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Secondary alteration to ancient oil reservoirs by late gas filling in the Tazhong area, Tarim Basin

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ABSTRACT

Ordovician carbonates have abundant resources of oil and gas in the Tazhong area of the Tarim Basin. Due to secondary alteration caused by multiple periods of oil and gas filling, especially late gas filling, fluids in ancient oil reservoirs are complex in nature, and multiple-phase oil and gas reservoirs, such as gas-condensate reservoirs, volatile-oil reservoirs, and normal oil reservoirs coexist horizontally. By examining the distribution, fluid physiochemical properties, biomarkers, gas isotopes, and fluid inclusions of these oil and gas reservoirs, this research has revealed that reservoir distribution is controlled by strike-slip faults, fracture-vuggy reservoir connections, and structural features, and that fluids of different-phase reservoirs are significantly different in physiochemical properties and in nature. Maturities of oil and gas are significantly different, suggesting that the area was filled at least twice by oil and gas of different maturities. Analysis of fluid inclusions shows that two types of inclusions are commonly developed: liquid–hydrocarbon inclusions in the first period and gaseous hydrocarbon inclusions in the second period, suggesting that oil filled at an earlier time and gas filled at a later time. It is proposed that gas-condensate reservoirs were formed after late gas invasion altered ancient oil reservoirs. Features of light hydrocarbons, such as wax and aromaticity, indicate the direction and intensity of gas-washing fractionation; biomarker parameters prove that, in terms of oil and gas maturity, gas-condensate reservoirs > volatile-oil reservoirs > normal oil reservoirs. The process of oil and gas accumulation in the Tazhong area is reproduced, and an accumulation model is proposed for multiple-phase oil and gas. In addition, a method is provided for evaluating the relative intensities of secondary alteration to early reservoirs by late gas filling, which is significant in exploration for oil and gas in deep layers and in prediction of hydrocarbon phases.

1. Introduction

With ever-increasing exploration for oil and gas, exploration has inevitably extended into deep layers (Zhu and Zhang, 2009). Under high temperature and pressure in deep layers, crude-oil cracked gas is generated in large quantities and affects the overlying oil reservoir during its upward migration. Therefore, secondary alteration by late gas filling in oil reservoirs has attracted substantial attention. Some researchers believe that, under high temperature and pressure, gas intrudes into an oil reservoir, but at the same time, phase separation and gas escape occur, causing gas condensates to increase in crude oil, which is called "phase fractionation" by Thompson (1987, 1988) and Van Graas et al. (2000) and "gas washing" by Losh et al. (2002). Gas invasion has been found in a number of petroliferous basins in the world, such as the Gulf of Mexico (Roberts and Carney, 1997), Eugene Island Block 330 (Meulbroek et al., 1998a, 1998b), the San Juan basin in the Mexican Gulf Coast (Thompson, 1980, 1987), offshore Taiwan (Dzou and Hughes, 1993), the South China Sea (Zhang and Zhang, 1991), offshore Indonesia (Schoell et al., 1985), offshore Alaska (Kvenvolden and Claypool, 1980), and the North Sea (Larter and Mills, 1991). Gas invasion can trigger certain changes in the fluids in an ancient oil reservoir. For example, Thompson (1980) studied the San Juan basin in New Mexico and found that gas carries more gas condensate after gas washing and that $\delta^{13}C$ in fluids shows a gradual tendency to become lighter from the center to the margin of the basin (Leythaeuser et al., 2007; Losh and Cathles, 2010; Sharaf and El Nady, 2006; Volk et al., 2002; Zhu et al., 2003; Masterson et al., 2001; Matyasik et al., 2000). The marked effects of gas invasion on fluid compositions and properties have been confirmed in several basins (Hammami et al., 1995; Zhang, 2000; Hammami and Ratulowski, 2007). When studying the Louisiana coastal basin, Losh et al. (2002) found that during gas invasion, the original normal alkanes in crude oil decreased by up to 91%, and that crude-oil density tended to decrease as gas invasion became stronger.

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Fractionation caused by gas invasion was evaluated according to component analysis of oil and gas fractions and enrichment of aromatic hydrocarbons and naphthenic acid in residual oil (Thompson, 1987, 1988). Some researchers have proposed that component exsolution caused by pressure decrease could measure changes in oil components and thereby measure the strength of gas invasion (Silverman, 1965), but others thought that this approach was limited because it is affected by many factors such as gas amount and pressure, not by gas invasion only (Losh et al., 2002). A continuous gas-washing model was also proposed, meaning that gas carries away some oil components as it flows away (Meulbroek, 1997; Meulbroek et al., 1998a, 1998b). Therefore, the secondary alteration of oil reservoirs caused by late gas filling should be evaluated, not by a single factor, but by a comprehensive study of multiple factors.

The Tarim Basin is an ancient, highly complex cratonic basin, has deep burial, and has suffered multi-cyclic superimposition and alteration with complex distribution of oil and gas (Huang et al., 2001; Jin, 2005; Zhu et al., 2013a). The Tazhong area is a structural unit rich in oil and gas which has the most complex distribution in the Tarim Basin. This area has many types of oil and gas reservoirs and fluids which are complex in nature, but it is generally agreed that the area experienced several stages of oil and gas filling (Zhang et al., 2004, 2011; Zhao et al., 2009; Yang et al., 2011; Zhu et al., 2011). At present, research on secondary alteration by late gas filling in the Tazhong area is in its initial stage, and a comprehensive comparative evaluation has not yet been achieved. On the basis of previous studies, this article reconstructs the oil and gas accumulation process in the Tazhong area, establishes an accumulation model of a multi-phase oil and gas reservoir, discusses the influence of gas invasion on fluid physiochemical properties and maturity and on other parameters, provides a comprehensive evaluation of secondary alteration to oil by late gas filling, and provides a quantitative method for evaluating the degree of alteration of oil and gas reservoirs.

2. Geology

The Tarim Basin is the largest petroliferous basin in China, with an area of 56×10^4 km^2 (Li et al., 1996) and is a typical superimposed basin. The Tazhong area is a long-developed successive ancient uplift zone located in the middle of the central uplift in the basin. It borders the Bachu faulted uplift to the west, the Tadong low uplift to the east, and strikes North-East. It is immediately next to the Manjiaer Depression to the north and to the Tangguzibasi Depression to the south (Fig. 1).

The Tazhong uplift is separated from the northern Manjiaer sag by the Tazhong 1 zone. It can be divided, from north to south, into three secondary structural units: the northern slope; the central uplift; and the southern slope. Oil and gas are produced mainly from the northern slope zone. In the Tazhong uplift, two secondary structural units, the Tazhong 1 break zone and the Tazhong 10 structural zone, are developed in the NW–SE direction, with an extension of over 200 km. Affected by several stages of tectonic movements, the Tazhong area has well-developed faults which can be divided into two systems according to size, time, and strata-cutting: the compressive thrust fault system in the NW–SE direction; parallel to the Tazhong 1 break zone and developed in the Caledonian period; and the strike-slip fault system that is nearly in the NE–SW and NS direction and was developed in the early Hercynian period. The former system “diverges westwards and converges eastwards”; the latter system develops differently to the east and west, with strike-slip faults more developed in the middle and west than in the east.

The drilled formations in the Tazhong area include, from new to old, the Cenozoic Quaternary, Neogene, and Paleogene; the Mesozoic Cretaceous and Triassic; the Paleozoic Permian, Carboniferous, Devonian, Silurian, Ordovician, Cambrian, and Sinian, with the Jurassic missing. The Ordovician strata consist of, from the bottom up, the Lower Ordovician Penglaiba Formation and the Yingshan Formation; the Upper Ordovician Lianglitage Formation and the Sangtamu Formation, with the Middle Ordovician missing; and the Upper Ordovician contacting unconformably with the overlying Silurian and underlying Middle and Lower Ordovician. The Penglaiba Formation is largely dolomite. The Yingshan Formation is mainly micrite, algen-cemented micrite, fine limestone, mud calcarenite, and sparry grain limestone, interbedded with thin fine dolomite and sandy dolomite, and can be divided into four lithologic parts. Because the Middle Ordovician sea level fell and local structures uplifted, the Yingshan Formation was denuded increasingly from NE towards SW, and the outcropped strata become older from north to south. The Lianglitage Formation is mainly light gray, sparry, sandy bioclastic limestone; organic skeleton rock; bioclast and sand bondstone; cryptomonas micrite; and cryptomonas clotted limestone and micrite. The Sanggetamu Formation is dominantly dark gray mudstone and calcareous mudstone, mingled with a little fine sandstone and thin limestone, and is the regional seal of the Ordovician oil and gas reservoirs.

The Carboniferous and Silurian sand reservoirs are dominantly primary porosity. The Ordovician carbonate reservoirs have less-developed primary porosity and are dominantly secondary dissolved pores and cavities, including cavities, fractures, and pores, with the reservoirs being highly heterogeneous.

Two suites of source rocks, the Cambrian Middle–Upper Ordovician and the Middle–Upper Ordovician, are developed in the Tarim Basin (Zhang et al., 2000; Zhang and Huang, 2005). Oil filling dominated in the late Caledonian and late Hercynian periods, and gas filling dominated in the late Himalayan period (Zhu et al., 2012a, 2013b). The late Caledonian oil reservoirs have been extensively damaged, and the presently preserved oil was accumulated largely in the late Hercynian period, which was the major accumulation period of marine oil in the basin (Zhu et al., 2012b, 2012c, 2013c); the Himalayan period was dominated by gas filling. Tectonic activities and petroleum filling in multiple periods complicated the distribution of the Ordovician oil and gas reservoirs, which have no uniform bottom water and edge water on a macroscopic scale and are quasi-layered, dissolved, fractured carbonate reservoirs. The Carboniferous and Silurian oil and gas reservoirs were not affected by late gas invasion (Zhu et al., 2012d, 2013d, 2013e). Because the Ordovician oil reservoirs were differently altered by late gas invasion, they can be classified into gas-condensate reservoirs affected by intensive gas invasion, oil reservoirs with gas top or volatile-oil reservoirs affected by weak gas invasion, and oil reservoirs not affected by gas invasion. These three types of reservoirs have no clear boundaries in their distribution.

3. Methodology

For purposes of this study, all the testing and production data of oil reservoirs generated in recent years were collected, and a great number of samples were also collected and tested. Samples of oil and gas were collected from important wells, and core samples of production wells were acquired. Among these, 37 samples were used to analyze oil and gas properties, 35 samples were used to analyze oil biomarkers, 33 samples were used for carbon isotopes, and 25 samples were used for inclusions.

(1) *Natural gas C-isotope analysis*: The measuring instrument was Thermo Delta V Advantage, the job was finished by