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Method and Experimental Study of 2-D NMR Logging

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Abstract

Two-dimension (2D) NMR measurements have been performed to provide more information for qualitative identification and quantitative evaluation of the reservoir-fluids both in numerical simulation and in laboratory experiments. The data acquired with variable echo spacing and waiting time was inverted by multi-exponential inversion method. We use these 2D inversion results to identify fluid types and calculate fluid-saturation. We also detect the distribution of internal field gradients of core samples which contain paramagnetic minerals.

Keywords

NMR logging, Transverse-Relaxation, Longitudinal-Relaxation, Diffusion-Coefficient, Gradient Fields

1. Introduction

Through measuring the resonance signal of proton in formation fluid, NMR technology can be used to obtain porosity, permeability, fluid saturation and pore-size distribution etc [1]. But it is always difficult to identify fluid types from T_1 or T_2 relaxation distribution measured by single CPMG pulse sequence because of the significant overlap in relaxation times. The calculation of fluid saturation is even more difficult. However, 2D-NMR measurements of T_2-D and T_2-T_1 with multiple CPMG pulse sequence can provide more information of different fluid types for formation evaluation. It makes the calculation of fluid saturation convenient and direct.

2. 2D NMR Well Logging Method

When the fluid-saturated sample is in a constant magnetic field gradient, the time variation of CPMG echo train can be written as [2-5],

$$M_{iks} = \sum_{j=1}^{m}\sum_{r=1}^{n}\sum_{l=1}^{p} f_{jrl} \exp(-t_i / T_{2j})(1 - 2\exp(-T_{Ws} / T_{1r}))\exp(-\frac{1}{12}\gamma^2 G^2 D_l T_{Ek}{}^2 t_i) + \varepsilon_{iks} \quad (1)$$

where $i = 1,...,N_{Ek}, k = 1,...,q, s = 1,...,w$, N_{Ek} is the number of echoes collected at the time t_i, q is the number of echo trains with different echo spacing T_{Ek} and w is the number of echo trains with different wait timing T_{Ws}. m, n and p are the numbers of pre-selected components of T_2, T_1 relaxation times and diffusion coefficients (D), respectively, that are all equally spaced on a logarithmic scale. G is the field gradient, M_{iks} is the amplitude of *ith* echo of the *kth* echo train using echo spacing T_{Ek} and wait time T_{Ws}; f_{jrl} is the proton amplitude at T_{2j}, T_{1r}, D_l. When the formation fluid is in constant gradient fields and the wait time is significantly longer than all values of T_1, then Eq. 1 can be simplified as,

$$M_{ik} = \sum_{j=1}^{m}\sum_{l=1}^{p} f_{jl} \exp(-t_i / T_{2j})\exp(-\frac{1}{12}\gamma^2 G^2 D_l T_{Ek}{}^2 t_i) + \varepsilon_{ik} \quad (2)$$

Similarly, Eq. 1 can be simplified as Eq. 3 when G is very small or TE is very short. In this case, the influence of diffusion can be ignored.

$$M_{is} = \sum_{j=1}^{m}\sum_{r=1}^{n} f_{jr} \exp(-t_i / T_{2j})(1 - 2\exp(-T_{Ws} / T_{1r})) + \varepsilon_{is} \quad (3)$$

If the samples are saturated with a single fluid (with known D) and the external field is uniform, the internal field gradient G_I can be a solved by the following equation,

$$M_{ik} = \sum_{j=1}^{m}\sum_{l=1}^{p} f_{jl} \exp(-t_i / T_{2j})\exp(-\frac{1}{12}\gamma^2 G_{Il}^2 D T_{Ek}{}^2 t_i) + \varepsilon_{ik} \quad (4)$$

From Eq. 2, 3 and 4, the 2D-NMR inversion methods derived from SVD or BRD algorithm can be performed to get the solution from multiple sets of echo trains [2-6].

2. Numerical Simulation and Laboratory Experiments

The formation water and crude oil with different viscosity always have wide distributions in relaxation times or diffusion coefficients in fluid saturated porous medium. It is difficult to identify them through any single property of T_2, T_1 or D. But in the combination of T_2-D or T_2-T_1, we can get much clearer 2D maps to identify fluid types and have more information to calculate saturation based on the contrast of D or T_1/T_2. Fig.1 shows the numerical simulation model generated by Gaussian distributions. It is assumed that the T_2 peak value of free water and of light oil is 800 ms, and that the diffusion coefficient is 2.5×10^{-5} cm^2/s and 10^{-6} cm^2/s, respectively; The T_2 peak value of bound water and heavy oil is 30 ms, and the diffusion coefficient is 2.5×10^{-5} cm^2/s and 10^{-6} cm^2/s, respectively. G is equal to 10 gauss/cm, and the saturation of each kind of fluids is assumed to be 25 %. Nine sets of echo trains are simulated with echo spacings equal to 0.2, 0.4, 0.6, 0.8, 1.2, 1.6, 2.4, 4.8 and 9.6 ms, respectively. In Fig. 1b, the free water peak is at (T_2 = 800 ms, T_1 = 1000 ms), the capillary bound water is at (T_2 = 50 ms, T_1 = 200 ms), the medium oil is at (T_2 = 100 ms, T_1 = 240 ms), and the heavy oil is at (T_2 = 10 ms, T_1 = 30 ms). We set the saturation of each kind of fluids at 25 %, the echo spacing at 0.2 ms and nine sets of waiting time from 0.3 ms to 10000 ms.

Fig. 2 shows the inversion results of the forward simulated models (Fig. 1a and b) with different SNR (signal to noise ratio). It shows that light oil and free water are separated clearly. However, the irreducible water and heavy oil peaks merge together and become more indistinguishable with the decreasing of the SNR because of the fast decay. The effective porosity can be calculated from these 2D maps. According to the cutoff curve (red dotted line), we can calculate the fluid saturations. The results are close to the value given in the numerical simulated model (Tab. 1).

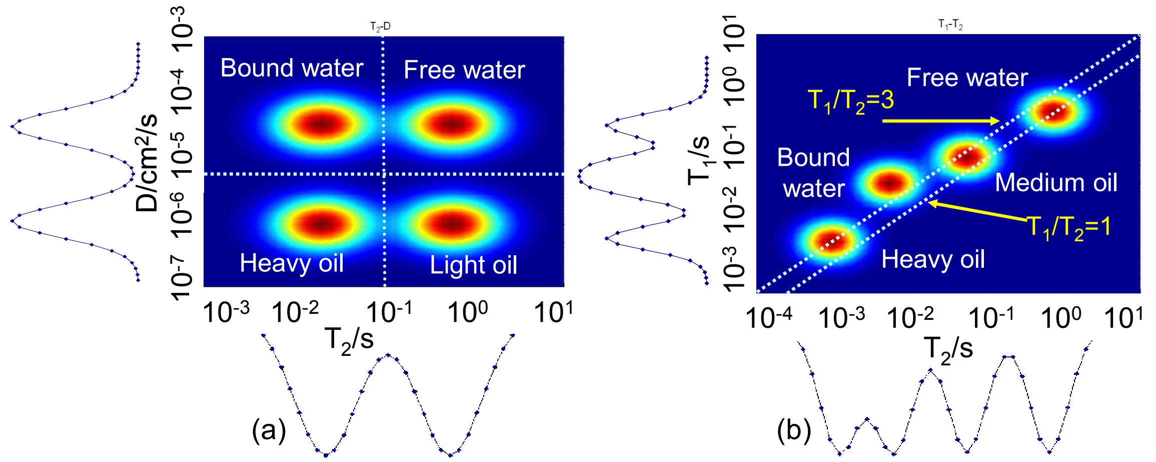

Fig.1: (a) Numerical simulated distribution of T_2-D of free water, bound water, light oil and heavy oil, (b) Numerical simulated distribution of T_2-T_1 of free water, bound water, medium oil, and heavy oil.

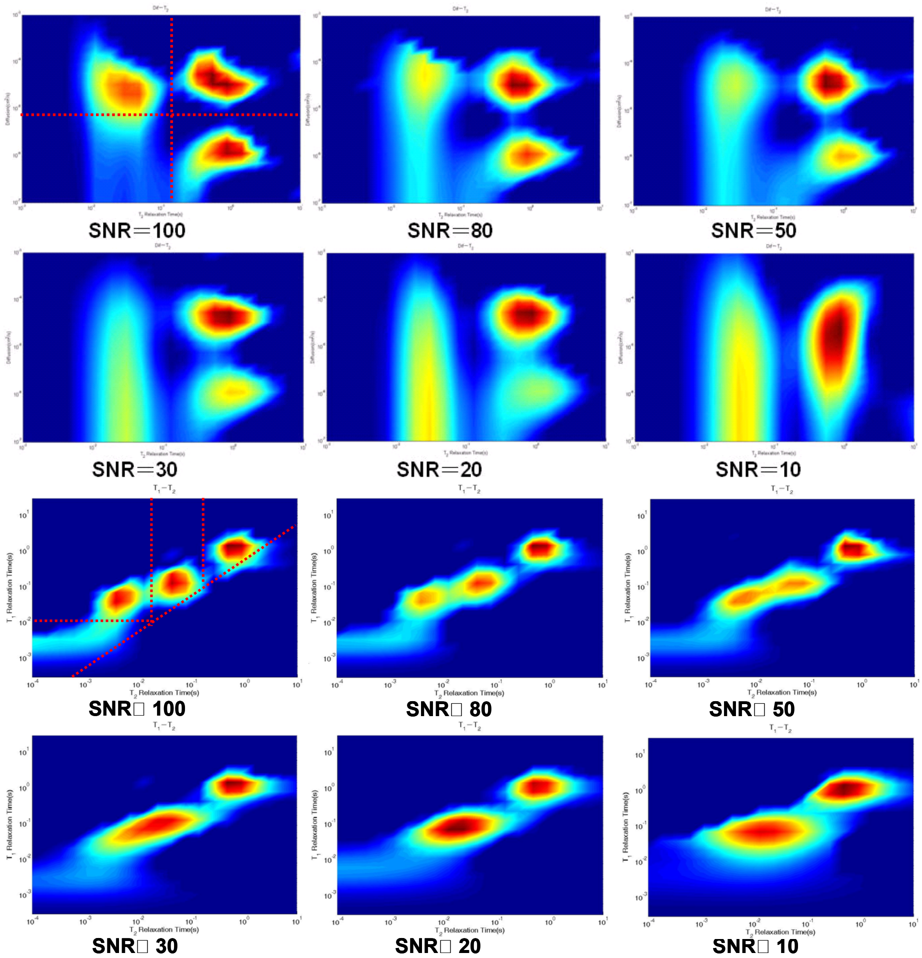

Fig.2: T_2-D (upper six panels) and T_2-T_1 (lower six panels) 2D-NMR with different SNR correspond to Fig. 1a and 1b respectively.

Table.1 contrast of saturation between forward numerical simulated models and inversion results

T_2-D 2D-NMR			T_2-T_1 2D-NMR		
Type	*S*	*S'*	Type	*S*	*S'*
Free water	25%	24.6%	Free water	25%	24.3%
Bound water	25%	28.0%	Bound water	25%	26.1%
Light oil	25%	26.1%	Medium oil	25%	24.1%
Heavy oil	25%	21.6%	Heavy oil	25%	25.5%

S means fluid saturation given in the simulated data, *S'* means calculated value from inversion results

Fig. 3a shows the T_2-T_1 2D inversion result of the data acquired in laboratory experiments. In this experiment, we have measured a manmade sandstone core (95 % sands and 5 % montmorillonite) saturated with 1000 ppm brine water. One peak in Fig. 3a is movable water with long T_2 in large pores, and the other peak is bound water with short T_2 in clay. Fig. 3b shows the result of a pure sandstone core that was first saturated with pure water and then displaced by transformer oil through the centrifuge method. In this figure, one peak is movable oil and the other peak is free water in small pore. Both of the measurements are performed on 2 MHz NMR core analysis instrument with uniform magnetic field. 9 sets of echo trains are acquired with TW logarithmically distributed from 0.3 to 10000 ms (Each echo train with waiting time of 0.3, 3, 10, 30, 100, 300, 1000, 3000, 10000 ms respectively). Fig. 3c shows T_2-G 2D-NMR map of the other core sample with paramagnetic impurity. The x-axis is T_2 and the y-axis is internal field gradients (G_I), which both equally spaced on a logarithmic scale, z-axis is proton density distribution. The cross sectional view at a fixed T_{2j} gives the distribution of internal gradients for that pore size. The integral curve of G_I is the apparent T_2 and the integral curve of T_2 is the apparent G_I.

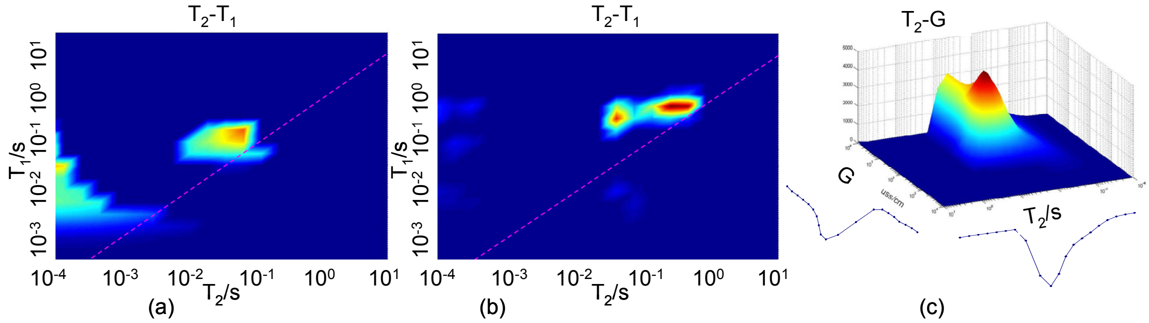

Fig.3: 2D maps of manmade cores measured by 2 MHz NMR core analysis instrument

3. Conclusions

2D or multi-dimensional measurements can be used to extract clear distributions of different types of fluids. But with the decrease of SNR, it becomes difficult to identify bound water and heavy oil from 2D map. The narrow area of the effective distribution of a T_1-T_2 2D map gives a challenge to fluid identification when the contrast between T_1 and T_2 is small. 2D-NMR can be used to calculate saturation of different types of fluid by using cutoff curves. T_2-G 2D-NMR can be applied to detect the apparent internal field gradients.

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