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## Advanced Petrophysical Approach for Characterizing Low Resistivity Reservoirs

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### Summary

Miocene carbonates are the most prolific reservoirs of the Mumbai High field in the western offshore basin of India. There are multiple carbonate reservoirs namely: L-I, L-II, L-III, L-IV, L-V and L-VI from shallower to deeper depths. Among all the layers, the LIII carbonates are well developed and have been extensively evaluated. The L-I reservoir is developed at the shallow level and developed in some parts of Mumbai High North field. Realistic petrophysical evaluation of this reservoir is challenging because of complex pore structure, low resistivity values and mineral assemblage other than pure calcite. Addition of nuclear magnetic resonance and spectroscopy provide a realistic evaluation of such kind of reservoirs.

**Key words:** Spectroscopy, Nuclear Magnetic Resonance, Low Resistivity

### Introduction

Mumbai High field is the biggest offshore oil field of India, which was discovered in 1974 & has been in production since 1976. This field is the largest contributor to Indian oil production and has been producing for more than three decades. This giant field is currently under active water injection to sustain the reservoir pressure and production. The L-I reservoir of Mumbai High is the shallowest limestone reservoir which produces oil, and has low resistivity character. Conventional open-hole well-log (gamma ray-density-neutron-resistivity) analysis results are not conclusive for reservoir characterization of such a complex reservoir.

In the present paper, we discuss a case study with an advanced petrophysical analysis to address the challenge of low resistivity values in L-I reservoir. Formation resistivity can be lower either due to mineralogical effects in the matrix, clay distribution or due to fluid character. Elemental capture spectroscopy is critical to minimize the uncertainty of lithological complexity; while nuclear magnetic resonance (NMR) is useful for better understanding of the fluid characteristics. An advanced petrophysical analysis was carried out for a comprehensive reservoir characterization of this low resistivity pay.

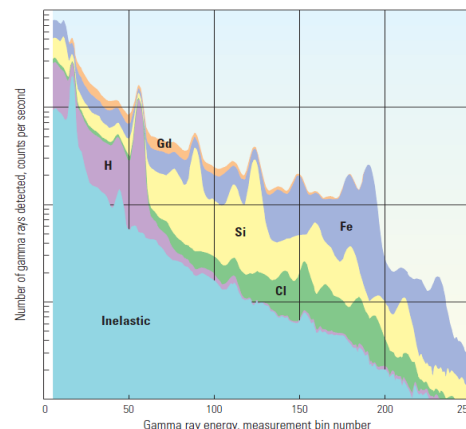


Figure 1: Gamma ray spectrum from elemental capture Spectroscopy tool (ECS\*) (Courtesy: Schlumberger Oilfield Review, Summer, 2005)

### Theory and Methodology:

#### Elemental Capture Spectroscopy

Elemental Capture Spectroscopy (ECS<sup>®</sup>) tool measures a gamma ray spectrum, or the number of gamma rays received by the detector for each energy level. The gamma rays are produced when high energy neutrons—from a minitron or from a radioactive source such as americium [Am] and beryllium [Be]—bombard the formation and lose energy through scattering, primarily by hydrogen.



When slowed down to thermal energy, a neutron that collides with the nucleus of certain atoms can be captured; in this process, the nucleus is excited, and it emits gamma rays with a distribution of energies that is characteristic of the element. These gamma rays may be degraded by scattering in the formation and the detector, but there is sufficient character in the final spectrum to recognize the peaks caused by different elements (Fig 1).

The next step is to calculate the proportion, or relative yield, of gamma rays due to each element. To do this, the measured spectrum is compared with the standard spectrum available for each individual element. The spectrum is inverted to obtain the yields of the principal contributing elements. These include some of the most diagnostic and abundant elements in sedimentary rocks, in particular silicon [Si], calcium [Ca], iron [Fe] and sulfur [S]. Titanium [Ti] and gadolinium [Gd] can also contribute significant signal and therefore must be solved for, even though they are not abundant elements. The yields of these six elements, all of which arise solely from the rock matrix, are quantitatively computed and used in further processing. Other elements, such as hydrogen [H] and chlorine [Cl], are also measured but used only qualitatively. The yields are only relative measures because the total signal depends on the environment and varies throughout the logged interval. To obtain the absolute elemental concentrations, additional information is needed—in this case from the principle of oxide closure. This principle states that a dry rock consists only of a set of oxides, the sum of whose concentrations must be unity. If we can measure the relative yield of all the oxides, we can calculate the total yield and the factor needed to convert it to unity. This normalization factor will then convert each relative yield to a dry weight elemental concentration. In practice, this process is not so straightforward. First, elements are measured, not oxides, but nature is helpful, because the most abundant elements exist in only one common oxide, for example SiO<sub>2</sub> for silicon. Thus, for most elements, an exact association factor supports conversion of the concentration of the element concentration to the concentration of the oxide.

Elements to mineral groups can be converted using the elemental concentrations. In this step the primary goal is an accurate and reliable total clay content or weight fraction, with remaining minerals being divided into carbonates or into quartz, feldspars and micas (QFM). Development of this technique was based on the study of more than 400 core samples from different environments (Schlumberger Oilfield Review, Summer- 2005).

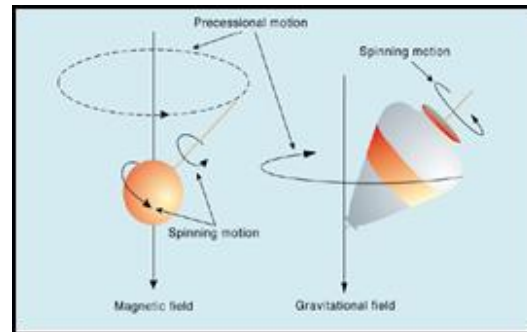


Figure 2: Movement of hydrogen nuclei (Courtesy: Hussein et al., 1999)

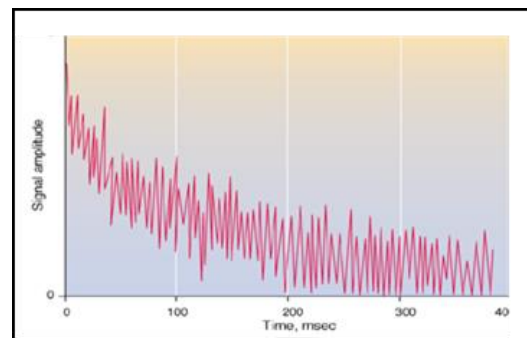


Figure 3: Signal amplitude decay trend of NMR measurement (Courtesy: Davis et al., 2002)

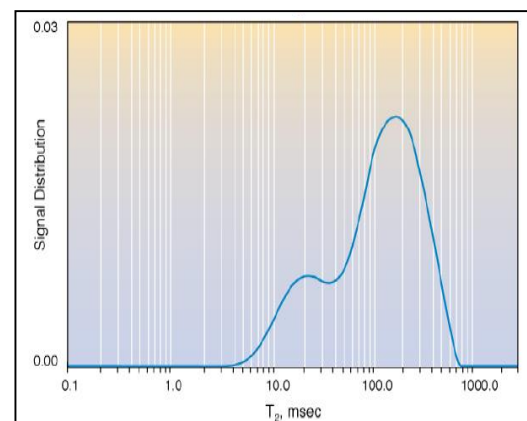


Figure 4: T<sub>2</sub> distribution of NMR measurement (Courtesy: Davis et al., 2002)

### ***Nuclear Magnetic Resonance***

The nuclear magnetic resonance (NMR) tool is designed to investigate the way in which hydrogen nuclei (protons) react in the presence of a static magnetic field and a pulsed radio frequency. Protons have a magnetic field and behave like spinning bar magnets. The magnetic moments tend to

align with the local static magnetic field provided by two magnets of the tool; over time, as more protons become aligned, this gives rise to a net magnetism. The NMR tool, placed beside the formation, emits a pulse radio signal at a frequency, amplitude and duration which turn these magnetized nuclei at right angles to the local magnetic field. When the pulsed radio signal is turned off the nuclei begin to recess as they try to return to their original state (Fig. 2). In doing so, they emit a radio signal which is measured by the NMR tool. The strength of this radio signal decays exponentially with time due to different mechanisms (Fig. 3). This exponentially decaying signal is mathematically converted to a  $T_2$  relaxation time distribution curve (Fig. 4).

NMR derived permeability can be estimated using this  $T_2$  distribution in two different established techniques. Timur-Coates equation uses the ratio of free fluid and bound fluid along with the total NMR porosity to determine the NMR permeability:

$$K_{Timur} = a \cdot \Phi^b (FFV/BFV)^c$$

Where, a, b and c are constants

FFV = Free Fluid Volume

BFV = Bound Fluid Volume

$\Phi$  = Total porosity using NMR method

## Results

The present case study is from an offshore well located in northern part of Mumbai High field. The well is a conventional deviated and drilled with water-based mud. Conventional open-hole logs were acquired (fig. 5). Based on gamma ray and density-neutron-resistivity log nature, the reservoir zone was possible to identify. However, reservoir characterization using these logs was not conclusive for mineralogy and fluid type. Elemental concentrations from elemental capture spectroscopy (ECS\*) revealed that there is a change in elemental concentration from calcium-rich to silica-rich in the reservoir zone (fig. 6). This can be interpreted as a presence of a limestone layer in association with a clastic silty formation below, which was not possible to identify based on conventional log data analysis. Such surprising mineralogical variation was addressed by the ECS\* and reduced the uncertainty related to formation matrix. However, the reasons for low resistivity were not very clear at this stage.

Nuclear magnetic resonance (CMR\*) data was acquired to characterize the fluid properties (fig. 7). It was observed that over the reservoir section, the proportion of capillary bound water was very high compared to high clay bound water presence in shale zone. It was also observed that the top limestone layer had very low free fluid porosity. As a result, there was no permeability. However, the lower silty zone had relatively high free fluid contribution, which resulted in a good permeability development. Continuous permeability from CMR\* was also validated by the wire line formation tester (MDT) measured station point results (fig. 8).

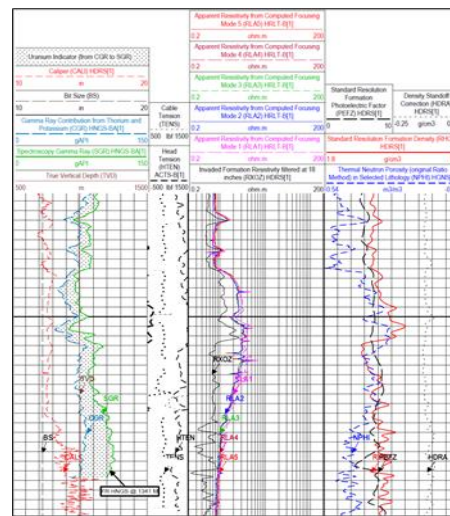


Figure 5: Open-hole logs

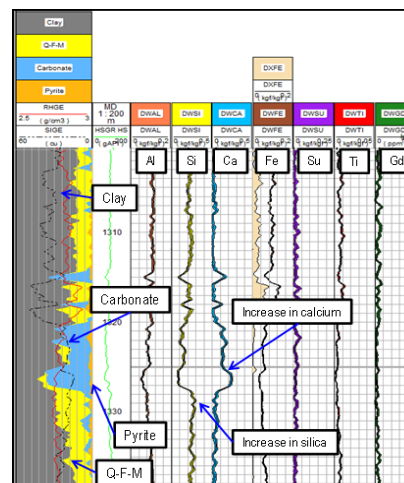


Figure 6: Elemental Capture Spectroscopy Results

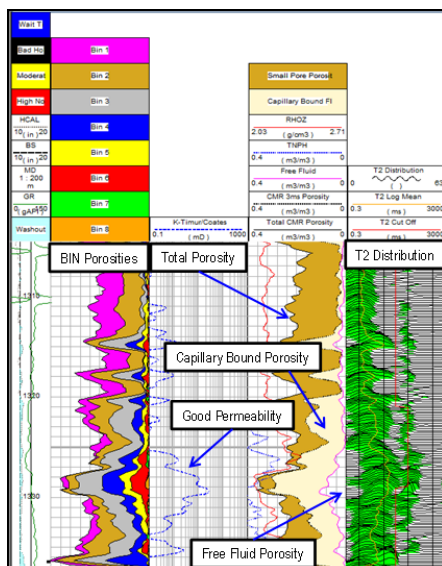


Figure 7: Nuclear Magnetic Resonance Result

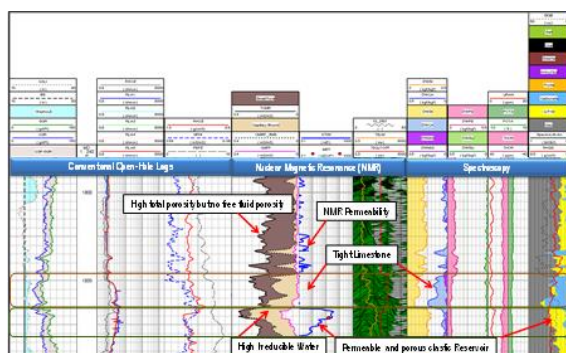


Figure 8: Advanced petrophysical analysis using NMR and spectroscopy data.

## Discussions and Conclusions

Mumbai High L-I limestone character is a bit different from the L-III limestone reservoirs. Conventional measurements are not capable to resolve the challenges of low resistivity with good oil production in such reservoirs. ECS\* and CMR\* data integration assisted in a comprehensive advanced petrophysical evaluation. Limestones were found as tight zones with very high proportion of capillary bound water, which leads to a poor permeability. Presence of such high amount of capillary bound water also pulls down the resistivity in tight limestones. Diagenesis of pure tight limestone was possibly converted into such micritic limestone with a little proportion of magnesium, which could lead to higher capillary bound water. Also presence of a little amount of

conductive pyrite mineral in limestone may be causing a drop in resistivity.

Elemental analysis from ECS\* results first time reported that this reservoir was not a pure limestone in character as there is a sudden change in elemental character. This established the fact that the limestones of L-I reservoir were underlain by a clastic silty zone, which was later on proved by the core data from a nearby well drilled subsequently. This silt zone had a good amount of free fluid porosity and permeability, which is the requirement for a good quality reservoir.

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