Review Article
A Comparison of Geological Characteristics of the Main Continental Shale Oil in China and the U.S.

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Shale oil is an important strategic resource in the future. The development and utilization of shale oil is a pivotal revolution in the field of fossil energy. The successful development in North America brings new thinking to the world. In recent years, there have been many definitions of shale oil, but no agreement has been reached in the petroleum industry. Marine shale oil is dominant in the United States (the U.S.), while continental shale oil is the counterpart in China. This study takes Uinta Basin, Ordos Basin, and Junggar Basin, for example, to make a comparison of the concept and geological characteristics of shale oil in continental basins between the U.S. and China. Different kinds of shale oil are generated due to the distinctions of sedimentary environments, hydrocarbon supply conditions, and sandy sediment development in different regions. High-quality source rocks have been developed in freshwater and salty water environments of continental lacustrine basins. The lithologies of the Uteiland Butte Member, Chang 7 Member, and Lucaogou Formation are lacustrine carbonate rocks, clastic rocks, and mixed sedimentary rocks, respectively. Results indicate that the lower pressure can be identified in continental basins in China. Furthermore, the comparison shows that the Chang 7 Member characterizes lighter crude oil and larger scale of "sweet spot" and the Lucaogou Formation developed a thicker target layer, while the Chang 7 Member is at a disadvantage of insufficient stratum energy and the Lucaogou Formation is difficult in heavier crude oil and higher oil viscosity.

1. Introduction

The development and utilization of shale oil is a pivotal revolution in the field of fossil energy. The resources of shale oil, a hotspot in the exploration of continuous (unconventional) oil and gas, are abundant with more than 100 petroliferous basins all over the world [1]. In 2013, the U.S. Energy Information Administration (EIA) estimated a total of 345 billion barrels of oil technically recoverable in shale play worldwide [2]. EIA and Advanced Resources International (ARI) identified a total risked shale oil in-place of 6753 billion barrels in the 2013 report [3]. With 21% of the world’s shale oil resources, the U.S. has become a shale oil power, leading the development of shale oil [4, 5]. Since the 21st century, the U.S. has been vigorous in the exploitation of marine shale oil, achieving the production of 1298 million barrels of oil in shale play in 2015, accounting for 45% of the year’s crude oil production [6, 7]. According to the latest data released by EIA, the production of shale oil in the U.S. reached 2827 million barrels in 2019, accounting for more than 60% of the total crude oil production, which is the dominant resource of oil production [8, 9]. Moreover, the total proved reserves in the U.S. shale plays have reached 23.24 billion barrels, while continental shale oil occupied less than 2% [9].

Compared with the U.S., shale oil reservoirs in China are mainly composed of organic-rich shale in continental lacustrine basins, and the theory of continental oil generation is a petroleum geological theory with Chinese characteristics, playing a key guiding role in the development of the petroleum industry. There are abundant reserves of continental shale oil that were mainly developed in continental basins such as Junggar, Ordos, Songliao, and Bohai Bay. These continental shale oils are mainly distributed in five strata, including Paleogene, Cretaceous, Jurassic, Triassic, and Permian [10]. EIA estimated a total of 32.2 billion barrels of technically recoverable shale oil in China [1], while the U.S.
Geological Survey (USGS) published that the technical recoverable continuous resources in Shahejie Formation of Bohai Bay Basin, Qingshankou Formation and Nenjiang Formation of Songliao Basin, and Ordovician of Tarim Basin are 2.0 billion barrels, 3.3 billion barrels, and 1.4 billion barrels in shale plays, respectively [11–13]. In 2019, the largest shale oil field in China was discovered in the source rock sequence of Chang 7 Member in Ordos Basin, adding 2.58 billion barrels of oil to the proved reserves and 4.99 billion barrels of oil to the predicted reserves [13]. In the same year, there was an unprecedented national demonstration zone of continental shale oil named Jimsar that was planned to reach the production of 7.2 million barrels of shale oil by 2021, and this number will be doubled in the next four years.

The enrichment of shale oil resources is influenced by many factors. Wood and Breyer et al. pointed out that the tectonic background has an important effect on the scale of shale oil enrichment [14, 15]. In addition, the geological characteristics of source rocks, reservoirs, and seals also play an important role. Based on the different occurrence media as well as the relationship between source rocks and reservoirs, shale oil has been classified into three types (matrix type, fracture type, and mixed type), according to Jarvie and Sonnenberg and Mechkel [16, 17]. The scale of “sweet spot” controls commercial development and shale oil production [9].

Currently, the related technologies of shale oil development include super long horizontal well, “a trip” well, three-dimensional well pattern, fine cutting, and repetition of hydraulic fracturing technology in the U.S. [18, 19]. In China, it is more inclined to use vertical well with conventional fracturing or volume fracturing, horizontal well with staged fracturing or volume fracturing, and in situ conversion technology [20, 21]. The horizontal well with volume fracturing and independent fracturing with joint production in multilayer is the main technology for medium-high maturity shale oil [22–26], while in situ conversion technology is an important technology for medium-low maturity shale oil. In 2020, Liu et al. innovatively proposed the layered three-dimensional development mode of shale oil [27].

In this review, we briefly retrospect the history of some differences between the U.S. and China in shale oil. In Section 2, we first check the various definitions of “shale oil.” In Section 3, we discuss the geological characteristics of the three basins as well as explain the differences, including the evaluation criteria of “sweet spot.”

2. Definition of Shale Oil

Recently, many scholars gave the definition of shale oil, but it is far from reaching a consensus. EIA defines shale oil (tight oil) as an industry convention that generally refers to oil produced from very-low-permeability shale, sandstone, and carbonate formations [28]. According to the Draft Standard for Geological Evaluation of Shale Oil issued by the Standardization Administration in 2019, shale oil refers to the oil produced from organic-rich shale sequences with the limitation of maximum thickness within 5 meters in siltstone, fine sandstone, or carbonate formations [29]. In addition, the maximum cumulative thickness accounts for less than 30% of the total thickness of shale sequences. More importantly, there is no natural production capacity or below the minimum limit of industrial oil production in shale play. It is a prerequisite to adopt special technological measures to obtain well production. Moreover, Zou et al. referred to a kind of oil resource that is in situ contained in shale reservoirs without obvious trap limitation and natural industrial production capacity [30].

At present, the most accepted definitions can be divided into narrow sense and broad sense. The understanding of the concept of shale oil by oil experts and scholars mainly focuses on the narrow aspect, but there are still great differences (see Table 1).

The accumulation of inside-source continental petroleum is the liquid hydrocarbon-rich accumulation retained or captured in situ in the source rocks of continental organic-rich shale sequences. Continental shale oil can be divided into two types in terms of maturity: medium-high maturity and medium-low maturity (see Figure 1). The maturity of organic matter is one of the decisive factors for the formation of continental resources in shale play [10]. Middle-high maturity shale oil with vitrinite reflectance ($R_o$) ranging from 1.0% to 1.5% is of high thermal evolution. In addition, there are abundant liquid hydrocarbon resources that can be developed. However, according to preliminary estimates in China, middle-low maturity shale oil with $R_o$ from 0.5% to 1.0% is much more technically recoverable than that of shale oil with medium-high maturity. The development potential of medium-low maturity shale oil has attracted widespread attention of oil companies, including Shell, Exxon Mobil, and Total Oil Companies, which are carrying out in situ conversion technology research and field pilot tests.

3. Results and Discussion

Compared with marine shale oil in the U.S., the formation and distribution of continental shale oil in China are characterized by a more complex geological background and tectonic sedimentary environment with diverse basin types, rapid change of lacustrine sedimentary system, and multi-stage adjustment and transformation. However, comparisons of continental shale oil have rarely been made before. This part compares the geological characteristics and sweet spot evaluation criteria of continental shale oil in the U.S. and China. The statistical table of geological characteristics of the basin is as follows (see Table 2).

4. Geological Background

The Uinta Basin with an area of 25,000 km$^2$ locates in eastern Utah and western Colorado, which contains fluval and lacustrine deposits of Eocene Lake Uinta bounded by Laramide uplifts and the Sevier fold and thrust belt. Thin-layer dolomite in the UteLand Butte Member (single layer thickness is 0.5–3 m) receiving much attention as a horizontal target is the first successfully developed reservoir of continental shale oil in North America [38–41].
The Uteland Butte Member, belonging to the lower part of the Green River Formation, was deposited in a major transgressive phase of the early freshwater stage of Eocene Lake Uinta before the main brackish-to-saline lacustrine interval [42, 43]. The Uteland Butte, also called the Basal Carbonate of the Green River Formation, is rich with abundant bivalves, gastropods, and ostracods that developed three dolomites sandwiched between D shale and C shale [44, 45]. Its burial depth ranges from 1000 m to 3000 m, and the thickness ranges from 15 m to 130 m (see Figure 2).

Using a geology-based assessment, USGS estimated the mean undiscovered resources of 214 million barrels of oil, 329 billion cubic feet of associated/dissolved natural gas, and 14 million barrels of natural gas liquids in the Uteland Butte Member.

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**Table 1: Definition of shale oil [10, 28–37].**

| Definition | Source |
|------------|--------|
| EIA | Shale oil (tight oil) is produced from very-low-permeability shale, sandstone, and carbonate formations. The distinction between shale oil and tight oil is avoided by using "unconventional resource in continuous-type accumulation." It was defined to include those oil and gas resources that exist as geographically extensive accumulations in coal sandstones and shales outside of the discrete well defined conventional trap. |
| USGS | Tight oil is found at unmineable depths in sedimentary rock formations that are characterized by very low permeability. While some of the tight oil plays produce oil directly from shales, tight oil resources are also produced from low-permeability siltstones, sandstones, and carbonates in close association with a shale source rock. |
| NPC | Shale oil is a kind of oil and gas resource that is in situ contained in shale reservoirs without obvious trap limitation and natural industrial production capacity. It includes the petroleum resources in the pores and fractures of shale as well as interlayers in the tight clastic rocks or carbonates. Shale oil is extracted from the oil-rich shale sequences (a large set of dark mud shales, high carbon shales, silt shales, and thin interlayer of sandstones). It is a continuous petroleum accumulation with ultralow porosity and ultralow permeability, mostly occurring in pore and fracture free or adsorbed. |
| Zou et al. | Shale oil is extracted from the oil-rich shale sequences (a large set of dark mud shales, high carbon shales, silt shales, and thin interlayer of sandstones). It is a continuous petroleum accumulation with ultralow porosity and ultralow permeability, mostly occurring in pore and fracture free or adsorbed. |
| Chen et al. | Shale oil is liquid hydrocarbon formed in the effective source rocks with free phase (condense oil) and adsorbed and dissolved phase (dissolved in gas, kerogen, and residual water). Similar to shale gas. Presenting in the pores and fractures of shales, carbonates, and sandstones within shale sequences, shale oil is adsorbed or free and can be exploited on an economic scale only through unconventional technological measures such as horizontal well fracturing technology. |
| Zhang et al. | Shale oil refers to the self-generated and self-stored continuous petroleum, adsorbed or free accumulation in the dark shales and mudstones as well as the interbed thin argillaceous siltstones and sandstones. The shale sequences are rich in organic matter with very low permeability. |
| Wu et al. | Shale oil is liquid hydrocarbon formed in the effective source rocks with free phase (condense oil) and adsorbed and dissolved phase (dissolved in gas, kerogen, and residual water). Similar to shale gas. |
| Dong et al. | Shale oil refers to the self-generated and self-stored continuous petroleum, adsorbed or free accumulation in the dark shales and mudstones as well as the interbed thin argillaceous siltstones and sandstones. The shale sequences are rich in organic matter with very low permeability. |
| Zhou et al. | The petroleum resources come from the mud-shale sequences which are not only source rocks but also reservoirs. |

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**Figure 1: Hydrocarbon generation, expulsion, and retention model of continental shale oil in China (modified from [10]).**

The Uteland Butte Member, belonging to the lower part of the Green River Formation, was deposited in a major transgressive phase of the early freshwater stage of Eocene Lake Uinta before the main brackish-to-saline lacustrine interval [42, 43]. The Uteland Butte, also called the Basal Carbonate of the Green River Formation, is rich with abundant bivalves, gastropods, and ostracods that developed three dolomites sandwiched between D shale and C shale [44, 45]. Its burial depth ranges from 1000 m to 3000 m, and the thickness ranges from 15 m to 130 m (see Figure 2).

Using a geology-based assessment, USGS estimated the mean undiscovered resources of 214 million barrels of oil, 329 billion cubic feet of associated/dissolved natural gas, and 14 million barrels of natural gas liquids in the Uteland Butte Member.
Table 2: The comparison of geological characteristics in Uteland Butte Member, Chang 7 Member, and Lucaogou Formation.

| Basin            | Uinta Basin          | Ordos Basin          | Junggar Basin        |
|------------------|----------------------|----------------------|----------------------|
| Member           | Uteland Butte Member | Chang 7 Member       | Lucaogou Formation   |
| Salinity         | Freshwater           | Freshwater           | Saline               |
| Facies           | Lacustrine           | Semideep and deep lacustrine | Deep and semideep lacustrine |
| Lithologies      | Carbonate            | Clastic rock         | Hybrid sedimentary   |
| Depth (m)        | 1000–3000            | 1200–2600            | 1500–4500            |
| TOC (%)          | 2–5                  | 2–20                 | 2–16                 |
| Rø (%)           | 0.55–1.1             | 0.7–1.2              | 0.6–1.1              |
| Kerogen          | Type I domain        | Type I-II            | Type I-II            |
| Porosity (%)     | 3–20                 | 9–15                 | 6–14                 |
| Permeability (mD) | 0.004–0.337          | 0.001–1.0            | <1.0                 |
| Density (g/cm³)  | 0.82–0.88            | 0.80–0.86            | 0.88–0.92            |
| Viscosity (mPa·s)| 1–4                  | 1.55 average         | 45.6–434.9           |
| Oil saturation (%)| 60–70               | 60–80                | 80–90                |
| Brittle mineral content (%) | 75 average           | 75–90                | 70–95                |
| Poisson’s ratio  | 0.15–0.35            | 0.20–0.30            | 0.20–0.30            |
| Pressure coefficient | 1.0–1.8            | 0.7–0.8              | 1.1–1.3              |

Figure 2: Stratigraphic and lithology of the Uteland Butte Member (modified from [44]): (a) GR curve of Uteland Butte Member (well UT15-30); (b) histogram of the middle Uteland Butte Member.
Butte Member of the Green River Formation, Uinta Basin [46]. The technically recoverable shale oil resources in the Uteland Butte Member are 177 million barrels [46].

Ordos Basin is a large multicycle craton basin located in northwest China. The Mesozoic shale oil in the Ordos Basin refers to the oil accumulation with medium-low maturity in the tight sandstone and shale reservoirs of the Chang 7 Member in the Yanchang Formation without long-distance migration [47]. The sedimentary period of Chang 7 Member was the largest flood period of the lake basin. During that time, rapid tectonic subsidence occurred. The shoreline of the lake expanded outward immediately, and a large oil shale sequence with wide distribution, large thickness, and stable oil content was deposited. The Chang 7 Member of the Upper Triassic is rich in shale oil with interbedded extensive source rocks and widespread fine-grained sandstones. A sequence of organic-rich shales and fine-grained sandstones with delta gravity flow is developed [48–50]. The Chang 7 Member and deposition of semideep and deep lacustrine can cover areas of $10 \times 10^4$ km$^2$ and $6.5 \times 10^4$ km$^2$, respectively [51, 52]. According to lithologic combination, sand concentration, and the thickness of sandstones, the shale oil in the Chang 7 Member could be divided into three categories (see Figure 3) [53].

The Chang 7 Member with interbedded black shales and dark mudstones in Ordos Basin was deposited in freshwater environment, which is the same as the Uteland Butte Member. The stratified enrichment of organic matter was influenced by deep volcanic activity, hydrothermal process, low sedimentation rate, and low terrigenous clastic compensation rate. Appropriate volcanic activities provide rich nutrient elements to the eutrophic water funding the biological growth in the lacustrine basin. Hydrothermal deposits, such as siliceous rocks, phosphorus and manganese ore, and carbonate nodules, presenting in the lacustrine basin of Ordos Basin, contribute to the flourishing of organisms and perform an obvious fertilization effect. The low sedimentation rate and terrigenous clastic compensation rate reduce the dilution of organic matter, anoxic or quiet reduction environment that is conducive to the preservation of organic matter, and the

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**Figure 3:** Lithology and categories of shale oil in Chang 7 Member.
extensive developed black shales and dark mudstones laid the foundation for abundant shale oil [54, 55]. The Chang 7 Member can be divided into three submembers: Chang 73, Chang 72, and Chang 71. The Chang 73 Submember is deposited in the period of high lake, mainly containing a sequence of organic-rich shales with thin sandstones. Fu et al. estimated geological resources of 28.8 to 43.2 billion barrels in the first type and prospective resources of 21.6 to 28.8 billion barrels in the second type in shale play [56]. It sheds light on a much more preponderance than the Uteland Butte Member.

Jimusar Sag, locating in Shaqiuhe-Qitai uplift of eastern Junggar Basin, is in a dustpan-like shape that faulted in the south part and overlapped in the north part which was deposited on the Middle Carboniferous fold basement [57]. The Permain Lucaogou Formation in Jimusar Sag was deposited in semideep and deep lacustrine together with high-quality source rocks [58]. As one of the oldest continental liquid hydrocarbon shale reservoirs in China, it is an eye-catching target for shale oil exploration.

The Lucaogou Formation is formed in the sedimentary environment of saline lacustrine basin depositing a set of mudstones, siltstones, carbonates, and other hybrid sedimentary under the comprehensive action of mechanical, chemical, and biological deposition (see Figure 4) [59]. As an oil-rich play with wide distribution, great thickness, high abundance, and extensive potential, the Lucaogou Formation covers the optimal exploration areas of nearly 1000 km². The upper, middle, and lower shale sequences of Lucaogou Formation are the most important source rocks of Jimusar Sag and also the reservoirs of crude oil [60]. The source rocks are mainly divided into five types: shale, mudstone, dolomitic shale, dolomitic mudstone, and silty mudstone. The accumulation of organic matter in Lucaogou Formation was due to not only the early volcanic activities which provided nutrients but also the flocculation facilitation of salt water.

Key assessment parameters of shale oil and nuclear magnetic resonance analyses by the small patch method were used to preliminarily calculate the resources. Shale oil in Jimusar Sag has great potential with a total shale oil in-place of 18.3 billion barrels, (theoretically) recoverable resources of 2.99 billion barrels, and technically recoverable of 0.29 billion barrels in shale play [61]. Using a volumetric method, Zhi et al. identified a total of 0.79 billion barrels of shale oil that are technically recoverable under the recovery ratio of about 3% of Lucaogou Formation, Jimusar Sag [60].

4.1. Source Rocks. The Uteland Butte Member contains type I kerogen and a small amount of type II along with high hydrocarbon content. Under the influence of organic matter productivity and preservation conditions, total organic carbon (TOC) mainly ranges from 2% to 5%, and under the influence of the severe subsidence after the deposition, $R_o$ varies from 0.55% to 1.1% (see Table 2). From two well cores, oil saturation index values in both are high, from nearly 100 mg-HC/g-TOC to more than 200 mg-HC/g-TOC. $T_{max}$ values are highly variable and range between 430 and 457°C (see Figure 5).

The depth of Chang 7 Member is relatively shallow, ranging from 1200 to 2600 m, and the thickness of mud shale is large, ranging from 30 to 60 m. Black shales are mainly developed at the base of Chang 7 Member. The Chang 71 Submember is deposited in the period of high lake, mainly containing a sequence of organic-rich shales with thin sandstones. Fu et al. estimated geological resources of 28.8 to 43.2 billion barrels in the first type and prospective resources of 21.6 to 28.8 billion barrels in the second type in shale play [56]. It sheds light on a much more preponderance than the Uteland Butte Member.
always higher than 100 mg-HC/g-TOC, and the highest reaches nearly 500 mg-HC/g-TOC, while in the source rock series, it is always lower than 100 mg-HC/g-TOC. This result indicates that the oil-bearing property of the Chang 7 Member is well developed.

Affected by the low energy of deep water, the distribution of shale in the whole area of Lucaogou Formation is relatively stable, with depth ranging from 1500 to 4500 m, which is much deeper than the other two. Lucaogou Formation contains type I-II kerogen along with the TOC varying from 2% to 16% and $R_o$ varying from 0.6% to 1.1%, which indicates the early stages of peak oil production.

4.2. Reservoir Characteristics. Compared with conventional reservoirs, the criteria for shale oil reservoirs are more complex, and the distribution and hydrocarbon generation capacity of source rocks are more rigorous. According to the dominant organic and lithologic characteristics, the shale oil resource system is classified into three types: (1) organic-rich mudstones with predominantly healed fractures, if any;
(2) organic-rich mudstone with open fractures; and (3) hybrid systems with a combination of juxtaposed organic-rich and organic-lean intervals [63]. Principle parameters of shale reservoir physical properties are porosity that controls oil storage potential, permeability that affects oil productivity, pore throat diameter that determines the shale matrix porosity, microfracture development, and shale reservoir fracturing ability [64]. There are terrigenous clastic and hybrid sedimentary reservoirs that are widely developed in continental shale sequences in China. Intergranular pores, intercrystalline pores, organic pores, dissolution pores, and bedding fractures are the most important reservoir spaces here.

The Uteland Butte interval consists of limestone, dolostone, calcareous mudstone, siltstone, and conversely rare sandstone. It is distinctive in its abundance of carbonate and lack of sandstone, which may have been caused by the rapid lake-level rise that makes siliciclastic sediments to deposit in proximal alluvial channels [65]. Of particular interest for horizontal drilling are three beds with up to 100% dolomite in Uteland Butte Member that may result from the increase of evaporation and the decrease of freshwater input as well as periodic warming. The dolomitic limestone is comprised of 10% quartz, 25% calcite, 63% dolomite, and 2% total clay in BBC’s acreage, indicating a high brittleness. Carbonate minerals are high in the range of 33% to 96%, and clay minerals generally less than 20% are mainly kaolinite, montmorillonite, and chlorite. Adjacent to the dolomite are highly fractured limestones [66]. The reservoir space of Uteland Butte Member is characterized by good physical properties, mainly intergranular pores, intercrystalline pores, and organic pores, with porosity ranging from 3% to 20% and permeability ranging from 0.004 to 0.337 mD (see Table 2). The span of porosity here is much wider than others. The existence of brittle calcareous inter- vals and porous dolomite provides a favourable condition for horizontal well drilling [67, 68].

The fine-grained deposits of Chang 7 Member in Ordos Basin are composed of five lithologies: fine sandstone, siltstone, black shale, dark mudstone, and tuff, with shale as the major part, interbedded with many thin layers of fine siltstone [53]. The Chang 7 Member has a porosity of 9%–15% and a permeability of 0.01–1.0 mD, which is a well-developed primary and secondary pore. Intergranular pores, dissolution pores, and clay mineral intercrystalline pores are predominant in the Chang 7 intrasource reservoir, and the pore is generally at the scale of micrometer to nanometer [51]. Shale laminae, sandy laminae, and microscopic laminae are common in the Chang 7 Member, in which laminae pores and shale pores form a complex pore system with high heterogeneity, effectively improving the physical properties of reservoirs [69]. It is high in content of brittle minerals leading by quartz and feldspar (see Figure 7), including quartz of 17%–80%, plagioclase and potassium feldspar of 9%–43%, and generally the total clays of 40%–50%.

With typical characteristics of self-generation and self-storage, Lucaogou Formation is a set of mud-shale intervals comprised of overlapped source rocks and reservoirs. Similarly, the crude oil migrated for an extremely short distance from source rocks to the well physical property reservoirs, arenaceous dolomite, and dolomitic siltstone, for instance. Principle minerals of reservoirs are dolomite, quartz, and plagioclase, while clay minerals are not common. From the XRD result of Wang et al., the contents of quartz, feldspar, dolomite, pyrite, and clay minerals are 20.9%, 25.4%, 26.2%, 0.9%, and 13.3%, respectively (see Figure 8) [70]. The porosity ranges from 6% to 14%, and the overlying pressure permeability is less than 1.0 mD. In addition to millimeter and micron pores, a large number of nanopores are also developed.

![Figure 6: Pyrolysis geochemical profile of H317 well (modified from [62]).](image-url)
4.3. Liquid Characteristics. The enrichment areas of shale oil tend to be in mature organic-rich shale formations that have produced oil on a large scale, generally with a characteristic of high-producing energy, low oil density, and high gas-oil ratio, which are easy for oil to flow and be exploited.

Shale oil in the Uteland Butte Member of Uinta Basin has a high oil saturation, which varies from 60% to 70%, with crude oil density of 0.82–0.88 g/cm³ and viscosity of 1–4 mPa·s (see Table 2). Through horizontal well, hydraulic fracturing, and acid treatment, commercial development has been realized in the central and northern depression of the basin.

Shale oil of the Chang 7 Member has a high oil saturation (60%–80%), low oil density (0.80–0.86 g/cm³), low pressure (pressure coefficient between 0.70 and 0.80), and mean viscosity of 1.55 mPa·s (see Table 2). The proportion of illite/smectite and montmorillonite in shale is high, and the fracture effect of reservoir reconstruction is poor. With optimal conditions for large-scale exploration and development, Chang 7 Member is the most potential and representative area for underground in situ conversion technology of shale oil in China [10], and it is also an important replacement field for sustained and stable oil production of Changqing.

The shale oil of Lucaogou Formation has a high oil saturation of 80%–90% and a crude oil density of 0.88–0.92 g/cm³. For the high content of isoparaffin, naphthene, colloids, and asphaltenes, the crude oil of Lucaogou Formation is generally sticky [71]. The Lucaogou Formation is dominated by normal pressure and weak overpressure, with pressure coefficient ranging from 1.10 to 1.30. The economy is the hinge to determine whether shale oil can be put into large-scale development in Jimusar Sag.

4.4. Evaluation of “Sweet Spot.” Source rock and seal are the key factors to control the scale of shale oil resources, but the development and scale of “sweet spot” are the key factors to control the commercial development and production of shale oil. The success and cost reduction of shale oil development in the U.S. are primarily due to the improved understanding of geology and, crucially, the finding of sweet spots.

“Sweet spot” indicates the favourable reservoir with richer oil, better property, easier transformation, and commercial development value in the whole oil-bearing continental source sequences. In other words, the target of shale oil enrichments and high-yield areas can be first explored and developed under the current economic and technical conditions, including geological sweet spots, engineering sweet spots, and economic sweet spots. In profile, it is named “sweet interval” and the “sweet spot” in lateral.

“Sweet interval” is the source rock system where oil and gas are relatively enriched or have relatively large potential. It has good oil content, superior reservoir conditions, and strong reformability. The preference of “sweet interval” is based on core, logging, and test data to identify the endogenous hydrocarbon quality, reservoir quality, engineering mechanical quality, and oil content.

Based on the geological conditions and sedimentary characteristics of continental reservoir series, “sweet interval” is divided into three types: interlayer, hybrid sediment, and shale, according to Jiao et al. [72]. The shale sequences of Uteland Butte Member, Chang 7 Member, and Lucaogou Formation feature overall oil and coexist sources and reservoirs. The dolomite of Uteland Butte Member interbeds with organic-rich limestones and shales, capturing shale oil, pertaining to the dolomitic “sweet interval” of hybrid sediment (see Figure 9). The reservoir of shale sequences in Chang 7 Member is mainly sandstone, mudstone, and shale. The favourable thin-layer sandstone reservoirs capture shale oil near the source to “sweet interval,” developing sandstone “sweet interval” of the interlayer. Shale oil of Lucaogou Formation in Jimusar Sag migrated from source rocks in a very short distance to arenaceous dolomite and dolomitic siltstone reservoirs with good physical properties, which belongs to arenaceous dolomite “sweet interval” of hybrid sediment.
Figure 8: The content of minerals of Lucaogou Formation in Jimusar Sag (modified from [70]).

Figure 9: Type of “sweet interval” in Uteland Butte Member, Chang 7 Member, and Lucaogou Formation.
The "sweet spot" is developed in source reservoir symbiotic shale sequences that can be transformed into the high-yield and rich zone by artificial reconstruction within the range of favourable source rocks. There are many parameters for the evaluation of "sweet spot," particularly organic matter abundance, organic matter maturity, oil saturation, pressure coefficient, gas-oil ratio, and brittleness index. The first two control the extent of the favourable area, while others determine the feasibility of shale oil production under the existing economic and technical conditions. Based on the geological characteristics of unconventional petroleum in China, Zou et al. published that the evaluation should be focused on source rock characteristics, lithology, physical property, brittleness, oil-gas possibility, and stress anisotropy [73]. Hu et al. stated that the "sweet spot" was mainly controlled by factors such as the thickness of organic-rich shale, thermal evolution degree, and natural fractures [74, 75].

In 2015, the USGS defined the Uteland Butte Carbonate Continuous Oil Assessment Unit on the basis of combining the primary parameters of overpressure with total thickness of Uteland Butte Member, dolomite, organic matter abundance, and thermal maturity; the estimated average estimated ultimate recoveries (EUR) in the "sweet spot" are 0.088 million barrels of oil, far higher than "nonsweet spot" of 0.046 million barrels of oil [46].

On lateral, the "sweet spot" of Chang 7 Member in Ordos Basin reaches 8000–10000 km², more than eight times the Uteland Butte Member. Cui et al. proposed to optimize the favourable play and lithology of Chang 7 Member in Ordos Basin according to three key parameters: geological index (maturity), economic index (oil content), and engineering index (mineral composition). It is determined that the "sweet spot" should be limited by the optimal exploration depth of 2000–2600 m, the maturity of 0.7%–1.1%, the organic matter abundance of no more than 6%, and the clay mineral of less than 50% [76].

Guided by the geological requirement of "sweet spot" in Lucaogou Formation, a set of multiparameter prediction technology covering geology, logging, geophysical exploration, and engineering of "sweet spot" has been carried out to put "sweet spot" into three types [77]. The classification of "sweet spot" in Lucaogou Formation is on the strength of reservoir parameters (porosity, air permeability, and thickness), source rock parameters (organic matter abundance, kerogen, and maturity), brittleness parameters (Poisson’s ratio and Young’s modulus), and geostress characteristic parameters (multiples of two horizontal principal stresses). Using small element volume and EUR analogy, the geological resources of "sweet spot" in the Lucaogou Formation are estimated to be about 8.78 billion barrels in shale play [77].

5. Conclusion

Correct understanding of shale oil resource potential in continental basins, identifying optimal core areas for shale oil enrichment, and developing adaptive engineering techniques for high and stable production are the key links to make breakthroughs in the exploration and development of continental shale oil in China. Through comparative analysis, there are similarities and differences between continental shale oil basins in the U.S. and China.

Two types of high-quality source rocks in freshwater and salty water environment have been developed in continental lacustrine basins. It is considered that high productivity of lake, preservation conditions in anoxic environment, and low terrigenous detrital compensation rate are the key factors for organic matter enrichment in freshwater environment. In addition, early volcanic activities, flocculation facilitation of salty water, and low energy positively contribute to the scale of shale oil accumulation in salty water environment.

The lithologies of the Uteland Butte Member, Chang 7 Member, and Lucaogou Formation are lacustrine carbonate rocks, clastic rocks, and mixed sedimentary rocks, respectively. The keys to the Uteland Butte horizontal play are thickness of the target dolomites and geopressure, while the development is restricted by the limited "sweet spot" and "sweet interval." Results indicate that the lower pressure can be identified in continental basins in China. Furthermore, the comparison shows that the Chang 7 Member characterizes lighter crude oil and larger scale of "sweet spot" and the Lucaogou Formation developed a thicker target layer, while the Chang 7 Member is at a disadvantage of insufficient stratum energy and the Lucaogou Formation is difficult in heavier crude oil and higher oil viscosity.

The exploration of shale oil in China should not only focus on the tight clastic rocks and carbonates associated with organic-rich source rocks but also attach great importance to the exploration of organic-rich brittle shale sequences and select the target interval for horizontal drilling. Moreover, it is important to find a new "sweet spot," expand the scale of the confirmed "sweet spot," strengthen basic theoretical research, and explore suitable stimulation technology.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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