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Depositional environment of oil shale within the second member of Permian Lucaogou Formation in the Santanghu Basin, Northwest China

Bo Liu[a,*], Achim Bechtel[b], Reinhard F. Sachsenhofer[b], Doris Gross[b], Reinhard Gratzer[b], Xuan Chen[c]

[a] Accumulation and Development of Unconventional Oil and Gas, State Key Laboratory Cultivation Base Jointly-constructed by Heilongjiang Province and Ministry of Science and Technology, Northeast Petroleum University, Daqing 163318, China
[b] Department of Applied Geosciences and Geophysics, Montanuniversitaet Leoben, Peter-Tunner-Strasse 5, 8700 Leoben, Austria
[c] PetroChina Turpan-Hami Oilfield Company, Hami 839009, China

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ABSTRACT

The non-marine Santanghu Basin in northwest China hosts one of the richest and thickest Permian lacustrine source rock intervals in the world. Conventional oil in Jurassic sandstone reservoirs and tight oil in the tuffaceous Permian Tiaohu Formation were sourced from mudrocks in the underlying second member of Lucaogou Formation, which also have tight oil potential proved by recent commercial discoveries. Based on inorganic and organic geochemistry, organic petrography, and stable isotope geochemistry, the depositional environment and the tight oil potential of the second member of Permian Lucaogou Formation were investigated. The data imply a gradual evolution of the depositional environment from a stratified, saline to a freshwater lake. The succession can be subdivided into a lower, middle, and an upper unit, each characterized by decreasing water salinity. High bioproductivity has been caused by the bloom of algae and photosynthetic cyanobacteria. Water column stratification accelerated the activity of methanothrophs, as indicated by low $\delta^{13}C$ values of hopanes. Biomarker composition provides evidence for decreasing contributions of cyanobacteria to the biomass and increasing abundance of Prasinophytae compared to other algae with decreasing salinity. Enhanced terrigenous organic matter input appeared during periods of high freshwater inflow. Low total organic carbon (TOC) contents in the lower unit are most likely caused by rapid sedimentation rate. High bioproductivity and excellent preservation conditions resulted in high TOC contents in the middle unit. Terrigenous organic matter input increased together with fresh water inflow in the upper unit, resulting in high TOC values during periods of possibly low sedimentation rates in a deep water column. The samples of the second member exhibit a good to very good potential to generate conventional oil. High TOC and extractable organic matter yields, together with the thickness of the fine-grained sediments, show that the middle and upper units of the second member of Lucaogou Formation hold significant tight oil potential. Mineralogical composition of this dolomite-rich shale with respect to abundance of brittle minerals (including quartz and carbonates) and rare clay testifies a good tight oil potential.

1. Introduction

Over the past decade the production of oil and gas from organic matter-rich shales has increased significantly (Newport et al., 2016). In contrast to sandstones, the fine-grained nature of shales hampered studies of their properties and origin (Potter et al., 2009). However, a number of studies have explored the relationship between shale geochemistry and depositional environments, providing a fuller understanding of the heterogeneous organic matter (OM) composition in lacustrine sediment (Didyk et al., 1978; Sachsenhofer et al., 2003; Bechtel et al., 2012; Strobl et al., 2015). The results mirror the complexity of sedimentary processes in lakes, affected by short-term fluctuations in lake level, sediment input, and basin subsidence (Carroll, 1998).

In recent years, discoveries of tight oil (including shale oil) in the Santanghu Basin have drawn more attention in China (Liu et al., 2015; Ma et al., 2016). Especially the Permian Lucaogou Formation, which is considered a “world class source rock”, is a potential tight oil exploration target, due to its favorable thickness and organic-richness in both the Junggar and Santanghu basins in NW China (Carroll, 1998; Liu

* Corresponding author.
E-mail address: liubo@nepu.edu.cn (B. Liu).

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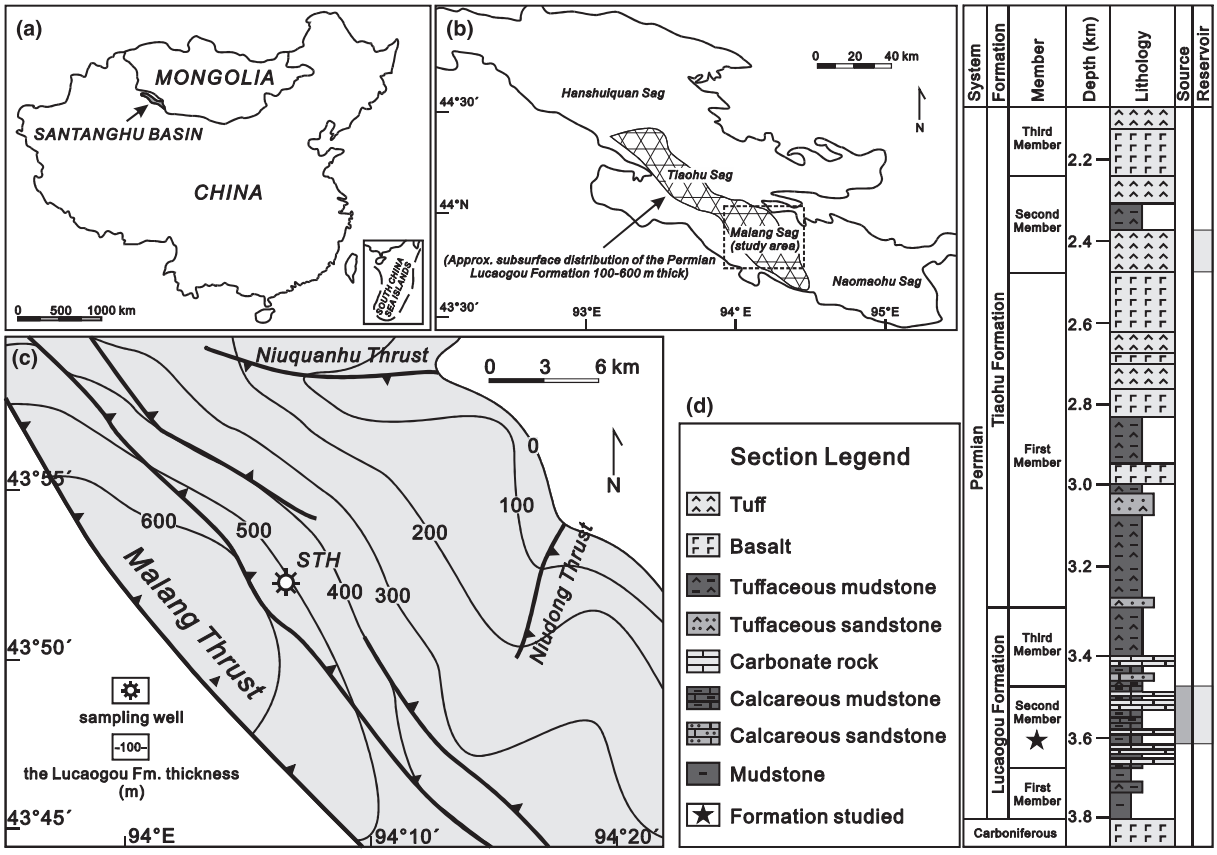

Fig. 1. Location of the Santanghu Basin (a) and the study area (b). Distribution of Lucaogou Formation in the study area and the position of the borehole STH (c). Lithological sketch of drill site STH Well (d).

et al., 2015).

Previous studies from the Junggar Basin showed that deposition of the Lucaogou Formation occurred at relatively high paleolatitudes (39–43° north) during a warm-temperate paleoclimate (Sharps et al., 1992). Carroll (1998) inferred that the Lucaogou lakes were salinity and thermal stratified. Although deposition took place near an oceanic embayment, no obvious evidence for a marine influence could be found (Liu et al., 2015). Information about primary productivity (Carroll, 1998; Xie et al., 2015) and the dominant species of algae and bacteria (Carroll, 1998; Tao et al., 2012; Xie et al., 2015; Cao et al., 2016) are available based on the studies in the Junggar Basin.

The Lucaogou Formation in the Santanghu Basin is less studied than in the Junggar Basin (Tao et al., 2012; Xie et al., 2015; Cao et al., 2016; Li et al., 2016; Wu et al., 2016). Moreover, only recent work by Hackley et al. (2016) used an integrated analytical program (Rock-Eval pyrolysis, XRD mineralogy, inorganic and organic petrography, and extract analysis) to provide information about the organic matter type, thermal maturity, and the conceptual model for Lucaogou deposition. Based on these results, the evolution from an under-filled to balance-filled lake in the Santanghu Basin has been proposed.

The aim of this study is to provide a detailed characterization of the depositional settings leading to the accumulation of oil-prone lacustrine sediments during middle Permian. The reconstruction of paleoenvironment and OM accumulation is based on vertical variations in bulk geochemistry, petrography, and biomarker composition within the Lucaogou Formation in the Santanghu Basin.

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 (Liu et al., 2012a). Sandwiched between the Tianshan and Altai mountains, this basin is an intracontinental superimposed basin that developed over an Early Palaeozoic collisional orogenic belt (Xiao and Santosh, 2014). The Santanghu Basin was a rift basin during the Late Palaeozoic and has been a foreland basin since the Mesozoic (Liu et al., 2010). Tectonic isolation resulted in a closed drainage by the Upper Permian and the deposition of carbonate-dominated lacustrine sediments in a sediment-starved intracontinental rift basin with mantle-originated hydrothermal fluids (Liu et al., 2012b; Li et al., 2013; Hackley et al., 2016). The central depression belt comprises four sags (Hanshuiquan Sag, Tiaohu Sag, Malang Sag and the Naomaohu Sag from the northwest to southeast), of which the Malang Sag, covering an area of ~1800 km^2, has been relatively well explored and was thus selected as the focus of this study (Fig. 1).

The Lucaogou Formation, up to 600 m thick, which has been regarded as a source rock, is known in the Malang Sag and the Tiaohu Sag. Its thickness decreases to the northeast because of pre-Jurassic erosion. Between the Carboniferous and the overlying volcanic rocks of the Permian Tiaohu Formation, a lacustrine mixed dolomitic-clastic sediment system, including thick mudstones, calcareous mudstones, carbonate rocks and other lacustrine fine-grained sediments developed in the Lucaogou Formation. The Lucaogou Formation can be divided into three members according to the sedimentary and rock electrical characteristics. From base to top, these members are named first, second and third member. The second member includes excellent oil-prone shales which were proved as main source rocks for oil in overlying reservoirs (Ma et al., 2016). This member was selected as the target layer for this study (Fig. 1).

3. Samples and methods

One hundred and one core samples from the second member of