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Application of TDA technique to estimate the hydrocarbon saturation using MRIL Data: A case study for a Southern Iranian Oilfield

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Abstract

Petrophysical evaluation of petroleum reservoirs is one of the most challenging tasks for hydrocarbon reserve determination. One critical petrophysical parameter is the water saturation which is normally calculated from Archie's equation. Carbonate reservoirs, however, due to their complex mineralogy are not good candidates for Archie's equation because Archie's parameters are strongly dependent on pore pattern distribution, type and distribution of clay content, wettability and mineralogical properties. In the present study, Magnetic Resonance Image Logging (MRIL) was used to determine water and hydrocarbon saturations using Time Domain Analysis (TDA) technique. The results of TDA technique indicated that the water and oil peaks are well separated in the light oil zones and the calculated saturations of hydrocarbon and water by using TDA were in agreement with water and oil saturation calculated from conventional logging measurements. Moreover, values of reservoir oil viscosities were estimated to be less than 10 cps by intrinsic T_1. This study shows that MRIL-based interpretation models are easy to apply because they require fewer unknowns as inputs and because MRIL response is not influenced by the resistivity model's parameters, water salinity, etc.

Keywords: *MRIL, Time Domain Analysis (TDA), Hydrocarbon Saturation, Water Saturation, Viscosity*

Introduction

One important application of the MRIL tool is the hydrocarbon typing near the wellbore. Two methods (activation sets) are generally used for hydrocarbon typing in conjugate with this logging tool: dual-TW method and dual-TE method. Dual-TW method is used to detect light hydrocarbons where dual-TE method is used to detect viscous oil (very long TE). A special activation set consist of dual-TW/dual-TE activation set is used for wildcat areas and production from unknown field (Chen *et al.*, 2000). MRIL data can be used to determine the hydrocarbon typing on the basis of the differences in either or both of the relaxation times (T1 and T2) or diffusivity of oil, water and gas. MRIL data can be analyzed independently or in conjugation with conventional logs. Independent processing of the MRIL data gives formation porosity and permeability as well as fluid types and fluid saturations in formations. By enhancing the relaxation times (T1 and T2) and diffusivity contrast between different fluid types which is possible through combination of pulse sequences and implementing a carefully designed logging program, one can determine the type of fluids within the formation (Howard *et al.*, 2001).

Time Domain Analysis (TDA), is a special technique developed for independent processing of MRIL data without using any conventional logs. The development of the TDA technique provides quantitative data about hydrocarbon saturations. TDA operates on the principle that different fluids have different rates of polarization, hence different relaxation times. In fact, Different fluids have different rates of polarization. For example, The T1 of gas and lighter oils (< 5 cp) is normally much longer than the T1 of water. Also, TDA provides corrections for under-polarized hydrocarbon hydrogen protons and hydrogen index effects. In TDA, the two CPMG (Carr-Purcell-Meiboom-Gill) echo trains are subtracted prior to inversion. Fundamentals of TDA method have been illustrated in figure 1.

Recently, Amirov investigated the application of MRIL-WD (MRIL-While Drilling) for measuring petrophysical properties of Shah Deniz wells in Azerbaijan like irreducible water saturation, porosity, etc. Results obtained from his investigation revealed that how effective MRIL data can be acquired while drilling and provide high quality measurements (Amirov, 2016). Oraby and Eubanks performed a case study on East Texas, USA to obtain petrophysical properties of the field by using MRIL tools.

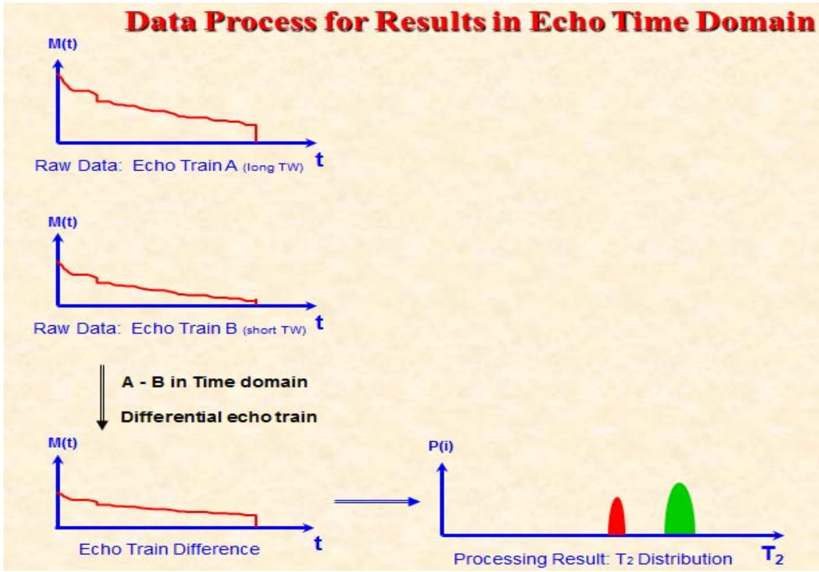

Figure 1. Hydrocarbon typing using TDA technique

Their investigation showed that MRIL logging was capable of determining the irreducible water saturation accurately and distinguished it from movable water saturation, an achievement that conventional logs were not able to provide. Moreover, they reported that better formation permeability was provided by MRIL logging with respect to conventional logging (Oraby & Eubanks, 1997). Mitchell et.al investigated the application of magnetic resonance imaging (MRI) for laboratory-scale core analysis and compared it with MRIL formation logging (Mitchell *et al.*, 2013). Mitchell studied the employment of three dimensional low field strength magnetic resonance imaging to monitor displacement process in oil recovery (Mitchell, 2014). McCarney et.al applied nuclear magnetic resonance (NMR) to estimate permeability anisotropy and proved that the data obtained from NMR permeability anisotropy are more valuable than the data obtained from core plug analysis (McCarney *et al.*, 2015).

In this study, TDA technique was used to determine water and hydrocarbon saturations and these saturations were then compared with petrophysical evaluation. It is known that the Archie's parameters in petrophysical evaluation, i.e. cementation and saturation exponents are not constant, particularly in heterogeneous reservoirs. In this study, however, they were assumed to be constant due to lack of lab results. To avoid inaccurate estimations caused from foregoing assumption in petrophysical evaluation which may lead to significant errors in the calculation of the water and hydrocarbon saturation, TDA method was used to detect hydrocarbon typing.

Methodology

The measurement mode used in this study is D9TWE2 which is a dual TE (500 0.9-msec echoes and 166 2.7-msec echoes) activation set where each echo spacing is acquired with two wait times of 12.988 and 1.000 seconds. A partial recovery measurement is also included. The activation parameters are given below:

TWL=12.988s,
TWS=1s
TES=0.9ms (NE=500)
Partial-Recovery measurement: TW=20ms, TE=0.6ms, NE = 10

The final output of the D9TWE2 activation consists of five groups of CPMG data which are introduced in table 1.

The aim of this study is to determine the hydrocarbon saturation, hydrocarbon viscosity and fluid distribution by TDA. In order to achieve these aims, the current study is divided into four steps; survey of log quality, signal processing, hydrocarbon analysis by TDA technique and hydrocarbon viscosity determination.

Survey of Log Quality

One important step to achieve accurate information from MRIL log and to obtain the highest level of data quality is a quality control step which is called the survey of log quality.

Table 1. Type of achieved groups of the CPMG data using D9TWE2 activation

Name of group	Time wait (TW)	Time echo(TE)	Number of echo(NE)
A	12.988 S	0.9 MS	500
B	1 S	0.9 MS	500
C	20 MS	0.6 MS	10
D	12.988 S	0.9 MS	166
E	12.988 S	2.7 MS	166

This survey involves calibration, verification (before and after the survey), operational setup, log recording, display of quality indicator, and final quality check. The log quality survey is performed on data before any MIRL preprocessing to guarantee the quality control of the data. Log quality is evaluated from different aspects like Q level, B1 field, noise indicators, etc., which are discussed in below paragraphs.

Checking Q Level

Each MRIL activation tool is designed to run at a specific Q level which is high, medium or low. Q level which is an estimation of coil quality is used to estimate the noise level of the data obtained from MRIL tool and is determined based on the Gain. MRIL tools monitor and calibrate in real time for downhole changes in system gain. Gain Corrects for downhole system sensitivity of the received signal which is influenced by the borehole environment (mainly borehole fluid) as it affects the loading of the antenna. Gain is influence by temperature, fluid resistivity and wellbore size. Therefore, the operating frequency of a tool should be set to achieve maximum gain which must be nearly constant as well. Abrupt changes or spikes in gain should not be present. Spiking usually indicates tool problems. For a particular MRIL too, the value of Gain determines the acquisition power (Q) level of the MRIL tool. Table 2 shows the Gain value versus the Q level (Ehigie, 2010; Stambaugh *et al.,* 2000).

Table 1. Gain versus Q level (Coates *et al.,* 1999)

Gain	Q Level
> 300	High
200 - 300	Medium
< 200	Low

Checking B1 Field

Another important step in MRIL tool's quality control is checking for B1 field which is used to acquire the CPMG sequence. The CPMG (Carr-Purcell-Meiboom-Gill) pulse train is a fundamental component of pulse sequences used for the measurement of dynamic processes by NMR spectroscopy (Thomas, 2013). B1 is the strength of this CPMG pulse that produces proton tipping and re-phasing and is measured using the test coil. The B1 Field should remain relatively constant. Small variations in B1 field occur when fluid conductivity and gain are changed. These variations are acceptable (Coates *et al.,* 1999).

Checking Noise Indicators

For each CPMG experiment, Noises are described by four indicators: offset (OFFSET), noise (NOISE), ringing (RINGING), and inter-echo noise (IENoise). These indicators are checked according to the Q level. NOISE and IENoise are inversely proportional to gain whereas RINGING is affected by echo spacing (TE). RINGING is much stronger for short TE than for long TE. The tool operating frequency must be selected to keep RINGING to a minimum. Table 3 shows the allowable range for these indicators. According to the experiences, NOISE and IENoise should not exhibit spiking, i.e., remains relatively constant (Coates *et al.,* 1999).

Checking the Chi

Chi is another indicator of MRIL log quality which is described by the differences between the calculated decay curve and the recorded echo amplitude. Common values of Chi are 2 or less. Values slightly greater than 2 are also acceptable in low-Q situations. Spiking usually indicate tool problems.

Checking the Low-Voltage Sensors

The MRIL quality-control procedure provides a set of low-voltage sensor data to ensure that the electronic cartridge works properly. Each low-voltage sensor should have values within the range shown in Table 4 (Coates *et al.,* 1999).

Also, the critical values of the voltages are shown in table 5.

Checking the temperature indicators

Three temperature indicators are normally reported during MRIL logging: Temp1, Temp2, and Temp3.

Table 3. Allowable Range for Noise Quality Indicators (Coates *et al.*, 1999)

Quality Indicator	**Allowable Range**
NOISE	$< 10(LowQ); < 8(MediumQ); < 5(HighQ)$
IENoise	$< 10(LowQ); < 8(MediumQ); < 5(HighQ)$
OFFSET	-30 to +30
RINGING	-40 to +40 (TE=1.2 ms), -60 to +60 (TE=0.6ms)

Table4. Low Voltage Sensor Mnemonic and Data Range (Coates *et al.*, 1999)

Sensor Name	**Real Time Display Mnemonic**	**Data Range**
15 Trans	V15T	14.8 _ 15.2
Ur 15 low	V15UM	19 _ 24
-5 Analog	V5AN	-4.9 _ -5.1
+5 Digital	V5D	4.9 _ 5.1
+5 Analog	V5A	4.9 _ 5.1
-15 Analog	V15N	-14.8 _ 15.2

Table5. Critical values of the voltages for low voltage sensors

Sensor Name	**Allowable Range**	**Allowable Tolerance**	**Allowable Std Dev.**
HV MIN	530 to 590	10	2.5
HV MAX	570 to 610	10	2.5

Temp1 is the temperature of the electronics cartridge flask, Temp2 is the temperature of the transmitter module, and Temp3 is the temperature of the magnet (Coates *et al.*,1999).

Figure 2 and 3 demonstrate that the quality of all curves were good for all depth intervals except for 2670-2675m and 2698-2705m interval that MRIL showed very strong mud signal due to washout. These intervals are known as bad-hole intervals and do not contribute into interpretation.

Also in Figure 3, the porosity measured from Short Wait Time, group B, is usually lower than that measured from a Longer Wait Time, group A, even if this time is not long enough for full polarization.

Signal Processing

Figure 4 shows steps of signal processing for the time-based MRIL which includes the raw echo time, gain, B1, high voltage in the tool, temperature of the magnet, transmitter and receiver. All these diagnostic measurements are made downhole.

Processing the MRIL logging data includes the following steps:

Bit Shifting

Depth matching must be performed before processing. MRIL data match with conventional (FULLSET) logging must be examined in this step.

Gain Adjustment

This step corrects complex (Real and Imaginary) echo trains to a determined signal phase angle and eliminates low amplitude bias created by magnitude computation. This correct usually utilizes limited echoes (i.e. echoes 2 - 9)

Stimulated Echo correction (Echo 1 & Echo 2)

The stimulated echo corrections factors, E1 and E2, consist of multipliers that are calculated for the first and the second echoes. They make these particular echoes fit the exponential curve relating porosity with the echo train amplitude curve. Normally Echo1 is artificially reduced in amplitude, while Echo 2 is increased. Echo1 is forced to fit the extrapolated amplitude of the exponential decay curve at the time of the first echo and Echo2 is simply forced to fit the exponential curve at the time of the second echo.

Power Correction

This step is used to correct for under/over tipping of the Hydrogen protons due to transmitting incorrect RF pulse amplitude.

Sodium Correction

This step is used to correct for the displacement of water (Hydrogen protons) by dissolved salts (Chlorine) within the resonant shell since CL reduces the measured signal.

MAP (Inversion)

The amount of L2 / L1L2 is used in this study to apply zeroth order regularization to invert CPMG data to a distribution of exponentials (T2 distribution). This method is used where the CPMG noise is non-Gaussian and where the data has outliers that will affect the result.

The standard deviation of the measured echoes and the calculated theoretical curve are compared. The equations are weighted according to the distance of the actual echoes from the theoretical curve. Those of about less than or equal to standard deviation will have the same weight, as in regular L2 minimization.

Those further away will be weighted about inverse proportionally to the distance from the theoretical curve. This solution is iterative. Once a temporary solution is attained, it is used to find the weights and to create the input for the next solution. This is done until convergence of the solution. In this study, only data from group A is used for interpretation (including porosity and permeability). Since data contained in group 'A' are long wait time, so polarization has performed perfect.

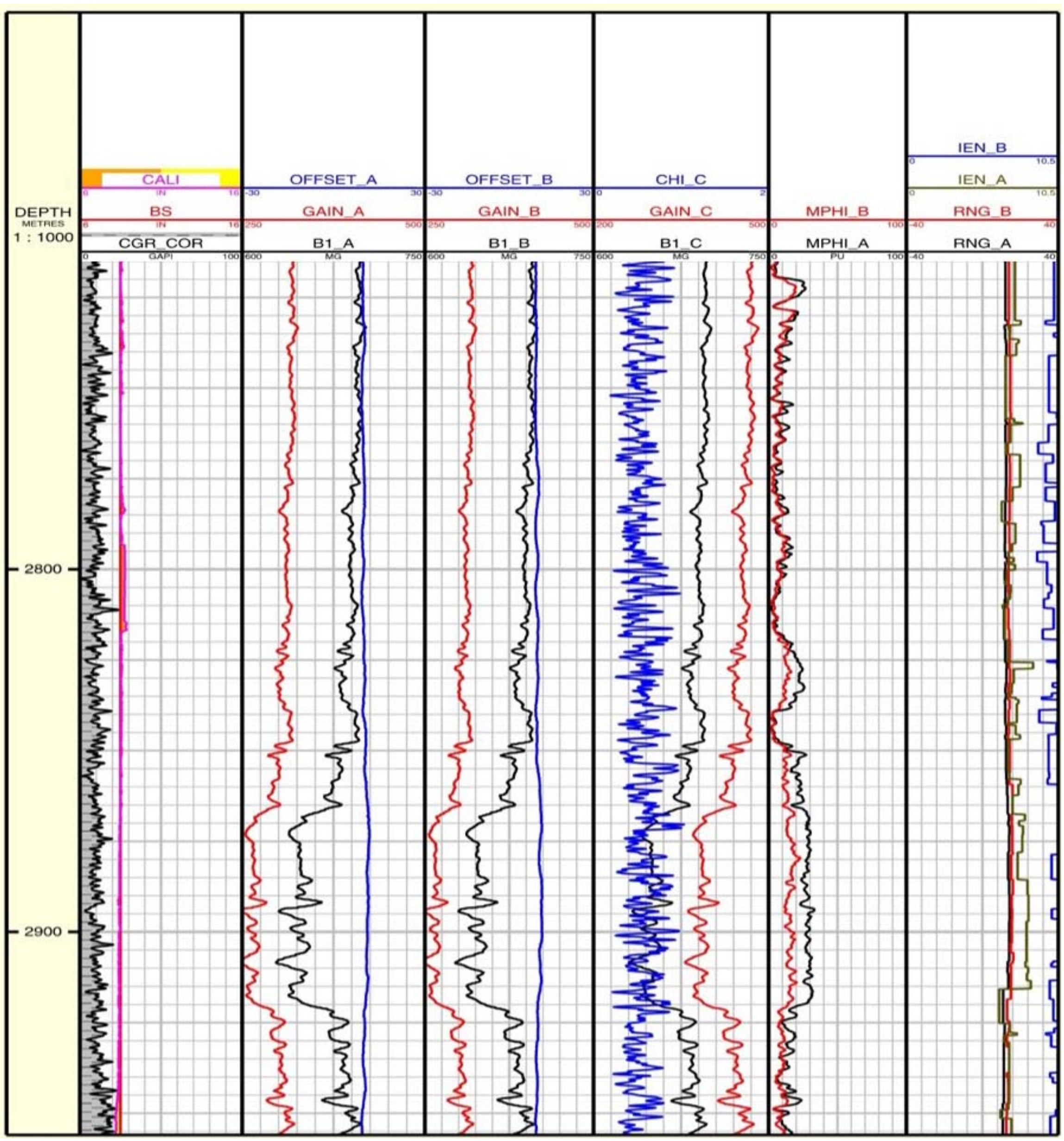

Figure 2. MRIL quality control curves

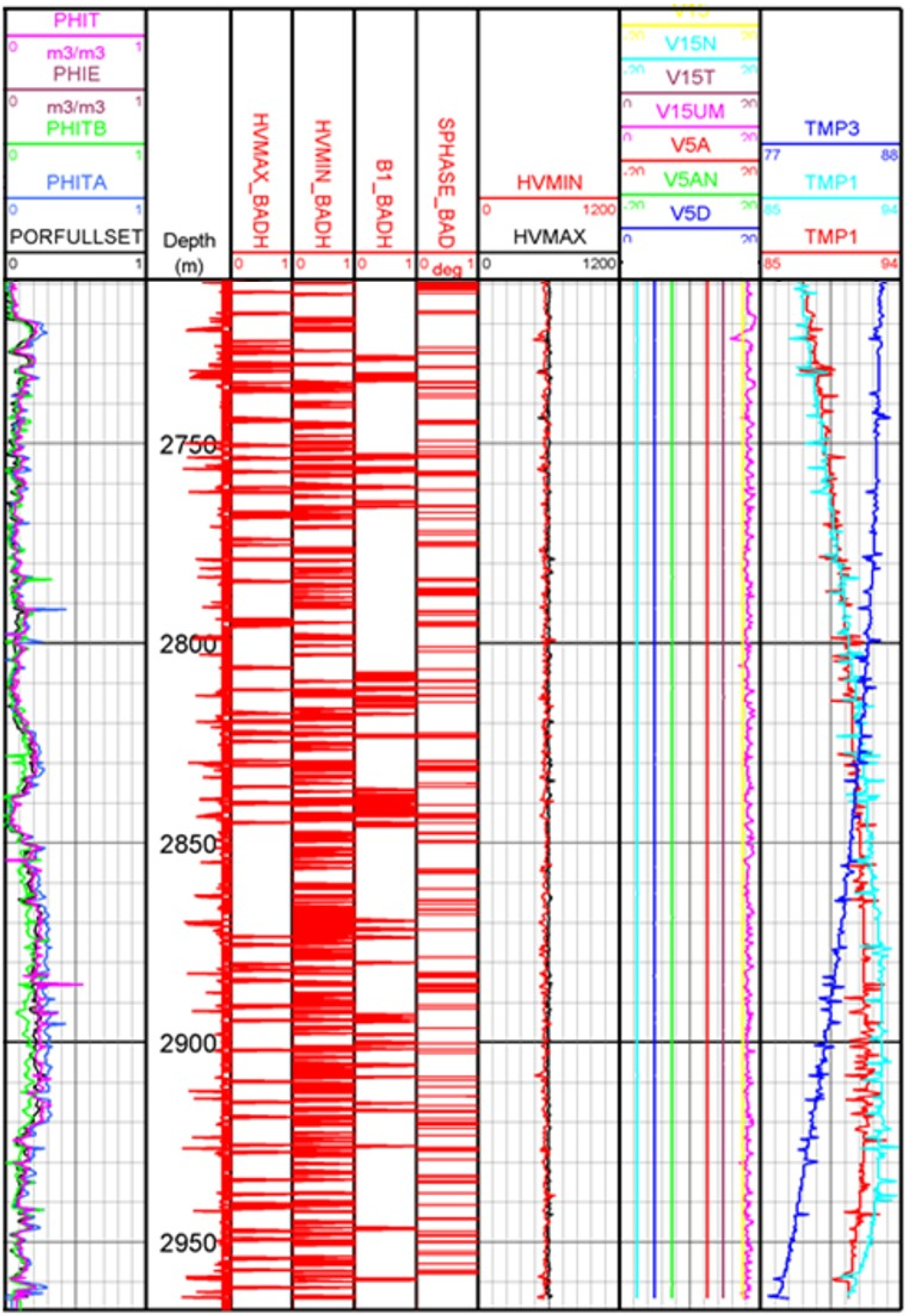

Figure 3. The results of the quality control for MRIL

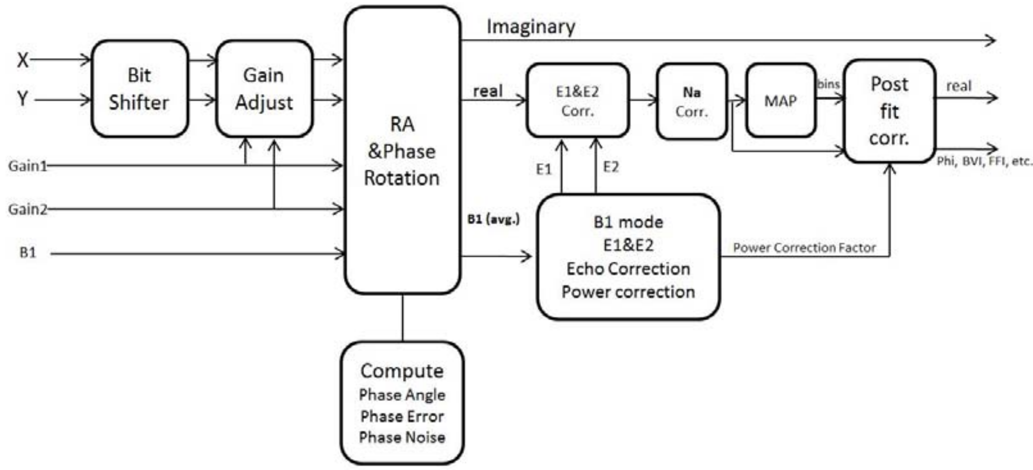

Figure 4. Signal processing steps(Coates *et al.*, 1999)

Also, permeability is calculated using Timur-Coate model since this model has the most flexibility for different fluid conditions. The result of processing the MRIL is indicated in figure 5. If core data is available, more accurate result can be used to update the permeability curve.

Hydrocarbon Analysis

TDA technique is normally used to acquire the hydrocarbon saturation. Indeed, The dual Tw model, using T_{WL} (long waiting time) and T_{WS} (short waiting time) measures two different echo train. If different waiting time from T1 relaxation is set, the signal will distribute differently in the echo trains. Then this difference can be used to calculate the hydrocarbon because T_1 of water is a little shorter than of light hydrocarbon zone.

Figure 6 shows the procedure of TDA method. As shown in this figure, the module performs an inversion of CPMG data generated from the subtraction of TW_S CPMG data from TW_L data. The resultant T_2 distribution will contain T_2 components associated with hydrocarbons.

The inversion routine automatically corrects for incomplete polarization due to insufficient wait time. If a polarization correction is not required, the wait time (TW) should be set artificially high. So, to calculate the true porosity, the apparent porosities must be corrected for incomplete polarization and Hydrogen Index. For this correction the following equations must be used(Coates *et al.*, 1999):

$$\phi_f^A = \Delta\alpha_f HI_f \phi_f$$

Where:

ϕ_f^A = apparent porosity of the fluid phase (oil or gas)

$\Delta\alpha_f$ = polarization function for the fluid phase

HI_f = Hydrogen Index of the fluid phase

ϕ_f = true porosity of the fluid phase

$$\phi_f^A = \Delta\alpha_f [\exp(-TW_S / T_{1f}) - \exp(-TW_L / T_{1f})]$$

Where:

TW_S = short wait time

TW_L = long wait time

T_{1f} = T_1 bulk of the fluid phase.

Figure 7 shows the concept of hydrocarbon correction. In fact, TDA provides corrections for under-polarized hydrocarbon hydrogen protons and hydrogen index effects.

Figure 8 shows the calculated saturation of oil and water using TDA technique. As it can be seen from this figure, for the depth interval of 2825 to 2925, oil and water signals are separated clearly even though many parameters like oil density, oil viscosity and wettability affect the T2 signal distribution of oil.

Viscosity Determination

Hydrocarbon viscosity is an important parameter affecting oil and gas recovery and economics. Fluid flow in porous media is inversely proportional to viscosity such that higher viscosity causes lower flow rate.

Viscosity is also an affecting parameter in enhance oil and gas recovery programs when two of more fluids are in contact with each other. Mobility ratio which is related to the ratio of viscosities of displacing and displaced phases is a factor that determines the ultimate recovery from a reservoir.

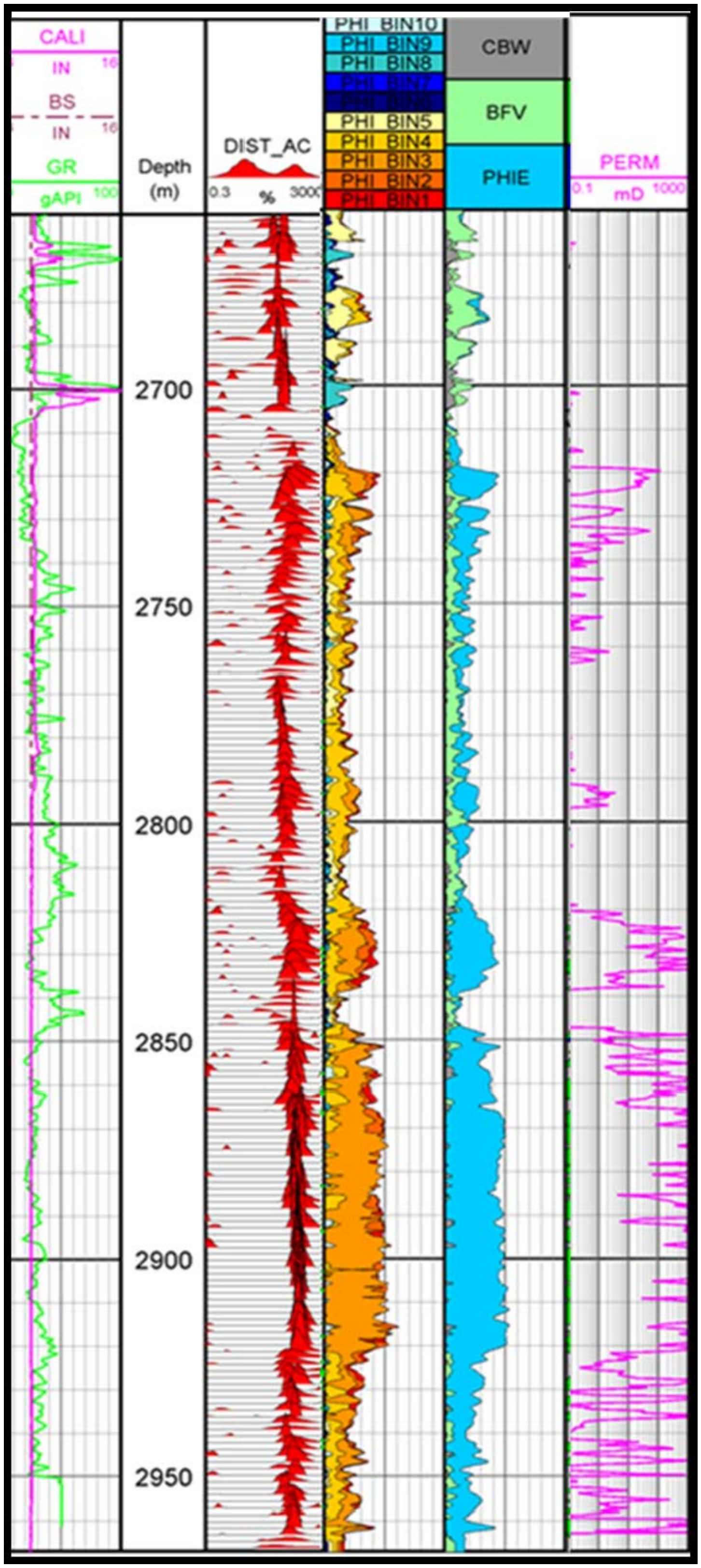

Figure 5. Achived petrophysical parameters from MRIL data

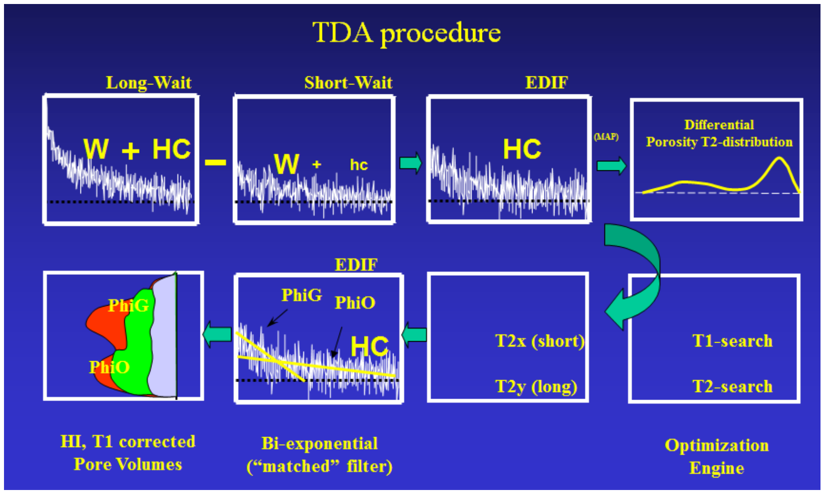

Figure 6. Step of process TDA technique

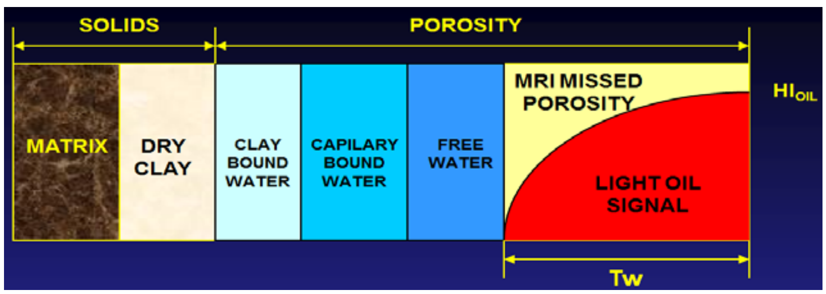

Figure 7. Schematic of hydrocarbon correction by using TDA technique

Integrated reservoir management is another field which is concerned with fluid viscosities since highly viscous oil reserves are not economical to produce and should not be included in early plans of field development. Therefore, determination of viscosity is an important step to perform before applying any production scenario on any field (Chen *et al.*, 2000).

Many laboratory procedures and devices are invented to determine the amount of fluid's viscosities. Different methods exist to determine the viscosity of fluids contained in a reservoir. Sampling is one direct method. Samples are obtained by well testing, down hole fluid samplers, etc., but the problem is that these samples are limited to a few depths or may be collected from separators which are associated with the entire producing interval. Therefore there is always the concern that these samples are not the in-situ reservoir fluids hence causing uncertainty in field development plans (Chen *et al.*, 2000).

One recent method to effectively determine the reservoir fluid's viscosity is by interpreting data obtained from MRIL logging tool. In this study, viscosity is calculated from T2LM, which is the geometric mean of the T_2 distribution, using Straley model. In fact, the values of viscosity of the reservoir fluids can be obtained from either intrinsic T_2 or T_1.

The Straley model is given by(Freedman and Heaton, 2004):

Viscosity = (1200 / T2LM) ^ $^{(1/0.9)}$

Where:

T2LM is T2 geometric mean in milliseconds (Freedman & Heaton, 2004).

The analysis performed in this study indicated that the viscosity values of the oil are less than 10 cps. Further, a good agreement is obtained for the viscosity estimates based on MRIL log data and laboratory pressure/volume/temperature (PVT) analysis. Value of oil viscosity obtained 7.8 cps under reservoir condition in the lab. Calculated values of viscosity are indicated in the last Column of figure 9.

Result and Discussion

Generally, the T2 of crude oil is a distribution of values rather than a single value that depends on viscosity. More viscous oils usually have a broader T2 distribution which is due to the difference in mobility's of the protons in different oil component.

Formation wettability also affects the location of oil component in the T2 distribution of the formation since for any wettability the heavy oil component of the T2 distribution is broad and fills the BVI portion of the distribution making detection of heavy oil with MRIL logging difficult.In case of mixed wettability which is one of the greatest challenges for MRIL application, the oil and water components of the T2 distribution are broad thus overlapping each other.

This overlapping does not affect the total porosity estimation of the reservoir but may have influence on erroneous determination of BVI, permeability and hydrocarbon type. In case of oil wet formations, BVI will be the bulk volume irreducible of oil and the water component will be in the free fluid portion of the distribution.

The reservoir studied in this study is water wet. Oil viscosity and API value in reservoir condition are estimated to be 7.8 centipoises and 22 degrees respectively.

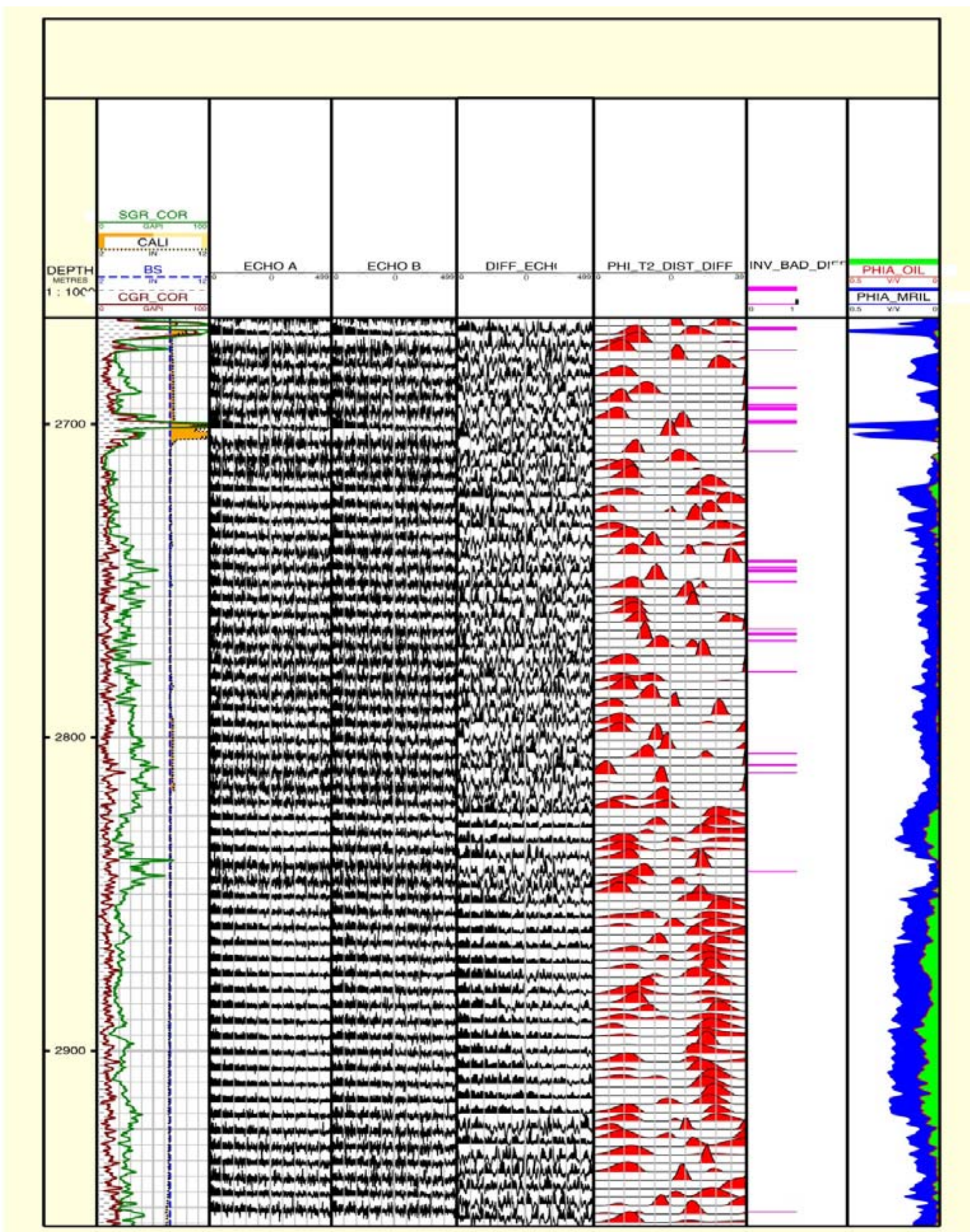

Figure 8. Calculated volume of oil and water by TDA technique

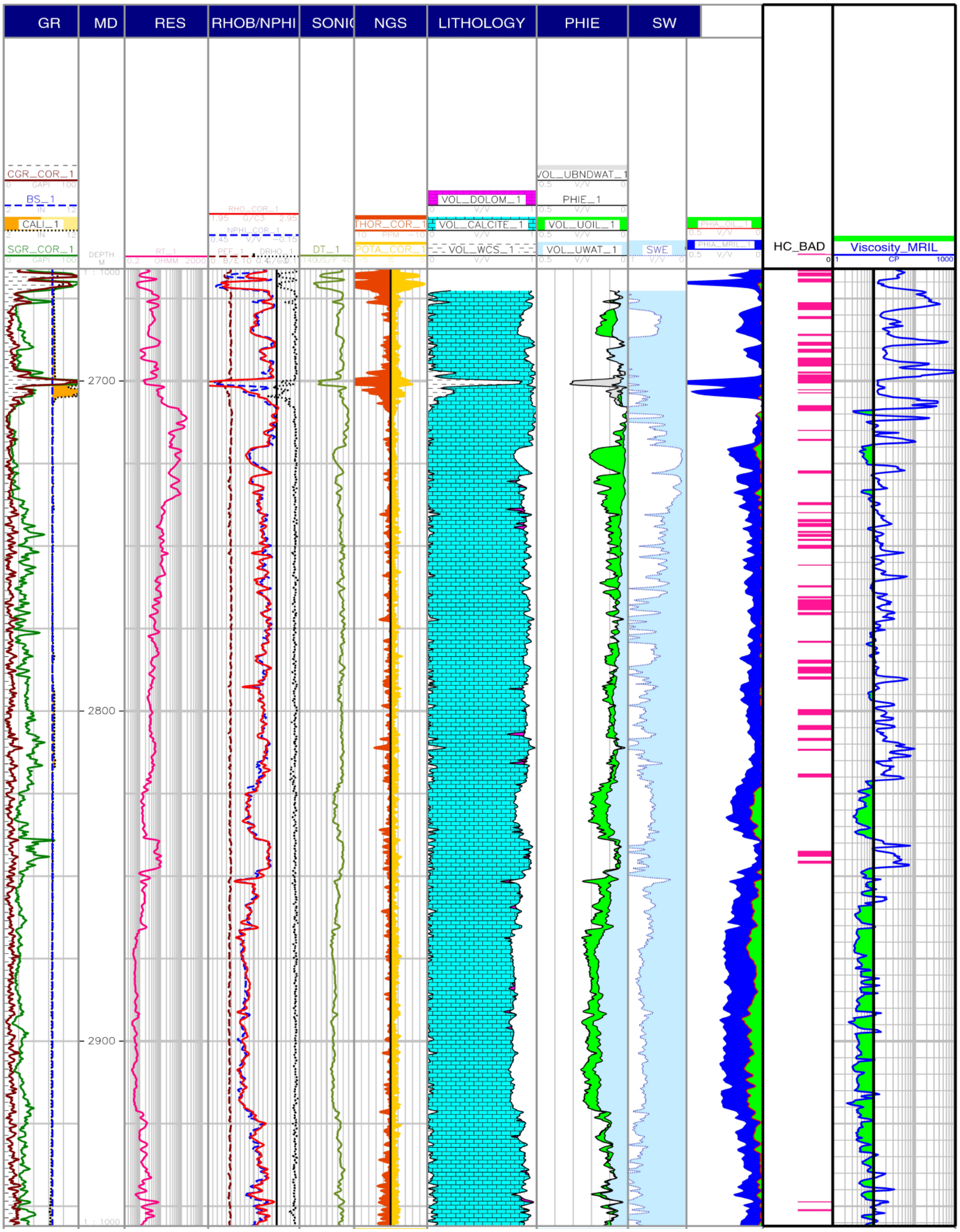

Figure 9. Comparison between hydrocarbon volumes obtained from conventional (FULLSET) logging and TDA. Calculated values of viscosity are indicated in the last Column.

The value of TW is sufficiently long so that the effect of T1 can be ignored. TE, on the other hand, is sufficiently short so that diffusion effects need not to be considered. Therefore, TDA can be useful in hydrocarbon typing in difficult environment. In order to guarantee the results of TDA, hydrocarbon saturation obtained from TDA is compared with hydrocarbon saturation obtained from conventional (FULLSET) logging as shown in figure 9. Figure 9 shows the fact that the results are matched and confirm each other.

Conclusion

In current study, MRIL logging-tool response is compared with the results obtained from conventional logging tools. MRIL loggings having benefits over conventional logging are also easier to apply since fewer unknowns are involved as input. The porosity value obtained from MRIL logging is independent of matrix minerals while being very sensitive to fluid properties. MRIL data can be used to differentiate clay-bound water, capillary-bound water, gas, light oil and viscous oils because of the differences in relaxation time. Moreover, MRIL responses are not influenced by the formation water salinity. MRIL logging data also provides information about pore size distribution, formation permeability, hydrocarbon porosity, vugs, fractures and grain size. TDA technique developed to assist in MRIL logging interpretation can help determine oil and water saturations and by appropriate estimation of relaxation times, MRIL logging tools can satisfactorily provide in-situ oil viscosity. The T2 of the oil peak correlates roughly with oil viscosity. The water and oil peaks are well separated in the light oil zones, which allow estimation of oil saturation by integrating the T2 distribution.

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