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Original Paper

Discovery of shale oil in alkaline lacustrine basins: The Late Paleozoic Fengcheng Formation, Mahu Sag, Junggar Basin, China

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ABSTRACT

A new type of shale oil in alkaline lacustrine sediments has been discovered in the Late Paleozoic Fengcheng Formation, Mahu Sag, Junggar Basin, China. The fine-grained sedimentary rocks deposited in this alkaline lacustrine environment can be divided into four types and eight sub-types: mudstone (with no alkali minerals), including massive dolomitic mudstone, and massive and laminated calcareous mudstone; dolomite, including massive argillaceous dolomite (with alkali minerals), and massive and laminated argillaceous dolomite (with no alkali minerals); evaporites; and pyroclastic rocks. The massive argillaceous dolomite (with alkali minerals) and pyroclastic rocks have the highest shale oil potential, with average oil saturation index (OSI) values of 344.67 and 124.65 mg HC/g TOC, respectively. Shale oil exploration in the representative well MY1 indicates that the Fengcheng Formation is thick and contains abundant natural fractures, brittle minerals, and mobile oil. The entire Fengcheng Formation is oil-bearing and contains three concentrated stratigraphic intervals of shale oil (i.e., sweet spots). Well MY1 indicates that, compared with source rocks developed in marine and sulfate-type saline basins, the fine-grained sedimentary rocks deposited in alkaline lacustrine environments can also have high shale oil potential. The co-existence and regular distribution of conventional and unconventional reservoirs in the Fengcheng Formation indicate that it is an ideal exploration target for multiple resource types.

1. Introduction

Shale oil is an important type of oil resource hosted in shales or fine-grained sedimentary rocks (Jarvie, 2012; Zou et al., 2013; Li et al., 2019). These oils occur mainly in matrix pores, micro-fractures, and thin silty intercalations in a free state, and are adsorbed onto mineral surfaces or enclosed by kerogen (Jarvie, 2012). Shale oil typically requires unconventional techniques to exploit (Zou et al., 2013). To date, most exploration for shale oil has targeted marine strata, such as the Bakken Formation in the Williston Basin and the Eagle Ford Formation in the Western Gulf Basin (Sonnenberg and Pramudito, 2009). In contrast, in China, where crude oil is present mainly in lacustrine basins, exploration for shale oil has focused on saline basins (e.g., the Paleogene Shahejie Formation in the Bohai Bay Basin and the Paleogene Qianjiang Formation in the Jianghan Basin; Li et al., 2015; Liang et al., 2017; Liu et al., 2019) and brackish water basins (e.g. the Cretaceous Qingshankou Formation in the Songliao Basin; Liu et al., 2019). Different from the shale oil reservoirs in marine settings, strata in terrestrial saline basins are characterized by strong heterogeneity (e.g., Lu et al., 2012; Li et al., 2019; Xia et al., 2019; Zou et al., 2019); therefore, the understandings of shale oil geology in marine settings cannot be directly extended to the formation of shale oil and guide exploration in lacustrine basins. To fill the knowledge gap, numerous studies have investigated lacustrine shale oil accumulation in China and the particularities were revealed. For example, in the Shahejie Formation, Bohai Bay Basin, the brittle minerals are mainly quartz and calcite, and Liang et al. (2017) and Li et al. (2020) proposed that large-scale dissolution fractures resulting from the dissolution of calcite laminae were key for shale oil enrichment. The lacustrine shale of the Qingshankou Formation in the Songliao Basin has seven lithofacies in terms of organic matter content, sedimentary structure, and mineralogy, all exhibiting rapid vertical and lateral changes controlled by the depositional setting and basin evolution (Liu et al., 2019).

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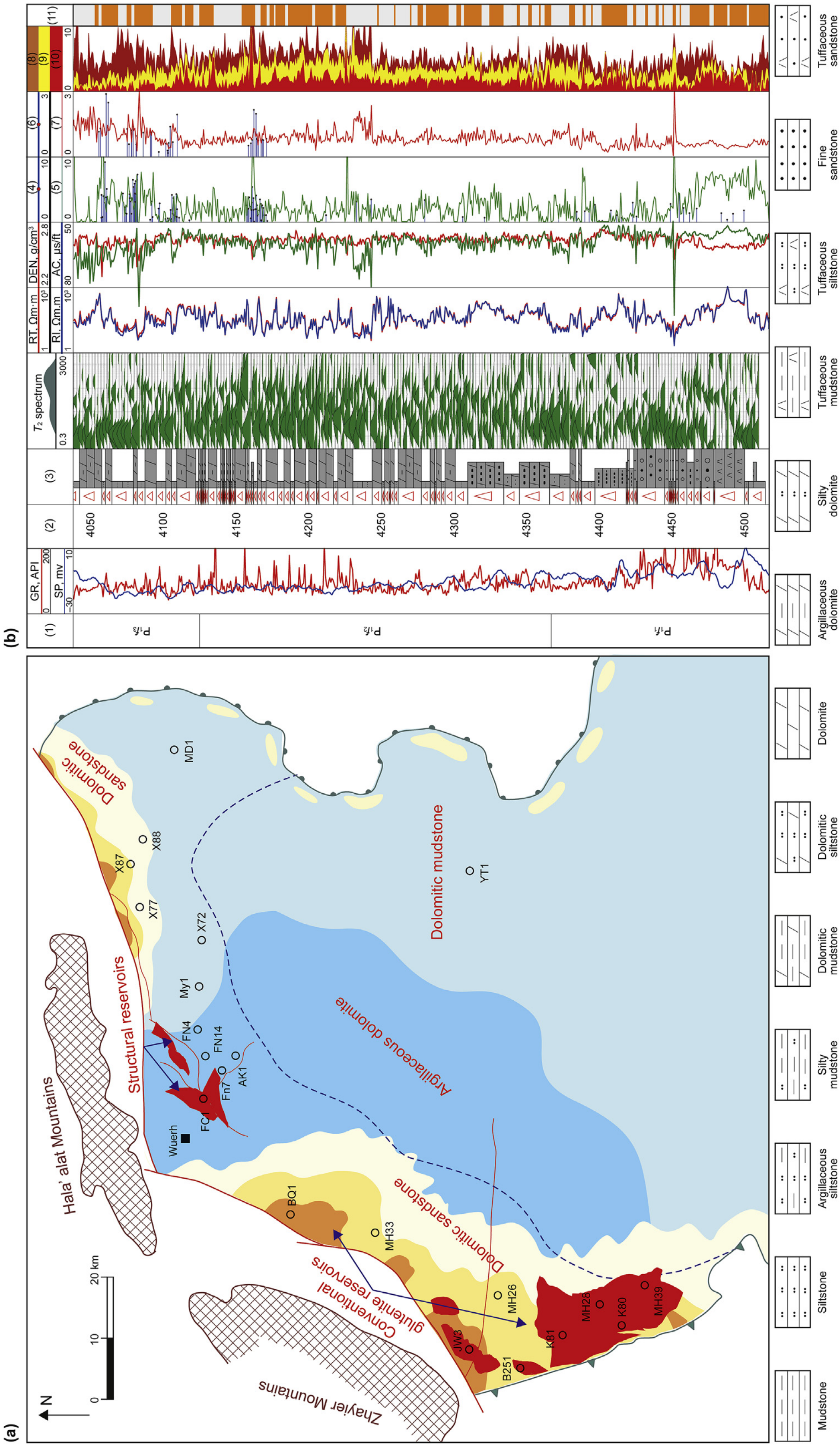

Fig. 1. Shale oil exploration map (a) and stratigraphy of the Fengcheng Formation (b) in the Mahu Sag, Junggar Basin. (1) Formation, (2) depth (m), (3) lithology, (4) measured porosity (%), (5) calculated porosity (%), (6) measured TOC content (wt.%), (7) calculated TOC content (wt.%), (8) total porosity (%), (9) valid porosity (%), (10) free fluid porosity (%), and (11) division of sweet spots.

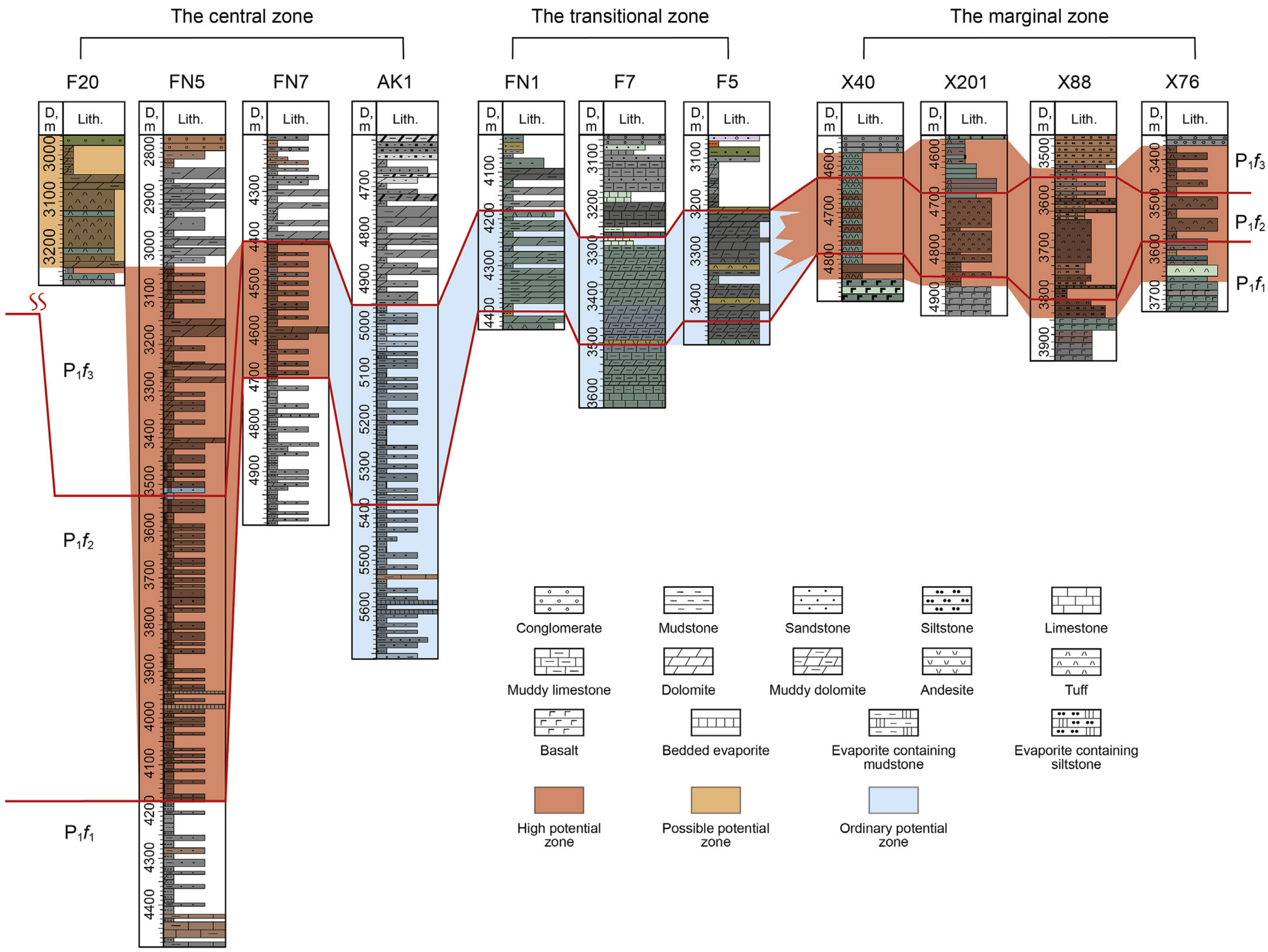

Fig. 2. Lateral zones of the Mahu Sag based on the carbonate mineralogy, showing possible favorable areas for shale oil exploration.

As unconventional oil and gas resources have become increasingly important, exploration in the Junggar Basin of NW China has begun to focus on shale oil (He et al., 2019; Liang et al., 2019; Liao et al., 2019; Xu et al., 2019; Zhi et al., 2019). Five potential units have been selected for shale oil exploration, including the Lucaogou Formation in the Jimusar Sag and piedmont-Bogda Mountain Sag (Guo et al., 2019; Lin et al., 2020), the Fengcheng Formation in the Mahu Sag (Xu et al., 2019; Zhi et al., 2019), and the Pingdiquan Formation in the Wucaiwan–Shishugou Sag and around the Beisantai Uplift (Zhi et al., 2019). The PetroChina Xinjiang Oilfield Company selected the Lucaogou Formation in the Jimusar Sag as the first target for shale oil exploration. After more than 10 years of exploration, a petroleum reserve of 1.11 billion tons has been proven, which can be exploited commercially and industrially. Thus, the Jimusar Sag in the Junggar Basin has become the first national site of shale oil exploration in lacustrine petroleum basins in China.

Recently, a one billion ton-scale oil field was discovered along the northwestern margin of the Junggar Basin (Kuang et al., 2012; Zhi et al., 2019). The hydrocarbons are sourced mainly from the Permian Fengcheng Formation, which contains the oldest alkaline lacustrine source rocks in this region (Cao et al. 2015, 2020). Hydrocarbon generation in the Fengcheng Formation was multi-stage, protracted, and oil-dominated, which distinguishes this formation from other lacustrine source rocks (Cao et al., 2015; Xia et al., 2020). The Fengcheng Formation is likely rich in shale oil, and represents a new type of shale oil system accumulated in an alkaline lacustrine basin. The PetroChina Xinjiang Oilfield Company conducted exploration for shale oil in the Fengcheng Formation. Geological investigations of the Fengcheng Formation have delineated the distribution of fine-grained sedimentary rocks, and a favorable zone for shale oil exploration with an area of >2300 km^2 was identified in the central Mahu Sag. In order to advance shale oil exploration in the Mahu Sag, well MY1 was drilled in a relatively shallow position of the slope area in the Mahu Sag in 2008. The industrial oil flow obtained by well MY1 is significant for shale oil exploration in the Mahu Sag.

In order to improve our understanding of shale oil systems in alkaline lacustrine settings, we report the formation and geological characteristics of such a shale oil system, mainly based on samples and data from well MY1.

2. Geological setting, samples and methods

The Mahu Sag is located in the western part of the central depression of the Junggar Basin, and is a foreland sag that formed during the middle–late Carboniferous to early Permian when the Junggar Block collided with the Kazakhstan Plate (Lei et al., 2017).

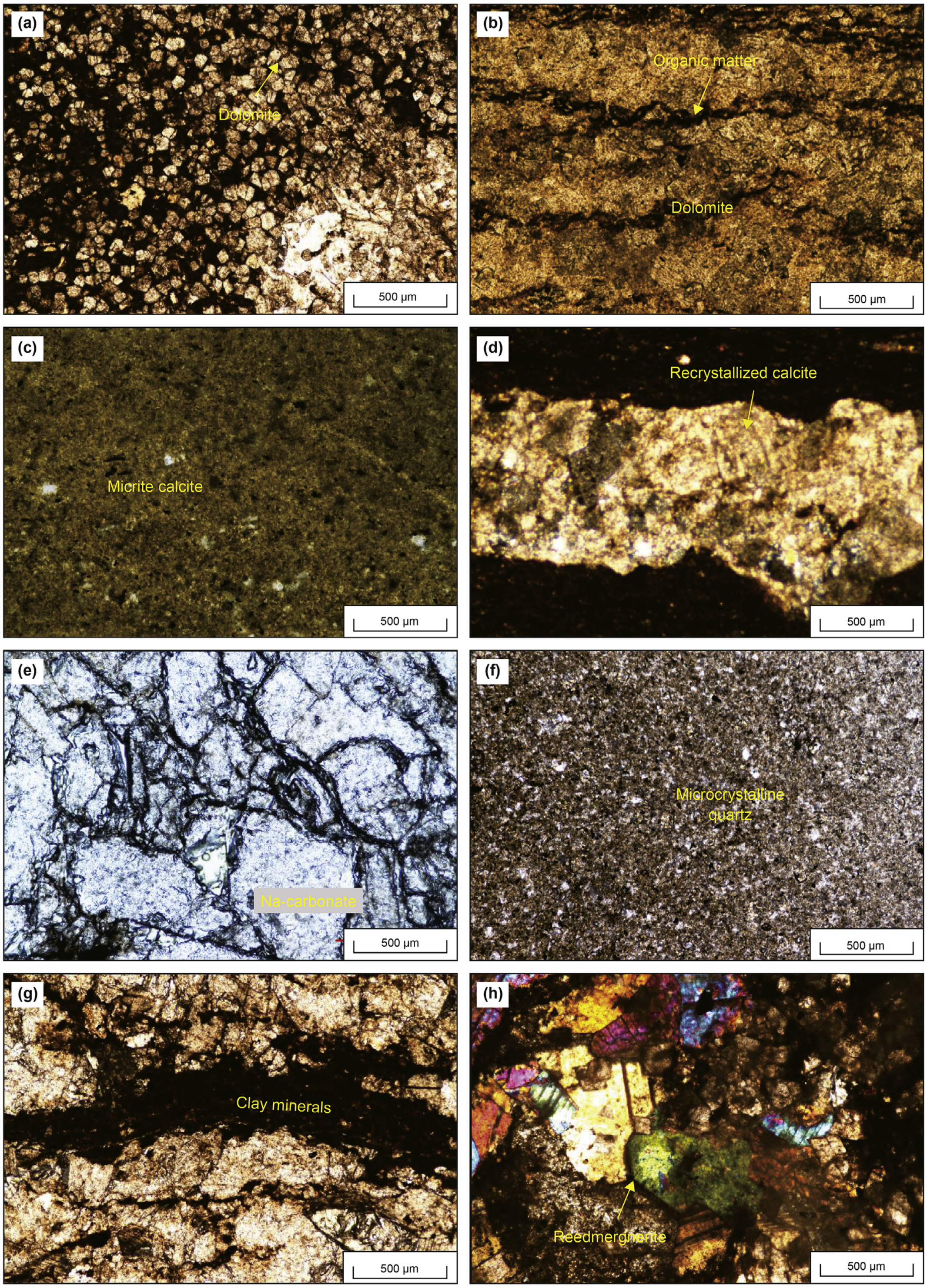

Fig. 3. Photomicrographs showing the petrography of samples from the Mahu Sag. (a) FN1 4254.00 m; (b) F5 3471.00 m; (c) F7 3177.24 m; (d) FN1 4342.00 m; (e) F20 3248.00 m; (f) F20 3269.10 m; (g) AK1 5665.00 m; and (h) FN1 4368.00 m.

The sag contains three sets of source rocks, which are the lower Permian Jiamuhe Formation, lower Permian Fengcheng Formation, and middle Permian Lower Wuerhe Formation. These are also important oil-bearing reservoirs. Combined with other oil reservoirs, including Carboniferous, Permian, Triassic, and Jurassic strata, these units form a complex petroleum system (Jin et al., 2007). Due to their burial depth (generally >4500 m), exploration of the Carboniferous and Permian strata is limited, and the Fengcheng Formation is regarded as being the main source rock. It is presently unclear whether the Fengcheng Formation has the capacity to store hydrocarbons and contain substantial oil accumulations.

The main part of the Fengcheng Formation comprises mixed types of sedimentary rocks that were deposited in an alkaline lacustrine environment (Zhang et al., 2018). The uplift and erosion of a thrust fault nappe along the northwestern margin of the sag

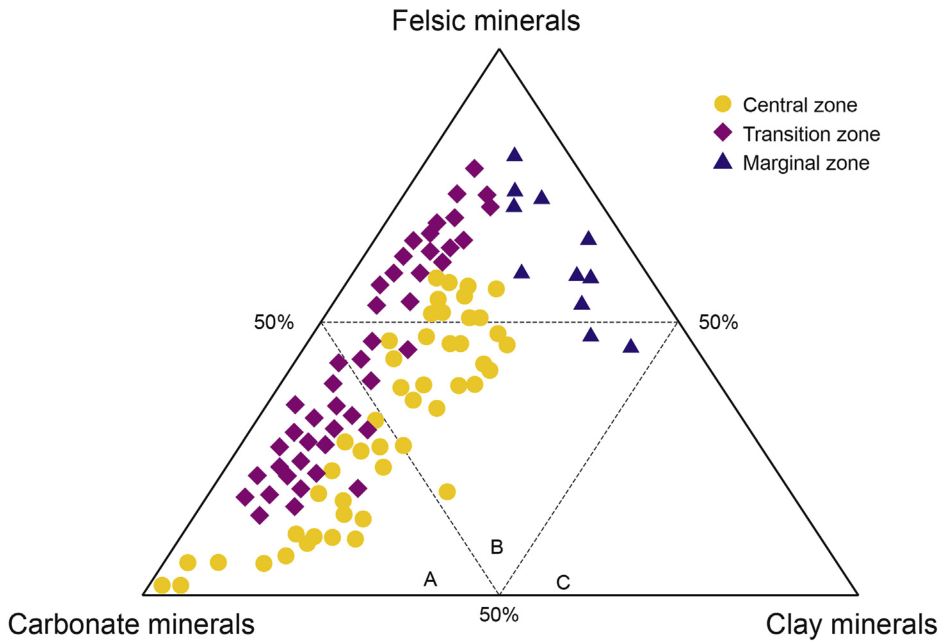

Fig. 4. Ternary diagram of the mineralogy of the Fengcheng Formation, Mahu Sag. A = dolomite/limestone/evaporite; B = siltstone and mixed rocks; C = mudstone.

provided abundant coarse sediment. The rapid deposition of this sediment resulted in the limited formation of fan delta deposits in the Fengcheng Formation (Zhu et al., 2015). A combination of terrigenous sedimentation, volcanism, and hydrothermal activity affected the Fengcheng Formation. Early exploration focused mainly on conventional glutenite reservoirs and nose-shaped uplift structures in the fault zone in the Mabei area, which identified significant oil reserves (Fig. 1a). Wells drilled into the Fengcheng Formation have encountered a thick sequence of fine-grained sedimentary rocks (Fig. 1b). The Fengcheng Formation contains abundant oil and gas, and logging results indicate that there are multiple thin oil layers distributed vertically in the formation. However, exploitation of the oil resources is challenging because of the low porosity and permeability. After the discovery of shale oil in the Lucaogou Formation, Jimusar Sag, two prospective areas for shale oil in the Fengcheng Formation were identified. Based on the lithofacies, the favorable areas are the inshore shallow lake and deep to semi-deep lake facies sediments. In the Mabei area, the area of the favorable zone (<5500 m depth) for shale oil exploration is 400 km^2, and the shale oil resources are nearly 500 million tons. In the Mahu Sag, the area of the favorable zone is nearly 2350 km^2, and thus should have higher shale oil potential. The well MY1 encountered inshore shallow lake facies sediments, thereby extending the area of shale oil exploration in the Mahu Sag.

To reveal basic geological and geochemical elements of the shale oil in the Fengcheng Formation, we analyzed 90 samples from the central, transitional and marginal zones of the alkaline lake. Detailed mineral compositions and organic geochemistry data were obtained through multiple methods, mainly including X-ray diffraction, and TOC and pyrolysis analyses. To further better understand this new type of shale oil system, detailed logging and seismic data of MY1 well were collected.

3. Results

3.1. Sedimentary features of the Fengcheng Formation

The Fengcheng Formation contains both source rocks and shale oil reservoirs. It was deposited in an alternating humid and arid setting, and contains three types of materials: terrigenous sediments, evaporites, and pyroclastic rocks. The fine-grained sedimentary rocks in the Fengcheng Formation range in thickness from 800 to 1800 m, and are the thickest in the east and the thinnest in the west. The Fengcheng Formation can be divided into three members (from base to top):

(1) P_1f_1 that comprises tuffs, pyroclastic rocks, and mudstones, which were deposited in association with volcanism.
(2) P_1f_2 that was deposited in high salinity and pH conditions in the central zone of the sag, which contains various alkali minerals (i.e., evaporitic carbonate minerals), and is dominated by dolomitic rocks. In the marginal zone of the sag, the main lithofacies in P_1f_2 is semi-deep lake facies mudstone to argillaceous dolomite.
(3) P_1f_3 that was deposited in progressively lower salinity and pH conditions. The upper part of P_1f_3 is mainly coarse clastic sediments (fan delta facies), whereas the lower part is mainly dark mudstones (shallow lake facies) (Qin et al., 2016; Xia et al., 2020).

Horizontally, the Mahu Sag can be divided into three zones according to the carbonate minerals present: the central, transition, and marginal zones (Fig. 2). The central zone has the highest salinity and pH, and the carbonate minerals are mainly alkali minerals and dolomite. Representative wells in the central zone are FN5, FN7, and F20. The transition zone has moderate salinity and pH that formed mainly dolomite and calcite, and contains no alkali minerals. This zone is delineated by the FN1, F5, F7, and MY1 wells. The marginal zone is in the northeastern part of the sag where volcanism was frequent. This zone has the lowest salinity and pH, and also has the lowest content of carbonate minerals. Wells X40, X201, X76, and X88 have been drilled in the marginal zone. Vertically, the Fengcheng Formation can be divided into four stages reflecting the evolution of an alkaline lake: the early onset (freshwater or low-salinity water), preliminary, strong, and terminal alkalinity stages. The complete evolution of the lake can be observed only in the central zone.

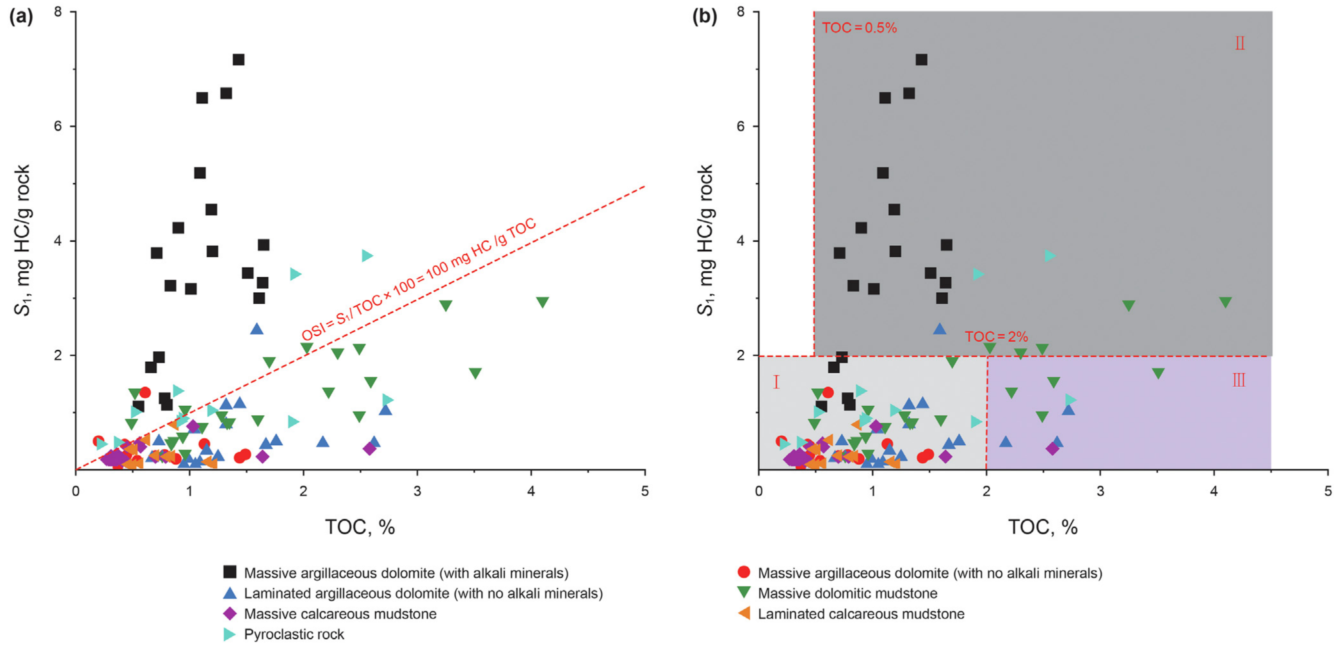

Fig. 5. (a) OSI (oil saturation index) values used to evaluate the shale oil potential of the different lithofacies. (b) Oil and TOC contents used to classify the shale oil into ineffective (I), enriched (II), and potential resources (III).

3.2. Petrography of the Fengcheng Formation

X-ray diffraction results and thin-section observations show that the compositions of the fine-grained sedimentary rocks in the Fengcheng Formation are complex (Fig. 3). In the central zone, the average content of carbonate minerals is 44.69 vol%, and dolomite and calcite are 26.03 vol%. Na-evaporites, such as wegscheiderite and shortite, are present with an average content of 18.66 vol%. The average contents of clay and other minerals, such as pyrite and reedmergnerite, are 15.11 and 7.74 vol%, respectively. In the transition zone, the content of felsic minerals is the highest (41.09 vol%), followed by carbonate minerals (average = 40.70 vol%). The average contents of clay and other minerals are 8.52 and 9.04 vol%, respectively. In the transition zone, Na-evaporites are rare, and dolomite occurs mainly in the first and second members of the Fengcheng Formation. In the marginal zone, the average contents of felsic, carbonate, and clay minerals are 58.99, 8.76, and 26.71 vol%, respectively.

The fine-grained sedimentary rocks in the Mahu Sag can be classified according to their lithofacies (Jiang et al., 2014; Lazar et al., 2015). Felsic, carbonate, and clay minerals are the three end-member mineral types used to classify the rocks. When the carbonate mineral content is > 50 vol%, the rocks can be classified as dolomite, limestone, or evaporite according to the dominant carbonate mineral; when the felsic mineral content is > 50 vol%, the rocks can be classified as siltstone; when the clay mineral content is > 50 vol%, the rocks are classified as clay-rich mudstone; when the contents of the three main mineral types are all <50 vol%, the rocks are classified as mixed rocks (Fig. 4).

Clay-rich mudstone is rare in the Fengcheng Formation. The grain sizes in the siltstone and mixed rocks are usually <62.5 μm, and can thus be termed mudstone. According to the type of secondary minerals, the mudstone and carbonate rocks can be further subdivided. Rocks that contain pyroclastic materials can be classified as pyroclastic rocks. Thus, the fine-grained sedimentary rocks in the Fengcheng Formation can be classified as: argillaceous dolomite (with alkali minerals); argillaceous dolomite (with no alkali minerals); dolomitic mudstone (with no alkali minerals); evaporate; calcareous mudstone; and pyroclastic rocks.

Rock structure is another key characteristic that can be used to distinguish lithofacies. There are two different types of laminae developed in rocks in the study area: alternating dolomite and organic matter laminae; alternating calcite and argillaceous laminae (felsic minerals and organic matter). The argillaceous dolomite and calcareous mudstone can be massive or laminated. There are no laminae in the other lithofacies.

In general, the fine-grained sedimentary rocks in the Fengcheng Formation can be classified into four types and eight sub-types: carbonate rocks including massive argillaceous dolomite (with or without alkali minerals) and laminated argillaceous dolomite (with no alkali minerals); mudstone including massive dolomitic, massive calcareous, and laminated calcareous mudstones (all with no alkali minerals); evaporites; pyroclastic rocks.

The distribution of the different lithofacies is indicative of the evolution of the sedimentary environment (Fig. 2). From the central zone to the marginal zone, the pH and salinity decreased gradually, and volcanic activities are frequent in the marginal zone, such that the lithofacies are definitely different. In the central zone, P_1f_1 is mainly massive calcareous mudstone, P_1f_2 is mainly massive argillaceous dolomite (with alkali minerals) and evaporite, and P_1f_3 is massive dolomitic mudstone. In the transition zone, P_1f_1 is mainly massive and laminated argillaceous dolomite (with no alkali minerals), P_1f_2 is mainly massive argillaceous dolomite (with no alkali minerals), laminated argillaceous dolomite (with no alkali minerals), and laminated calcareous mudstone, and in P_1f_3 massive calcareous mudstone is dominant. In the marginal zone, many of the rocks are tuffs, pyroclastic rocks, and volcanic breccias.

3.3. Shale oil potential in the different lithofacies

The pyrolysis parameter S_1, which represents hydrocarbons released at < 300 °C, is usually used to reflect the oil content in rocks. However, it is not a direct shale oil proxy, given that kerogen can adsorb some hydrocarbons and reduce the amount of shale oil

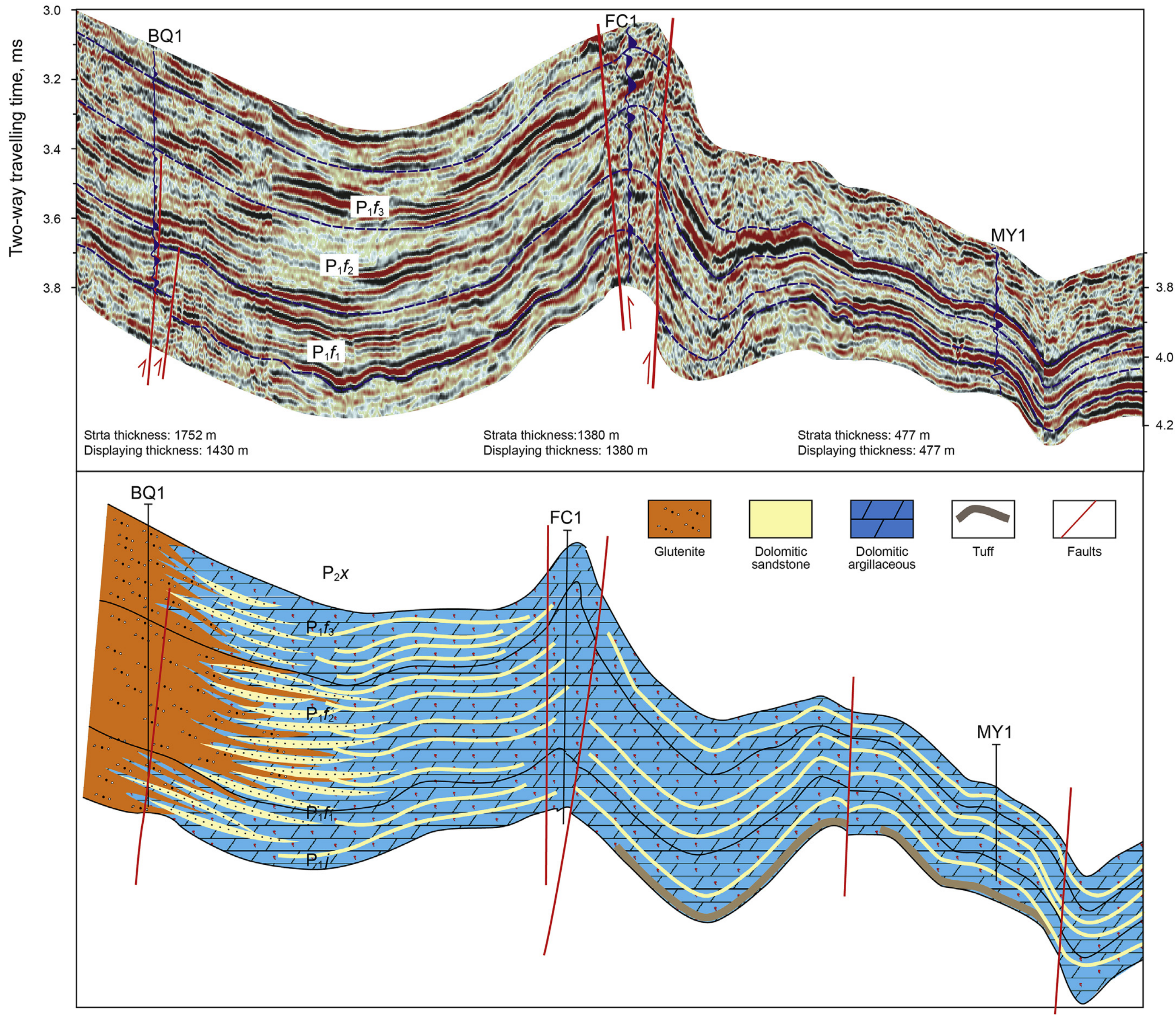

Fig. 6. Geological interpretation of the seismic profile of the Fengcheng Formation in the Mahu Sag from well BQ1 to X72.

(Jarvie, 2012; Shao et al., 2020). Thus, a geochemical proxy of the potentially producible shale oil is the oil crossover effect, which is the Rock–Eval-determined S_1 value relative to the total organic carbon (TOC) content, when the oil saturation index ($OSI = S_1 \times 100/TOC$) reaches a value of 100 mg HC/g TOC. This has been applied to classic examples of oil shales, such as the Bakken and Monterey shales (Jarvie, 2012; Borcovsky et al., 2017).

Fig. 5a shows the shale oil potential of different lithofacies in the Fengcheng Formation. The massive argillaceous dolomite (with alkali minerals) has the highest OSI values (average = 344.67 mg HC/g TOC), and the pyroclastic rocks have the second highest (average = 124.65 mg HC/g TOC). The massive dolomitic mudstone, with an average OSI value of 80.63 mg HC/g TOC, is ordinary in terms of its shale oil potential. In contrast, the remaining lithofacies have low OSI values with average values of 56.37 mg HC/g TOC for the massive argillaceous dolomite (with no alkali minerals), 41.39 mg HC/g TOC for the laminated argillaceous dolomite (with no alkali minerals), 45.15 mg HC/g TOC for the massive calcareous mudstone, and 39.57 mg HC/g TOC for the laminated argillaceous mudstone.

Lu et al. (2012) proposed a new grading evaluation scheme for shale oil potential, in which the shale oil resources can be divided into three levels: ineffective, enriched, and potential resources. In the Mahu Sag (Fig. 5b), samples that plot in zone I (TOC <2 wt%; $S_1 < 2$ mg/g rock) are mainly ineffective resources, as the rocks fail to generate sufficient hydrocarbons to meet the adsorption needs of the rocks. When the samples plot in zone II (TOC >0.5 wt%; $S_1 > 2$ mg/g rock), the rocks are regarded as enriched resources, as the reservoirs are oil-saturated. If the samples plot in zone III (TOC >2 wt%; $S_1 < 2$ mg/g rock), they are potential resources, indicating that the organic matter is immature (Sandvik et al., 1992; Lu et al., 2012). It should be noted that the choice of grading parameters needs to be considered in detail when used to evaluate shale oil potential (Lu et al., 2012; Li et al., 2015).

In general, the massive argillaceous dolomite (with alkali minerals) and pyroclastic rocks have the highest shale oil potential. The

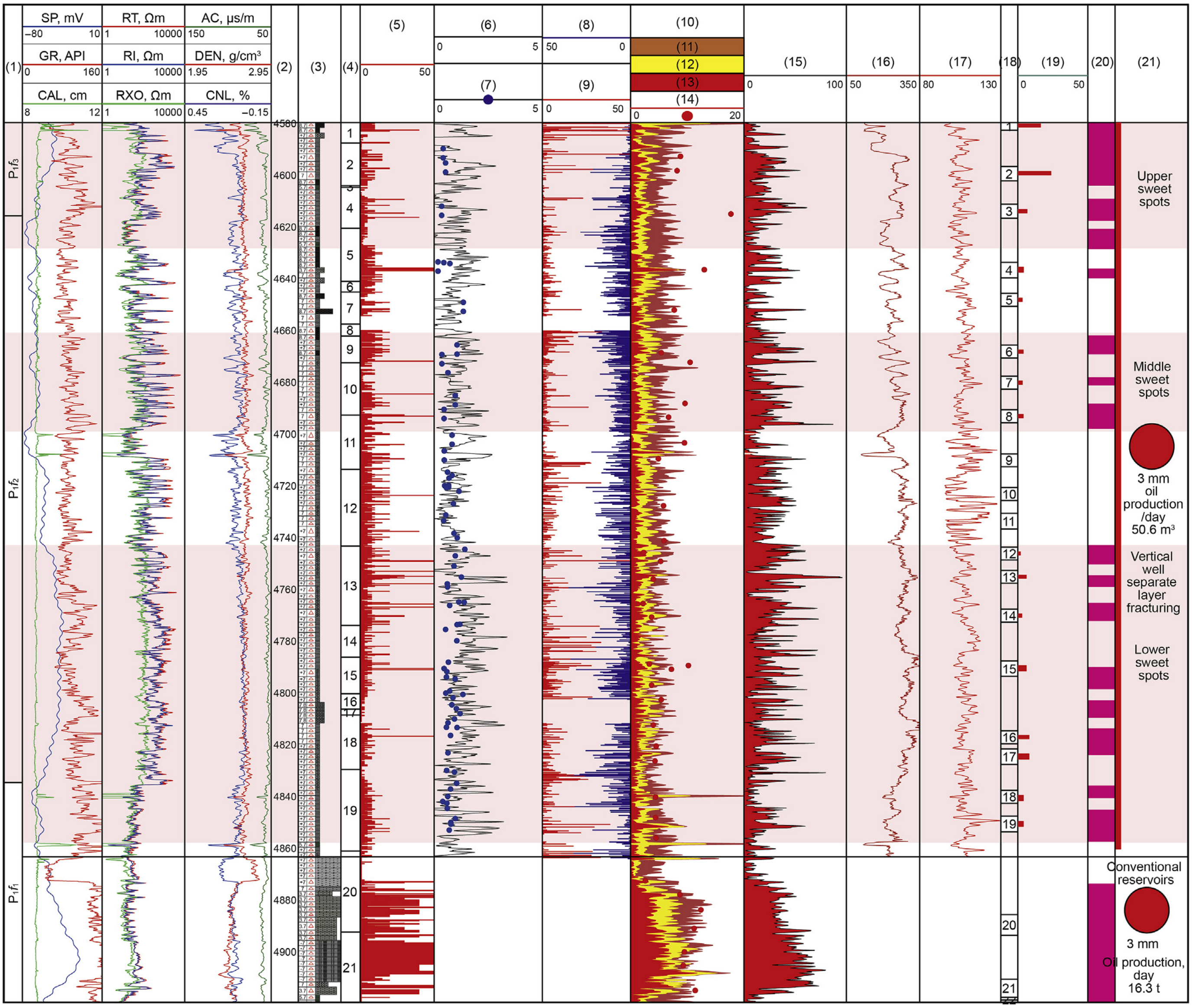

Fig. 7. Logging data for well MY1. Denotation of the numbers in the heading: (1) Formation, (2) depth (m), (3) lithology, (4) coring intervals, (5) oil-bearing area (%), (6) calculated TOC content (wt.%), (7) measured TOC content (wt.%), (8) $CaCO_3 \cdot MgCO_3$ content (wt.%), (9) $CaCO_3$ content (wt.%), (10) interpreted porosity (%), (11) total porosity (%), (12) valid porosity (%), (13) free fluid porosity (%), (14) measured porosity (%), (15) interpreted oil saturation (%), (16) brittleness index, (17) fracturing pressure (MPa), (18) peroration number, (19) production profile (%), (20) interpreted oil intervals, and (21) oil testing.

massive dolomitic mudstone is expected to have shale oil potential in the future, whereas all the other lithofacies have relatively low shale oil potential.

4. Discussion

4.1. Implications for shale oil exploration in an alkaline lacustrine basin

The slope and central zones with stable structures are the center of hydrocarbon generation in the Mahu Sag, in which a significant amount of shale oil exists. Thus, in 2019, the MY1 well was drilled in the shallow–plain area in the north of the sag (Fig. 6). This well had abundant oil and gas shows in the Karamay (T), Baikouquan (T), Lower Wuerhe (P), Xiazijie (P), and Fengcheng formations (P). There were two oil testing layers, which are in the tuffs and clastic sediments of P_1f_1 and unconventional shale oil strata in P_1f_2–P_1f_3, both of which yielded industrial oil flows (Fig. 7).

Well MY1 has significant implications for exploration of shale oil in the Fengcheng Formation in the Mahu Sag:

(1) The cored intervals in well MY1 are mainly thick layers of dolomitic mudstone interbedded with thin layers of dolomitic or argillaceous siltstone, and these rocks are tight and fine-grained. More detailed (i.e., cm-scale) description of the cores identified 1727 layers with different lithologies, indicating high-frequency interbedding. Geochemical data showed that the hydrocarbons in well MY1 are autogenous or only experienced very short distance migration, which is typical of shale oil (Fig. 7).
(2) The entire Fengcheng Formation contains oil, but there are no concentrated sweet spots. Compared with shale oil in the Lucaogou Formation, the shale oil in the Fengcheng Formation is more dispersed, but can still be divided into sweet-

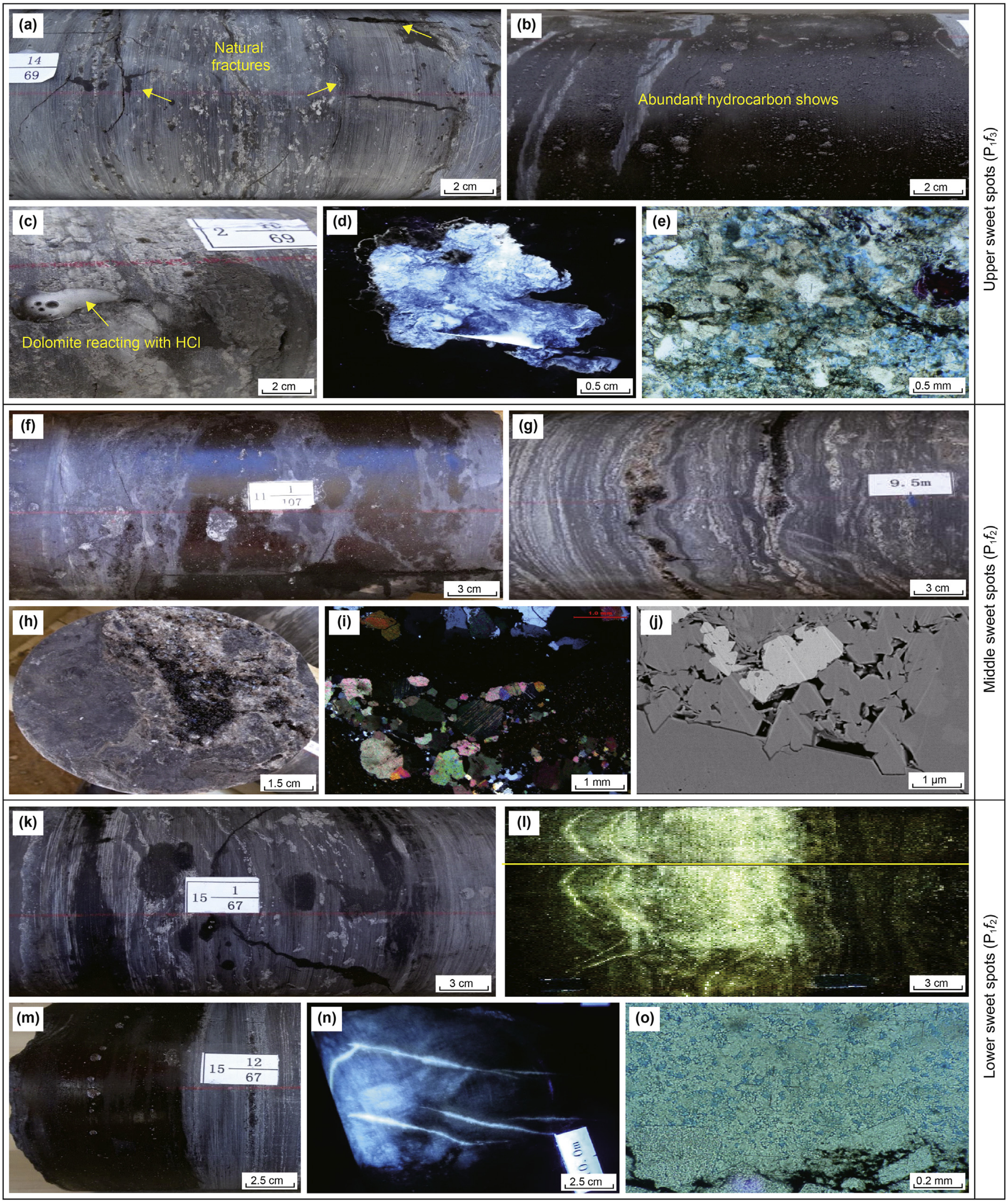

Fig. 8. Characteristics of different shale oil reservoirs in well MY 1. (a) dolomitic siltstone interbedded with silty mudstone, fractures develop well and show abundant hydrocarbons, 4591.0 m; (b) dolomitic siltstone, rock matrix contains oil, 4595.6 m; (c) calcareous dolomite, carbonate minerals react with HCl and form gas bubbles, 4589.8 m; (d) dissolution pore in calcareous dolomite showing blue fluorescence, 4589.8 m; (e) dolomitic siltstone, primary interparticle pores and dissolution pores in casting thin section, 4591.9 m; (f) silty dolomite, micro-fractures and rock matrix contain hydrocarbons and alkali minerals can be observed, 4693.2 m; (g) dolomite interbedded with alkali mineral layer, dissolution pores contain hydrocarbons, 4702.6 m; (h) hydrocarbons in dissolution pores, 4705.3 m; (i) silty dolomite, laminated reedmergnerite and shortite present in drainage fracture, 4705.8 m; (j) dolomite, nano-scale interparticle pores under SEM, 4705.8 m; (k) argillaceous dolomite interbedded with dolomitic siltstone, fractures contain

spot intervals, e.g., the three intervals in MY1 well (Fig. 8). The Fengcheng Formation consists mainly of dolomitic mudstone, dolomite, and dolomitic siltstone, with the former being dominant. The pore types are variable in the Fengcheng Formation. Macroscopic fractures (about 1 cm wide) and matrix pores, which include nano-to micro-scale pores, can be observed in thin-sections and core samples (Fig. 8). In well MY1, there are three sets of rocks with different lithologies (from base to top): (a) dolomitic siltstone interbedded with dolomitic mudstone that was deposited in a freshwater to slightly saline environment; (b) dolomitic mudstone with alkali minerals that was deposited in an alkaline environment; and (c) dolomitic siltstone and mudstone with some calcite that was deposited in a slightly saline environment. These three different combinations of rocks determined the characteristics of the shale oil reservoirs. Based on testing results of the fluid-producing profiles, the shale oil in well MY1 is from fractures and matrix pores. During the initial stage of well opening, fractures were the main fluid pathway, and only intervals with fractures yielded liquids. As the trial production time became longer, each perforated interval contributed to oil production, and the oil content became gradually stable. An analysis of the lithologies and other various parameters, such as the rock brittleness, hydrocarbon generation potential, and reservoir porosity, identified favorable intervals for shale oil (i.e., the base of P_1f_3, middle of P_1f_2, and base of P_1f_2 to the top of P_1f_1; Figs. 7 and 8). The porosity inferred from logging data for well MY1 and the measured porosity range from 5% to 10%, with an average of 4.8%. The porosities of most logging intervals are <5%, and only several thin layers (i.e., a few meters thick) have relatively high porosities (i.e., >10%). The upper and lower favorable intervals for shale oil consist mainly of dolomitic siltstone, and have a large amount of matrix pores. The middle favorable interval consists of dolomite with alkali minerals, which has a good capacity for hydrocarbon storage, but is poor for hydrocarbon generation.

(3) The Fengcheng Formation contains abundant natural fractures and brittle minerals, which are favorable for the formation of a complex fracture network system. Microfractures have a density of 2–15 per meter in cores from well MY1, and the oil-bearing ability of the fractures is good. Sonic testing identified 24 groups of E–W-trending fractures, which are mainly semi-filled or have high impedance. The height of these fractures does not exceed 150 cm, and these contribute to the complex fracture network system. In addition, the petrophysical parameters for well MY1 revealed brittleness, which means the Fengcheng Formation should be easy to transform during shale oil extraction.

(4) Crude oil in the Fengcheng Formation is good quality and has high mobility, which favors the production of shale oil. Cores stored in air lost light hydrocarbons, and the oil and gas shows decreased. In general, the Fengcheng Formation in wells FN14 and FN4 is gas-bearing. The density and freezing point of shale oil in the Fengcheng Formation are 0.8904 g/cm^3 and −14 °C, respectively, and these values are lower than those for shale oil in the Lucaogou Formation. This is because the shale oil in the Fengcheng Formation is high-mature, whereas that in the Lucaogou Formation is low-mature to mature. The viscosity of crude oil in the Fengcheng Formation is 35 mPa s (50 °C) and 14 mPa s (80 °C), while the viscosity of crude oil in the Lucaogou Formation is > 150 mPa s (50 °C) and 45 mPa s (80 °C). This indicates better mobility of shale oil in the Fengcheng Formation (Fig. 9).

(5) Techniques suitable for drilling wells and oil production in the Fengcheng Formation have been explored. The complex lithology and abundance of natural fractures in the Fengcheng Formation presents some complications during drilling, such as a slow penetration rate, difficulty in controlling the well deviation, and high risk in well control. The drilling of the MY1 well allowed new drilling techniques to be optimized. The depth of the shale oil reservoirs in the Fengcheng Formation is > 4500 m, and the reservoirs are dispersed and have a strong compression resistance. During the process of reservoir transformation, the adoption of a new drilling method involving fine partial pressure casing of vertical wells increased the oil production efficiently. In addition, the use of a new type of fracturing fluid avoided reactions between the dolomitic rocks and fracturing fluid.

4.2. Prospects for shale oil exploration in an alkaline lacustrine basin

The Fengcheng Formation in the Mahu Sag was deposited in an alkaline saline lacustrine environment, which differs from marine, freshwater, and sulfate saline basins worldwide and in China (Table 1). The MY1 well identified shale oil in the Fengcheng Formation. This shale oil will be able to gradually replace conventional oil resources in the Junggar Basin. In addition, the successful application of new methods, including drilling and completion technology and separate-layer fracturing in a vertical well, provides a basis for the exploration and exploitation of shale oil in the Fengcheng Formation. The spatial distribution of the different types of reservoirs, including the glutenite oil reservoirs in fault zones, tight dolomitic sandstone oil reservoirs in the Mahu 28 well, and tuff oil reservoirs of P_1f_1 in the X72 well, highlight the co-existence of conventional and unconventional reservoirs. This requires a new strategy for comprehensive exploration and exploitation of multiple resource types in this oil–gas system.

The shale oil intervals in well MY1 are deeper than 4500 m, and are in the mature stage (0.9% <R_o<1.2%). The density and viscosity of the shale oil are 0.8914 g/cm^3 and 21.65 mPa s, respectively. The well MY1 is located in a structurally high position and, in lower areas, the physical properties of the crude oil (e.g., viscosity and density) should be more conducive to oil flow. Therefore, the MY1 well is expected to push shale oil exploration to depths of >4500 m.

In summary, compared with the shale oil in the Lucaogou Formation in the Jimusar Sag, the shale oil in the Fengcheng Formation in the Mahu Sag has both advantages and disadvantages for exploration and exploitation. The disadvantages include the deep burial depth, difficulties in identification and delineation of the sweet spots, and technical challenges in drilling. However, the source rocks are of higher maturation, and thus generate lighter crude oil, which promotes the mobility of hydrocarbons in reservoirs. The scattered distribution of sweet spots can be overcome by the application of an innovative method of separate-layer fracturing and production from a vertical well, as shown by the MY1 well. Current logging data also show that the formation pressure index of shale oil intervals in the Fengcheng Formation ranges from 1.2 to 1.4, and the predicted value will exceed 1.7 as the burial depth increases. A higher formation pressure is beneficial for shale oil exploration.

hydrocarbons, 4786.6 m; (l) dolomitic siltstone, rock matrix contains hydrocarbons, 4771.3 m; (m) dolomitic siltstone interbedded with dolomitic mudstone, the siltstone intervals contain hydrocarbons, 4788.9 m; (n) fractures contain hydrocarbons showing blue fluorescence, 4781.6 m; (o) silty dolomite, residue interparticle, 4790.8 m.

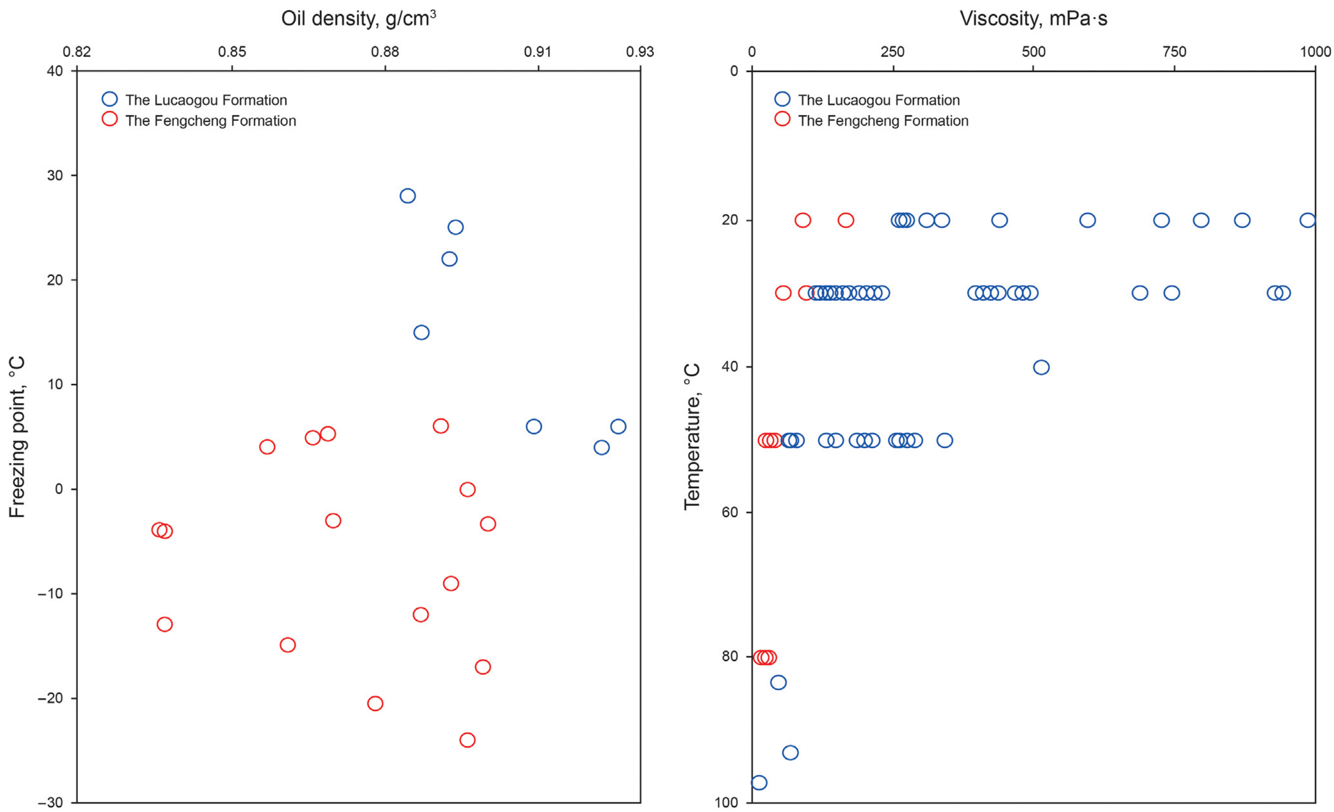

Fig. 9. Comparison of the oil physical properties (a) and viscosity–temperature (b) relationship between the Fengcheng and Lucaogou formations in the Mahu and Jimusar sags, respectively.

Table 1
Comparison of shale oil characteristics between the Fengcheng and Lucaogou formations in the Mahu and Jimusar sags, respectively.

Formation		The Lucaogou Formation, Jimusar Sag	The Fengcheng Formation, Mahu Sag
Structural settings	Type of basins	Depression basin	Foreland basin
	Sedimentary environment	Terrestrial saline lake basin	Terrestrial saline lake basin (alkaline)
	Structural strength	Stable	Intense in the marginal, stable in the central
	Thickness of strata (m)	20–330	50–1800
Source rocks	Residual organic matter content (%)	1.08–26.66/4.02 (71)	0.84–4.01/2.41 (91)
	Type of kerogen	Type I–II, few type III	Type I–II
	R_o (%)	0.48–1.12/(low mature to mature)	0.85–1.4/(mature to high mature)
	Thickness of valid source rock (m)	20–260	50–300
	Area (km^2)	1500	4258
Sweet spots	Lithology	Fine-grained dolomitic sandstone, dolomite	Fine-grained dolomitic sandstone, dolomite
	Type of reservoir	Residual interparticle pores, micropores, dissolution pores	Primary pores, intercrystallite pores, micro-fractures, secondary dissolution pores
	Valid porosity (%)	5.52–19.84/9.59	3–13/4.4
	Depth (m)	2500–4500	4500–5500
	Thickness (m)	40–90	50–280 (MY1 well 269m)
	Pressure index (g)	1.1–1.3	>1.5
	Natural fractures	Underdeveloped (2–4 strips per meter)	developed (2–15 strips per meter)
Rock mechanics	Young's modulus (GPa)	15–28	35–60
	Brittleness index	40–43	45–55
	Uniaxial compressive strength (MPa)	137–182	113–344
	Stress difference (MPa)	6–12	7–8
Fluids	Oil density (surface) (g/cm^3)	0.87–0.93	0.833–0.887
	Viscosity (50 °C) (mPa.s)	49.91–510.35/222.26	23.27–178.33/122.97
	Freezing point (°C)	4–28/13.57	−22–7/−8.8
	Gas-oil ratio (m^3/m^3)	17	82–110

The latest resource evaluation predicted that the shale oil resource potential of the Fengcheng Formation is only 420 million tons. The evaluation area was only 382 km^2, and was limited to depths of <4500 m in the Wuxia fault zone. This evaluation is based on the selection of key parameters according to the Lucaogou Formation in the Jimusar Sag, which results in an erroneously conservative evaluation for the Fengcheng Formation. For example, the thickness of shale oil intervals, mean porosity, and oil saturation are 45 m, 5.25%, and 45%, respectively, in the Lucaogou Formation in the Jimusar Sag. In contrast, in the MY1 well, the average thickness of the favorable shale oil zones is 293 m and the interpreted oil saturation ranges from 40.9% to 74.6%, with an average of 56.4%. Thus, it is evident that the shale oil resources in the Fengcheng Formation are underestimated. In addition, the presently known shale oil intervals in the Fengcheng Formation revealed by drilling are mostly located in the slope area of the foreland depression, where the strata are usually thinner than 500 m. These wells do not reflect the central area of the foreland depression, where the strata are usually >1500 m thick (Fig. 7). Moreover, the area that contains shale oil and is < 4500 m in depth is approximately 1350 km^2, which is nearly equivalent to the area of the Jimusar Sag. The area of the shale oil intervals that are shallower than 5500 m is nearly 2350 km^2, while that for the Jimusar Sag is only 1278 km^2. Thus, the Fengcheng Formation has higher shale oil potential than the Lucaogou Formation.

Horizontal well techniques used to improve oil production are suitable for the Lucaogou Formation in the Jimusar Sag, where upper and lower sweet spots can be distinguished. The shale oil in the Lucaogou Formation has low maturity and mobility, and the formation pressure index is < 1.3, thus this formation needs large-scale fracturing to exploit. In contrast, the entire Fengcheng Formation contains shale oil. These factors, including the local enrichment of shale oil in the Fengcheng Formation, good crude oil mobility, and formation pressure index of up to 1.7, enabled the vertical MY1 well to achieve initial production success. It also became evident that only three-stage fracturing can form complex fracture networks and achieve an ideal effect on reservoir transformation. Other stages fracturing among the total nine stages fracturing were prone to forming single or parallel cracks, and thus failed to transform the shale oil intervals. PetroChina Branch Company has recently begun horizontal well exploration in the upper sweet spots of the Fengcheng Formation, as well as vertical well exploration in the semi-deep to deep lake facies. The combination of exploration by horizontal and vertical wells is an efficient development model for shale oil exploitation in the Fengcheng Formation, and elsewhere in the Mahu Sag.

5. Conclusions

The Fengcheng Formation contains one of the best source rocks in the Mahu Sag, Junggar Basin, and provides a considerable number of hydrocarbons to the Kebai–Wuxia area along the northwestern margin and slope area of the western Mahu Sag. However, little oil and gas exploration has been conducted in the fine-grained sedimentary rocks. The success of the MY1 well demonstrated the shale oil potential of the Fengcheng Formation, and also explored reservoir transformation techniques that differed from those applied to the Lucaogou Formation. The MY1 well reflects a shift in oil and gas exploration from fault to slope zones, shallow to deep depths, and conventional to unconventional resources, which is relevant to regional hydrocarbon exploration.

The shale oil exploration in the Fengcheng Formation of the Mahu Sag has identified a new field with great potential. Although deeply buried, the shale oil resources in the Fengcheng Formation are abundant, mobile, and easy to transform. These features make the fine-grained sedimentary rocks in the Fengcheng Formation a promising unconventional target for exploration. The Fengcheng Formation is also characterized by the regular co-existence of conventional and unconventional oil reservoirs. There are various types of oil-bearing systems around the Fengcheng Formation, including in-source, out-source, and near-source systems. In the future, it will be necessary to conduct further geological research, such that shale oil exploration can transition to profitable exploitation in the Junggar Basin.

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References

Borcovsky, D., Egenhoff, S., Fishman, N., et al., 2017. Sedimentology, facies architecture, and sequence stratigraphy of a Mississippian black mudstone succession—the upper member of the Bakken Formation, North Dakota, United States. AAPG (Am. Assoc. Pet. Geol.) Bull. 101, 1625–1673. https://doi.org/10.1306/01111715183.

Cao, J., Lei, D.W., Li, Y.W., et al., 2015. Ancient high-quality alkaline lacustrine source rocks discovered in the lower Permian Fengcheng Formation, Junggar Basin. Acta Pet. Sin. 36, 781–790. https://doi.org/10.7623/syxb201507002 (in Chinese).

Cao, J., Xia, L.W., Wang, T.T., et al., 2020. An alkaline lake in the Late Paleozoic Ice Age (LPIA): a review and new insights into paleoenvironment and petroleum geology. Earth Sci. Rev. 202, 103091. https://doi.org/10.1016/j.earscirev.2020.103091.

Guo, X.G., He, W.J., Yang, S., et al., 2019. Evaluation and application of key technologies of "sweet area" of shale oil in Junggar Basin: case study of permian Lucaogou formation in jimusar depression. Natural Gas Geoscience 30 (8), 1168–1179. https://doi.org/10.11764/j.issn.1672–1926.2019.05020 (in Chinese).

He, W.J., Wang, X.L., Zou, Y., et al., 2019. The geological conditions, resource potential and exploration direction of oil in Junggar Basin. Marine Origin Petroleum Geology 24 (2), 75–84. https://doi.org/10.3969/j.issn.1672-9854.2019.02.008 (in Chinese).

Jarvie, D.M., 2012. Shale resource systems for oil and gas: Part 2—shale oil resource systems. In: Breyer, J.A. (Ed.), Shale Reservoirs—Giant Resources for the 21st Century, vol. 97. AAPG Bulletin, pp. 89–119. https://doi.org/10.1306/13321447M973489.

Jin, A.M., Lou, Z.H., Cao, F.F., et al., 2007. Characteristics and origin of subperessure in Mahu—pengyijingxi composite petroleum system. Nat. Gas. Ind. 3, 33–35 (in Chinese).

Jiang, Z.X., Zhang, W.Z., Liang, C., et al., 2014. Characteristics and evaluation elements of shale oil reservoir. Acta Pet. Sin. 35, 184–196. https://doi.org/10.7623/syxb201401024 (in Chinese).

Kuang, L.C., Tang, Y., Lei, D.W., et al., 2012. Formation conditions and exploration potential of tight oil in the Permian saline lacustrine dolomitic rock, Junggar Basin, NW China. Petrol. Explor. Dev. 39 (6), 657–667 (in Chinese).

Lazar, O.R., Bohacs, K.M., Macquaker, J.H.S., et al., 2015. Capturing key attributes of fine-grained sedimentary rocks in outcrops, cores and thin sections: nomenclature and description guidelines. J. Sediment. Res. 85, 230–246. https://doi.org/10.2110/jsr.2015.11.

Lei, D.W., Chen, G.Q., Liu, H.L., et al., 2017. Study on forming conditions and exploration fields of the Mahu giant oil (gas) province, Junggar basin. Acta Geol. Sin. 91 (7), 1604–1619 (in Chinese).

Li, M.W., Ma, X.X., Jiang, Q.G., et al., 2019. Enlightenment from formation conditions and enrichment characteristics of marine shale oil in North America. Petroleum Geology and Recovery Efficiency 26 (1), 13–28. https://doi.org/10.13673/j.cnki.cn37-1359/te.2019.01.002 (in Chinese).

Li, J.J., Wang, W.M., Cao, Q., et al., 2015. Impact of hydrocarbon expulsion efficiency of continental shale upon shale oil accumulations in eastern China. Mar. Petrol. Geol. 59, 467–479. https://doi.org/10.1016/j.marpetgeo.2014.10.002.

Li, W.W., Cao, J., Shi, C.H., et al., 2020. Shale oil in saline lacustrine systems: A perspective of complex lithologies of fine-grained rocks. Mar. Petrol. Geol. 116, 104351. https://doi.org/10.1016/j.marpetgeo.2020.104351.

Liang, C., Cao, Y.C., Jiang, Z.X., et al., 2017. Shale oil potential of lacustrine black shale in the Eocene Dongying depression: Implications for geochemistry and reservoir characteristics. AAPG (Am. Assoc. Pet. Geol.) Bull. 101 (11), 1835–1858. https://doi.org/10.1306/01251715249.

Liang, S.J., Luo, Q.S., Wang, R., et al., 2019. Geological characteristics and exploration practice of unconventional Permian oil resources in the Santanghu Basin. China Petroleum Exploration 24 (5), 624–635. https://doi.org/10.3969/j.issn.1672-7703.2019.05009 (in Chinese).

Liao, Z.W., Hu, W.X., Fu, X.G., et al., 2019. Geochemistry of upper Permian siliceous rocks from the lower Yangtze region, southeastern China: implications for the origin of chert and Permian Ocean chemistry. Petrol. Sci. 16, 252–266. https://doi.org/10.1007/s12182-018-0293-3.

Lin, H.X., Song, M.S., Wang, S.Z., et al., 2020. Shale oil resource evaluation in complex structural belt of superimposed basin: A case study of middle Permian

Lucaogou Formation in Bogda area, southeast margin of Junggar Basin. Petroleum Geology and Recovery Efficiency 27 (2), 7–17. https://doi.org/10.13673/j.cnki.cn37-1359/te.2020.02.002 (in Chinese).
Liu, B., Wang, H.L., Fu, X.F., et al., 2019. Lithofacies and depositional setting of a highly prospective lacustrine shale oil succession from the Upper Cretaceous Qingshankou Formation in the Gulong sag, northern Songliao Basin, northeast China. AAPG (Am. Assoc. Pet. Geol.) Bull. 103 (2), 405–432. https://doi.org/10.1306/08031817416.
Lu, S.F., Huang, W.B., Chen, F.W., et al., 2012. Classification and evaluation criteria of shale oil and gas resources: discussion and application. Petrol. Explor. Dev. 39 (2), 249–256 (in Chinese). doi: CNKI: SUN: SKYK.0.2012-02-018.
Qin, Z.J., Chen, L.H., Li, Y.W., et al., 2016. Paleo-sedimentary setting of the lower permian Fengcheng alkali lake in Mahu sag, Junggar Basin. Xinjing Pet. Geol. 37 (1), 1–6. https://doi.org/10.7657/XJPG20160101 (in Chinese).
Sandvik, E.I., Young, W.A., Curry, D.J., 1992. Expulsion from hydrocarbon sources: the role of organic absorption. Org. Geochem. 19, 77–87. https://doi.org/10.1016/0146-6380(92)90028-v.
Shao, D.Y., Zhang, T.W., Lucy, T.K., et al., 2020. Experimental investigation of oil generation, retention, and expulsion within Type II kerogen-dominated marine shales: Insights from gold-tube nonhydrous pyrolysis of Barnett and Woodford Shales using miniature core plugs. Int. J. Coal Geol. 217, 103337. https://doi.org/10.1016/j.coal.2019.103337.
Sonnenberg, S.A., Pramudito, A., 2009. Petroleum geology of the giant elm coulee field, Williston Basin. AAPG (Am. Assoc. Pet. Geol.) Bull. 93 (9), 127–153. https://doi.org/10.1306/05280909006.
Xia, L.W., Cao, J., Wang, M., et al., 2019. A review of carbonates as hydrocarbon source rocks: basic geochemistry and oil-gas generation. Petrol. Sci. 16, 713–728. https://doi.org/10.1007/s12182-019-0343-5.
Xia, L.W., Cao, J., Stüekenb, E.E., et al., 2020. Unsynchronized evolution of salinity and pH of a Permian alkaline lake influenced by hydrothermal fluids: A multi-proxy geochemical study. Chem. Geol. 541, 119581. https://doi.org/10.1016/j.chemgeo.2020.119581.
Xu, L., Chang, Q.S., Feng, L.L., et al., 2019. The reservoir characteristics and control factors of shale oil in Permian Fengcheng Formation of Mahu sag, Junggar Basin. China Petroleum Exploration 24 (5), 649–660. https://doi.org/10.3969/j.issn.1672-7703.2019.05.011 (in Chinese).
Zhang, Y.Y., Li, W., Tang, W.B., 2018. Tectonic setting and environment of alkaline lacustrine source rocks in the Lower Permian Fengcheng formation of Mahu sag. Xinjing Pet. Geol. 39 (1), 48–54. https://doi.org/10.7657/XJPG20180106 (in Chinese).
Zhi, D.M., Song, Y., He, W.J., et al., 2019. Geological characteristics, resource potential and exploration direction of shale oil in middle-lower permian, Junggar Basin. Xinjing Pet. Geol. 40 (4), 389–401. https://doi.org/10.7657/XJPG20190402 (in Chinese).
Zhu, S.F., Liu, X., Ma, X., et al., 2015. The development characteristics of tight clastic reservoirs in the lower Permian Fengcheng Formation in Wu-Xia area of the Juggar Basin. Geol. J. China Univ. 21 (3), 461–470. https://doi.org/10.16108/j.issn1006-7493.2015061 (in Chinese).
Zou, C.N., Yang, Z., Cui, J.W., et al., 2013. Formation mechanism, geological characteristics and development strategy of nonmarine shale oil in China. Petrol. Explor. Dev. 40 (1), 14–26 (in Chinese).
Zou, C.N., Yang, Z., Zhang, G.S., et al., 2019. Establishment and practice of unconventional oil and gas geology. Acta Geol. Sin. 93 (1), 12–23. https://doi.org/10.19762/j.cnki.dizhixuebao.2019002 (in Chinese).