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Research paper

Geochemical and tight reservoir characteristics of sedimentary organic-matter-bearing tuff from the Permian Tiaohu Formation in the Santanghu Basin, Northwest China

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ABSTRACT

Tuff reservoirs have been found in petroliferous basins but have not been sufficiently studied. The discovery of the Permian Tiaohu Formation reservoir in the Santanghu Basin in Northwest China has offered an excellent opportunity to further enhance our knowledge of the tuff's geochemical and reservoir characteristics. The tuff reservoir has the peculiar property of being a sedimentary organic-matter-bearing tuff. In this study, an integrated analysis of the organic geochemistry, elemental and mineral compositions, quartz crystallinity, pore types, and tight reservoir characteristics was conducted based on samples from the 20–30 m-thick tuffs. The extracted tuff samples have total organic carbon (TOC) values of 0.5–1.0 wt.%, total hydrocarbon yield values of 2–6 mg/g, and hydrogen index values of 20–336 mg HC/g TOC. The organic matter consists predominantly of Type III and II_2 kerogens, and the temperature of the maximum yield of pyrolysate varies from 420 to 450 °C, which reflects the oil-generating capacity of the rock. The physical properties of the tuff are characterised by high porosity (varying from 10% to 25%) and low permeability. The air permeability mainly ranges from 0.01 to 0.50 mD. The devitrification of vitreous textures within the tuff primarily dictates the reservoir's characteristics, i.e., the greater the degree of devitrification, the higher the porosity of the reservoir. Vitric tuffs have reservoirs with higher porosity than crystal-vitric tuffs, and the degree of devitrification is generally controlled by the burial depth (temperature) and organic matter (organic acid) content. Vitric tuffs with high porosity and permeability are usually located far from the crater and within the central–lower part of the reservoir. This research may influence geologists to pay more attention to the exploration value of this special type of reservoir in other regions.

1. Introduction

As global demand for oil and gas rises and the output from conventional sources decreases, the development potential of unconventional sources of hydrocarbons has gradually become the new focus of attention in many countries. Shale reservoirs have yielded large amounts of gas from horizontal drilling and multi-stage fracturing technology. This same technology has been applied to tight reservoirs with low porosity and permeability, such as the Bakken Formation in Williston Basin in the United States (Fic and Pedersen, 2013). Tight oil generally refers to accumulations of petroleum in tight sandstones and tight carbonates (Clarkson and Pedemen, 2011; Jia et al., 2012a,b). Following this rapid expansion in shale gas extraction, tight oil has become the most active field of hydrocarbon exploration and development in the world (Kuhn et al., 2012).

A number of considerable differences exist between the tight oil in the Permian Tiaohu Formation in the Santanghu Basin and tight oil that has been discovered in other areas (Liang et al., 2014). (1) This reservoir is tight tuff, not shale, tight sandstone, or tight carbonate. (2) The oil is medium rather than light oil, with a density of 0.89–0.91 g/cm^3. (3) The oil is not in situ oil, and no close contact exists between the source rock and the reservoir. (4) The tuff reservoir was formed by the upward migration of oil from the source rocks in the Permian Lucaogou Formation through faults in

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volcanic lava that was several hundred meters thick. However, the tight oils in the Tiaohu Fm. and elsewhere are all from tight reservoirs. They are unconventional reservoirs, where horizontal wells and multistage hydraulic fracturing are necessary for commercial productivity (Zou et al., 2012; Hegazy, 2013; Khan, 2013).

Explosive volcanic eruptions can produce large amounts of fine-grained pyroclastic material, which may be spread laterally over large areas by wind drift (Kolata et al., 1987; Huff et al., 1992; Königer et al., 2002; Huff, 2008; Qiu et al., 2014). Tuffs are, in turn, formed from the ash that is ejected during volcanic eruptions (Gong et al., 2010). Sedimentation occurs either when tuffaceous material falls directly into a lake, termed 'primary airfall type', or is transported into a lake by water, i.e., 'water carrying resedimented type' (Atri et al., 1999; Haaland et al., 2000; Dunggen et al., 2010; Qiu et al., 2011). The Tiaohu Fm. tuff was mainly formed by volcanic ash that was deposited into a lake without weathering or extensive transportation. The rapid accumulation of volcanic ash, accompanied by the build-up of gases such as H_2S, SO_2, SO_3, and HCl, led to the deaths of aquatic organisms, which contributed organic matter to the Tiaohu Fm. tuff. Periods of volcanic dormancy then allowed aquatic organisms to become re-established, which resulted in renewed enrichment in organic matter (Wang et al., 2011; Li et al., 2014).

Oil and gas have been discovered in some tuff reservoirs, e.g., the Jatibarang oil and gas field in Indonesia (Thomas Kalan and Sitorus, 1994); the Samgori oilfield in the Republic of Georgia (Grynberg et al., 1993); green tuff oil and gas reservoirs in the Akita and Niigata Basins, Japan (Tomaru et al., 2009); the tuff reservoir in Qingxi Sag, China (Li et al., 2004); the tuff reservoir in the Erlian Basin, China (Gao et al., 2006); and the Urho oilfield in the Junggar Basin, China (Gong et al., 2010). These tuff reservoirs, which lack original sedimentary organic matter, contain few primary interparticle pores; secondary dissolution pores and fractures constitute the main pore types, thus differing greatly from the tuff in the Santanghu Basin.

Therefore, the two principal objectives in this study are as follows: (1) to illustrate the particular characteristics of this type of tight reservoir and to provide insight into the geochemical and petrographic characteristics, pore types, and petrophysical properties of sedimentary organic-matter-bearing tuffs; and (2) to discuss the effect of original sedimentary organic matter on micropore formation in tuffs, the main factors that affect the petrophysical properties of tuff reservoirs, and the distribution of the tuffs. These studies can provide useful data for understanding and predicting tight tuff reservoirs in the Santanghu Basin. Furthermore, the results of this investigation could be useful for researchers in other parts of the world where similar situations are found.

2. Geological setting

The Santanghu Basin, which is located in the north-eastern Xinjiang Uygur Autonomous Region of China, is bordered by the Republic of Mongolia to the north, the Turpan-Hami Basin to the south, and the Junggar Basin to the west. Sandwiched between the Tianshan and Altai mountains, this basin is a superimposed basin that developed over an Early Palaeozoic basement. The Santanghu Basin was a rift basin during the Late Palaeozoic and has been a foreland basin since the Mesozoic (Liu et al., 2010). The basin is aligned NW–SE, measures approximately 500 km long and 40–70 km wide, and covers an area of ~2.3×10^4 km^2. The Santanghu Basin can be divided into three tectonic units: the NE thrust fold belt, central depression, and SW thrust fold belt (Xu et al., 2013). The central depression belt comprises four uplifts and five sags, of which the Malang Sag, covering an area of ~1800 km^2, is the most important secondary structural unit. This depression has been relatively well explored and was thus selected as the focus of this study (Fig. 1a).

The Santanghu Basin was an intraplate rift basin during the Permian (Xiao et al., 2004a, 2004b). The basin has experienced a number of tectonic movements, and the regional faults are well developed (Hu et al., 1999; Li et al., 2005). Volcanoes continued to erupt frequently throughout the Late Palaeozoic, and the faults provided channels for volcanic eruptions. The Lucaogou and Tiaohu Formations developed during a period of active volcanism. Volcanism was weak during the deposition of the Lucaogou Fm., during which mudstones, lime mudstones, dolomitic mudstones, and other lacustrine fine-grained sediments developed, forming excellent source rocks (Gao et al., 2010; Ma et al., 2012). However, volcanism was more intense when the first member of the Tiaohu Fm. was deposited (Zhu et al., 2005). A basalt layer that was 200–600 m thick formed in most parts of the basin because of crustal thinning, asthenospheric upwelling, and lithospheric subsidence (Nelson, 1992; Hu et al., 2000; Chen and Jahn, 2004). Subsequently, the volcanism gradually weakened, and a 20–30 m-thick tuff formed at the bottom of the second member of the Tiaohu Fm. The tuff reservoir contains abundant oil, and many wells have achieved commercial oil after performing hydraulic fracturing with horizontal wells (e.g., Well M58H reached a stable oil flow rate of approximately 20 m^3/d after performing hydraulic fracturing for over a year). Lacustrine sediments that consisted primarily of tuffaceous mudstones and mudstones were deposited directly over the tuff reservoir. The burial history in Well M56 suggests that the Tiaohu Fm. reached its maximum palaeoburial depth during the Late Cretaceous and was then uplifted (Fig. 2). Therefore, the main diagenesis (e.g., compaction, mineral growth, and mineral transformation) occurred before the Late Cretaceous. An oil–source correlation has revealed that the crude oil in the tuff reservoir is derived from source rocks in the lower Lucaogou Fm. (Ma et al., 2015). Oil migrated vertically through faults and accumulated in the upper tuff reservoir during the Late Cretaceous (Cao and Liu, 2007), so the tight oil in the Tiaohu Formation was not formed in situ (Fig. 1b).

3. Samples and methods

3.1. Sample selection

Samples were obtained from cores from eight existing drilling wells in the Malang Sag to examine the geochemistry and reservoir characteristics. Samples were obtained from horizontal core plugs (2.5×5 cm) that were drilled parallel to the bedding plane to test the porosity, permeability, and pore throat radius. The tuff samples were subjected to an oil-wash treatment prior to the testing because they were oil-bearing. Organic geochemistry, thin section, cathodoluminescence, scanning electron microscope (SEM), pore throat radius, and petrophysical property (porosity and permeability) analyses of the tuffs were undertaken at the State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing. X-ray diffraction (XRD) analysis of the whole-rock minerals, XRD analysis of the quartz crystallinity, and elemental analysis were completed at the Micro Structure Analytical Lab of Peking University.

3.2. Analysis of organic geochemistry

Pyrolysis analysis of 34 core samples was performed with Rock-Eval. The measured parameters included S_1 (free hydrocarbons), S_2 (hydrocarbons cracked from kerogen), S_3 (carbon dioxide released from organic matter), and T_{max} (temperature of the maximum yield