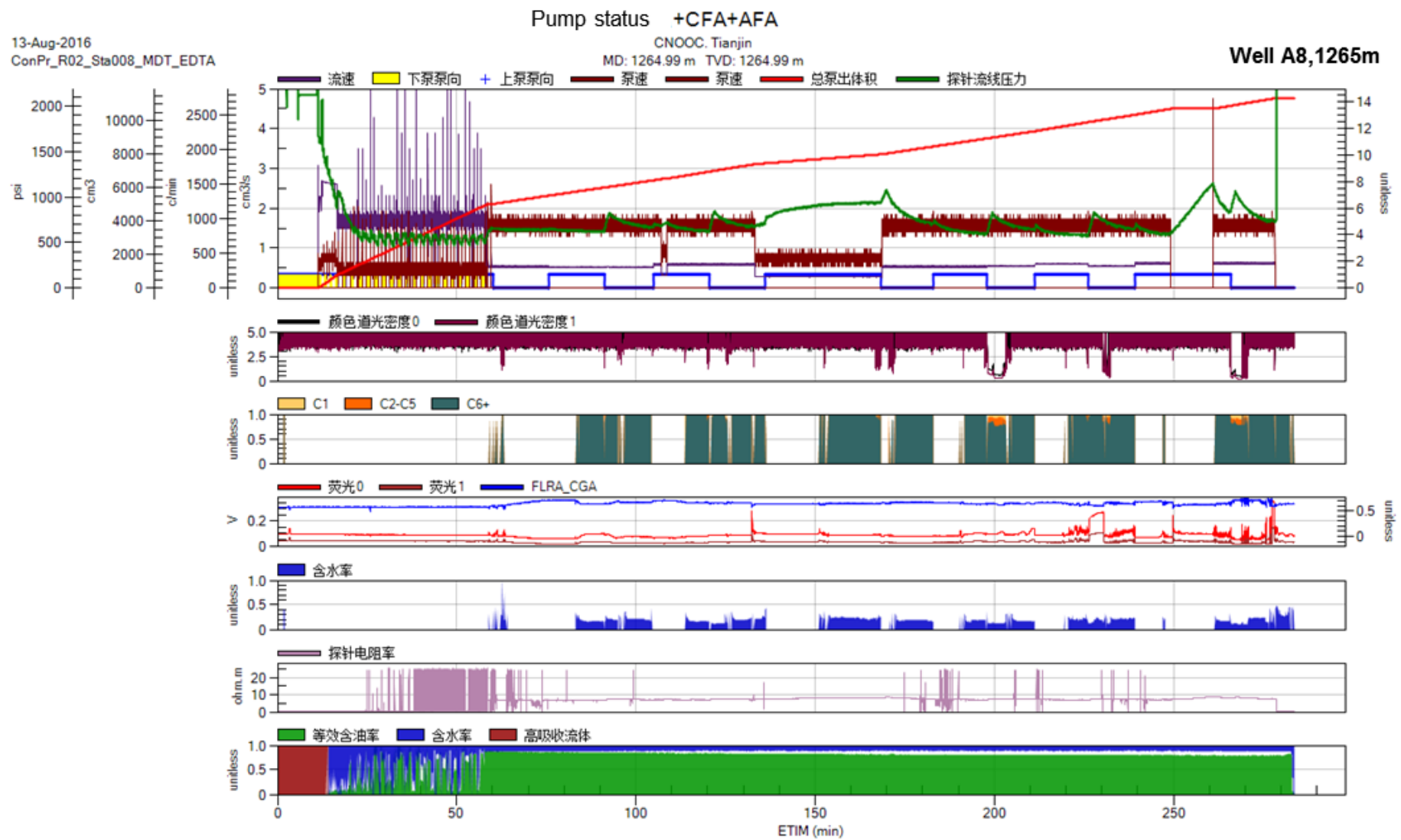


Figure 6. Downhole fluid analysis data when pumping with Modular Formation Dynamics Tester Tool.

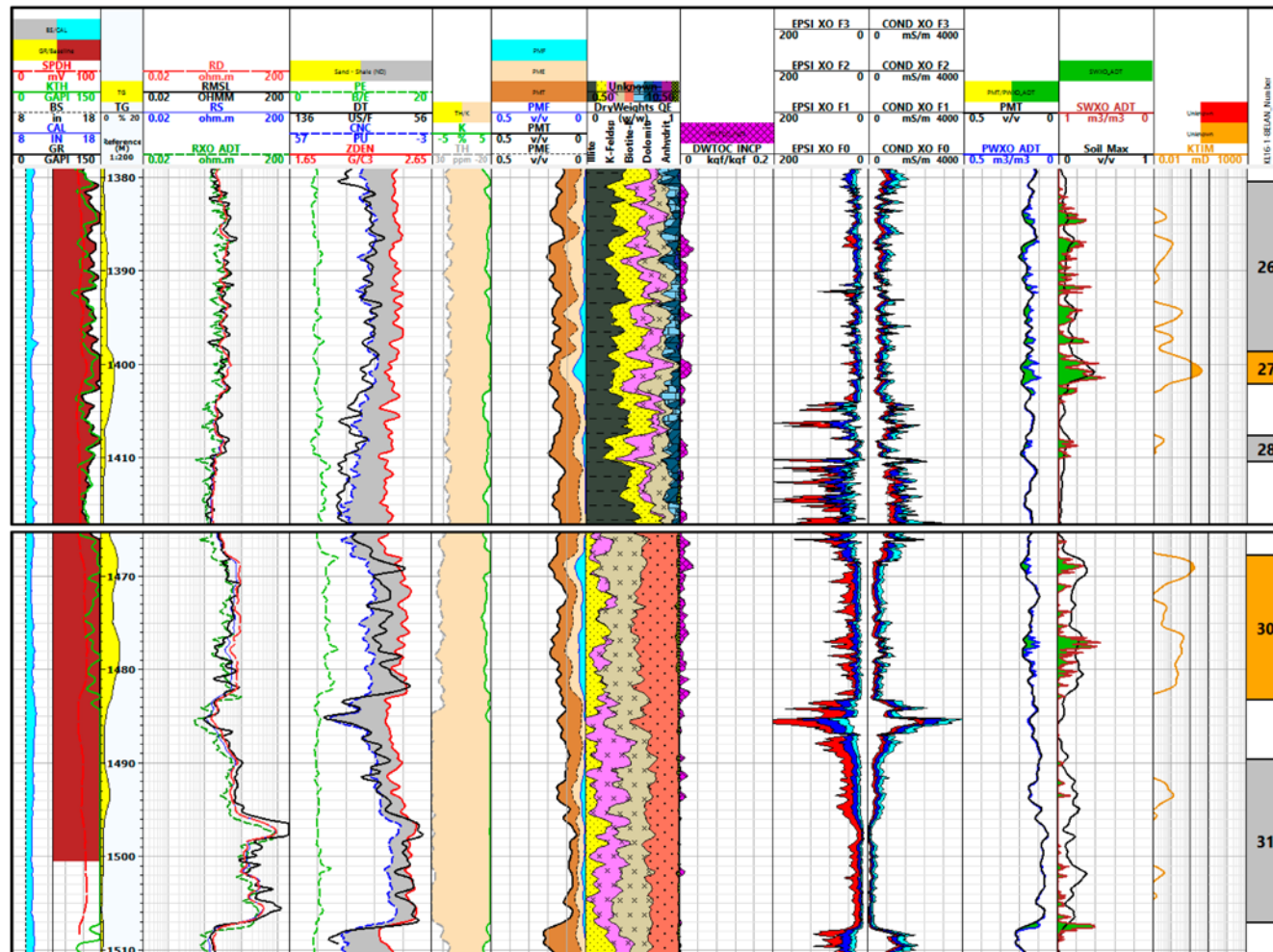


Figure 7. Petrophysical evaluation results of bottom section for Well A8. Track 1: GR, SP, Caliper. Track 2: Depth and total gas. Track 3: Dual lateral logs, RXO inverted from array dielectric tool. Track 4: Neutron, density and compressional slowness. Track 5: Thorium and potassium. Track 6: Nuclear magnetic resonance porosities, including total porosity, capillary porosity and free fluid porosity. Track 7: Mineralogy profile from spectroscopy. Track 8: Total organic carbon. Track 9: Permittivities from array dielectric tool. Track 9: Conductivities from array dielectric tool. Track 10: NMR total porosity vs. water filled porosity from the array dielectric tool. Track 11: oil saturation from the array dielectric tool vs. maximum oil saturation from free water porosity by total porosity. Track 12: permeability from NMR. Track 13: interpretation result, red stands for oil zone, orange stands for poor oil, grey stand for dry zone.

Material	Real Dielectric Constant ϵ'	Imag. Dielectric Constant ϵ'' (1Ghz)
Water	56 to 80	0.2 to 20
Air, Gas	1	0.0
Oil	2.0 to 2.2	0.0
Kerogen	2.2-3.3	0.0
Sandstone	4.65	0.1
Limestone	7.5 to 8	0.01
Dolostone	6.8	0.01
Anhydrite	6.3	0.001
Pyrite	80	200
Clay	5-6	.1-.25

Table 1. Dielectric constant for several materials encountered in formation evaluation.