SPE 64406

Nuclear Magnetic Resonance Log Evaluation of Low- Resistivity Sandstone Reservoirs By-Passed by Conventional Logging Analysis

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This paper was prepared for presentation at the SPE Asia Pacific Oil and Gas Conference and Exhibition held in Brisbane, Australia, 16–18 October 2000.

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 is 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 been only available as a supplement tool, to provide additional information on the producibility of the reservoir. The main limitation of NMR, however, has been the cost and time of acquiring data.

This paper shows that in the case of low resistivity reservoirs NMR is very cost-effective tool and helps to accurately determine 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 nature and rock properties. This paper presents four examples of low resistivity reservoirs. Analysis of NMR data of low resistivity reservoirs has helped to identify the producibility of these zones, to determine lithology independent porosity and to 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 nature of the two formations and then the height of the oil column. This was based mainly on high contrast of NMR relaxation parameters.

Introduction

In formation evaluation, resistivity logs are the mains pay zones identifiers because of resistivity contrast between oil zone and water zone. If, however, a pay zone exhibits low resistivity, these logs become incapable of identifying the producing zones and also of indicating water mobility. Because of this limitation, many potentially productive zones with high irreducible water saturation are overlooked. Control of water production and identification of low resistivity pay zones with high irreducible water saturation of two formation evaluation problems in many fields in the Middle East and other fields around the world.

There is many reasons 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 water - free hydrocarbons are produced. The mechanism responsible such high water saturation is usually described as being caused by 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 conversion from ionic to electronic conduction and vise versa. This lead 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, distribution of pyrite and the measuring frequency of the electrical current.[1]

The problem of low resistivity reservoirs usually is not one of being able to determine the presence of hydrocarbons. Generally, standard log analysis will identify the hydrocarbon bearing zones. The problem is to be able to predict that little or no water will be produced even though log analyses indicate that the formation has high water saturation. The most promising candidate to solve this problem is the nuclear magnetic resonance log. NMR log can identify water free production zones, correlate bound fluid volume with clay minerals inclusions in the reservoir, and identify hydrocarbon type. [2-4]

The connection between NMR measurements and petrophysical parameters stem from the strong effect that the rock surface has on promoting magnetic decay of saturating fluids. The longitudinal relaxation time (T1) is the parameter of high interest for estimating petrophysical properties, but the 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[5] found that there are magnetic gradients between pore fluids and the iron bearing rock minerals. These gradients will make the diffusion movements of oil and water out of the frequency domain, resulting in faster T2 decay. This faster T2 decay will result in underestimation of the effective porosity and lead to difficulties in the determination of 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; thereby the resistivity is higher than normal. While in oil bearing zone the associated water is a mix of fresh and salt water, so the resistivity is lower than normal and variable. Such oil reservoirs also show a high level of connate water saturation that causes a further depression of formation resistivity. Considering these two abnormal changes in water and oil zones, it will be quite difficult to identify the pay zone from resistivity log. The use of NMR log has clearly solved this problem. The problem is so-called low contrast resistivity reservoirs showing high contrast NMR relaxation times. [6]

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 showing a low contrast resistivity reservoir. Before analyzing the field examples, the basic principles of NMR and their effect on the interpretation are discussed.

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 porosity, non-productive and productive porosity. 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 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 accurately pressure and temperature to account for their effect on NMR results in natural gas reservoirs.[7-11]

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 porosity. MPHI is the effective porosity from NMR (fluid fractions of the rock except for clay bound fluids, all porosity with T2 above 3 ms). MCBW represents the clay- bound water porosity with T2 less than 3 ms. MFFI, the free fluid index, includes all movable fluids (hydrocarbon and free water) with T2 more than 33 ms in sandstone. 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).

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 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.[13-14]

Freedman et al [15] has introduced new method called Density- Magnetic Resonance (DMR) for evaluating gas-bearing reservoir. The method combines total porosity from the NMR tool (TCMR) and 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 Coates-Timer equation in gas bearing formations

In certain case of low resistivity reservoirs with water saturation greater than 50% and being able to produce water free hydrocarbon, this is attributed to the inclusions of clays. Generally standard log analysis will identify these reservoirs. But, the problem is how to be able to predict that little or no water will be produced. Zemanek [3] has proposed certain technique to solve this problem. This technique was based on the comparison between irreducible water saturation (Swi) derived from laboratory NMR surface area and water saturation (Sw) deduced from conventional log analysis. If Sw is less than or equal to Swi, free water hydrocarbon will be produced and if Sw greater than Swi, water will be produced.

Field Examples

The movement of oil exploration into new areas is normally accompanied by new problems. Well log interpretation is not excluded. In the case of low resistivity reservoirs, resistivity logs analysis shows high water saturation but water free hydrocarbon will be produced. The standard logs fail to predict this phenomenon. This section presents different field examples to show how NMR log can help to solve this problem.

Field Example 1 Fig. 3 shows a suite of logs from an offshore Gulf of Mexico well drilled in low-resistivity Pleistocene sandstone formation[3]. Water saturations calculated from induction resistivity log and using resistivity exponents measured on 12 core samples have shown that water saturation is generally greater than 50 %, the water saturation values go from 25% to 74%. **Fig. 4a** shows water saturation from induction log and density porosity as function surface area. The core analyses shows that these oil sands are not clean, there are clay/silt size inclusions. The samples consist of 14 to 34 wt % of less than 30 μm material. These clays present high surface area on which water adheres, and the water, which is only several molecular layers thick on the surfaces, is bound and cannot move. The induction log responds to the total water (free and bound); therefore, water saturation has exceeded 50% and water free hydrocarbons are produced. Capillary analyses of these dirty cores have shown high irreducible water saturation. The source the high capillarity is the existence of large to moderate surface area clay minerals. Capillary attraction holds water to grain surface, hence, the actual water can be high, but dry oil is produced.

The main 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 are the most readily technique to identify these low resistivity reservoirs. The proposed technique is applied in the studied as follow:

1. NMR surface area measurements were conducted on the 12 core samples
2. Specific surface areas using equation ($As = A_{NMR}[(1-\phi)/\phi]\rho_{ma}$) were calculated
3. S_{wi} from capillary pressure curves were plotted as shown in **Fig. 4b** and find

The correlation equation between Swi and As for each sample (correlation equation is $S_{wi} = 1 - e^{(-0.0047As+0.24)}$, r = 0.982).

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

5. Compare between S_w and S_{wi}, water free hydrocarbon will be produced over the interval where S_w less or equal to S_{wi}. Water will be produced where S_w is greater than S_{wi}. The comparison between **Figs. 4a and 4b** 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 showed dry oil production.

The above approach-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 steps 1 and 2, use correlation equation in step 3 and proceed steps 4 and 5 for the selected core samples.

Field Example 2 **Fig. 5** presents logging data for a gas well drilled in the Western Desert, Egypt. The main producing formation in this well is Middle Cretaceous Kharita formation. Kharita is a shaly sand formation ,[16]. This glauconitic sandstone is very heterogeneous; it is a mixture of silt, very fine sands and glauconite. This complex lithology formation is characterized by high grain surface area, thus, its irreducible water saturation is high. Resistivity logs read 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 being the micoporosity and the high capillarity,[10]. The NMR data shown in **Fig. 5** indicates 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 as shown in track 3. The true porosity is derived from density log other than NMR and neutron logs. At depth A all porosity logs (MSIG, PNSS and PDSS) 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 the Western Desert fields, thereupon, it is recommended to run NMR in new wells to better identify these low resistivity reservoirs.

Field Example 3 This is an example of low contrast resistivity Early Cretaceous sandstone reservoir, Saudi Arabia,[6]. In these sandstone reservoirs, the water bearing formations contain relatively fresh water, thus show high resistivity. The pay zones contain mixed water (brine and fresh) which make formation resistivity variable and lower than the normal values. These sandstone reservoirs are characterized by high level of irreducible water saturation that provokes more resistivity depression. The relatively high water zone resistivity and low pay resistivity created low contrast resistivity 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 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 Spectrum (MDS) was used to isolate water signal from hydrocarbon signal. This modified model has 3 passes at three waiting time groups. The use of MDS was to overcome the NMR interpretation problem due the absence of nearby water zone required to observe T2 distribution change between water zone and oil zone on the normal T2 distribution curve.

The illustrated model in **Fig. 7** was developed for T_{1oil}=1s and $T_{1\ water}$=2.5s. The model includes T2 distribution at 6s, 2s and 0.5s waiting times **(Fig.7a-c)** and 3 passes of MDSs with varying water/oil ratios **(Fig.7d-f)**. MDS have 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 models response from a to f. But 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 Figure.9. The oil peak was observed at 1200ms. Neutron/density porosity and CMR porosity profiles are shown in track 6. The three DMS passes shown in tracks 2, 3 and 4 identified oil signal at 1200 ms and water signal at 300ms. Free fluid index shown in track 6 illustrates that oil will be produced. Formation tester was run afterward and confirmed oil in all three sand bodies. This example tested the ability of NMR log to identify oil zone already bypassed by resistivty log analyses and considered as water zone.

Conclusions

NMR technology proves to be very 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 more accurate estimate of the reserves through the identification of low resistivity reservoirs that have already been bypassed by the resistivity logging interpretation. However, the interpretation of NMR data requires caution and experience to ensure that the suitable cutoff values are selected 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 twofold. Firstly, NMR helped to identify low resistivity reservoirs and low contrast resistivity reservoirs. Such reservoirs have not been often identified, heretofore, with resistivity data interpretation. Secondly, NMR can provide 1) detailed porosity information, and thus it can replace conventional porosity logs as porosity tool and fluids 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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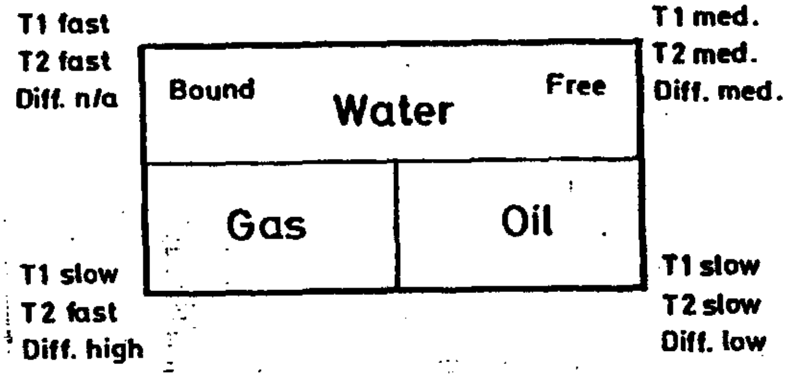

Fig.2. NMR parameters (T1, T2 and Diffusion) for water , oil and gas under reservoir conditions.[10]

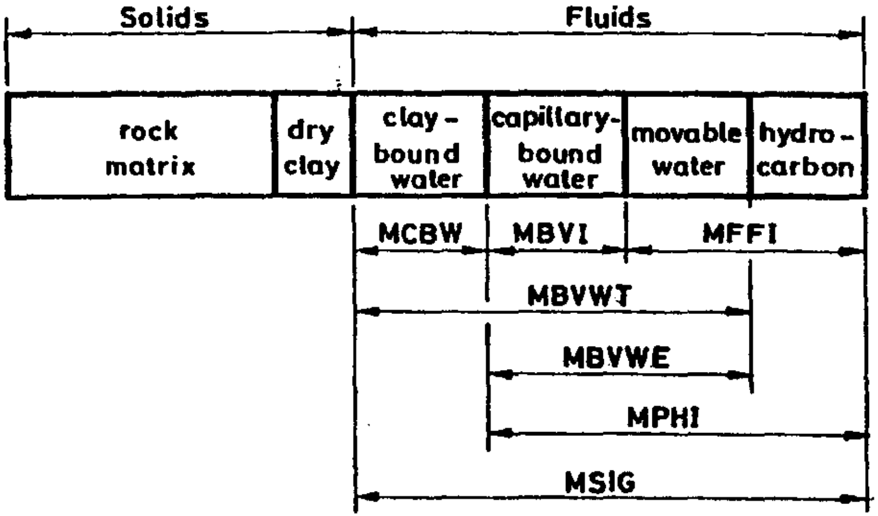

Fig.1. The standard rock porosity model for all pore fluids.[10] (MSIG total porosity, MPHI effective porosity, MBVWE bulk volume water effective, MBVWT bulk volume water total, MFFI free fluid index, MBVI bulk volume irreducible water and MCBW clay bound water)

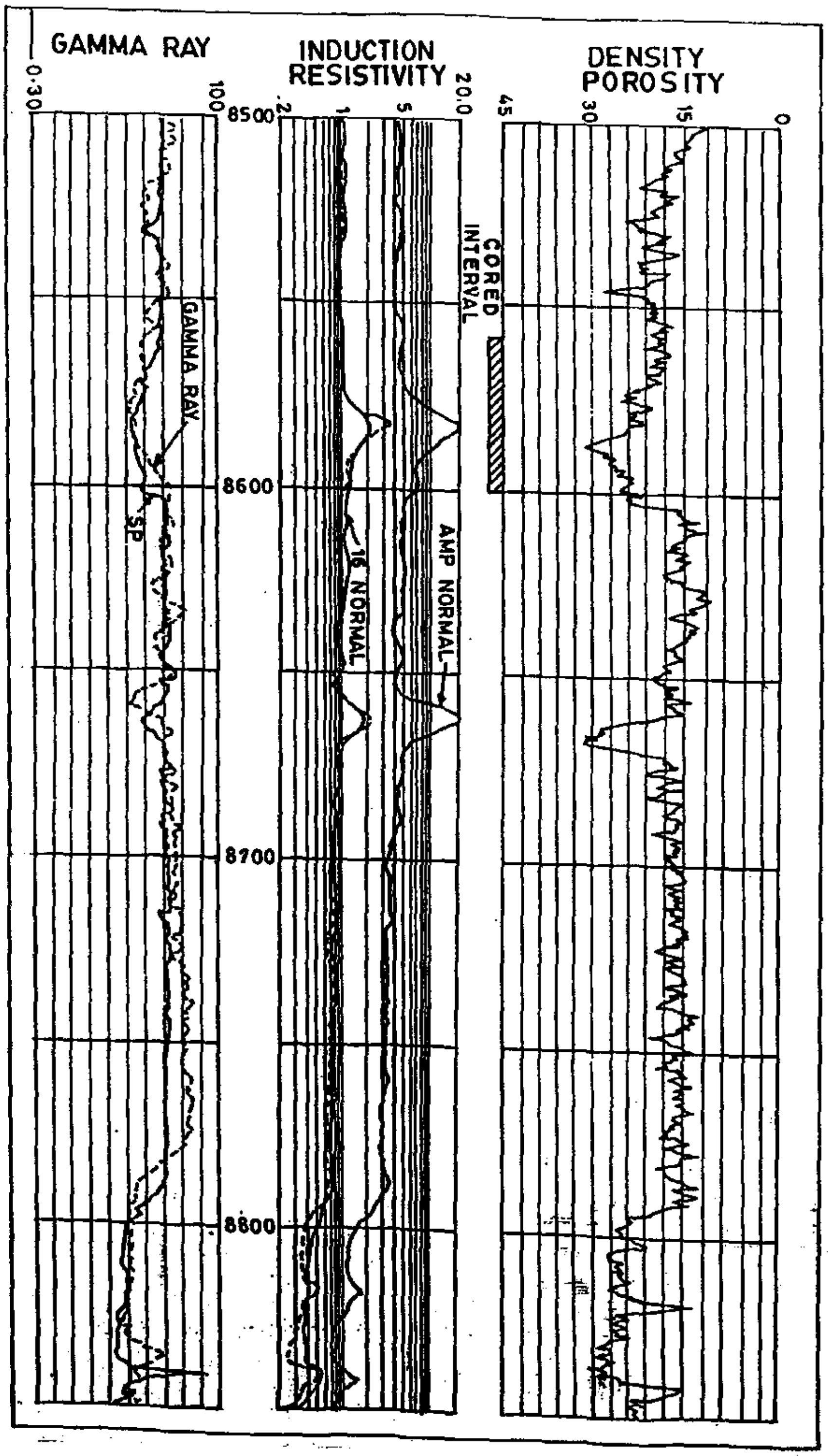

Fig.3. Logs for well in low resistivity reservoir.[3]

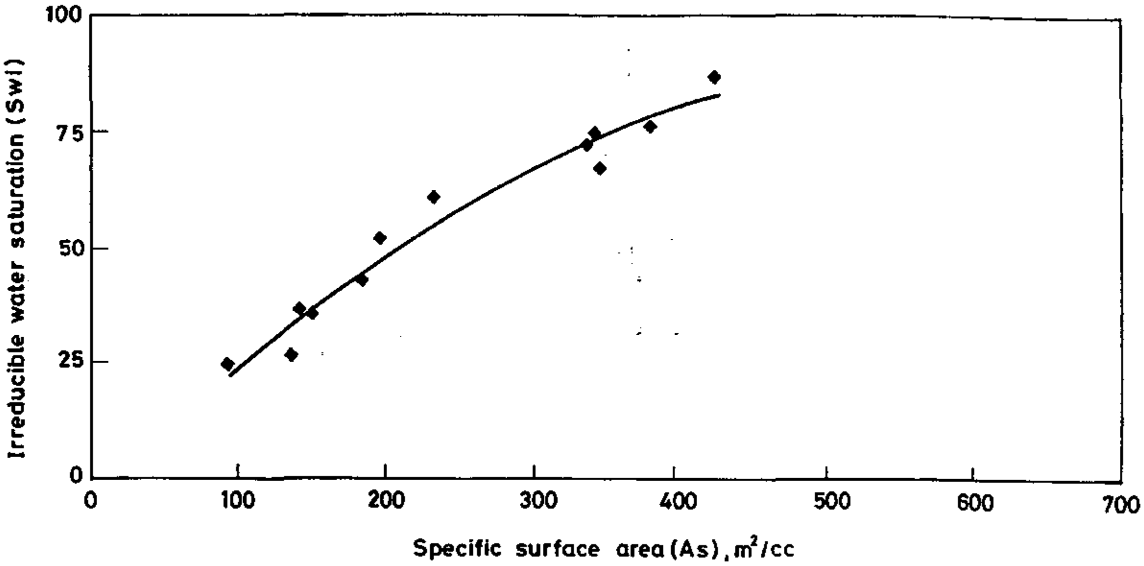

Fig.4b. Irreducible water saturation versus grains surface area

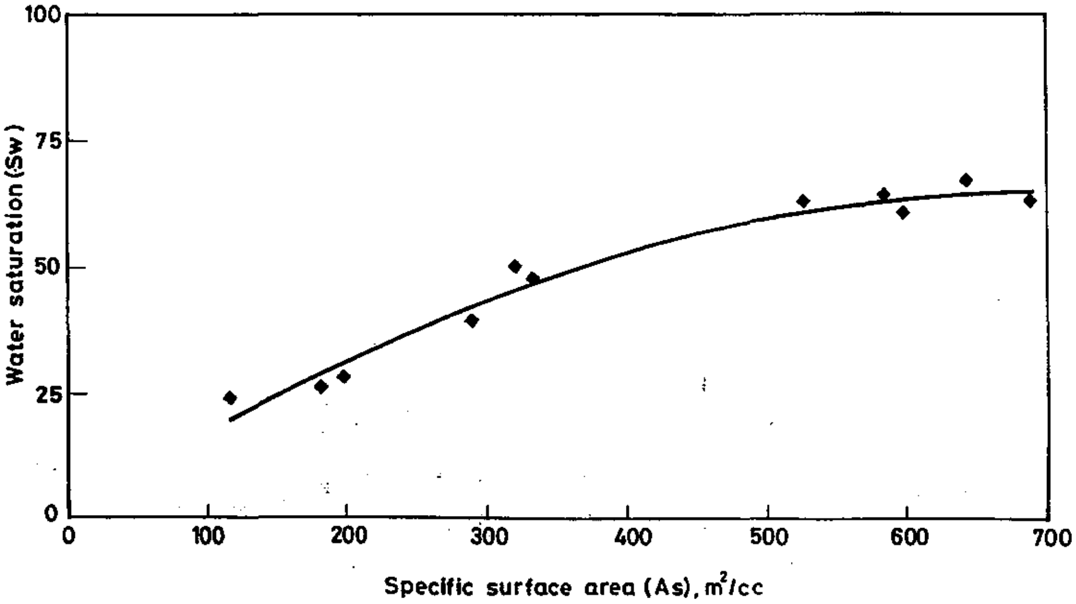

Fig.4a. Water saturation from induction log versus grains surface area.

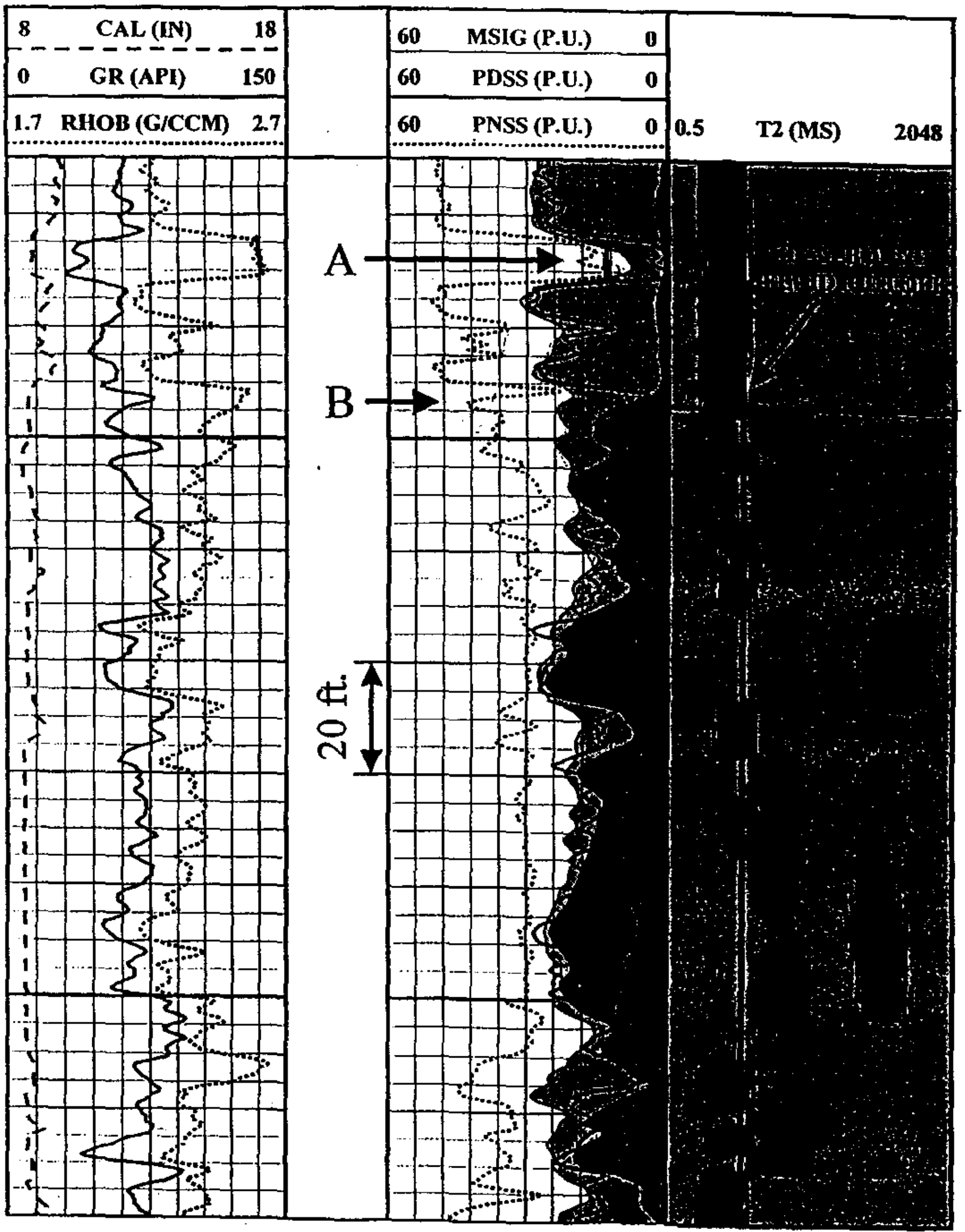

Fig.5. Logging suite for well in low resistivity sandstone reservoir.[10]

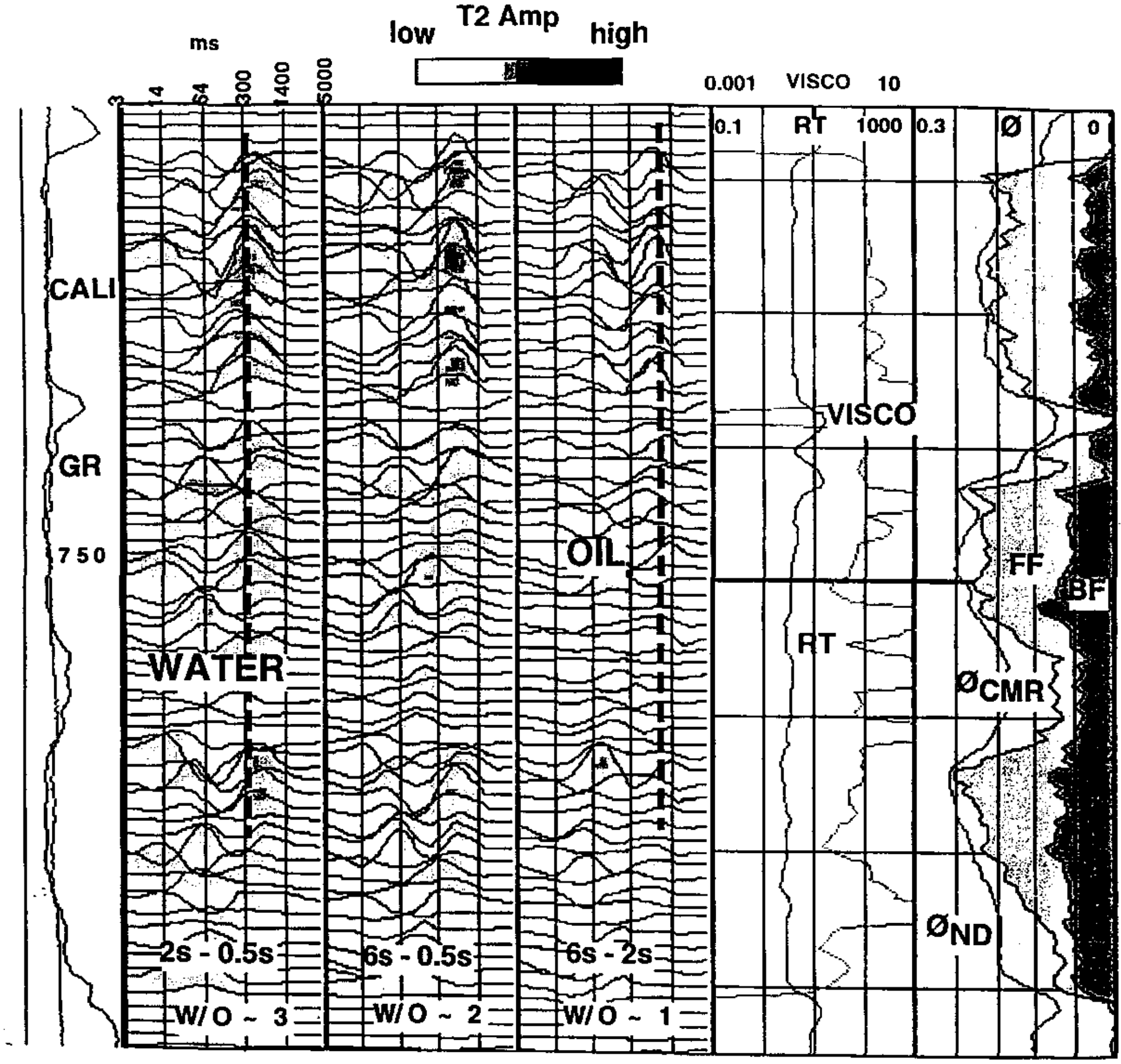

Fig.6. Modified differential spectrum and logging suite for well in low contrast resistivity reservoir.[6]

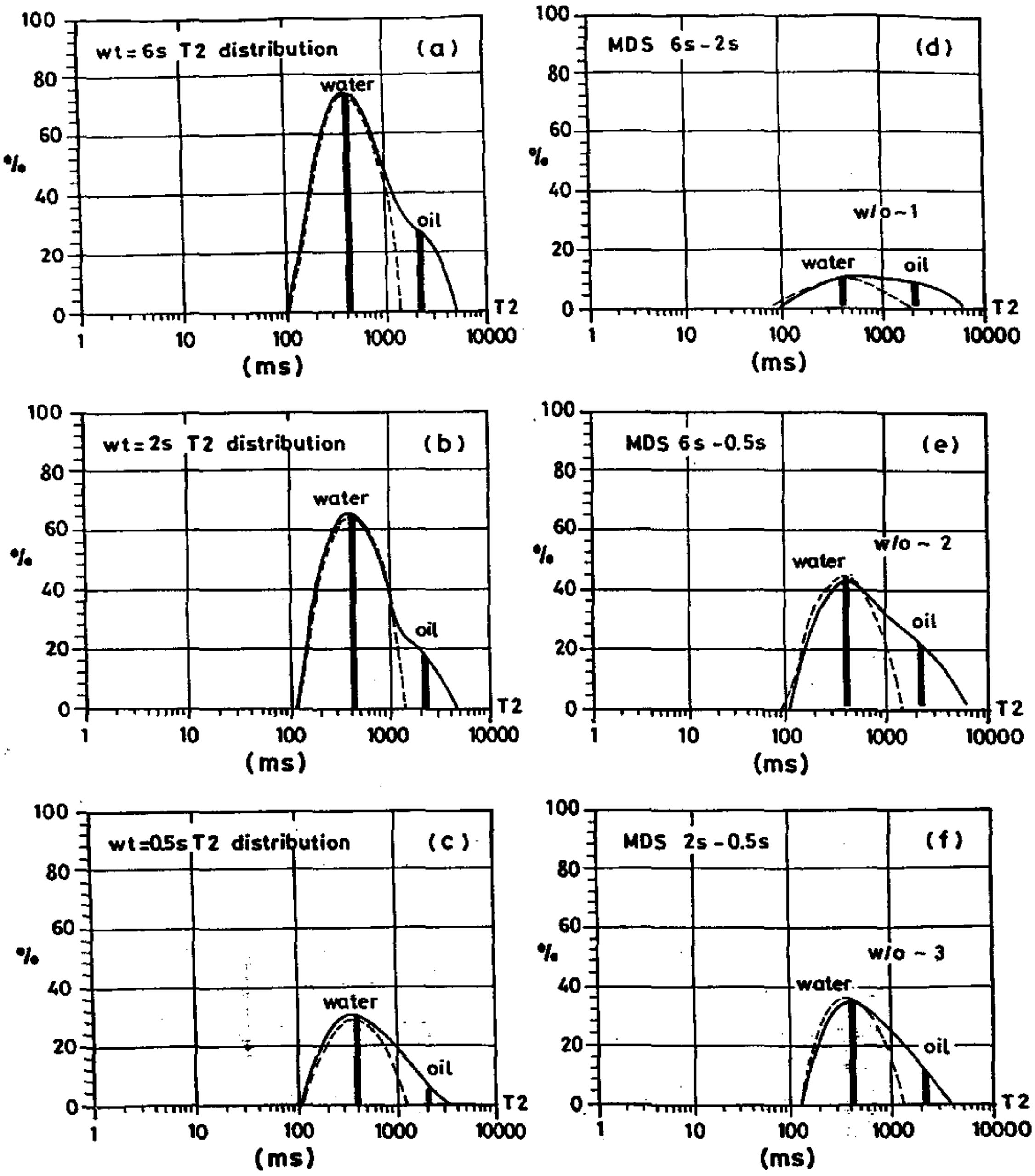

Fig.7. Modified differential spectrum and T2 distribution at different waiting times and varying water/oil ratio for well in low contrast resistivity reservoir.