Quantitative Characterization of Bitumen in the Complex Carbonate of Sichuan Basin: A Case Study

Gang Wei[1(✉)], Zuo-an Zhao[2], Yu-ran Yang[2], Li-chuan Deng[1], and Xian-lei Zeng[1]

[1] Baker Hughes, a GE Company, Houston, USA
{Gang.wei,Lichuan.deng,Xianlei.Zeng}@bhge.com
[2] Southwest Oil and Gas Field Company, CNPC, Chengdu, China
{Zhaozuoan,Yangyuran}@petrochina.com.cn

Abstract. In Sichuan Basin, Southwest of China, the occurrence of bitumen has been reported in the deep-buried carbonate gas field, where the reservoir spaces are mainly dissolved pores and vugs. The bitumen occupies the pore volume and blocks the flow channel of fluid, adversely impacted on the reservoir performance. Hence, identification and quantification of bitumen are critical for the reservoir evaluation. However, lacking of contrast from conventional logs between bitumen and other fluids makes it difficult to differentiate them. Fortunately, with the invention of some hi-end logging tools, the identification of bitumen is becoming reliable, even the quantification is becoming possible. In this case, nuclear magnetic resonance (NMR) and neutron spectroscopy tools are used, originally to acquire the accurate porosity and mineralogy. The NMR response of bitumen is dominated by short transverse relaxation times (T2), providing an opportunity to identify bitumen by porosity deficit. With the application of 2D NMR, the saturation and fluid density could be determined, which are important inputs of bitumen quantification. High-energy pulse neutron tool measures the main element of bitumen, such as carbon (C) and sulfur (S) from collision of fast neutron, and calculates the grain density, providing another crucial parameter to calculate the pore volume occupied by bitumen. This case study demonstrates the bitumen volume derived from the combination of NMR, neutron spectroscopy and conventional logs. The presence of bitumen

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is validated by cores. Based on the bitumen analysis, engineer could optimize their completion and acid fracturing strategy to improve the reservoir performance; meanwhile geologist could further study the evolution progress of reservoir. This method applies to those conventional reservoirs that suffer the harm of bitumen, and is also suitable in the heavy oil evaluation.

Keywords: Bitumen · Nuclear magnetic resonance · High-energy pulse neutron logging

1 Introduction

Located in Southwest of China, Sichuan Basin is well known by petroleum industry for its very thick carbonate formation and the huge gas reserve. The methane split from oil as a product of thermal decomposition, at the same time the heavy molecular composition left bituminized. That bitumen distributes in pores, vugs and fractures as observed from drilling cores, and it is extremely viscous and immovable. DENGYING IV, one of those reservoir formations, has a very low porosity due to buried more than 5000-meter-deep; each well in this field need to be acid fractured for stimulation. However, the bitumen occupies the pore volume and blocks the flow channel, reducing the production rate and making stimulation less effective. The quantitative characterization of bitumen is therefore becoming crucial when it is present in significant amount.

NMR porosity deficit, as a response to short transverse relaxation times (T2) of Bitumen, has been discussed by many Petrophysicists. In this work, we will integrate NMR with neutron spectroscopy and conventional log, and introduce a more accurate approach for bitumen volume estimation.

2 NMR Porosity Deficit of Bitumen

NMR logging tool measures the hydrogen in the rock by detecting the decay of signal amplitude. In reservoir system, hydrogen is mostly present in water and hydrocarbons. Therefore, after calibration with water, we are able to convert the signal amplitude to apparent porosity. Bitumen, as one kind of hydrocarbon, contains hydrogens should be detected NMR. However, the signal decay of bitumen is very fast, predominately determined by its extreme viscosity. In this field, the NMR response of bitumen is more like rock matrix rather fluid and undetectable by NMR tool due to hardware limitation. As a result, the porosity volume filled by bitumen will be missing in NMR porosity (see Fig. 1).

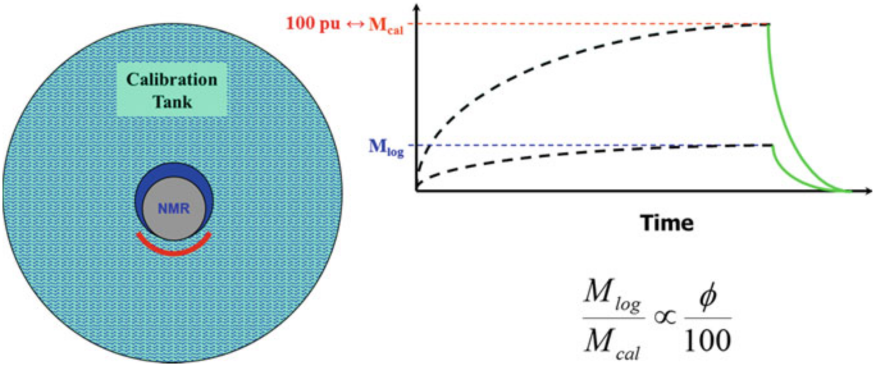

Fig. 1 NMR measurement principle for bitumen

The other way around, conventional porosity log such as triple combo, respond to all the matrix and fluids within the sensitive volume, including the bitumen filled pores. Compare to triple combo log, the NMR porosity will be smaller when bitumen is present, in other words, NMR porosity deficit will appear. In some cases, we use the difference between NMR and triple combo approximately as the bitumen volume. Nevertheless, the triple combo response to bitumen is different from water and oil, the difference makes this quantification method not accurate enough.

3 Neutron Spectroscopy Response to Bitumen

Neutron spectroscopy tool emits high-energy neutron into formation from a pulse neutron source. As the fast neutrons are passing through the formation, they present two types of interaction with atoms of different elements, namely inelastic collision and capture process. These interactions produce gamma photons with energy characteristic for these elements involved. After recorded by BGO sensor then analyzed with specialized software, those gamma ray spectrums reveal the elements constituting the rock as well as their weight fraction.

Carbon and sulfur are two main composition elements of bitumen, and detectable for neutron spectroscopy tool. In this discussed carbonate formation, carbon also present in rock matrix, making it difficult to tie the carbon from log directly to the presence of bitumen. Firstly, we have to perform geochemistry analysis with all the elements from the log, calculating the mineralogy and the carbon needed to constitute the carbonates. After deducting the carbonate carbon from the total logged carbon, the remaining or excess carbon will represent hydrocarbon filled in pores. By utilizing excess carbon and sulfur together, the identification will be much more reliable (see Fig. 2).

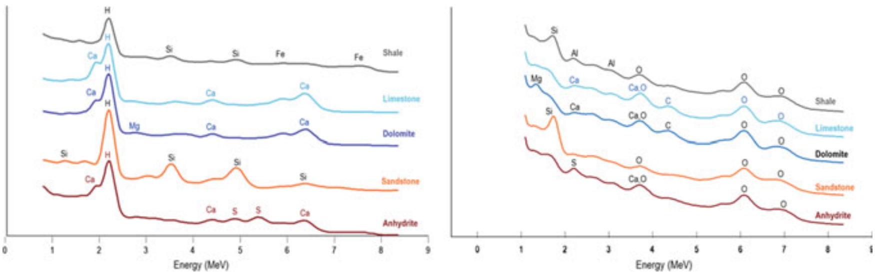

Fig. 2 Neutron Spectroscopy Response to different elements

Figure 3 shows two examples in this discussed field using carbon and sulfur to identify bitumen filled zone. In these two wells, both drilling core and neutron spectroscopy are available along with the slam log. It is very clear that excess carbon and sulfur always show up simultaneously on the log, and with the appearance of them, the black bitumen are visible from the cores. In the meantime, there is no clue of presence of bitumen from the slam log.

These two examples illustrate the success of bitumen identification in a comparative way between neutron spectroscopy log and core, and prove that this methodology is reliable.

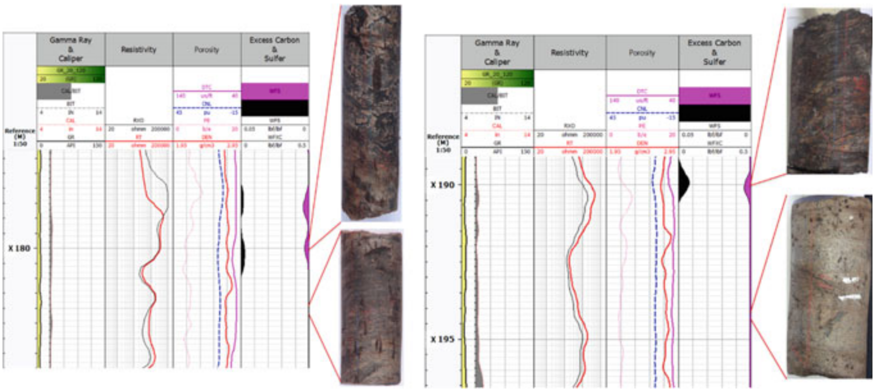

Fig. 3 Log processed result and bitumen in the core fracture

At this step, the rock matrix density, or grain density (ρ_{Grain}) is also calculated based on minerals of rock and their weight fraction. It is a very important parameter of volumetric model and we will discuss later.

4 Fit-for-Purpose Petrophysical Volumetric Model

In previous section, we discussed a quick but qualitative identification for reservoir bitumen. In this section, adding bitumen into the conventional volumetric model, we will use a revised model to quantify bitumen volume and calculate the corrected total porosity.

Density log, or neutron and acoustic, will respond to the rock matrix and entire pore inside the sensitive volume, no matter those pore are fluid filled or bitumen filled (see Fig. 4), it can be modelled using Eq. (1). The matrix density (ρ_{Grain}) is calculated with mineralogy analysis in last section. Bitumen density $(\rho_{Bitumen})$ is from laboratory analysis or field experience.

$$\rho_{bulk} = \rho_{Bitumen} \cdot \emptyset_{Bitumen} + \rho_{Fluid} \cdot \emptyset_{Fluid} + (1 - \emptyset_{Bitumen} - \emptyset_{Fluid}) \cdot \rho_{Grain} \tag{1}$$

NMR log will only see the fluid filled pore; it does not detect the bitumen, as Eq. (2).

$$\emptyset_{Fluid} = MPHS_{Total} \tag{2}$$

The fluid density derives from Eq. (3) using saturation of fluids in pore, which are water and gas in discussed case. Given gas composition, formation pressure and temperature, it is simple to calculate the gas density (ρ_{Gas}).

$$\rho_{Fluid} = \rho_{Gas} \cdot S_{Gas} + \rho_{Water} \cdot (1 - S_{Gas}) \tag{3}$$

To solve the bitumen volume, fluid filled porosity, saturations are crucial inputs, and we will discuss separately in next section.

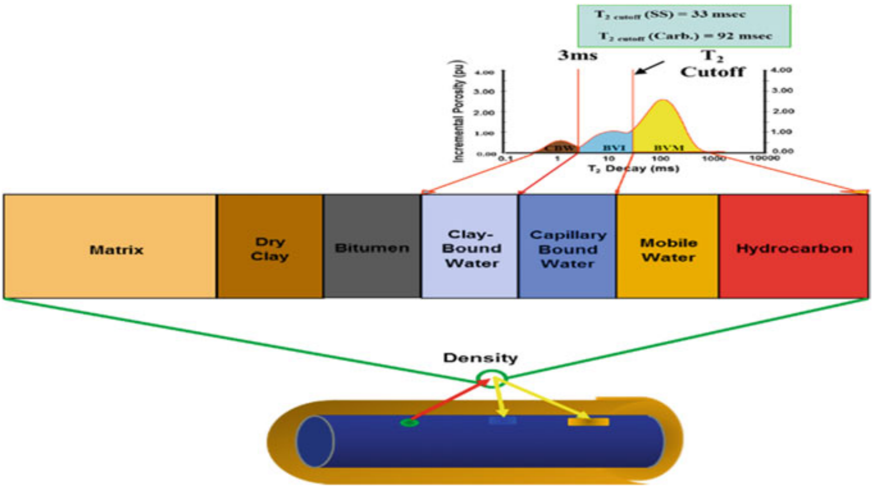

Fig. 4 T2 distribution based NMR interpretation principle

5 Gas Saturation and HI Corrected Porosity with 2D NMR

As we already discussed, NMR logging actually measures the hydrogen in rock and gives apparent porosity with calibration to pure water. The apparent porosity is therefore subject to the proton density of a reservoir fluid compared to pure water at standard temperature and pressure, i.e., hydrogen index. The hydrogen index (HI) of gas is much smaller than water, and varies with its composition, pressure and temperature. As a result, the apparent porosity in this gas field is underestimated.

To make HI correction for apparent NMR porosity, the HI under reservoir condition and gas saturation are necessary. The former is very easy to calculate with known gas composition, temperature and pressure, but the latter is more complicate to solve.

In traditional way, log analyst use Archie equation to calculate saturation. It is an empirical relationship between resistivity and porosity log of a rock. However, in this kind of gas reservoir, the NMR porosity is underestimated and density porosity is inaccurate with the presence of bitumen, the true total porosity is yet to solve. The dual lateral resistivity log has a very deep depth of investigation, and measures the uninvaded formation. Therefore, the resistivity-derived saturation is not suitable for the HI correction of NMR log, which has a very shallow depth of investigation and only measures the flushed formation.

2D NMR (T1/T2 vs. T2) provides us a mean to separate the apparent gas porosity from the total apparent porosity. Three different T2 relaxation mechanisms, which are bulk, surface and diffusion relaxation, affect T2 measurements made on porous media as Eq. (4).

$$\frac{1}{T_{2,app}} = \frac{1}{T_{2,Bulk}} + \frac{1}{T_{2,Surface}} + \frac{1}{T_{2,Diffusion}} \tag{4}$$

Only two of them control the T1 measurements with the exception of diffusion as Eq. (5).

$$\frac{1}{T_1} = \frac{1}{T_{1,Bulk}} + \frac{1}{T_{1,Surface}} \tag{5}$$

Gas has a very high diffusion coefficient compared to other reservoir fluid, say water and oil. This high diffusion does not affect the T1 properties of methane, but has a significant shortening effect on the apparent T2 of methane. The $T_1/T_{2,app}$ ratio of methane will be much bigger than water and oil, making it easy to separate the gas from

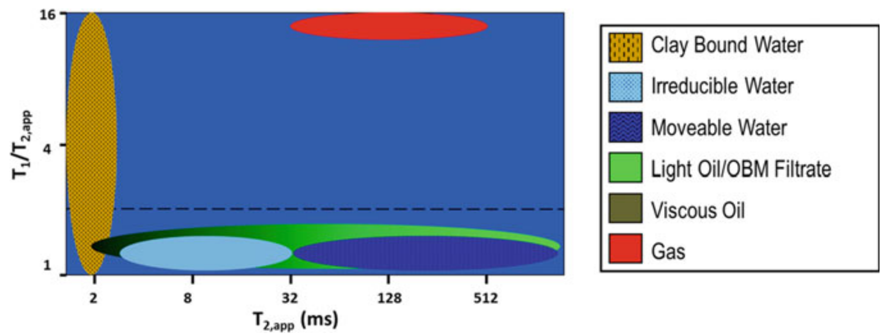

Fig. 5 2D NMR interpretation principle

other pore fluids on 2D NMR cross plot (Hursan et al. 2005) (see Fig. 5). Then it is possible to derive the HI corrected porosity and gas saturation from Eqs. 6 and 7.

$$MPHS_{Total} = MPHS_{Total,app} - MPHS_{Gas,app} + \frac{MPHS_{Gas,app}}{HI_{Gas}} \tag{6}$$

$$S_{Gas} = \frac{MPHS_{Gas,app}}{HI^{*}_{Gas} MPHS_{Total}} \tag{7}$$

Plugging into Eqs. (1), (2) and (3), the bitumen filled pore volume is finally solved out.

The calculated result are plotted in Fig. 6. The fifth track shows the excess carbon existing and the sixth track shows the bitumen contents.

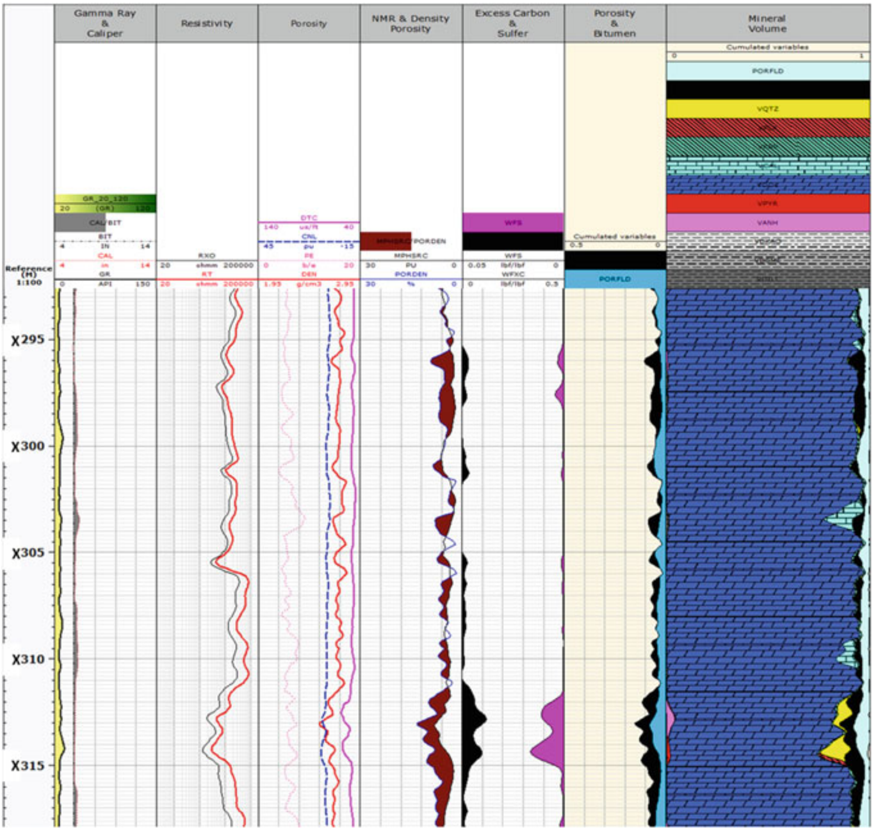

Fig. 6 A processed result shows some bitumen contents

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