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Formation mechanism of the Donghe Sandstone residual oil zone in the Tarim Basin, NW China

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ABSTRACT

The residual oil zone (ROZ) with near-residual oil saturation is a naturally water-flooded interval adjacent to an oil-bearing reservoir. It has become a promising development target for the technical progress of enhanced oil recovery. The hydrocarbon show, bitumen distribution and grains containing oil inclusions all indicate the presence of ROZs in the Donghe Sandstone Member of the Tazhong4 and Hade Oilfields in the Tarim Basin. Analysis of the two ROZ examples reveals that a stable paleoreservoir and structural adjustment are significant elements of the ROZ-forming process. The ROZ of the Tazhong4 Oilfield is defined as a reactivated fault ROZ (RFROZ) lying between the paleo oil-water contact (OWC) and producing-OWC. Paleo-hydrocarbons leaked through the reactivated faults, and the current oil saturation has a positive proportion to baffle frequency. The ROZ in the paleo trap northwest of the current reservoir in the Hade Oilfield is defined as a migratory trap ROZ (MTROZ). Paleo-hydrocarbons migrated through connected sand bodies. The current oil saturation in the MTROZ has a positive proportion to baffle frequency and negative proportion to petrophysical properties. The microscopic occurrence state of the residual oil in ROZs was analyzed with direct computed tomography (CT) scanning. The displacement experiments coupled with CT scanning aimed to reveal the different occurrence states of the residual oil in the major stage of natural water flooding in the ROZ-forming process. In the microscopic view, the formation of both RFROZ and MTROZ is a process of clustered flow converting to discontinuous flow, and the clustered flow can be scattered to a larger extent in a high permeability zone. The ROZ development feasibility was preliminarily researched. Low-salinity water flooding after the displacement of the formation water in the etching model provided experimental corroboration for remobilizing the residual oil.

1. Introduction

The residual oil zone (ROZ) is an area of growing interest as a potential extension field with the decreasing production benefit of high water-cut reservoirs. A naturally waterflooded interval adjacent to the oil-bearing reservoir is defined as the ROZ (Melzer et al., 2006), and it is technically recoverable mainly through application of unconventional methods. The meteoric water displacement of the original hydrocarbon accumulation attributed to tectonics or active aquifers leads to an ROZ. Two genetic types, regional basin tilt and altered hydrodynamic flow, have been noted in the San Andres Formation in the Permian Basin (Melzer et al., 2006; Pathak et al., 2012; West, 2014; Kuuskraa et al., 2017). A large quantity of residual oil exists under the tilted oil-water contact (OWC) in the Permian Basin, and a primary assessment put the recoverable reverses at 11.9 billion barrels (bbl) from 30.7 billion bbl of ROZ resources based on CO_2-enhanced oil recovery (CO_2-EOR) and depressurizing the upper ROZ (DUROZ) (Koperna et al., 2006; Honarpour et al., 2010; Jamali et al., 2017). The pure ROZ pilot project in the Seminole Oilfield yielded approximately 20,000 bbl/d based on CO_2-EOR (Trentham, 2015). Inspired by the enormous resource potential for this emerging oil play, significant ROZs have been discovered in the North Sea, Permian and Williston Basins (Bhullar et al., 1999; Melzer et al., 2006; Gong and Gu, 2015; Yang and Qing, 2016; Burton-Kelly et al., 2017). However, reports of ROZs in clastic reservoirs are still missing, as in the deep zone (Aleidan et al., 2017). Therefore, this paper will introduce two newly identified ROZs under the horizontal OWC in the Donghe Sandstone Member in the Tarim Basin, Northwest China. The application of computed tomography (CT) contributes to the microscopic research on the residual oil in ROZs. Two technological advancements, CT scanning conducted

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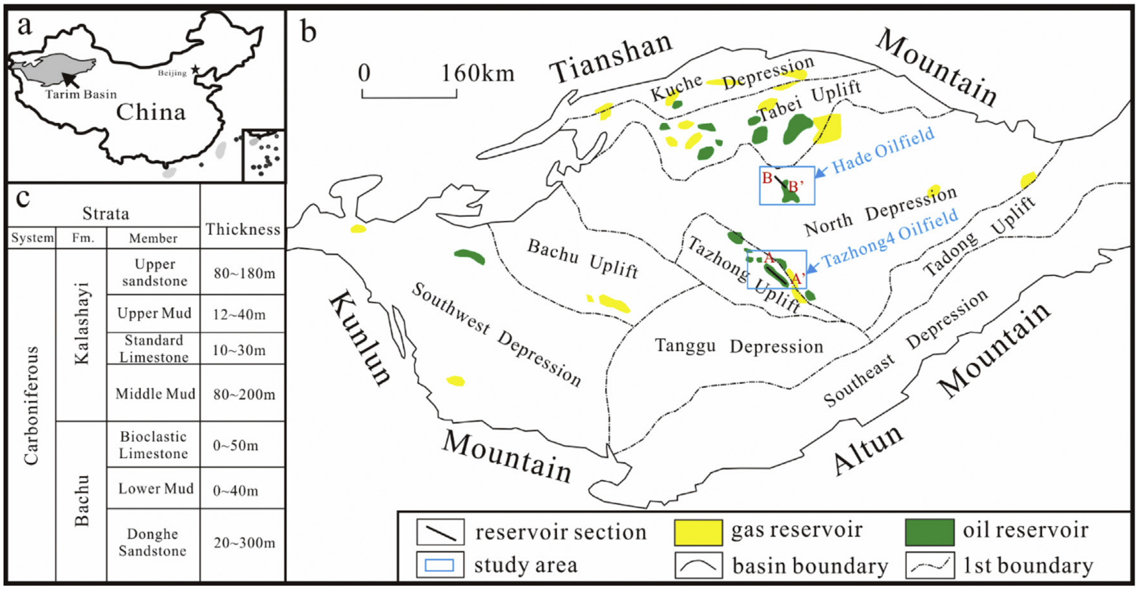

Fig. 1. Location and stratigraphic column of the study area
(a) Location of the Tarim Basin in China. (b)Tectonic unit map of the Tarim Basin and location of the study area, with the Hade and Tazhong4 Oilfields. (c) Stratigraphic column of the study area.

during the water displacing oil experiments and quantitative occurrence state characterization of oil, enable accurate descriptions of residual oil in the process of ROZ formation (Iglauer et al., 2010, 2012; Li et al., 2017). In this study, integrated well logging interpretation, geochemical analysis, thin sections, lithology and core-flood experiments were used to analyze the geological features and formation mechanism of the ROZ in both macroscopic and microscopic views. In addition, the ROZ development feasibility using low-salinity water flooding as an appropriate EOR approach is preliminarily investigated. It is hoped that these results can provide a guide for the exploration and development of ROZs.

2. Geological setting

The Tarim Basin, located in Northwest China, is the largest oil-bearing basin in China, covering an area of 560,000 km^2 (Fig. 1) (Pang et al., 2018). The Donghe Sandstone was widely deposited in an early stage of the Carboniferous marine transgression, and the thickness of the large-scale shore sandstone varies from 20 m to 300 m (Zhu et al., 2013; Li et al., 2016). One of the Donghe Sandstone ROZs lies in the Tazhong4 Oilfield of the Tazhong Uplift, and another lies in the Hade Oilfield of the North Depression (Fig. 1b). In these two tectonic units, stable Lower Mud Member sediments cover the Donghe Sandstone Member. The Tazhong Uplift experienced intense lifting and denudation during the late Caledonian Movement, and frequent adjustment in the Mesozoic (Jiang et al., 2017). The North Depression went through uplifting during the early Hercynian Movement after a long-term subsidence, and subsided sequentially until the Cenozoic (Han et al., 2014). Afterwards, the Tazhong Uplift and North Depression underwent an apparent adjustment in the process of the Himalayan Movement (Wang et al., 2004; Zhang et al., 2012). Approximately 100 wells have been drilled in the Tazhong4 Oil field, and the average porosity and permeability of the Donghe Sandstone reservoir are approximately 18% and 263 mD, respectively. The current temperature and pressure are 107.5 °C and 36.7 MPa, respectively. The Donghe Sandstone reservoir in the Hade Oilfield has over 200 wells, with porosity and permeability characteristics of 16% and 205 mD, respectively. The current temperature and pressure are 115.0 °C and 43.7 MPa, respectively.

3. Material and experiment

Well logging interpretation data, thin sections, oil samples and primary core descriptions for the Donghe Sandstone reservoir from 11 wells in the Tazhong4 and Hade Oilfields were collected from the Institute of Petroleum Exploration and Development, Tarim Oilfield Company, and the grains containing oil inclusions (GOI) data of TZ402 well were also obtained. The well logging data entail oil saturation, porosity, permeability and baffle explanations acquired from interpretation models based on all 29 coring wells in the study area. Four core plugs were taken from the Donghe Sandstone for CT scanning (Table 1, Fig. 2, Fig. 3). Tiny samples drilled from core plugs S1 and S3 were scanned directly by the Versa nanoVoxel-3502E X-ray Microscope (VXM)with 2 μm resolution (Li et al., 2017). The following step is image processing and 3D core construction (Ohtsu, 1979; Silin et al., 2004; Buades et al., 2008; Li et al., 2017).

Direct CT scanning of samples aims to reveal the microscopic occurrence state of the residual oil in the ROZ, whereas water displacing oil experiments coupled with CT scanning were designed to shed light

Table 1
Core samples from the Donghe Sandstone Member residual oil zone.

No.	Well	Depth (m)	Core plug		Experiment sample		Porosity (%)	Permeability (mD)	Wettability
			Diameter (mm)	Length (mm)	Diameter (mm)	Length (mm)			
S1	TZ4-7-17	3705.52	25.1	78.6	2.0	5.0	/	/	/
S2	TZ4-7-17	3707.21	25.4	82.6	8.0	50.1	14.2	128.9	Water-Wet
S3	HD113	5174.86	24.9	79.4	2.0	5.0	/	/	/
S4	HD113	5174.80	25.3	72.6	7.9	50.0	18.8	436.1	Water-Wet