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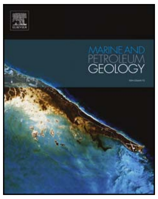

Research paper

Characteristics and factors controlling reservoir space in the Cretaceous volcanic rocks of the Hailar Basin, NE China

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ABSTRACT

We discuss the types, capacity, formation mechanisms, and main controlling factors of oil and gas reservoir spaces in Early Cretaceous acidic volcanic rocks of the Hailar Basin, NE China, where asphalt-bearing volcanic rocks are exposed at the surface. We have made systematic observations and analyses on macroscopic (outcrop) and microscopic (optical microscope, SEM, and fluorescence analyzer) scales. Acidic volcanic reservoirs contain reservoir spaces comprising primary and secondary porosity, which are dependent on primary and secondary processes during their formation. Primary porosity typically accounts for a large contribution to enhanced reservoir quality. More importantly, it is a prerequisite for migration, alteration, and filling by inorganic fluids and petroleum, which provides a foundation for the development of secondary porosity. The development of secondary porosity, especially alteration-related pores, can significantly modify the petrophysical characteristics of a rock. In addition to the processes of porosity formation, the quality of volcanic reservoirs is influenced by factors such as lithology, lithofacies, and tectonism. Lithological differences result in variations in the type and intensity of pore development. Pyromeride and glassy lava commonly exhibit high reservoir capacities. The porosity of different lithofacies typically follows the order of conduit facies > extrusive facies > effusive facies > explosive facies. Tectonism is necessary for the formation of reservoir spaces and for the migration, permeation, and accumulation of oil and gas. Reservoir quality is often positively correlated with the size and density of tectonic fractures.

1. Introduction

Volcanic reservoirs, a unique type of hydrocarbon reservoir, are drawing great attention worldwide. They have been discovered in many parts of the world (e.g., Schutter, 2003), especially in the Pacific Rim areas such as China (Wang and Chen, 2015; Chen et al., 2017), Japan (Magara, 2003), the United States (Nakata, 1980), and Argentina (Sruoga et al., 2004; Sruoga and Rubinstein, 2007). The lithologies of volcanic reservoirs range from basalt to rhyolite, over a wide range of ages. Volcanic reservoirs are commonly characterized by thick producing formations, high productivity, and large-scale reserves (e.g., Feng, 2008; Lenhardt and Götz, 2011; Zou, 2013; Chen et al., 2016b).

Since the early 20th century, volcanic reservoirs have been explored for oil and gas, and have received much attention from China's exploration and production industry. Within China, large oil and gas reservoirs have been discovered in Mesozoic and Cenozoic volcanic rocks in the Songliao, Bohai Bay, Hailar, and Erlian basins, and in Paleozoic volcanic rocks in the Junggar, Santanghu, Tarim, and Sichuan basins (Luo et al., 2005; Wu et al., 2006; Feng, 2008; Liu et al., 2010; Chen et al., 2010; Zou et al., 2010; Chen et al., 2016a; Jiang et al., 2017). The Qingshen gas field, discovered in Lower Cretaceous volcanogenic successions in the Xujiaweizi rift depression in the Songliao Basin, is the most productive gas reservoir in eastern China. Recently, more than 300 × $10^9\ m^3$ of natural gas (ca. 2 × 10^9 bbl oil equivalent) has been discovered in the Xujiaweizi rift depression (Feng, 2008), showing the great potential for the exploration and development of volcanic reservoirs.

The primary task in volcanic oil and gas exploration is to identify volcanic reservoirs and exploit them commercially. Reservoir type, capacity, and the main controlling factors are the focus of volcanic reservoir research (Mathisen and McPherson, 1991; Levin, 1995; Sruoga and Rubinstein, 2007; Liu et al., 2010). Previous studies have investigated reservoir type and capacity based on factors such as lithology, lithofacies, processes involved in the formation of volcanic rocks, and tectonism. Schutter (2003) and Zou (2013) outlined the influence of lithology on reservoir capacity in volcanic basins worldwide.

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Wang et al. (2003), Wang and Feng (2007), and Wang and Chen (2015) speculated that volcanic reservoirs are controlled mainly by volcanic facies and facies combinations. Sruoga and Rubinstein (2007) divided processes that contribute to the formation of volcanic rocks into primary and secondary, and identified a series of sub-processes. Hawlander (1990), Remy (1994), Luo et al. (1999, 2005), Gao et al. (2007), Felice et al. (2014), and Chen et al. (2017) discussed the genetic connection between the processes of porosity formation and reservoir space types. Other studies have examined the effects of devitrification (Zhao et al., 2009), alteration, and diagenesis (Mathisen and McPherson, 1991; Luo et al., 2005; Tian et al., 2013; Wang and Chen, 2015; Zhu et al., 2016; Jiang et al., 2017) on reservoirs and their capacity. These studies of volcanic rocks have been of great benefit to hydrocarbon exploration efforts.

However, most of previous studies mainly focused on the mineral composition, rock structure, experimental petrology, petrography, and geochemistry of volcanic rocks (e.g., Davis and McPhie, 1996; Denton et al., 2009), meaning that the characteristics of reservoir spaces and their capacity, to some extent, are currently unconstrained. For example, many studies have considered spherulite geometry, formation mechanisms (Keith and Padden, 1963; Lofgren, 1971, 1974; Fowler et al., 2002; Gránásy et al., 2005; Watkins et al., 2009), and relationships with crystal growth rate (Swanson, 1977; Lofgren, 1974), but the characteristics, formation mechanisms, and capacity of intra- and interspherulite porosity have received little attention. Although the characteristics and formation mechanisms of perlitic textures and lithophysa cavities have been investigated (e.g., Davis and McPhie, 1996; Denton et al., 2009), no previous study has examined their capacity. Recent studies have shown that devitrification micropores and alteration-related pores are important reservoir spaces, and mechanisms for their formation have been proposed (Gimeno, 2003; Zhao et al., 2009; Tian et al., 2013). Unfortunately, the distribution of petroleum components within devitrification micropores remains unclear, and a comprehensive study on intraspherulite pore systems involving devitrification micropores and alteration-related pores is lacking. The relationship between volcanic facies and reservoir capacity is also controversial (Wang et al., 2003; Wang and Feng, 2007; Wang and Chen, 2015; Chen et al., 2016a). The relationship between the number density of tectonically induced fractures and the reservoir quality of volcanic rocks is also unconstrained. Therefore, additional data and studies are required.

We have discovered a succession of continuously exposed asphalt-bearing volcanic rocks on the western boundary of the Hailar Basin (HB), NE China, which we consider an analog for volcanic reservoirs exposed at the surface. This outcrop not only shows the types, characteristics, reservoir capacity, and distribution of volcanic reservoir spaces, but also the relationship amongst the reservoir quality of volcanic rocks and lithology, lithofacies, tectonism, and sequence of processes they have undergone. Furthermore, outcrop studies avoid the limitations of drillcore observations, making this area an ideal natural laboratory in which to conduct a systematic study on volcanic reservoirs. This paper focus on the main types, reservoir capacity, formation mechanisms, and main controlling factors of reservoir spaces in acidic volcanic rocks. The results are expected to improve the understanding of the characteristics and factors controlling reservoir space in volcanic rocks and may serve to assess the quality of volcanic reservoirs.

2. Geological setting

The HB is a Mesozoic–Cenozoic petroliferous fault-bounded volcanic basin within the late Mesoproterozoic to Carboniferous Central Asian Orogenic Belt (CAOB) between the North China and Siberian cratons (e.g., Sengör et al., 1993; Xiao et al., 2003) (Fig. 1a). It is situated to the south of the Mongol–Okhotsk Suture, on the western flank of the Great Xing'an Range, an uplifted section of the extending CAOB. In this region, the Mongol–Okhotsk suture closed in the late Paleozoic–Early Jurassic, resulting in significant lithospheric thickening (e.g., Zorin, 1999; Tomurtogoo et al., 2005). In the Late Jurassic–Early Cretaceous, post-orogenic collapse or delamination resulted in extension of the thickened lithosphere (e.g., Zorin, 1999; Wang et al., 2006). This regional extension triggered the contemporaneous eruption of basic and acidic (more basic rocks at the beginning of volcanism) rocks during ca. 160–110 Ma in the HB and adjacent areas (e.g., Wang et al., 2006; Zhang et al., 2008; Li et al., 2014).

The NE-trending HB comprises two uplifts and three depressions that are subdivided into 16 sags (Fig. 1b). Late Mesozoic–Cenozoic units in the basin mainly comprise, from oldest to youngest, the Middle Jurassic–Lower Cretaceous Tamulangou Formation; the Lower Cretaceous Tongbomiao, Nantun (together also known as the Shangkuli Formation), Damoguaihe, Yiliekede, and Yimin formations; the Upper Cretaceous Qingyuangang Formation; and the Quaternary System (Fig. 1c and d and Fig. 2). The tectonic evolution of the basin involved an initial rifting stage (the deposition period of the Tamulangou Formation), followed by the formation of fault-bound depressions (the deposition period of the Tongbomiao and Nantun formations) and a fault-sag transformation stage (the deposition period of the Damoguaihe, Yiliekede and Yimin formations) (e.g., Sun et al., 2011) (Fig. 2).

Approximately 4.2×10^8 bbl of oil and $113.3 \times 10^8\,\mathrm{m}^3$ (ca. 7.6×10^7 bbl oil equivalent) of natural gas are estimated to be contained within the HB (Feng et al., 2004a). The source rocks are concentrated within the Nantun and Damoguaihe formations, and to a lesser extend in the Tongbomiao Formation (Fig. 2). Total organic carbon (TOC) contents of dark mudstones are typically $> 2\%$ and $> 1\%$ in the Nantun and Damoguaihe formations, respectively (Feng et al., 2004a). Kerogen in dark mudstone of the Nantun Formation is predominantly type II with minor type I, whereas that in the Damoguaihe Formation is types II and III (Feng et al., 2004a, 2004b).

The study area is located along the western boundary of the HB (Fig. 1b), within the Hulun Nur Sag, which is the largest sag in the Jalai Nur depression. Dark mudstone that accumulated in the sag has a thickness of > 792 m (Feng et al., 2004b). Oil and gas are contained primarily within volcanic rocks of the Lower Cretaceous Shangkuli Formation (Figs. 1b and 2). The NE–SW-trending basin-controlling Erguna Fault, which connects the volcanic rocks to the source rocks, acted as a channel for oil and gas migration (Fig. 1b, d).

The lithologically complex acidic volcanic rocks that yield zircon U–Pb ages of 136–125 Ma (Li et al., 2014) are widely exposed in the study area. The lower section consists of pyroclastic rocks which represent the explosive facies of the early stage of volcanic eruptions. The central section contains mainly rhyolites (vesicular rhyolite and pyromerides in particular), representing the effusive facies of the intermediate stage of volcanic eruptions. The upper section consists of pyroclastic lavas, cryptoexplosive breccias, and interbedded pyromerides and glassy lavas, representing extrusive and conduit facies of the late stage of volcanic eruptions. Together, these rocks represent the products of a complete volcanic eruption cycle. The diverse types of asphalt-bearing reservoir spaces, which are the focus of this paper, are observed mainly in the central and upper sections, within the effusive, extrusive, and conduit facies. The characteristics of the above-mentioned volcanic facies are listed in Table 1, and a cross-section through the volcanic rocks is shown in Fig. 3.

The term “pyroclastic lava” is used here to refer to transitional rocks between lava and pyroclastic rocks, which resulted from the consolidation of magma-cemented pyroclasts. Such lithologies are commonly produced during the extrusion of silicic magma near craters (e.g., Qiu, 1985; Wang et al., 2010) (Fig. 3c). The term “cryptoexplosive breccia” refers to a series of in situ breccia and jigsaw-fit structure that form by underground explosions because of the high pressure of volatiles coupled with fluids following a major volcanic event (e.g., Qiu, 1985; Wang and Chen, 2015) (Fig. 3f).