Characteristics of lacustrine mixed marlstone tight oil reservoir in Shahejie Formation of Shulu Sag, Bohai Bay Basin, North China

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Abstract. A suite of lacustrine mixed marlstone is developed in the lower third member of the Shahejie Formation (Es3l) in the Shulu Sag, Bohai Bay Basin, and it is a tight oil reservoir which acts as both source bed and reservoir bed. According to the rock fabric characteristics, the marlstone in Es3l can be divided into two types: lamellar marlstone (stratigraphically mixed) and massive marl (structurally mixed). Both of them contain minerals dominated by calcite, followed by dolomite, and minor quartz, feldspar and clay minerals. The marlstone in Es3l is a typical ultra-low porosity and ultra-low permeability tight reservoir. Its pore space is classified into two types and eight sub-types, and the matrix pores are mainly nano-scale pores. The lamellar marlstone reservoir shows better physical properties and pore structure than the massive marlstone reservoir. Both the chloroform asphalt “A” content and rock pyrolysis S0+S1 are high, and oil-bearing is universally observed. The development of “sweet spot” is jointly controlled by sedimentary facies, rock fabric, organic matter abundance and maturity, structural fractures.

1. Introduction
Mount(1985)[1] first proposed the concept of “mixed sediments”, together with four genetic types. Based on the characteristics of mixed sedimentation of carbonate and terrigenous clastics in the Devonian Qujing Formation in the Qujing area of China, Yang Chaoqing(1990)[2] put forward the term “mixed rock” which was defined as a class of sedimentary rocks consisting of terrigenous clastics, carbonate particles and lime mud. In a broad sense, mixed rock is originated from: (1) the mixing of carbonate component with terrigenous clastic component; or (2) the frequent alternation of carbonate rock and terrigenous clastic rock[3]. In the Shulu Sag of Bohai Bay Basin, North China, a suite of mixed rock comprising lacustrine carbonate lime mud and terrigenous carbonate clastics developed in the lower third member of the Shahejie Formation (Es3l)[4-7], which has high organic matter abundance and large thickness. It acts as both the source bed in the sag and the reservoir bed for tight oil exploration.

2. Geological setting
The Shulu Sag is an important oil-rich sag in the Bohai Bay Basin, covering an exploration area of about 700 km². Structurally, it presents as zones in north-south and belts in east-west (Figure 1.A). In the early stage of Es3, the sag contained three sub-sags from the south to the north, and three structural units (the eastern steep slope belt, the central trough belt, and the western gentle slope belt) from the...
It was most active in the Paleogene, giving rise to the strata in Es\(^3\) and above. Es\(^3\) can be subdivided into five third-order sequences (SQ1–SQ5) and 15 parasequence sets \[^5\]. Mixed marlstone, which spreads in both transgressive system tract (TST) and high-stand system tract (HST) of each sequence (Figure 1.B), was mainly formed in the shallow lake–deep lake sedimentary environment. On the E-W stratigraphic section, the marlstone in Es\(^3\) is observed as a wedge, thick in the east and thin in the west; it is mainly distributed in the gentle slope belt and deep depression zone, with the thickness of 100~1500 m, and the largest thickness observed in the central zone of the sag.

3. Characteristics of marlstone tight oil reservoir

3.1 Petro-mineralogy

According to the rock fabric, the marlstone in Es\(^3\) can be divided into two types: lamellar marlstone and massive marlstone. The lamellar marlstone is deposited by the interbedded mixing of carbonate component and terrigenous clastic component, being a kind of mixed rock in broad sense, with alternating light and dark rhythmic lamina observed under the microscope (Figure 2). The bright lamina is mainly formed by chemical precipitation, with relatively simple mineral composition (mainly micritic calcite and dolomite) and orange-colored cathodoluminescence. The dark lamina is mainly formed by mechanical deposition, with complex mineral composition and dark and messy cathodoluminescence. Laminae may exhibit different forms depending on the distance from the source area, the supply of source and the location of the source (Figures 2. A–H).
Figure 2. Petrological characteristics of marlstone in Es3 in the Shulu Sag, Bohai Bay Basin. A–B: Lime mudstone/marlstone unequally interbedded with micrite containing terrigenous clastic; C–D: Lime mudstone/siltstone equally interbedded with micrite; E–F: Wavy bedding formed by lime mudstone and micrite containing terrigenous clastic; G–H: Graded bedding formed by siltstone and marlstone or micrite; I–J: Massive lime mudstone/marlstone mainly composed of terrigenous components; K–L: Massive micrite/marlstone mainly composed of endogenous lime mud.

The massive marlstone is deposited by the structural mixing of terrigenous component and endogenous component, being a kind of mixed rock in narrow sense. The former is mainly composed of organic-rich argillaceous and terrigenous carbonate clastics (mainly calcite), with uneven spherulitic pyrite occasionally (Figure 2.I), and shows dark and messy cathodoluminescence (Figure 2.J). The latter is mainly composed of in-situ sedimentary micritic calcite, with only a small amount of terrigenous carbonate sand clastic, quartz, and clay minerals (Figure 2.K), and shows uniform organic-colored cathodoluminescence (Figure 2.L). This type of marlstone was mainly deposited in semi-deep lake to deep lake environment, and contains terrigenous micrite when the supply of terrigenous clastic is sufficient or micrite when the supply of terrigenous clastic is insufficient.

The terrigenous clastic in the marlstone in Es3 is mainly carbonate sand clastic. Both lamellar marlstone and massive marlstone have mineral composition dominated by calcite (50%–90%), followed by dolomite (5–35%), and clay mineral, quartz and feldspar (totally <10%).

3.2 Physical properties

The marlstone in Es3 is a typically ultra-low porosity and ultra-low permeability tight reservoir. The gas logging porosity is generally below 4.0%, and the horizontal permeability is mostly lower than $10^{-3}$ $\mu$m$^2$. Overall, the lamellar marlstone reveals a porosity higher than the massive marlstone. Before washing oil, the porosity measured by the helium porosimeter ranges from 0.5%–2.5%, with an average of 1.47%, for the lamellar marlstone, and ranges between 0.1% and 2.0%, with an average of only 0.76%, for the massive marlstone; after washing oil, the porosity increases obviously by 1.07% and 0.6% for lamellar marlstone and massive marlstone, respectively, indicating that some pores are filled with crude oil or asphalt under geological conditions. Due to the presence of laminated fractures, the lamellar marlstone has a higher horizontal permeability ($1.6 \times 10^{-3}$ $\mu$m$^2$) than that ($0.49 \times 10^{-3}$ $\mu$m$^2$) of the massive marlstone.
3.3 Pore space
The pore space in the marlstone in Es₃¹ is roughly divided into two types: pores and fractures (Figure 3). According to the genesis and morphology, pores are subdivided into: intergranular pore, dissolution pore, intercrystalline pore, intragranular/intracrystalline pore, and organic pore. Fractures are subdivided into: laminated fracture, structural fracture, and organic shrinkage fracture.

3.4 Pore structure
The marlstones with different rock fabrics are apparently distinct in pore distribution. The lamellar marlstone shows a strong heterogeneity of pore distribution. For the lime mudstone and lime siltstone laminae formed by mechanical deposition, matrix pores of various genesis are developed, and the pores are distributed in quasi-lamellar manner. For the micrite laminae formed by chemical precipitation, which are very tight, pores are underdeveloped. The massive marlstone with uniform fabric presents uniform spatial distribution of various matrix pores.

The lamellar marlstone and massive marlstone reservoirs are also very different in pore structure. The former contains abundant micro-fractures (laminated fractures), micro-scale medium-large pores (pore diameter ≥ 1 μm) and nano-scale micropores (pore diameter < 1 μm), suggesting the characteristics of dual or multiple pore media. The latter contains less micro-fractures and micro-scale medium-large pores, and reveals the pore structure worse than that of the lamellar marlstone. Both types of marlstone tight reservoirs are dominated by nano-scale pore throats, with micro-scale pore-throats generally less than 35%. However, the lamellar marlstone has the average proportion of micro-scale pore throats higher than that of the massive marlstone.

Figure 3. Pore space of the marlstone in Es₃¹ in the Shulu Sag, Bohai Bay Basin.

The sedimentary facies control the thickness, rock fabric and organic matter abundance of the marlstone. In general, the mixed marlstone developed in the semi-deep lake to deep lake environment has large thickness (up to 1000 m) and high TOC (above 4.0%), indicative of favorable facies belt for the development of marlstone reservoir.

Rock fabric here refers to the development degree of marlstone laminae or silt interlayer, which has obvious control on the porosity, permeability and pore structure of marlstone reservoir. The reservoir porosity, permeability, movable fluid saturation and NMR pore structure index of the lamellar marlstone are better than those of the massive marlstone.
The organic matter abundance controls the marlstone reservoir mainly in two aspects. On the one hand, it affects the development of pores in marlstone. On the other hand, it controls the oil content of the reservoir. Marlstones with high organic matter abundance can produce a large amount of organic acid in the early stage of hydrocarbon generation, allowing the creation of dissolution pores which can help improve the reservoir physical properties. For the “self-generation and self-preservation” tight oil reservoir, the level of TOC largely determines how much crude oil can be generated and retained. The positive correlation between the TOC and the rock pyrolysis S0+S1 or chloroform asphalt “A” of the Es3 marlstone indicates that the organic matter abundance has a significant control on the oil content, and the sample with TOC>2.0% has higher oil content.

 Compaction is one of the key factors leading to the decrease of porosity in clastic reservoirs during the burial process. For the mixed marlstone, which is not a typical clastic rock, there is no significant negative correlation between porosity and burial depth, indicating that compaction during burial process has no significant effect on the reduction of porosity in marlstone reservoir. However, burial depth significantly controls the maturity of organic matter. The deep trough area are characterized larger burial depth and higher organic matter maturity of marlstone than the slope area. Thus, a large number of organic pores can be formed in the deep trough area.

 Structural fractures are important storage space for oil, and also can significantly improve the permeability of the reservoir. High-angle structural fractures and laminated fractures are stacked to form a "fracture network", which is conducive to the enrichment and production of crude oil. Obviously controlled by fault distribution, the fractures in Es3 are mainly developed in the vicinity of the slope and fault belts, but underdeveloped in the deep trough area of the sag.

 It is revealed that the marlstone intervals with high TOC at TST and HST of SQ2–SQ3 in the western slope area and SQ2–SQ5 in the trough area can be taken as targets for tight oil exploration. The slope and trough areas are separated from the main fault by a certain distance, where the marlstone zones with structural micro-fractures and high organic matter abundance are favorable enrichment zones of tight oil.

4. Conclusions
There are two types of mixed marlstone tight reservoirs in Es3 in the Shulu Sag, namely, lamellar marlstone and massive marlstone. The pore space in such reservoirs can be divided into two types and eight sub-types. The matrix pores are mainly nano-scale pores. The physical properties and pore structure of the lamellar marlstone reservoir are superior to those of the massive marlstone. The marlstone in Es3 is universally oil-bearing. Lamellar marlstone shows a high heterogeneity of oil occurrence, but has better oil-bearing property than the massive marlstone. Development of favorable reservoir in the Es3 marlstone is controlled by multiple factors, such as sedimentary facies, rock fabric, organic matter abundance, burial depth, and structural fractures. The “sweet spot” of tight oil is mainly distributed in the inner zone of the gentle slope and the trough area of the sag.

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