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Middle Permian environmental changes and shale oil potential evidenced by high-resolution organic petrology, geochemistry and mineral composition of the sediments in the Santanghu Basin, Northwest China

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ABSTRACT

Shales in the Middle Permian Lucaogou Formation have been considered as one of the most important unconventional reservoirs in NW China, due to their excellent shale oil and tight oil potential. Based on the data of previous organic geochemical studies, the overall evolution of the ecosystem in the lake, water conditions and organic matter sources have been outlined. Here we present the results of the mineralogical and organic-petrological examinations and the Rock-Eval pyrolysis, on samples of a fine-grained, mixed carbonate-clastic sedimentary succession from the Santanghu Basin, providing new detailed insights into paleoenvironmental evolution and lake level changes. In addition, shale oil potential was further evaluated on this oil-prone shale.

Analytical results from a total of 196 shale samples from the second member of the Lucaogou Formation, collected from one newly drilled core, indicate algal/microbial sources of organic matter, classified by Rock-Eval pyrolysis as type I kerogen. Samples characterized by lower hydrogen index (HI) values (type II kerogen) contain increased contributions of terrigenous organic matter, evidenced by enhanced inertinite and vitrinite contents. Vertical variations in mineralogical and bulk geochemical composition reflect an evolution from a saline, anoxic to a deep, freshwater lake. Two environmental changes subdivided the sequence into three units. The boundary between the lower Unit I and the middle Unit II is characterized by the drastic decrease of smectite and K-feldspar contents and a sharp increase in total organic carbon (TOC) content. The upper Unit III is distinguished by high TOC/S ratios. Based on variations in petrography and carbon isotopes of hopanes, the middle Unit II can be further subdivided into two parts reflecting changes in water level of the lake. All the periods of high-water level are characterized by higher lamalginite contents (> 40 vol%) and higher HI values than those obtained from sediments deposited during periods of shallower water levels. Deposition in a shallow lake is evidenced by increased dolomite and decreased lamaginite contents. Lake level fluctuations, indicated by mineralogical and geochemical parameters, are associated with changes in organic matter sources, leading to the great variability in mineral content, organic petrography and hydrocarbon generation potential. High TOC and brittle minerals contents, micro-nanopores system and large thickness of the shale show that the Lucaogou Formation holds a significant shale oil potential in areas where oil window maturity is reached.

1. Introduction

Technological advances in the last few years resulted in increased oil production from marine shales (Curiale and Curtis, 2016). Moreover, intense geochemical and organic petrological studies provided comprehensive information on the organic matter in marine shales (Hackley and Cardott, 2016). In contrast, the level of knowledge of lacustrine shales is relative low (Curiale and Gibling, 1994), probably because organic matter in lacustrine oil shales is extremely variable and influenced by different factors, such as bioproductivity, water chemistry, freshwater supply and water stratification (Meyers and Ishiwatari, 1993). Accordingly, amount and type of organic matter may vary significantly, both vertically and laterally. Lake level fluctuations and associated changes in water column stratification are the key parameters influencing organic matter accumulation in lacustrine sediments (Jia et al., 2013; Xu et al., 2015). Along with Rock-Eval and mineralogical

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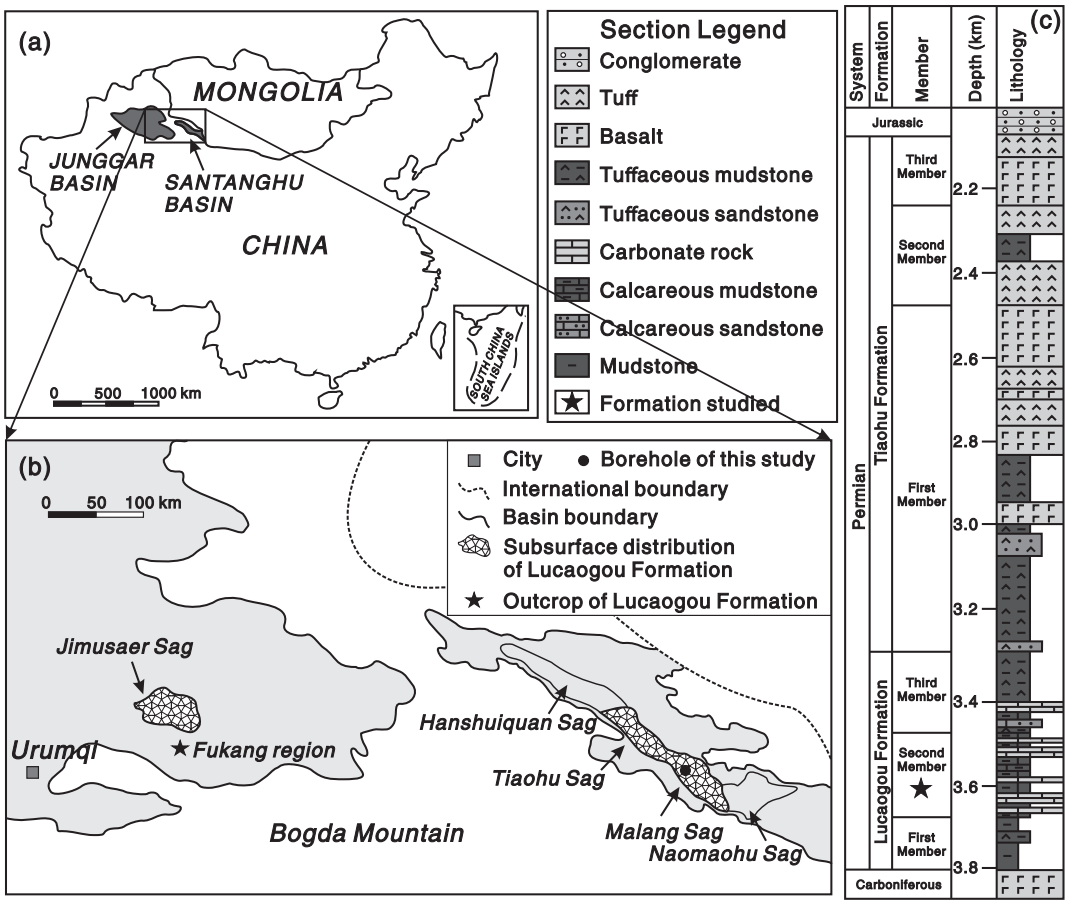

Fig. 1. (a) Generalized map showing location of Santanghu and Junggar Basins. (b) Simplified distribution of the Lucaogou Formation and the position of the borehole in this study. (c) Lithological sketch of drill site.

analyses, organic petrographic studies can provide detailed information about the type of organic and inorganic matter, as well as its origin and the depositional environment (Boucsein and Stein, 2009; Hackley et al., 2010; Dutta et al., 2011; Eble, 2012). They also provide insights into water level fluctuations of the lakes.

The middle Permian Lucaogou Formation is one of the most important lacustrine source rocks in the Junggar and Santanghu basins in northwestern China (Fig.1; Carroll, 1998; Liu et al., 2012a). Recently, discoveries of giant tight oil and shale oil reservoirs were made in the Lucaogou Formation in both basins (Liu et al., 2015; Wu et al., 2016). The paleo-environment during deposition of the Lucaogou Formation changed between deep, density-stratified lakes and shallow saline depressions. Distinguished from other shale sequences, the deposits are characterized by lacustrine, mixed carbonate-clastic, fine-grained sediments (Xie et al., 2015; Liu et al., 2017).

Detailed petrological and geochemical data of the Lucaogou Formation in the Junggar Basin have been used as indicators of paleo-environment and hydrocarbon source potential. Previous studies showed that oil shales recovered from boreholes in the Junggar Basin contain abundant lamalginite and minor land plant debris (Xie et al., 2015; Hackley et al., 2016). The organic matter of samples outcropping in the Fukang region of the Junggar Basin (Fig. 1b), contain a high amount of unstructured bituminite and mineral-bituminous groundmass with a high oil generation potential (Tao et al., 2012).

Due to the later discovery of unconventional petroleum potential, the sediments of the Santanghu Basin are not thoroughly studied. Recent organic petrological research in the Santanghu Basin conducted by Hackley et al. (2016) showed that the organic matter of the Lucaogou Formation mainly consists of fluorescent amorphous material and telalginite in the lower section, and increased inertinite contents in the upper section. Based on geochemical proxies of the Lucaogou shales, the upward variation of abundance and type of organic matter was interpreted to exhibit a gradual evolution from a shallow, stratified saline lake to a freshwater lake (Liu et al., 2017).

The aim of this study is to reconstruct the evolution of the Lucaogou lake and to determine the shale oil potential of the Lucaogou Formation. To reach these goals, macerals of different origin and mineral percentages are quantified. These data are used together with geochemical data published on the same sample set by Liu et al. (2017) to obtain insights into water level and salinity fluctuations of the lake. In order to obtain high-resolution information, the study of the roughly 200-m-thick succession is based on a total of nearly 200 samples.

2. Geological setting

The Santanghu Basin in northwestern China is located east of the large Junggar Basin (Fig. 1a) and northeast of the Bogda Mountain (Fig. 1b). This basin evolved as a rift basin during the Late Palaeozoic and has been a foreland basin since the Mesozoic (Liu et al., 2010). The central depression belt of the Santanghu Basin comprises four tectonically derived sags (from northwest to southeast: Hanshuiquan Sag, Tiaohu Sag, Malang Sag, and Naomaohu Sag), of which the Malang Sag (Fig. 1b), with an area of ~1800 km^2, has been relatively intensely explored and was selected as the focus of this study.

The Santanghu Basin includes a Permian succession that comprises the Lucaogou Formation and the Tiaohu Formation intercalated between Carboniferous volcanic rocks and overlying Jurassic clastic rocks (Fig. 1c). A lacustrine, mixed carbonate-clastic sedimentary succession with thin laminated calcareous mudstones and dolomitic mudstones, forms significant oil shale deposits in the Lucaogou Formation. The