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Organic geochemistry and reservoir characterization of the organic matter-rich calcilutite in the Shulu Sag, Bohai Bay Basin, North China

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ABSTRACT

Although extensive studies have been conducted on unconventional mudstone (shales) reservoirs in recent years, little work has been performed on unconventional tight organic matter-rich, fine-grained carbonate reservoirs. The Shulu Sag is located in the southwestern corner of the Jizhong Depression in the Bohai Bay Basin and filled with 400–1000 m of Eocene lacustrine organic matter-rich carbonates. The study of the organic matter-rich calcilutite in the Shulu Sag will provide a good opportunity to improve our knowledge of unconventional tight oil in North China. The dominant minerals of calcilutite rocks in the Shulu Sag are carbonates (including calcite and dolomite), with an average of 61.5 wt.%. The carbonate particles are predominantly in the clay to silt size range. Three lithofacies were identified: laminated calcilutite, massive calcilutite, and calcisiltite–calcilutite. The calcilutite rocks (including all the three lithofacies) in the third unit of the Shahejie Formation in the Eocene (Es_3) have total organic carbon (TOC) values ranging from 0.12 to 7.97 wt.%, with an average of 1.66 wt.%. Most of the analyzed samples have good, very good or excellent hydrocarbon potential. The organic matter in the Shulu samples is predominantly of Type I to Type II kerogen, with minor amounts of Type III kerogen. The temperature of maximum yield of pyrolysate (T_{max}) values range from 424 to 452 °C (with an average of 444 °C) indicating most of samples are thermally mature with respect to oil generation. The calcilutite samples have the free hydrocarbons (S_1) values from 0.03 to 2.32 mg HC/g rock, with an average of 0.5 mg HC/g rock, the hydrocarbons cracked from kerogen (S_2) yield values in the range of 0.08–57.08 mg HC/g rock, with an average of 9.06 mg HC/g rock, and hydrogen index (HI) values in the range of 55–749 mg HC/g TOC, with an average of 464 mg HC/g TOC. The organic-rich calcilutite of the Shulu Sag has very good source rock generative potential and have obtained thermal maturity levels equivalent to the oil window. The pores in the Shulu calcilutite are of various types and sizes and were divided into three types: (1) pores within organic matter, (2) interparticle pores between detrital or authigenic particles, and (3) intraparticle pores within detrital grains or crystals. Fractures in the Shulu calcilutite are parallel to bedding, high angle, and vertical, having a significant effect on hydrocarbon migration and production. The organic matter and dolomite contents are the main factors that control calcilutite reservoir quality in the Shulu Sag.

1. Introduction

The potential for unconventional oil and gas exploration is huge and has broad implications (Jarvie et al., 2007). In some areas the unconventional resource has become an important component of the oil supply, such as the Eagle Ford play in south Texas (Mullen, 2010), the Bakken play in the Williston Basin (Sonnenberg and Pramudito, 2009). Tight oil, in the future, is the main exploration domain of unconventional petroleum in the world (Kuhn et al., 2012; Jia et al., 2012). With the success of the Bakken tight oil play in the U.S., low-permeability (tight) oil reservoirs have emerged as a significant source of the oil supply in North America (Clarkson and Pedersen, 2010). There are numerous potential unconventional resource plays in China, such as those in the Songliao Basin, the Bohai Bay Basin, and the Ordos Basin (Zou et al., 2010; Dai et al., 2012). Tight oil is expected to be an important new source of the oil supply in China. The Bohai Bay Basin is the largest oil and gas production basin among the petroliferous basins in China (Zhou, 2008), which produced 74.352 million tons oil equivalent in 2009. With the increasing difficulty of exploitation of conventional

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petroleum in the Bohai Bay Basin, unconventional oil resources will be an important supplementary source. Lacustrine carbonate deposits which are widely developed in the Eocene lacustrine depressions in the Bohai Bay Basin are generally considered to be potential oil exploration targets as they are always rich in organic matter or/and adjacent to source rocks (Jiang et al., 2007).

Generally, unconventional tight oil is crude oil that is found within reservoirs with very low permeability. Some tight oil is extracted directly from shales or organic matter-rich carbonates (e.g. the Shulu calcilutite in China, the focus of this study, estimated to have 2.7 billion barrels of recoverable oil, PetroChina Huabei Oil field estimate), and other tight oil resources are found in low-permeability siltstones, sandstones, and carbonates that occur close to a shale source rock (e.g. the Bakken tight oil play in the U.S. with estimates of recoverable resources ranging from 3.65 BB of oil to 4.3 BB, USGS estimate).

The Bakken Formation is a rock unit from Late Devonian to Early Mississippian age that covers approximately 520,000 km^2 of the Williston Basin. This formation consists of three members: lower shale, middle silty dolomite, and upper shale (Dow, 1974; LeFever, 2006). The middle dolomite member is the principal oil reservoir and ranges in thickness from 3.1 to 12.2 m. Both the upper and lower shale members are organic matter-rich marine shales that act as hydrocarbon source rocks (Sonnenberg and Pramudito, 2009).

The Shulu Sag is located in the southwestern corner of the Jizhong Depression, Bohai Bay Basin (Fig. 1), and has developed a set of thick Eocene lacustrine carbonates with high organic matter contents (Fig. 2). Many Oil-bearing tight calcilutite pools have been discovered in the Shulu Sag, with an average oil production up to 43.64 m^3/day (Wang et al., 2007). The lacustrine calcilutite sequence in the Shulu Sag is also a tight oil play and has become an important exploration target for the PetroChina Huabei Oilfield (Su et al., 2007; Hao et al., 2007). However, unlike the Bakken tight oil, the calcilutite in the Shulu Sag acts as both a source rock and a reservoir for oil (Hao et al., 2007; Jin et al., 2008). Compared with the Bakken Formation, the lacustrine calcilutite sequence in the Shulu Sag covers a smaller area (400 km^2) but has a larger thickness, which is usually 600 m and may reach 1 km in the center of the sag.

Extensive studies have been performed on fine-grained rocks in recent years to better understand unconventional petroleum reservoirs (Schieber et al., 2007; Aplin and Macquaker, 2011; Loucks and Ruppel, 2007, 2009, 2012). However, most of the studies were conducted on mudstones (shales) and few studies have investigated fine-grained carbonate rocks (Bera et al., 2012). Currently, the research on the calcilutite reservoir in the Shulu Sag primarily concerns its fracture characteristics (Su et al., 2007; Hao et al., 2007; Wang et al., 2007; Kuang et al., 2008). The organic

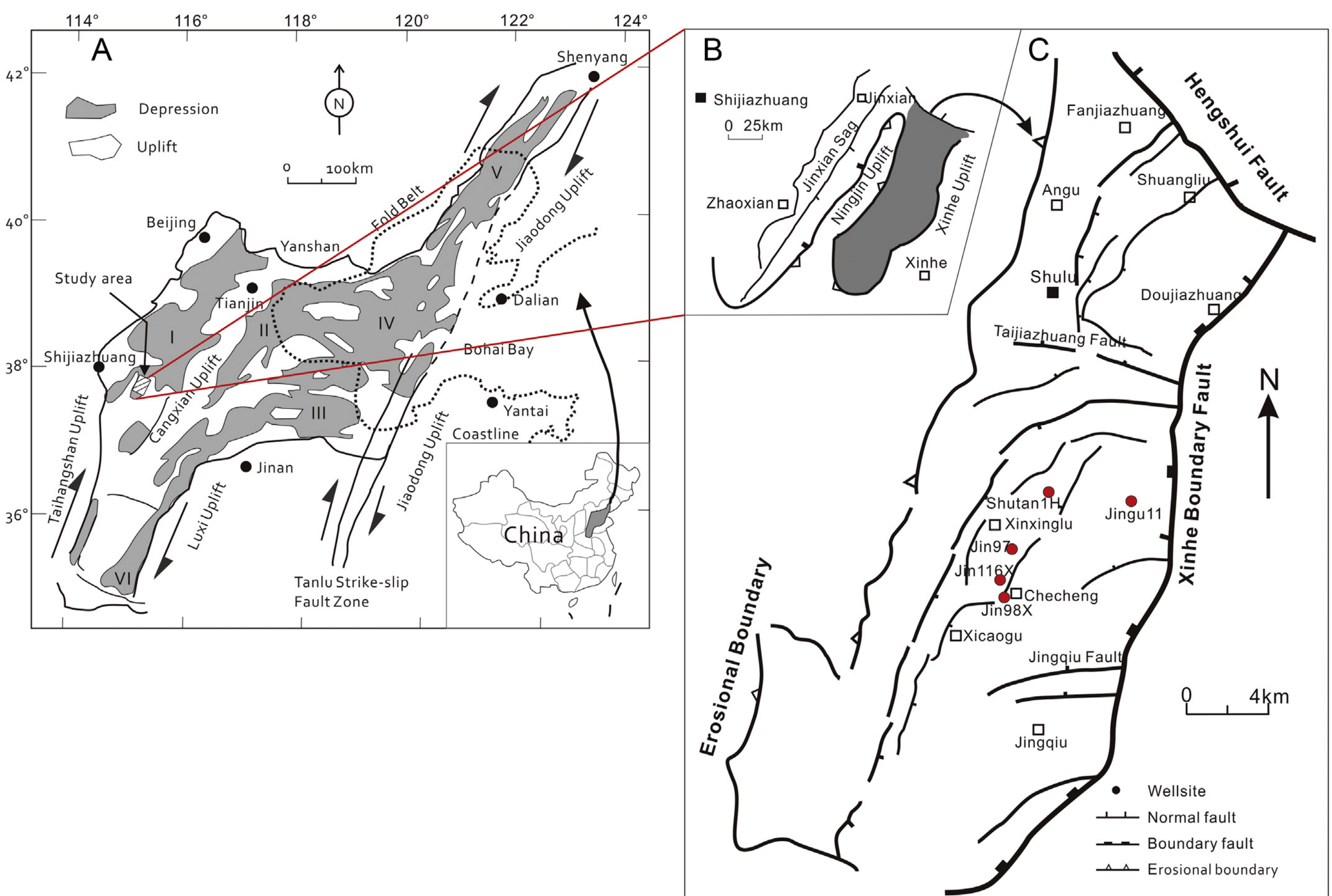

Figure 1. Location and structural map of Shulu Sag half-graben. (A) Tectonic setting of the Shulu Sag half-graben during the Eocene, located in the southwestern corner of the Jizhong (central Hebei Province) Depression (I). Other sub-basins in Bohai Bay of North China are the Huanghua Depression (II), the Jiyang Depression (III), the Bozhong Depression (IV), the Liaohe Depression (V), and the Dongpu Depression (VI). (B) Sketch of the Shulu Sag. (C) Structural map of the Shulu half-graben. Three segments are delimited by the Taijiazhuang and Jingqiu faults (modified after Jiang et al., 2007).