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A new experimental methodology to investigate formation damage in clay-bearing reservoirs

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ABSTRACT

Understanding mechanisms and performance of formation damage induced by sensitive clay minerals in reservoirs is crucial for avoiding productivity loss at any reservoir development stage. This paper proposes a new experimental methodology which organically integrates core flow experiment with nuclear magnetic resonance (NMR) (NMR T2 spectrum and NMR image) and quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) to investigate alkali sensitivity damage mechanisms in a low-permeability reservoir. It distinguishes itself from existing techniques by providing comprehensive, quantitative information on alterations of clay and pore morphology and distribution in the damage, and directly visualizing sensitivity damage processes. Water blocking experiment (WBE) designed to research potential effect of sensitivity damage on oil well productivity was also performed. The alkali sensitivity damage mechanism of clay dispersion and migration was clearly characterized and effectively identified by the NMR T2 spectra and MR images. Further, result of QEMSCAN pinpoints that kinds of the clay triggering the damage are mainly chlorite and illite. Moreover, it was found by the QEMSCAN that the generation of silicide precipitation duo to reactivity of rock framework with hydroxide is also an important alkali sensitivity damage mechanism. Result of WBE demonstrates that alkali sensitivity damage can significantly accelerate decline of oil relative permeability and reduce residual oil saturation, both of which are detrimental for oil recovery of a reservoir. Such an experimental methodology could also be employed to research any other reservoir sensitivity damage types, such as salt sensitivity, acid sensitivity and so on.

1. Introduction

In 1944, Johnston and Beeson were among the first to report permeability impairment of clay-containing reservoirs with decrease in the salinity of pore water from evidence of 1200 core samples (Johnston and Beeson, 1945). Engelhardt and Tunn reported similar observations in 1955 (Engelhardt and Tunn, 1955). Since then, a number of formation sensitivity damage experiments were performed and they proved the existence of sensitivity types of salt, velocity, acid, alkali (Bartko et al., 1995; Shi et al., 2003; Monaghan et al., 1959; Nguyen et al., 2005). Formation sensitivity damage can cause large decrease in well productivity and its repair is usually difficult and expensive. Moreover, such damage is easily triggered by simple processes in any phase of drilling, completion, fracturing, acidizing, workover, and steam injection (Porter, 1989). Hence, prevention of formation sensitivity damage is of great significance for oilfield development. In particular, the extent of damage tends to be much greater in low-permeability reservoirs than in conventional reservoirs owing to the fine pores and intricate pore networks in the former reservoirs. This has been proved by the experience in Nanyang sag, which has an tight formation with an average permeability of 1.935×10^{-3} μm^2 and average porosity of 6.02%. Oil well production in Nanyang sag usually decreases by a large margin instead of increasing after large-scale hydraulic fracturing. Core flow experiments indicated that formation sensitivity damage caused by the incompatible fracturing fluids is the cause of this productivity impairment (Qiu et al., 2005; Chen, 2012). However, the damage mechanisms are still not known well.

Traditional methods of studying formation sensitivity damage mechanism mainly relied on core flow experiment in conjunction with petrographic analysis methods including scanning electron microscopy (SEM) (Gray and Rex, 1966; Rahman et al., 1995; Ge et al., 2006), X-ray diffraction (XRD) (Amorim et al., 2007; Elraies and Basbar, 2015) or X-ray fluorescence (XRF) (Elraies and Basbar,

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Nomenclature

PII	permeability impairment index
k_0	permeability tested before damage (10^{-3} μm^2)
k_1	permeability tested after damage (10^{-3} μm^2)
E_R	oil recovery
E_D	displacement efficiency
E_V	sweep efficiency
S_{oi}	initial oil saturation
S_{or}	residual oil saturation

2015), and CT scanning (Longeron et al., 1995). However, each approach above has its limit either for non-quantification, finite precision, or for destructive sample preparation (Desbois et al., 2011). And using any of these methods alone will only produce information limited to the individual character of the method. In addition, existing studies were mainly performed for conventional reservoirs with relative high permeability and porosity. The unconventional reservoirs, such as tight oil/gas reservoirs and shale gas reservoirs which have recently received much interest because of the very large reserves are composed of ultrafine pore networks (Zou et al., 2012). Recognition of formation damage mechanism in these pores needs better-resolution techniques and more comprehensive and quantitative information.

Techniques of NMR and QEMSCAN are introduced in this paper to recognize alkali sensitivity damage mechanisms in Nanyang tight oil reservoirs. The NMR has been successfully employed to study a large range of petrophysical phenomena, transport processes and chemical reactions inside porous media (Guan et al., 2002; Looyestijn and Hofman, 2006; Johannesen et al., 2007; Borysenko et al., 2009; Frosch et al., 2000). Recently, NMR T2 spectrum test was adopted to study sensitivity damage mechanism for water sensitivity in conventional reservoirs (Liu et al., 2013; Zhu, 2014). In addition to T2 spectrum test, magnetic resonance imaging (MRI), which is capable of revealing damage mechanism visually, was also conducted in this study. Moreover, we improved the NMR apparatus by combining it with the core flow apparatus. This assembled apparatus can be used to conduct an online test of the NMR data, thus avoiding the troubles and loss of accuracy resulting from the removal of the cores from the core gripper many times in an experiment. The QEMSCAN is an automated mineralogy identification method in combination of high resolution SEM, XRD, and database technique. In the past decade, this method has been employed in other industries like coal combustion (Golab et al., 2013), characterization of metal ores (Andersen et al., 2009), and archeology (Knappett et al., 2011). Recently, it is gaining widespread interest in oil and gas industry. A literature review of application examples was offered by Sølling et al. (2014). We introduce this distinguished technique herein to reveal distribution and content transformation of minerals in porous media in the process of alkali sensitivity damage, thus deeply investigating the damage mechanisms in perspective of mineralogy.

It is generally known that formation sensitivity damage is detrimental for oil and gas production. To study the effect of sensitivity damage on fluid flow in reservoirs, WBE was conducted for Nanyang tight oil reservoirs. Water blocking is denoted as oil or gas relative permeability reduction caused by water invasion and phase trapping. So far, literature reports about water blocking tend to focus on gas reservoirs (Kamath and Laroche, 2003; Bazin et al., 2010; Bahrami et al., 2012). And there is still no research concerning effect of formation sensitivity damage on water blocking.

This work provides a novel integrated methodology for studying formation sensitivity damage in clay-bearing reservoirs. Research results demonstrate high potential of the methodology in generating unbiased, comprehensive and quantitative information on the recognition of sensitivity damage mechanisms, and in the quantitative evaluation of effect of sensitivity damage on oil production. This research will also be significant for some other industrial processes such as evaluating effect of damage inhibition measures, aiding optimal design of stimulation fluids, and advancing near-well simulation methods in clay-bearing reservoirs.

2. Experimental principles

2.1. NMR T2 spectrum test

In NMR, the pore distribution in a reservoir rock is obtained by recording the time dependence of nuclear magnetization generated by the proton (^{1}H) nuclear spins of fluids in the rock. The measured magnetization decay is described by the relaxation time which varies among pores of different sizes since it is mainly influenced by the pore surface-to-volume area ratios. Therefore, the magnetization decay of a rock as obtained by NMR is actually a superposition of decaying signals from pores of different sizes. Through mathematical inversion of the decay, the relaxation time spectrum (T2 spectrum) is generated.

A typical T2 spectrum is shown in Fig. 1, from which lots of reservoir physical information can be obtained. The area under the curve of a specific range of relaxation time is proportional to the pore volume of the corresponding pore size level. Generally, pores in a core saturated with water can be classified into three size levels, namely, clay bound pores (CBP), capillary bound pores (CABP), and free pores (FP) (Prammer et al., 1996). In CBP, water absorbs on surface of clay particles thanks to electrostatic interaction. In CABP, water is kept by capillary force. But in FP, water can flow unrestrictedly. In oil reservoirs, CBP and CABP are generally considered as small pores while FP are considered as big pores. These three levels are separated by two cutoff values of relaxation time in T2 spectrum. According to statistical law of many low-permeability oilfields in China, T2 cutoff values of CBP/CABP and CABP/FP are respectively 1 ms and 10 ms (Liu et al., 2013; Xu and Guo, 2014).

2.2. MRI

In MRI, the NMR responses of protons are recorded as a function of their spatial positions, which is achieved by adding a gradient magnetic field to the external magnetic field. Then, the MR image that allows visualizing the heterogeneous distribution of pores in a core is built by processing the recorded spatial information through Fourier transform and image reconstruction technique. Every MR image is a gray scale image composed of pixels, and the brighter the pixels in a specific zone, the higher is the porosity of that zone. Dark zones in an image represent rock framework. With the help of MR images acquired before and after the core being exposed to high pH value fluid, pore distribution transformation caused by alkali sensitivity damage can be clearly observed.

2.3. QEMSCAN

The experimental system of QEMSCAN acquires energy dispersive X-ray spectrum (EDXS) generated by energy dispersive