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Petrophysical evaluation of low-resistivity sandstone reservoirs with nuclear magnetic resonance log

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Abstract

The combination of conventional logs, such as density, neutron and resistivity logs, is proven to be very effective in the evaluation of normal reservoirs. For low-resistivity reservoirs, however, an accurate determination of the petrophysical parameters with the conventional log reservoirs is very difficult. This paper presents two cases of low-resistivity reservoirs and low-contrast resistivity reservoirs, where conventional logs fail to determine the petrophysical properties of reservoirs, mainly, low-resistivity and low-contrast resistivity reservoirs. The problems of these reservoirs are that conventional logging interpretation shows high water saturation zones, but water-free hydrocarbon would be produced. In the case of low-resistivity contrast reservoirs, it is very hard to determine water hydrocarbon contact with resistivity logs. Nuclear magnetic resonance (NMR) has only been available as a supplementary tool to provide additional information on the producibility of the reservoir. The main limitations of NMR have been the cost and time of acquiring data.

This paper shows that in the case of low-resistivity reservoirs, NMR is a very cost-effective tool and is of help in accurately determining the reservoir rock petrophysical properties. In the analysis of NMR data, several aspects of NMR technique have been used: (1) T1/T2 ratio for fluid identification, (2) the difference between NMR-derived porosity and total porosity to determine the types of clay minerals, (3) NMR relaxation properties to identify fluids composition and rock properties. This paper presents four examples of low-resistivity reservoirs. Analysis of the NMR data of low-resistivity reservoirs has helped identify the producibility of these zones, determine lithology-independent porosity and distinguish between bound and free water. For the case of low-contrast resistivity reservoir, where there was little resistivity contrast between water-bearing formation and oil-bearing formation, NMR has been able to identify the fluid composition of the two formations, as well as the height of the oil column. This was based mainly on the high contrast of NMR relaxation parameters. © 2001 Published by Elsevier Science B.V.

Keywords: Low resistivity; Low-resistivity contrast; NMR; Sandstone reservoir

1. Introduction

In formation evaluation, resistivity logs are the main pay zone identifiers because of the resistivity contrast between the oil zone and water zone. If, however, a pay zone exhibits low resistivity, these logs become incapable of identifying the producing zones and of indicating water mobility. Because of this limitation, many potentially productive zones with high irreducible water saturation are overlooked. Control of water production and identifica-

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tion of low-resistivity pay zones with high irreducible water saturation are problems in many fields in the Middle East and in other fields around the world.

There are many reasons that lead to low-resistivity pay zones. It is of crucial importance to know the origin of this phenomenon. The problem with these zones is that the resistivity data interpretation indicates high water saturation, but oil or even dry oil will be produced. The reasons for low-resistivity phenomenon are classified mainly into two groups. The first group consists of reservoirs where the actual water saturation can be high but with water-free hydrocarbons being produced. The mechanism responsible for such high water saturation is usually described as microporosity. The second group consists of reservoirs where the calculated water saturation is higher than the true water saturation. The mechanism responsible for this high water saturation is described as being caused by the presence of conductive minerals, such as clay minerals, metal sulfides, graphite and pyrite, in a clean reservoir rock. Pyrite is a common heavy mineral associated with marine sedimentary rocks. It has a good electrical conductivity that is usually comparable to, or even higher than, the conductivity of the formation water. The crystals of pyrite may form a continuous network even at low pyrite concentrations. Measured resistivity on dry pyrite ranges from 0.03 to 0.8 Ω m. Pyrite's conduction is of metallic (electronic) nature and, consequently, any transfer of current between water and pyrites is based on the conversion from ionic to electronic conduction and vice versa. This leads to polarization at the water–pyrite interfaces, with the corresponding frequency-dependent electrical properties. Thus, the electrical properties of porous rocks with pyrites are strongly dependent on the amount and distribution of pyrite and the measuring frequency of the electrical current (Clavier et al., 1984).

Generally, standard log analysis will identify the hydrocarbon-bearing zones. The problem with low-resistivity reservoir is the ability to predict whether little or no water will be produced, even though log analyses indicate that the formation has high water saturation. The most promising technique to solve this problem is the nuclear magnetic resonance (NMR) log. The NMR log can identify water-free production zones, correlate bound fluid volume with clay mineral inclusions in the reservoir, and identify hydrocarbon type (Hamada and Al-Awad, 1998; Zemanek, 1989).

The connection between NMR measurements and petrophysical parameters stems from the strong effect that the rock surface has in promoting magnetic decay of saturating fluids. The longitudinal relaxation time (T1) is the parameter of interest for estimating petrophysical properties, but NMR only measures the transverse relaxation time (T2), which is influenced by the inclusion of paramagnetic minerals, such as (iron-bearing) chlorite, in the low-resistivity pay zones. La Torraca et al. (1995) found that there are magnetic gradients between the pore fluids and iron-bearing rock minerals. This gradient will create a faster T2 decay, thereby resulting in an underestimation of the effective porosity, and lead to difficulties in determining bound and free fluids.

The phenomenon of low-contrast resistivity pay zones is encountered in reservoirs where there is little resistivity difference between water-bearing and oil-bearing zones. In low-contrast resistivity reservoirs, the water-bearing zone contains relatively fresh water; therefore, the resistivity is higher than normal. On the other hand, in an oil-bearing zone, the associated water is a mix of fresh and salt water, so the resistivity is lower than normal and is variable. Such oil reservoirs also show a high level of connate water saturation that causes further depression in the formation resistivity. Considering these two abnormal changes in water and oil zones, it will be quite difficult to identify the pay zone from the resistivity log. The use of NMR log has clearly solved this problem. The problem is the so-called low-contrast resistivity reservoirs showing high contrast NMR relaxation times (Ayan et al., 1997).

This paper presents the wealth of information provided by NMR log to determine more accurately than conventional logs the petrophysical properties of low-resistivity reservoirs. Four field examples will be presented; three examples are for low-resistivity reservoirs and one example shows a low-contrast resistivity reservoir. Before analyzing the field examples, the basic principles of NMR and their effect on the interpretation are discussed.

2. NMR porosity

The fact that NMR porosity depends only on the fluids content of the formation, unlike density/neutron porosity, which is influenced by both fluids and surrounding rocks, makes NMR measurements much more capable than conventional logs to furnish clay-corrected, nonproductive and productive porosities. The strength of the NMR signal is proportional to the number of hydrogen atoms in NMR tool-dependent rock volume. In zones containing light hydrocarbon, where the hydrogen index is less than unity, NMR porosity will typically underestimate true porosity in proportion to the hydrogen index. In this formation, there is a separation between density and neutron porosity, which indicates light hydrocarbon. For oil and water, NMR results can be expressed as the percentage of fluid volume of the rock volume. The number of hydrogen atoms in gas depends strongly on temperature and pressure. Hence, it is important to estimate the pressure and temperature accurately to account for their effect on NMR results in natural gas reservoirs (Hassoun and Zainalabedin, 1997; Hamada et al., 1999; Oraby et al., 1997; Coates et al., 1997).

In the literature, there has been some confusion in defining and using the results of NMR porosity data. To clear out this confusion, Fig. 1 shows the standard rock porosity model. MSIG denotes the total water content porosity. MPHI is the total porosity from NMR (fluid fractions of the rock excluding clay bound fluids). MCBW represents the clay-bound water porosity. MFFI, the free fluid index, includes all movable fluids (hydrocarbon and free water). MBVI, the capillary-bound water, is defined as all porosity measured with T2 between 3 and 33 ms. MBVWT represents all bulk volume water (free-, capillary-, and clay-bound water).

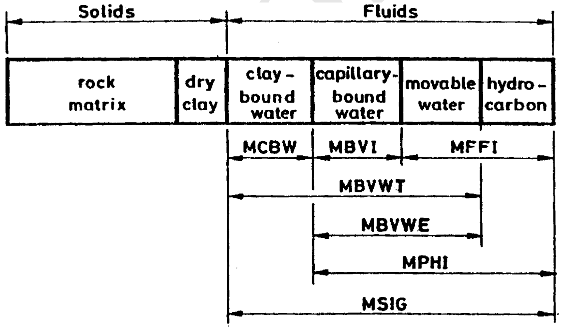

Fig. 1. The standard rock porosity model for all pore fluids (Menger and Prammer, 1998) (MSIG, total porosity; MPHI, effective porosity; MBVWE, bulk volume water effective; MBVWT, bulk volume water total; MFFI, free fluid index; MBVI, bulk volume irreducible water and MCBW, clay-bound water).

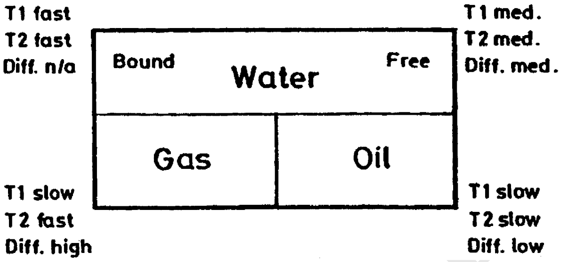

Fig. 2. NMR parameters (T1, T2 and diffusion) for water, oil and gas under reservoir conditions (Menger and Prammer, 1998).

3. NMR and fluids type

New methods for acquiring and processing NMR log data enable signals from gas, oil and water to be unambiguously separated and, in many cases, quantified. These methods exploit the combined effects of T1 and diffusion-based contrast on log response. The T1 contrast separates the water and light hydrocarbon (oil and gas). Gas and oil signals are then separated based on the large contrast in the diffusion-induced T2 relaxation times for gas versus liquid. Fig. 2 shows, in a qualitative way, the NMR properties for water, oil and gas under typical reservoir conditions. Laboratory NMR data show that both T1 and T2 vary over several orders of magnitude depending on fluid type. Hence, to allow reliable fluid typing, linear gradient field NMR tools have to be capable of measuring relaxation times from less than 1 ms to several seconds (Coates et al., 1997; Menger and Prammer, 1998).

Freedman et al. (1998) have introduced a new method called Density Magnetic Resonance (DMR) for evaluating gas-bearing reservoirs. The method combines the total porosity from the NMR tool (TCMR) and the density-derived porosity (DPHI). The method provides gas-corrected total formation porosity and flushed-zone gas saturation. Gas-corrected total porosity also improves permeability estimates made using the Coates–Timer equation in gas-bearing formations.

Certain low-resistivity reservoirs with water saturation greater than 50% can produce water-free hydrocarbon; this is attributed to the inclusion of clays.

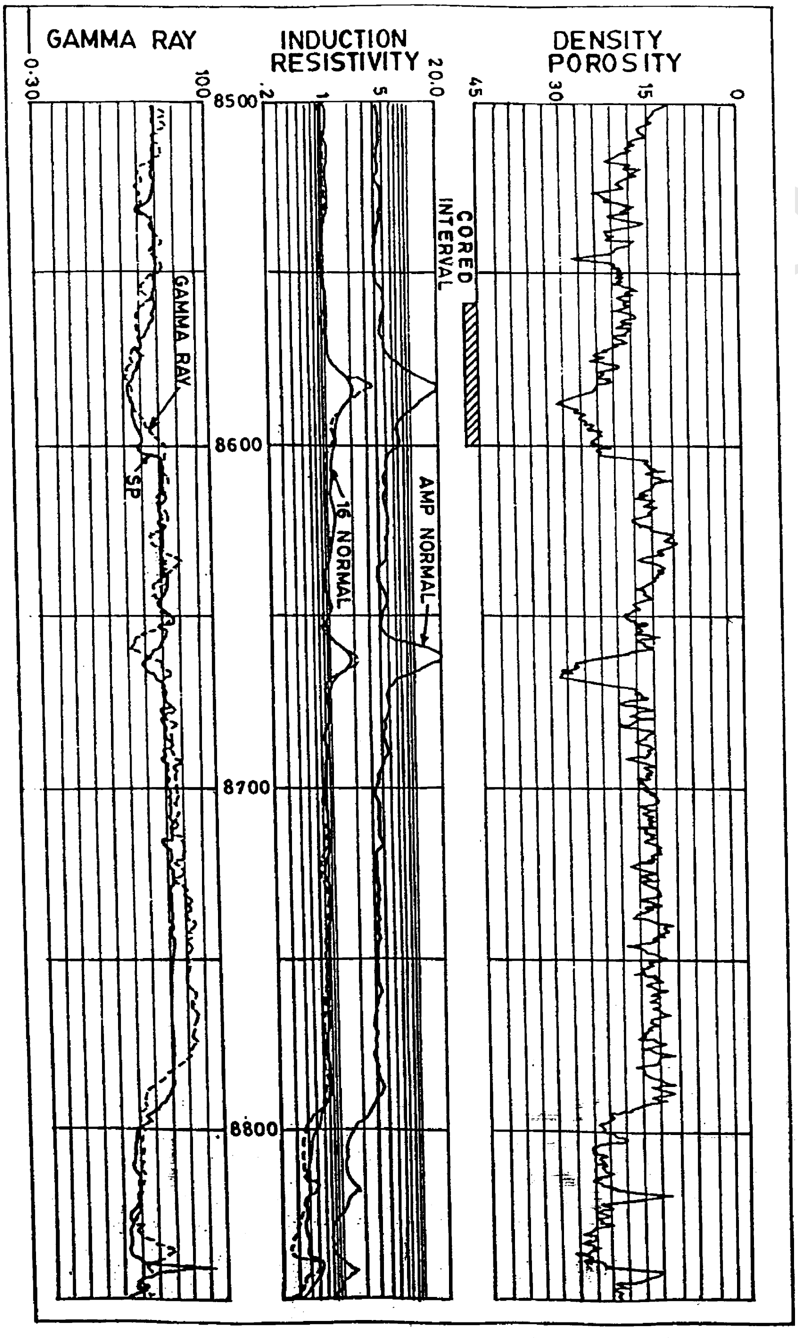

Fig. 3. Logs for well in low-resistivity reservoir (Zemanek, 1989).

Generally, standard log analysis will identify these reservoirs. However, the problem is how to predict whether little or no water will be produced. Zemanek (1989) has proposed a certain technique to solve this problem of high water saturation. This technique was based on the comparison between irreducible water saturation (S_{wi}) derived from laboratory NMR surface area and water saturation (S_w) deduced from conventional log analysis. If S_w is less than or equal to S_{wi}, water-free hydrocarbon will be produced, and if S_w is greater than S_{wi}, water will be produced.

4. Field examples

4.1. Field example 1

Fig. 3 shows a suite of logs from an offshore part of the Gulf of Mexico well drilled in a low-resistivity Pleistocene sandstone formation. Water saturations calculated from induction resistivity log, and using the resistivity exponents measured from 12 core samples show that water saturation is generally greater than 50%, with the water saturation values going from 25% to 74%. Fig. 4a shows water saturation from induction log and density porosity as a function of surface area. The core analyses show that these oil sands are not clean; there are clay/silt-size inclusions. The samples consist of 14–34 wt.% of the material, which is less than 30 μm. The water adherence to the surface area of the clays and water, which is only several molecular layers thick on the surface, is bound and cannot move. The induction log responds to the total water (free and bound), therefore, calculated water saturation exceeds 50%, but water-free hydrocarbons are produced. Capillary analyses of these dirty cores show high irreducible water saturation.

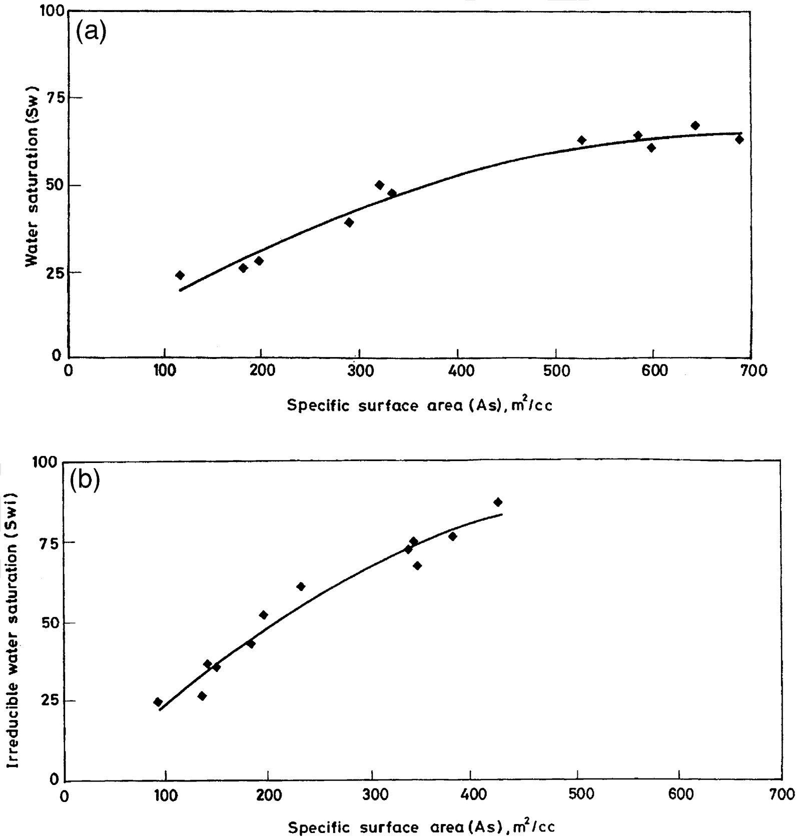

Fig. 4. (a) Water saturation from induction log versus grains surface area. (b) Irreducible water saturation versus grains surface area.

The problem is to predict the little or no water that will be produced, even though log analyses indicate high water saturation. NMR measurements on sidewall core samples can readily identify these low-resistivity reservoirs. The proposed technique applied in the study is as follows.

(1) NMR surface area measurements were conducted on the 12 core samples.

(2) Specific surface areas using the equation $A_s = A_{NMR}[(1-\phi)/\phi]\,\rho_{ma}$ were calculated.

(3) S_{wi}s from capillary pressure curves were plotted, as shown in Fig. 4b, and the correlation equation between S_{wi} and A_s for each sample (correlation equation is $S_{wi} = 1 - e^{(-0.0047A_s + 0.24)}$, $r = 0.982$) was found.

(4) Water saturation (S_w) from induction log and density log data were found.

(5) Compare S_w and S_{wi}, water-free hydrocarbon will be produced over the interval, where S_w is less or equal to S_{wi}. Water will be produced where S_w is greater than S_{wi}. The comparison between Fig. 4a and b shows that S_w is generally less than S_{wi}; this indicates that this section will produce water-free hydrocarbon. This was confirmed when the well was tested and dry oil was produced.

The approach above using laboratory NMR is recommended when the downhole NMR measurements are not available. To predict the probability of water production for a new well in the same low-resistivity reservoir, start by using steps 1 and 2, use

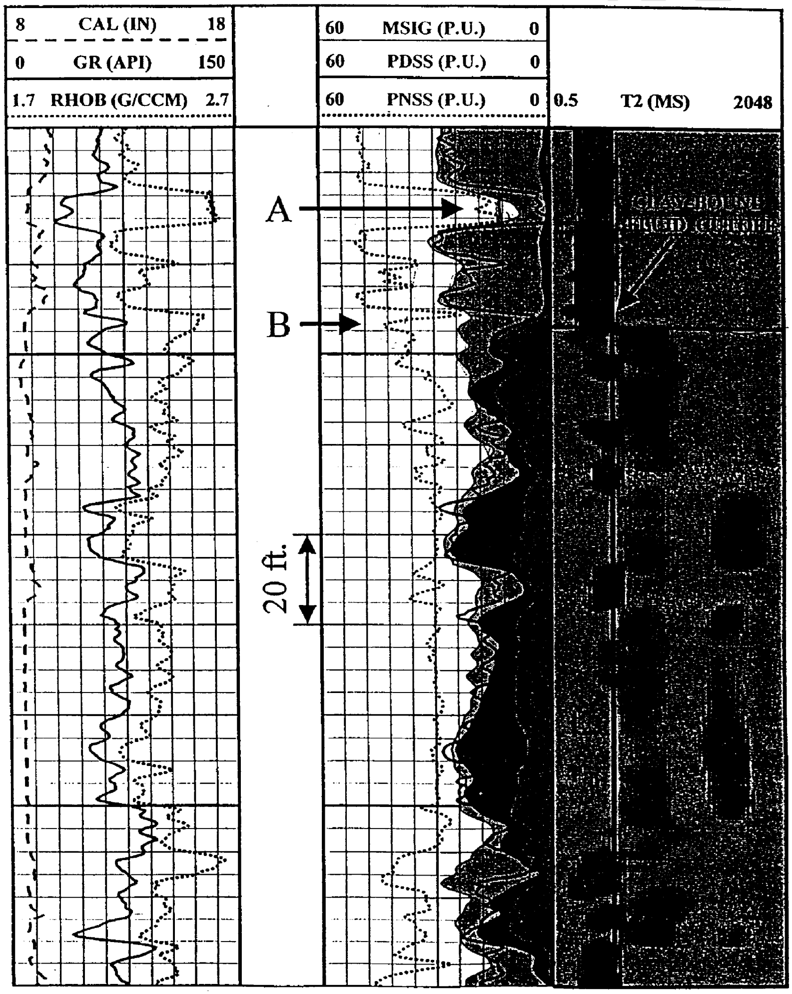

Fig. 5. Logging suite for well in low-resistivity sandstone reservoir (Menger and Prammer, 1998).

the correlation equation in step 3, and proceed to steps 4 and 5 for the selected core samples.

4.2. Field example 2

Fig. 5 presents logging data for a gas well drilled in Western Desert, Egypt. The main producing formation in this well is the Middle Cretaceous Kharita formation. Kharita is a shaly sand formation (Kenawy, 1998). This glauconitic sandstone is very heterogenous; it is a mixture of silt, very fine sands and glauconite. This complex lithology formation is characterized by high grain surface areas, thus, its irreducible water saturation is high. Resistivity logs read at about 1 Ω m against pay zones, and the log analyses have shown high water saturation (80–90%). However, the wells produce water-free hydrocarbon. The main mechanism of this case is with its mico-porosity and high capillarity. The NMR data shown in Fig. 5 indicate that there is a considerable amount of free fluid (gas and water) below depth B, while there is very little free fluid above depth B, as shown in track 2. This was based on the cutoff value of 33 ms (this cutoff is based on the results of the laboratory NMR analysis for core samples from the Kharita formation), as shown in track 3. The true porosity is derived from the density log other than the NMR and neutron logs. At depth A, all porosity logs (NMR porosity (MSIG), Neutron porosity (PNSS) and density porosity (DSS)) are going down to about 10 p.u., while the true porosity is about 25 p.u. The case of this well is common in Western Desert fields; thereupon, it is recommended to run NMR in new wells to better identify these low-resistivity reservoirs.

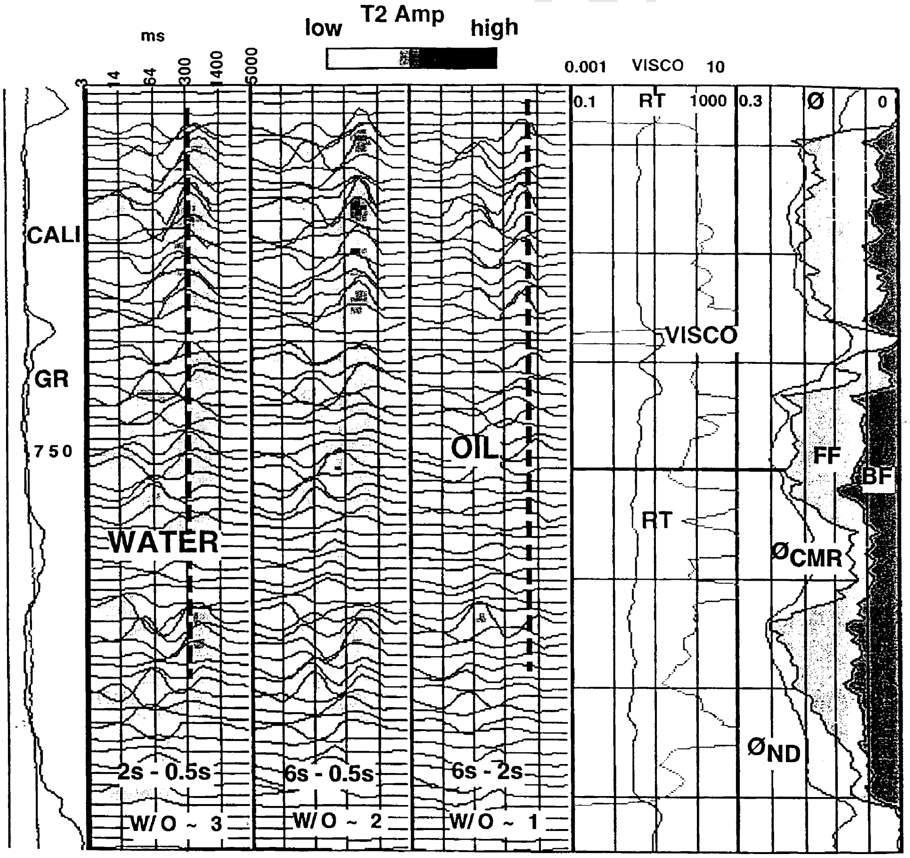

Fig. 6. Modified differential spectrum and logging suite for well in low-contrast resistivity reservoir (Hassoun and Zainalabedin, 1997).

4.3. Field example 3

This is an example of a low-contrast resistivity Early Cretaceous sandstone reservoir in Saudi Arabia. In these sandstone reservoirs, the water-bearing formations contain relatively fresh water, thus showing high resistivity. The pay zones contain mixed water (brine and fresh), which makes the formation resistivity variable and lower than the normal values. These sandstone reservoirs are characterized by high levels of irreducible water saturation that lower resistivity. The relatively high water zone resistivity and low pay resistivity create low-resistivity contrast between pay zone and water zone. This low contrast resistivity makes the pay zone identification from resistivity log a very tedious job. Fig. 6 presents a logging suite run in an oil-producing well from low-contrast resistivity reservoir. In track 1, GR shows that there are three sand bodies, and the resistivity reading in track 5 shows resistivity values in the range of 3–4 Ω m; these are typical values for water-bearing zone in central Saudi Arabia fields. This well is producing hydrocarbon with little water. NMR logging was used to solve this resistivity interpretation problem. The NMR logging technique works well in the low-contrast resistivity reservoirs, based on the contrast in the relaxation parameters (T1, T2 and diffusion) between water (free and bound) and hydrocarbon (oil and gas), as shown in Fig. 2. The technique of Modified Differential Spec-

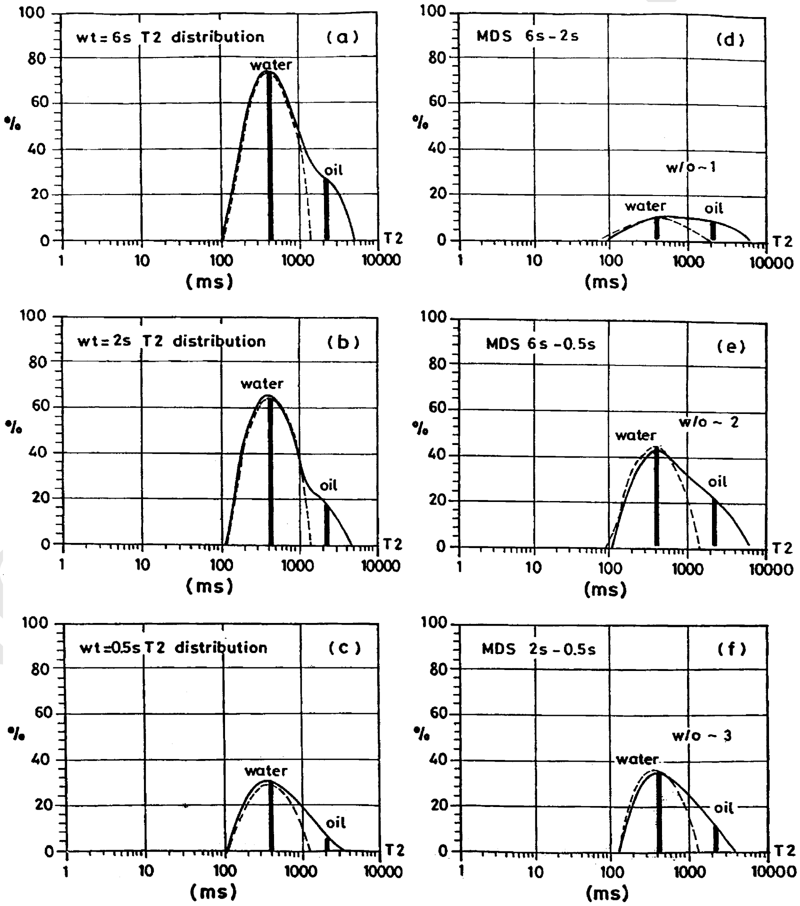

Fig. 7. Modified differential spectrum and T2 distribution at different waiting times and varying water/oil ratio for well in low-contrast resistivity reservoir.

trum (MDS) was used to isolate the water signal from the hydrocarbon signal. This modified model has three passes at three waiting time groups. The use of MDS was to overcome the NMR interpretation problem due to the absence of nearby water zone required to observe T2 distribution change between the water zone and oil zone on the normal T2 distribution curve.

The illustrated model shown in Fig. 7 was developed for T1 (oil) = 1 s and T1 (water) = 2.5 s. The model includes T2 distribution at three waiting times: 6, 2 and 0.5 s (see Fig. 7a–c), and three passes of MDSs with varying water/oil ratios: 1, 2 and 3 (see Fig. 7d–f). MDS has shown a symmetrical spectrum around the peak at 300 ms in the case of water for all waiting times, which are shown by the broken curve in the model response from a to f. However, in the case of oil and water, the model spectrum (solid curve) lost symmetry and shifted with respect to the ideal water peak in all waiting times, as shown in Fig. 7.

Neutron/density porosity and CMR porosity profiles are shown in track 6, Fig. 6. The three DMS passes shown in tracks 2, 3 and 4 of Fig. 6 at three waiting time groups are: 2–0.5 s and $W/O = 3$, 6–0.5 s and $W/O = 2$ and 6–2 s and $W/O = 1$, identified oil signal at 1200 ms and water signal at 300 ms. The free fluid index shown in track 6 illustrates that oil will be produced. Formation tester was run afterward and confirmed the oil in all three sand bodies. This example tested the ability of NMR log to identify oil zone already bypassed by resistivity log analyses, and considered as water zone.

5. Conclusions

NMR technology proves to be essential in formation evaluation and, more specifically, in low-resistivity reservoirs. The capability of NMR to differentiate between movable and immovable fluids has helped the log analysts to a more accurate estimate. However, the interpretation of NMR data requires caution and experience to ensure that the suitable cutoff values are selected based on local laboratory NMR analysis on core samples, and that reliable conclusions are reached from the measured and calculated parameters, especially in carbonate reservoirs.

The contribution of NMR information in the evaluation of the field examples discussed in this paper is two-fold. Firstly, NMR helped identify low-resistivity reservoirs and low-contrast resistivity reservoirs. Such reservoirs have often been missed, heretofore, with resistivity data interpretation. Secondly, NMR can provide (1) detailed porosity information, thus, it can replace conventional porosity logs as porosity tool and fluid type identifier; (2) quantitative information about pore fluids (clay-bound water, capillary-bound water, free water, oil and gas) and (3) prediction of little or water-free oil production, even though the resistivity log indicates high water saturation.

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