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Sedimentary Patterns and Stratigraphic Trap Models of Deeply Buried Intervals in the Baxian Depression, North China

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Abstract: The Baxian depression is a typical half-graben located in the Jizhong sub-basin, north China. Commercial petroleum traps have been discovered in the Jizhong sub-basin. However, the 3rd and 4th members of the Shahejie Formation in this sub-basin have been poorly explored. These two members, belonging to the Lower Paleogene age, are buried deeply in the depression. Favorable petroleum reservoir conditions exist in such deep intervals of the half-graben due to the presence of different types and extent of deltas and turbidity fans in various areas. In fact, three types of turbidite fans are developed in the sag below the transitional belt on the eastern gentle slope. This work summarized three stratigraphic trap belts, i.e., the steep slope, gentle slope, and sag. On the steep slope, structural-stratigraphic traps with small-scale delta fronts and turbidite sandbodies are well developed. On the gentle slope, hydrocarbons generally accumulate in the large-scale delta front, onlapping beds and those sandbodies adjacent to unconformities. In the sag, petroleum trap models are typically characterized by pinched-out turbidite sandbodies. Stratigraphic traps were easily formed in turbidite fans below the eastern transitional belt. The petroleum traps that have already been discovered or predicted in the study area indicate that stratigraphic traps have favorable petroleum exploration potential in deeply buried areas (depth >5000 m) in a half-graben basin or depression.

Key words: half-graben, stratigraphic trap, transitional belt, turbidite fan, Baxian depression, Jizhong sub-basin

1 Introduction

In the past, hydrocarbon exploration has depended mainly on structural analysis (Reymond and Stampfli, 1996). Recently, stratigraphic analysis in hydrocarbon exploration has been gaining increasing attention. The definition of stratigraphic traps has been continuously improved over the past few decades (Levorsen, 1966; Rittenhouse, 1972; Milton and Bertram, 1992; Charpentier and Cook, 2004; Corcoran, 2006). Moreover, studies on the exploration for stratigraphic petroleum reservoirs have made significant progress (Walker, 1978; Ghazi and Schmidt, 1995; Reymond and Stampfli, 1996; McCaffrey and Kneller, 2001; Prather, 2003). Continuous progress has also been made in the exploration of stratigraphic reservoirs in rift basins in eastern China (Zou Caineng et al., 2005; Li Changbao, 2007; Feng Youliang et al., 2009). Half-graben basins generally comprise depression areas and lower parts of slopes with burial depths of >4000 m (Tuo Jincai et al., 1999). Although significant progress has been made in research on the sequence stratigraphy of continental strata and formation mechanisms of ultra-deep clastic reservoirs (Ma Yongsheng et al., 2016), stratigraphic reservoir exploration in deeply buried areas has proven to be difficult. Favorable source rocks and advantageous hydrocarbon accumulation conditions are present in the deeply buried area of the Xinglonggong (XLG) region. Commercial hydrocarbon accumulations have been discovered in these areas at shallow burial depths; for example, the Eocene Dongying Formation and the 1st member of the Shahejie Formation in the XLG area. Two drilled wells (XJ4 and XL1) with penetration depths exceeding 5000 m have revealed that petroleum may be accumulated at burial depths greater than 4500 m. This possibility encourages petroleum geologists to explore the

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more deeply buried areas in the half-graben for stratigraphic petroleum reservoirs. Economic petroleum accumulation in these intervals is dominated by two important factors of reservoir quality and traps.

This study aims to (1) illustrate the sedimentary characteristics of the half-graben and describe three types of turbidite fans in different system tracts; (2) construct stratigraphic trap models in deeply buried intervals; and (3) analyze appropriate stratigraphic traps and their reservoir quality in deeply buried intervals. This study proposes favorable exploration areas for stratigraphic reservoirs; these proposed areas may assist in expanding and shifting peroleum exploration efforts from shallow areas to more deeply buried areas of half-graben basins. From this case study, we deduce that economic hydrocarbon accumulations exist in deeply buried intervals of half-graben basins or depressions.

2 Data and Methodology

This study employed seismic, well log, core, and well test data. Twenty key wells were selected (Fig. 1); two typical core wells were chosen from the key wells for the descriptions of lithology and sedimentary structures. The

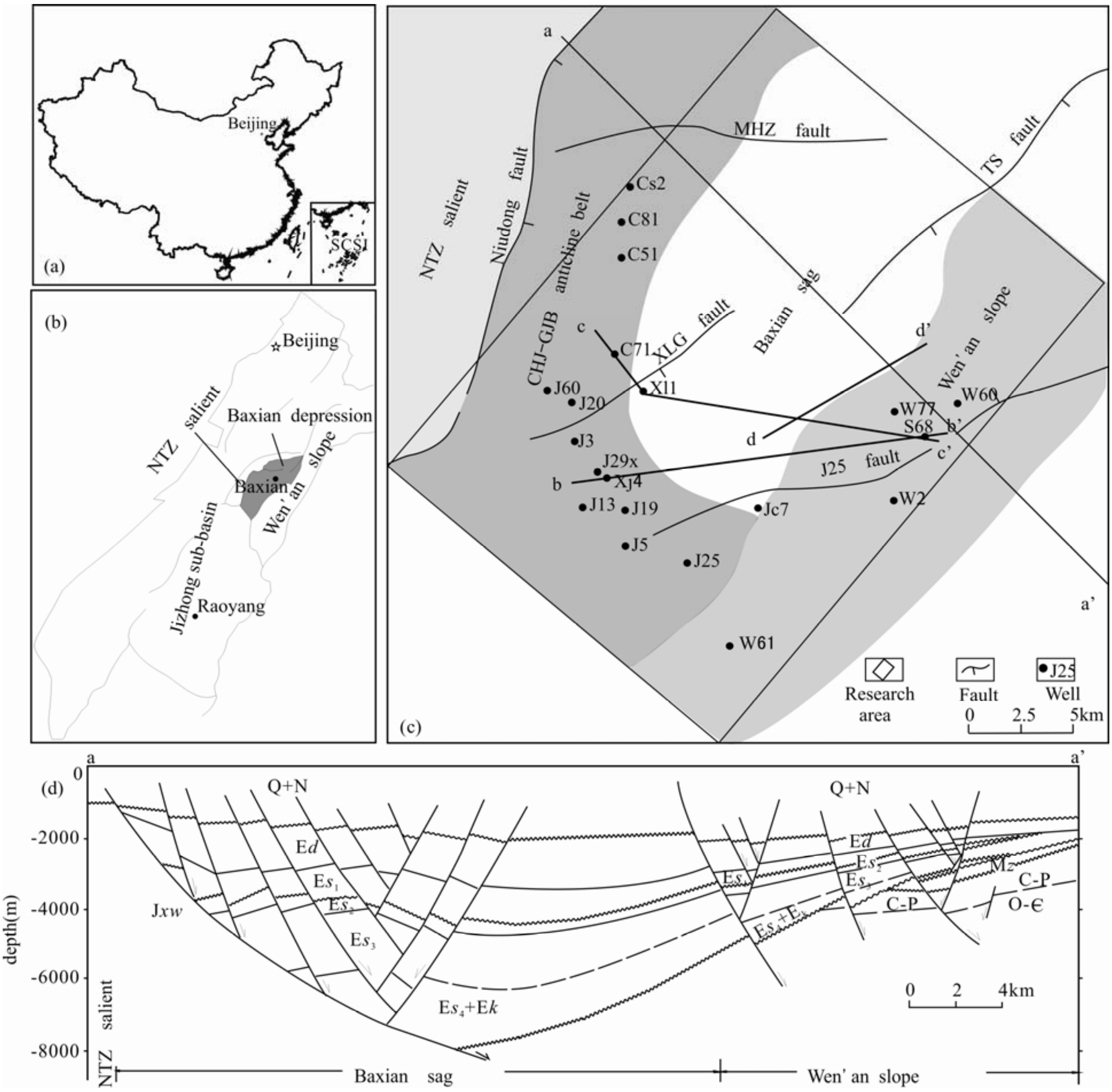

Fig. 1. Tectonic position of the study area (XLG). The study area is the southern part of the Baxian depression in the Jizhong sub-basin of northern China (a, b, and c). The study area comprises three parts (c and d): (1) the western part is the CHJ–GJB anticlinal belt; (2) the eastern slope is the Wen'an slope; and (3) the middle area is the Baxin sag. The Niudong fault is the western boundary of the study area.

data on reservoir porosity, permeability, and hydrocarbon-bearing characteristics were either calculated or obtained from wireline logs and core samples provided by the Huabei Oil Field Company of the China National Petroleum Corporation.

The sequence stratigraphy discussed in this study is based on previous studies of the basin tectonic and sedimentary settings. In addition, petroleum system theories were used to discuss basic petroleum accumulation conditions in deeply buried areas. To describe the differences in depositional settings among the gentle slopes, steep slopes and sag, we determined the sedimentary patterns within the sequence stratigraphic framework and constructed petroleum trap models suited to deeply buried areas of a half-graben of this type. Finally, by integrating drilled wells and reservoir properties (porosity and permeability), the deeply buried strata in the study area were concluded to have significant petroleum exploration potential.

3 Geological Setting

The study area (XLG) is located in the central part of the Baxian depression in the Jizhong sub-basin of North China and extends eastward to the middle section of the Wen'an slope. XLG is bounded by the western Niudong fault and is adjacent to the Niutuozhen (NTZ) salient (Figs. 1a, b and c). Within the study area are the Chaheji–Gaojiabao (CHJ–GJB) anticlinal belt, the inner belt of the Wen'an slope, and parts of the Baxian sag. Several major faults such as the XLG fault, the Jia25 (J25) fault and the Taishan (TS) fault are also included (Fig. 1c).

4 Sequence Stratigraphy

The 3rd and 4th members of the Shahejie Formation (Es_3 and Es_4) are the major components of the deeply buried intervals. Es_3 is subdivided into three sub-units: Es_3U, Es_3M and Es_3L. The lithologies of the Es_4 and the lower Es_3 (Es_3L) are similar: gray to dark-gray shales interbedded with gray-black carbonaceous shales, light-gray sandstones, and shaly siltstones. The upper part of the middle Es_3 (Es_3M) comprises halite and gypsum interbedded with oil shales, whereas the lower part of the middle Es_3 primarily comprises light-gray shaly siltstones and dark-gray and gray-black shales. The upper Es_3 (Es_3U) is characterized by purple, light-gray, and greenish -gray shales with interbedded light-gray sandstones. Gypsum, gypsum shales, halite, and gypsum-bearing shales are present in the Es_3U in the southwestern part of the study area. However, only a few wells (XJ4 and XL1) located in the western part of the study area (Fig. 1) have been drilled to this layer due to its great depth.

The Baxian depression is a dustpan-shaped depression (Zhang Yiming et al., 1999) with large-scale faults to the west and onlapped beds to the east (Fig. 1d; the location of the section is shown in Fig. 1c). The cross section (Fig. 1d) indicates that the depression is a typical half-graben. Tectonic activity in this area resulted in relatively deep burial in the west and shallow burial in the east. As to their sequence stratigraphy framework, Es_4 and Es_3 can be divided into the following five sequences from bottom to top: SQ1, SQ2, SQ3, SQ4, and SQ5 (Fig. 2). This arrangement is consistent with Pan's view of sequence stratigraphy (Pan Wenli et al., 2010).

The lacustrine basin began to shrink during the deposition of Es_3 (Es_3U) after lake levels increased during the deposition of the Es_4 and the early to middle periods of the Es_3 (Es_3M-L). This lake shrinking coincides with the overall lacustrine basin evolution in the Jizhong sub-basin (Zhang Yiming et al., 1999). The western area of the Baxian depression has large-scale faults and very thick deposits, whereas the eastern area is shallowly buried and has relatively thin deposits. In addition, tectonic movement caused three obvious unconformities in Es_4 and Es_3 (Fig. 2): T5 (the boundary between Es_2 and Es_3), T6 (the boundary between Es_3 and Es_4), and T7 (the bottom surface of Es_4). These tectonic uplift activities also caused the erosion and hiatus of the Wen'an slope to the east. The unconformities listed above can be easily identified on seismic profiles (Fig. 2).

We established a sequence stratigraphic framework model (Fig. 2) by tracing the important geological surfaces (e.g., sequence boundaries (SB) and maximum flooding surfaces (MFS)) on a seismic section. Unconformities located to the east have caused parts of the sequences to be missing. The lacustrine onlap scale varies by sequence (Fig. 2). An obvious transitional belt is present between the slope on the eastern slope and the sag. Transitioning from the slope to the sag, stratigraphic traps can easily form near the hydrocarbon source rocks. Consequently, favorable conditions exist for stratigraphic petroleum reservoirs in areas below the transitional belts.

5 Petroleum Discoveries

In the past, primarily intervals located at relatively shallow burial depth, such as the Dongying Formation (E*d*), the 1st and 2nd members of the Shahejie Formation (Es_1 and Es_2), and the upper 3rd member of the Shahejie Formation (Es_3U) were the major hydrocarbon targets in the Baxian depression. Three oil pools have been discovered in the Es_3U (C71, C3, J29x), with an oil area of 8.3 km^2 and geological reserves of about nine million tons

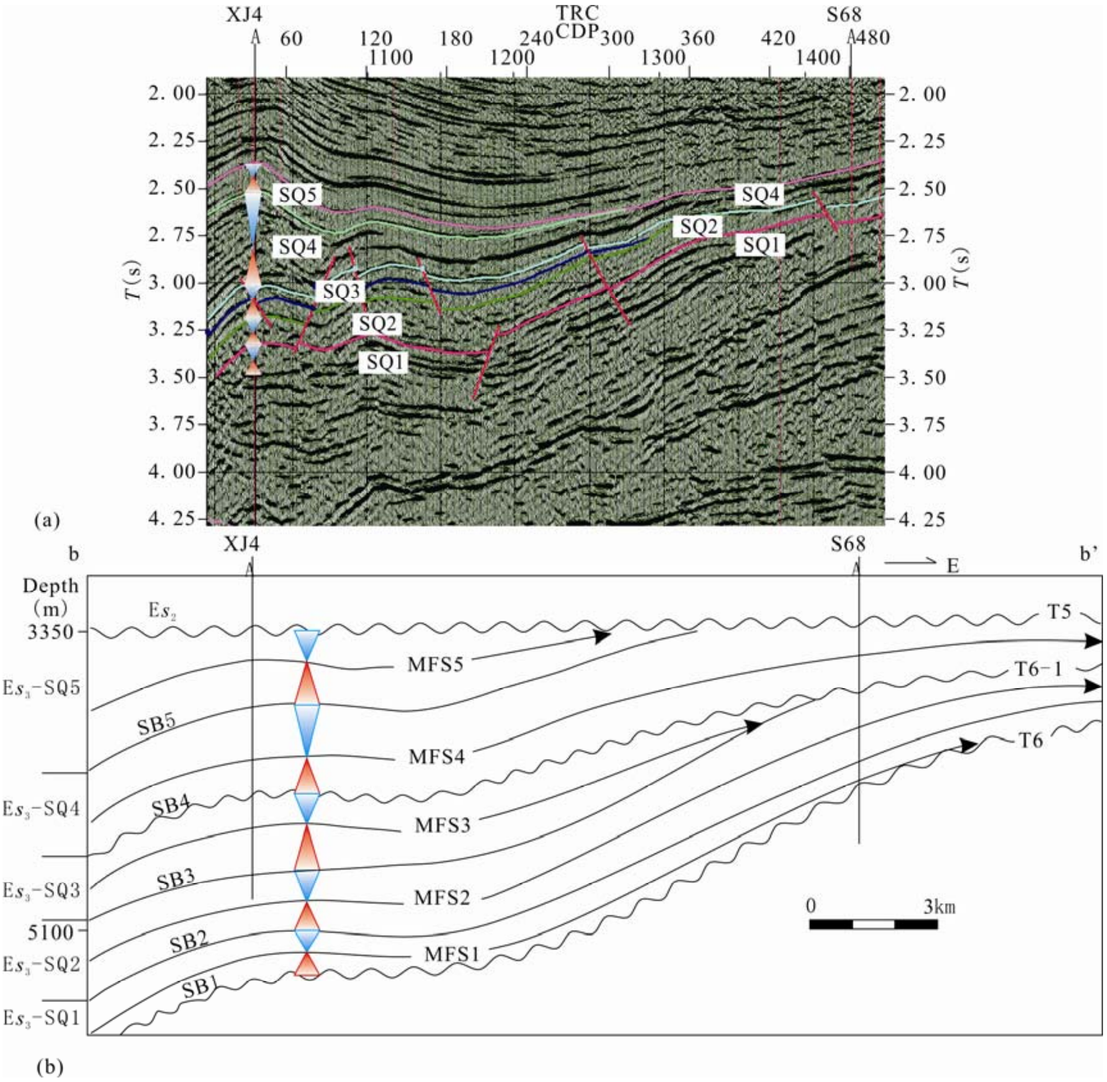

Fig. 2. Sequence stratigraphy correlation model (a, seismic section; b, sequence stratigraphy pattern). The E*s*$_3$ member is divided into five sequences. Three sequence boundaries (SBs) are unconformities: T5, T6–1, and T6. Truncated by two unconformities (T5 and T6–1), two sequences (SQ5 and SQ3) are not developed on the eastern slope; the position of the section (b–b') is shown in Fig. 1c. E*s*$_3$, 3rd member of Shahejie Formation; E*s*$_2$, 2nd member of Shahejie Formation.

of oil. However, drilled wells have rarely penetrated the top of the E*s*$_3$U formation in this area. A sandstone reservoir with profitable hydrocarbon content was discovered when the Well XJ4 was drilled to a depth of 4598–4670 m in the lower part of the E*s*$_3$. The oil production test produced 5.13 tons of oil and 5383 m^3 of gas per day, indicating favorable accumulation conditions and promising exploration potential in deeply buried areas. In particular, intervals buried to depths of over 4500 m in the Well XL1 also show significant economic hydrocarbon accumulations. The petroleum discoveries discussed above show that the exploration potential in deeply buried intervals is excellent.

In addition, the strata transporting petroleum gradually became younger from the Baxian sag to the outer belt of the Wen'an slope (Lu Xuejun et al., 2010). We studied the E*s*$_3$ and E*s*$_4$ source rocks and their adjacent reservoirs in deeply buried areas because they exhibit good potential for hydrocarbon generation and migration.

6 Sedimentary Patterns

The Jizhong sub-basin was dominated by fluvial deltas during the entire depositional period of E*s*$_4$ and E*s*$_3$ (Ji Youliang et al., 2009). During the deposition of E*s*$_4$ and E*s*$_3$, the Baxian depression had a sedimentary environment similar to that of the Jizhong sub-basin. Depositional filling patterns on the gentle eastern slope significantly differ from those on the western slope due to the half-graben features resulting from tectonic activity. We used two drilled wells to analyze the differences in sedimentary patterns between the two slopes (Fig. 3). The Well XL1, located adjacent to the western slope, reveals subaqueous sedimentary facies with abundant coarse-grained sediments (Fig. 3a); in contrast, the Well S68 on the eastern slope exhibits a fluvial or delta-plain environment (Fig. 3b).

By combining well data, seismic data, and sequence stratigraphy interpretation (Fig. 4), we constructed a theoretical depositional filling pattern (Fig. 3c). We assumed that fan or braided deltas with wide lobes would exist on the steep western slope. Furthermore, we predicted that fluvial deltas (bird foot-type and dendritic lobe-type) with relatively fine-grained sediments would prevail on the gentle eastern slope. Our model also indicated that turbidite fans may be found in deeply buried areas of the sag. This depositional filling pattern is similar to that of typical half-graben basins (Yu Xinghe et al., 2007). Large-scale and fine-grained turbidite fans were deposited at the foot of a transitional belt located between the gentle slope and the sag. This kind of fine-grained turbidited fans should be similar to deepwater turbidite lobe deposits (Zhang Leifu et al., 2017). In fact, three turbidite fans were identified in different system tracts with different depositional characteristics: progradation in the lowstand system tract (LST); retrogradation in the transgression system tract (TST); and channel filling in the HST (Fig. 5). Large-scale turbidite fan reservoirs are

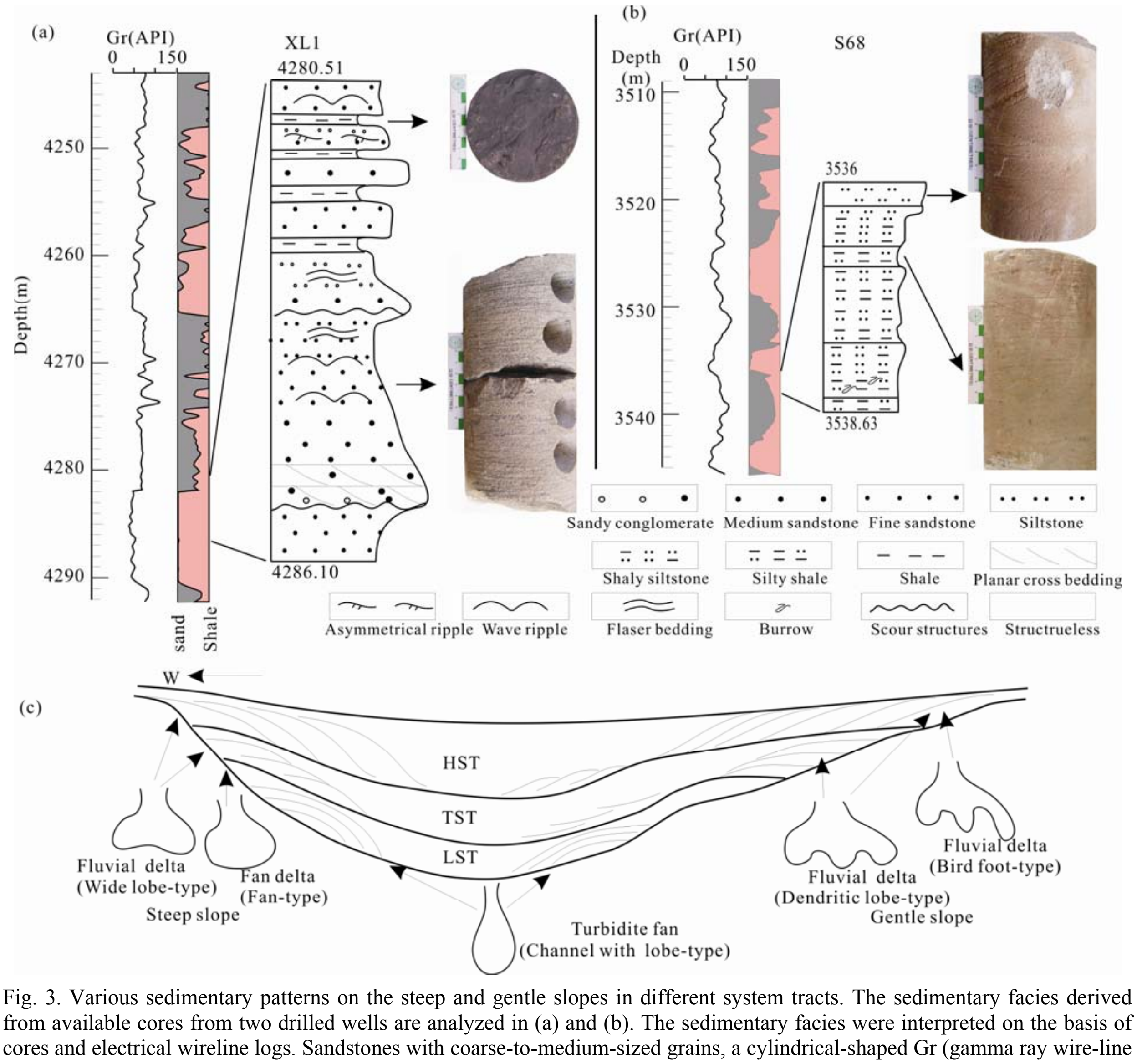

Fig. 3. Various sedimentary patterns on the steep and gentle slopes in different system tracts. The sedimentary facies derived from available cores from two drilled wells are analyzed in (a) and (b). The sedimentary facies were interpreted on the basis of cores and electrical wireline logs. Sandstones with coarse-to-medium-sized grains, a cylindrical-shaped Gr (gamma ray wire-line log) curve (the API record readings of Gr of sandstones are relatively small), and dark gray shales prevail in the Well XL1. However, the API record readings of Gr of sandstones in Well S68 are relatively high, indicating that the fraction of fine-grain-sized sandstones is greater than that of coarse-grain-sized sandstones. In addition, the bell shape Gr curve (grain size fining up-wards) is the main pattern of sandstones interbedded with purple shales in Well S68. The sedimentary facies of other wells were interpreted on the basis of electrical well-logging curves (Gr). (c) is a theoretical depositional filling pattern in this type of half-graben.

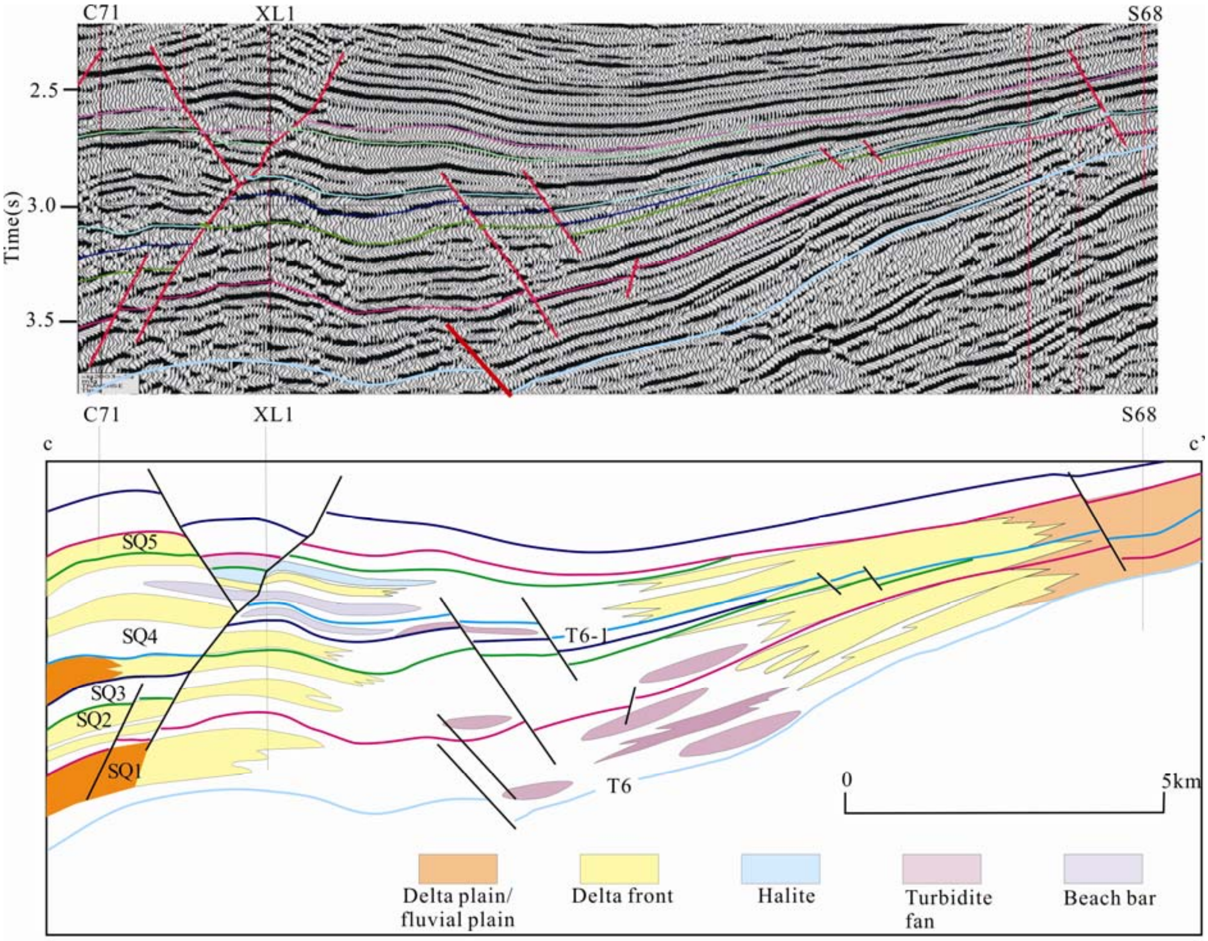

Fig. 4. Sequence stratigraphy interpretation of a seismic section in the study area. The location of the section is shown in Fig. 1c. Seismic reflection phenomena were used to indicate special sedimentary facies (for example, in Fig. 5, the interpretation of turbidite fans at the foot of the eastern transitional belt). The depositional filling pattern (Fig. 3c) was obtained from the seismic section.

likely to form in the east at the foot of the transitional belt where the sediments are abundant (Fig. 5).

Different types of deltas with various distribution shapes are generated by sediments from three primary directions (Fig. 3) (Xie Xiaojun et al., 2008). During the deposition of Es_4 and Es_3, turbidite fans formed in front of deltas (Fig. 6). Moving from north to south, the western part of the study area comprises three different depositional zones along the Niudong fault. In the northern segment, a lobate-shaped fluvial delta with a shallow lacustrine beach bars formed as a result of the sufficient sediment supply from the northwest. The middle segment of the Niudong fault, whose topography is marked by steep terrain, exhibits fan deltas that mainly emerge along the root of the Niudong fault. Lobate-shaped, fine-grained deltas formed as a result of the adequate supply of clastic materials from the southwest (Fig. 6) in the southern section of the Niudong fault, where the terrain is relatively low due to the weak tectonic activity of the fault.

Fluvial deltas with dendritic lobes are predominant in the eastern part of the study area. These deltas rapidly prograde onto the lower part of the slope or the sag due to relatively low accommodation on the gentle slope. Delta-front sediments slump onto the lower part of the slope near the transitional belt to form relatively large-scale turbidite fans. Lacustrine shales are the major components of the center of the study area. Sediments in the southwest formed a bird foot-shaped delta along the strike of the sag (Fig. 6).

7 Petroleum Trap Models

Based on the structural features and sedimentary facies, we identified various favorable stratigraphic petroleum traps in three structural belts: the steep slope to the west, the gentle slope to the east, and the sag (Fig. 7).

7.1 Traps on the steep slope

7.1.1 Composite structural-stratigraphic traps

The Niudong and other related faults control local

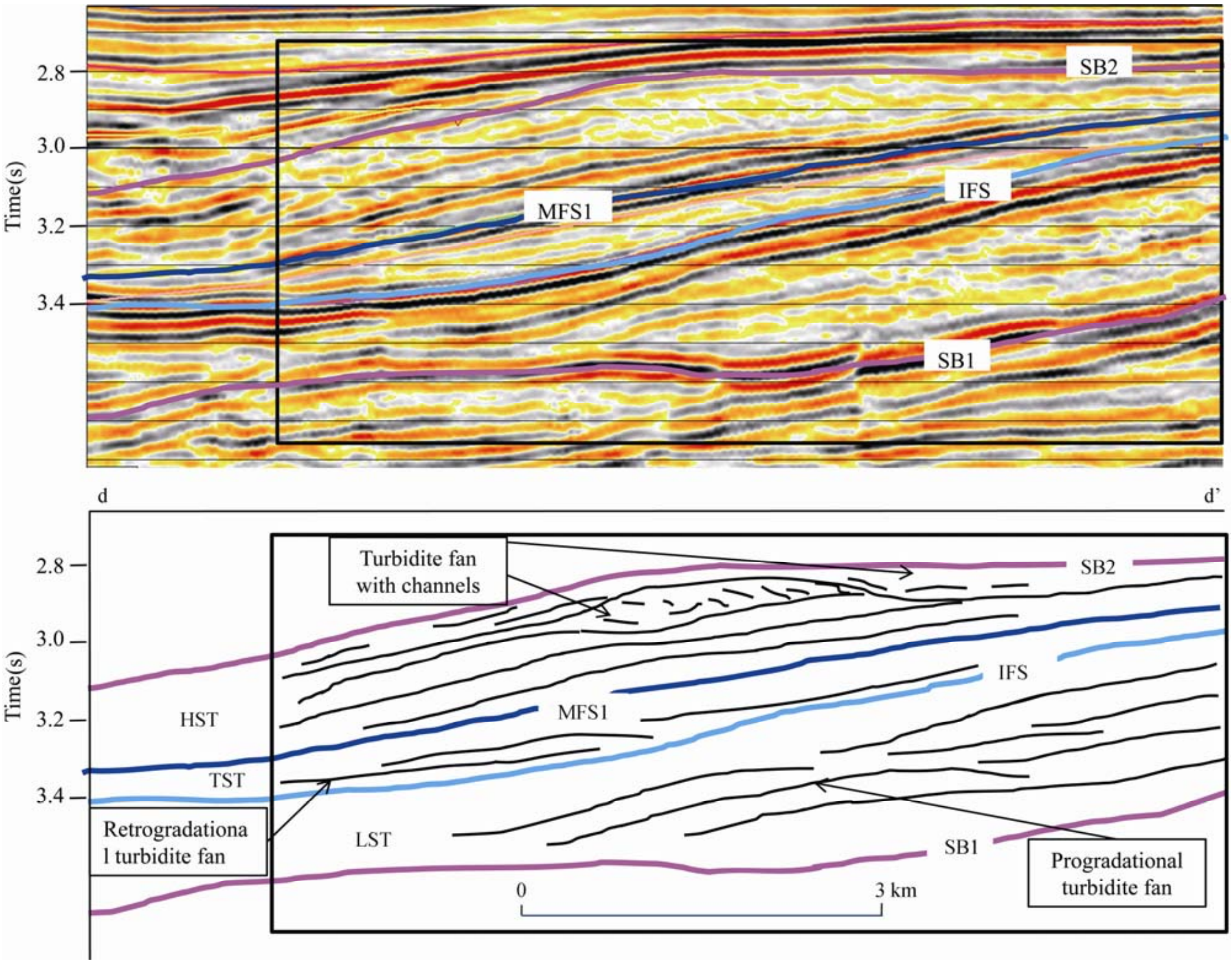

Fig. 5. Three different types of turbidite fans interpreted from a seismic section of the eastern slope. Turbidite fans are located in front of the eastern delta front (as shown in Fig. 6). The location of the section (d–d') is shown in Fig. 1c.

secondary structures in the Es_4 and Es_3 on the steep western slope. The high system tracts of the SQ2, SQ3, and SQ5 sequences show the typical secondary structures; one of these structures with petroleum accumulations is visible in the well XL1. The reservoirs are mainly dominated by fan delta front reservoirs and faults; therefore, composite structural-stratigraphic traps are likely to occur on the steep western slope (Fig. 7; trap type ①).

7.1.2 Delta front sandstone stratigraphic traps

During the Es_4 and Es_3 depositional periods, the southwestern part of the CHJ–GJB structure (location shown in Fig. 1c) began to rise/move upward and erode; consequently, abundant sediments were deposited in the sag, where they formed deltas. Tectonic compression and tectonic inversion generated an anticlinal structure. Subaqueous distributary channels of delta-front and stratigraphic traps pinch out upwards because of tectonic activity (Fig. 7; the west, trap type ②).

7.2 Traps on the gentle slope

7.2.1 Large-scale delta front lithologic traps

The gentle eastern slope (the Wen'an slope) had favorable conditions for the formation of large-scale deltas because of the abundant sediment supply. Changes in lake levels produced sedimentation patterns, such as progradation and retrogradation, in these deltas. Delta-front sandstone interbedded with shale created favorable assemblages for reservoirs and seal rocks, leading to the formation of delta-front stratigraphic traps (Fig. 7; trap types ④ and ⑤).

Significant petroleum accumulation potential is present in the Liuxi area of the Raoyang depression, which is adjacent to the Baxian depression in the Jizhong sub-basin. Exploration activity has revealed 50 million tons of original oil in place (OOIP) in the Liuxi area (Wang Zhihong et al., 2005; Yi Shiwei, 2005; Liu Zhen et al., 2007), which indicates the significance of this kind of stratigraphic trap.

7.2.2 Stratigraphic onlapping and unconformity traps

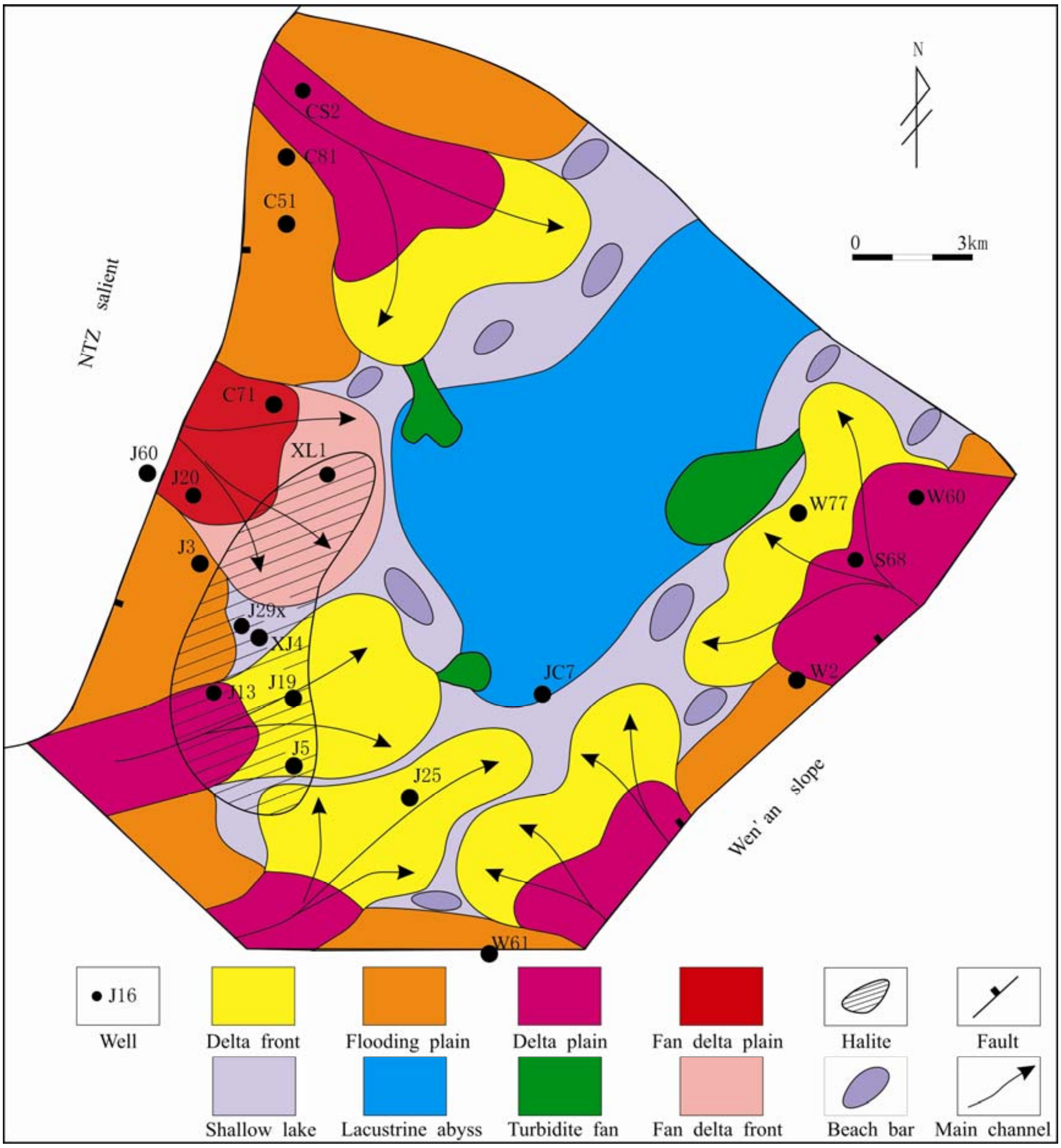

Fig. 6. Sedimentary pattern of sequence SQ1 in the study area. In the lacustrine environment, deltas are very well developed. A fan delta system is present along the downthrown wall of the Niudong fault in the western part of the study area. In the sag, the variable-scale turbidite fans that are present in front of the delta fronts have formed favorable stratigraphic petroleum reservoirs. NB, Halite deposited in sequence SQ4 provides a very important seal for petroleum accumulations in the western part of the study area.

The LST and TST of each sequence in the Jizhong sub-basin are likely to form stratigraphic onlapping reservoirs (Zhao Xianzheng et al., 2007). As discussed above, the study area is characterized by faulting in the west and onlapping in the east. Therefore, the deltas in the eastern part of the study area may contain stratigraphic onlap traps. These traps either overlay unconformities (Fig. 7; trap type ④) because of delta retrogradation or underlay unconformities due to tectonic uplift (Fig. 7; trap type ⑥). However, petroleum accumulation may be limited by the prevention of hydrocarbon preservation by faulting or unconformities.

7.3 Traps in the sag

7.3.1 Fan delta front and lenticular traps

During the deposition of Es_3 and Es_4, the movement along the middle-northern section of the Niudong fault suddenly increased, resulting in large fault displacements and steep terrain. As a result of fault activity, numerous small turbidite fans formed along the Niudong fault in the western part of the study area. The upward sandstone pinch-out and lenticular sandstone traps formed because of tectonic inversion during the deposition of the Es_2. These two types of small-scale petroleum traps are primarily located in the north-central part of the sag (Fig. 7; trap type ③).

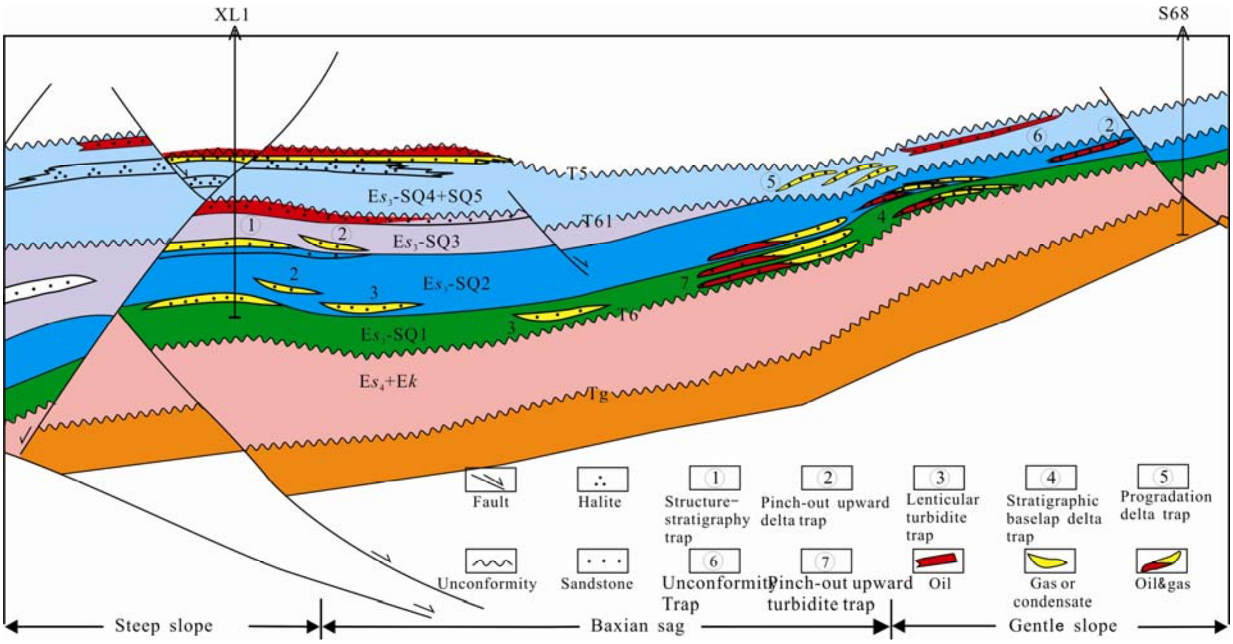

Fig. 7. Petroleum trap model of the 3rd member of the Shahejie Formation in the study area. Seven types of traps have formed in the three parts, the steep slope, gentle slope, and sag, of this study area. Various petroleum trap types are present in the different areas.

7.3.2 Turbidite fan traps

The strata thickness abruptly decreases near the transitional area and results in overlap, pinch-out, and erosion phenomena in the inner belt of the Wen'an slope on the edge of the Baxian sag (Figs. 1c and d). Multiple faults acting on various sandbodies generated nose-like fault blocks (Xin Weijiang et al., 2008). Influenced by the transitional belt to the east, several large-scale turbidite fans interbedded with mature hydrocarbon-source rocks are observed in the eastern part of the sag. These fans are likely to form stratigraphic traps (Fig. 7; trap type ⑦). This type of petroleum trap is primarily present in the SQ1 and SQ2 sequences because the transitional belt has relatively steep palaeomorphology between the gentle slope and the sag. The typical example shown in Fig. 5 indicates that the depositional characteristics of turbidite fans vary in different system tracts.

The abovementioned stratigraphic traps are important to estimate the petroleum exploration potential of deeply buried intervals in the study area. In particular, the inner belt of the eastern slope (within the sag at the foot of the eastern transitional belt) is the most important area for stratigraphic petroleum accumulation.

8 Reservoir Properties

The key factors in petroleum accumulation in traps in deeply buried intervals in this type of half-graben are reservoir physical properties. Based on electrical well-logging data, the cut-off for oil reservoir porosity in the Baxian depression is greater than 10% and the permeability cutoff is greater than 10×10^{-3} μm^2. However, for gas-bearing reservoirs, the porosity cutoff is about 7%, and the permeability cutoff is about 0.5×10^{-3} μm^2 (Fig. 8).

Due to the burial depth, not all sand bodies in Es_4 and the lower part of Es_3 have good reservoir physical properties. For example, the reservoir porosity with a burial depth exceeding 4500 m in Well XL1 (penetrated depth >5400 m, Fig. 9) ranges from 5% to 9.4% with an average porosity of 6.33% and permeability ranges from 0.01×10^{-3} μm^2 to 3.67×10^{-3} μm^2 with an average value of 0.6×10^{-3} μm^2. The reservoir properties of deeply buried intervals (>4500 m) may make them unsuitable for crude oil accumulation but favorable for natural gas accumulation. However, this is not always the case; as discussed above, commercial oil was discovered in Well XJ4 at a burial depth >4500 m. These conditions also exist in Well XL1 (Fig. 7 shows several gas-bearing intervals in SQ2 and SQ3). The excellent reservoir characteristics of these sandstones, despite their extreme burial depth, can be explained as follows: overpressure developed in these reservoirs as a result of rapid deposition, which probably caused a delay in compaction (Roure et al., 2003). This situation is quite common in such half-graben basins or depressions. Therefore, economic petroleum accumulations may be present in deeply buried areas in this type of basin.

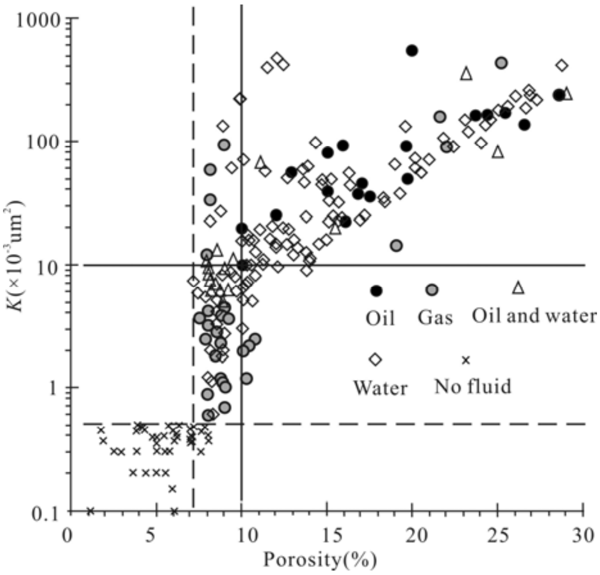

Fig. 8. Porosity and permeability cutoffs of petroleum reservoirs in the Baxian depression. The porosity and permeability of oil-bearing reservoirs are more than 10% and 10×10^{-3} μm^{2,} respectively. The cutoffs for gas-bearing reservoirs are lower, 7% and 0.5×10^{-3} μm^2, respectively. Data are based on the interpretation of electrical well logs correlated to core test data.

9 Discussions of the Petroleum System

To discuss the advantageous conditions for petroleum accumulation in deeply buried intervals in the study area, we used the Magoon's concept of petroleum systems (Magoon, 1994).

9.1 Source rocks

The Baxian sag plays a major role in hydrocarbon generation in the Baxian depression (Zhao Xianzheng et al., 2011a). Three effective hydrocarbon source layers are present: Es_1, Es_3, and Es_4 (Liang Hongbin et al., 2002; Gong Yuling et al., 2008; Li Xin et al., 2008). Among these, the source rocks in Es_1 are very important for petroleum accumulation in shallowly buried intervals (Liu Hua et al., 2011); the other two sets of source rocks in Es_3 and Es_4 are important for petroleum generation in deep intervals. According to source rock sample analysis in Well XL1, shales in Es_3M-L and the upper part of Es_4 are comparatively good source rocks, whereas shales in the lower part of Es_4 are medium-quality rocks (Li Xin et al., 2008). In particular, during the SQ2 and SQ3 periods, in which large-scale lacustrine transgression occurred, a thick layer of dark shale accumulated and evolved into an active source rock. For example, Es_4 and Es_3 hydrocarbon source rocks were buried deeply in certain areas of the CHJ–GJB structural belt (Fig. 1; west of the study area), where they reached a mature stage. Hence, both condensate and natural gas have been generated in the deeply buried region.

In addition, two sets of gas source rocks are present in the northern part of the Jizhong sub-basin: Carboniferous

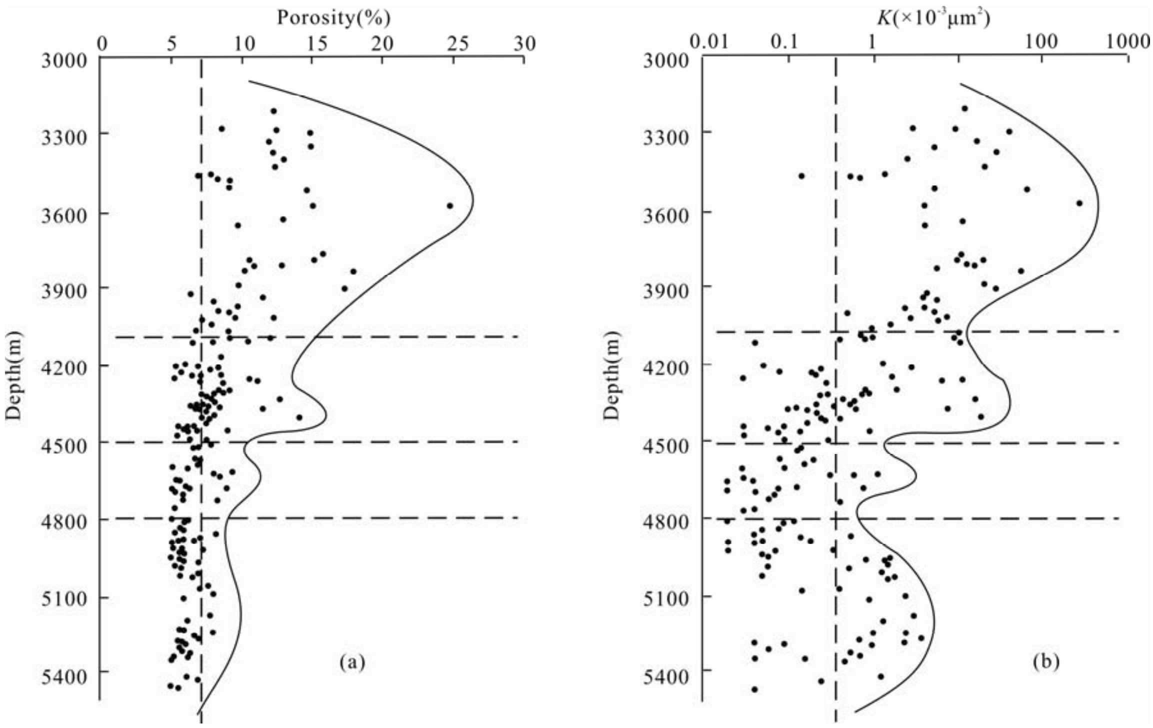

Fig. 9. Variations of porosity (a) and permeability (b) with depth. Porosity and permeability remain suitable for gas accumulation at burial depths of more than 4500 m. An interesting phenomenon is that permeability may increase and exceed 2×10^{-3} μm^2 at depths of >5100 m.

coal and Paleogene dark shale. These source rocks provide favorable conditions for petroleum generation and preservation in natural gas reservoirs (Liang Hongbin et al., 2002; Fang Jie, 2004). Most traps in deeply buried areas in Es_4 and Es_3 are surrounded by high-quality source rocks. Consequently, deeply buried hydrocarbon reservoir accumulations are primarily natural gas or condensate reservoirs and are concentrated mainly in Es_3L and Es or below Es_4.

9.2 Reservoir rocks

Delta front sandbodies are the main reservoirs interbedded with source rocks (Ji Youliang et al., 2009). The decreasing lacustrine water level caused delta progradation, resulting in a large sheet of delta-front sand with favorable physical properties. Moreover, deeply buried favorable reservoirs have been shown to exist (Zhao Xianzheng et al., 2011b). As mentioned above, deltaic sandbodies are the primary components of the intervals of typical proven reservoirs located at depths between 4500 m and 4670 m in Well XJ4.

The reservoirs that form in this region are highly diverse and abundant because various sedimentary facies are present in Es_4 and Es_3. In particular, turbidite fan reservoirs in front of delta fronts may have been formed (Figs. 5 and 6). As discussed above, these reservoirs have good reservoir properties despite their extremely deep burial depths.

9.3 Seal rocks

Preservation conditions are one of the important factors to successfully find hydrocarbon (Xu Guosheng et al., 2014), and seal rocks are critical for petroleum preservation. Halite is abundant in the western part of the study area, but only well XJ4 penetrates the halite layer, which has a total thickness of about 270 m. Relatively thick shales are present in the middle section of Es_3 and can be seen in well XJ4. The total shale thickness is about 400 m, and a single shale layer may attain a thickness of 90 m. This shale provides favorable conditions for seal rocks in Es_4 and Es_3.

During the deposition of the Es_2 member, the climate was dry and the lacustrine basin shrank; consequently, a salt lake formed in the CHJ–GJB anticlinal belt (Pan WenLi, 2010). The lithology of the salt lake is composed of shales interbedded with gypsum and gypsiferous mudstones with a total thickness of about 340 m; it is considered to represent a set of good seal rocks.

9.4 Overlying strata and petroleum generation–migration–accumulation

According to the basin modeling results, Es_4 and Es_3 source rocks in the Baxian sag started to generate and gradually expel abundant hydrocarbons between 30 and 20 Ma (Li Xin et al., 2008; Jiang Fujie et al., 2010; Li Wentao and Chen Honghan, 2011). Oil generation peaked at a burial depth of approximately 4600 m. When the burial depth reached 5100 m, the average temperature was likely as high as 176 °C and condensate and wet gas could be generated (Jiang Fujie et al., 2008; Li Xin et al, 2008). Therefore, the overlying Paleogene strata beneficial to oil generation are Es_4, Es_3, Es_2, Es_1, and E*d*. Condensate and wet gas generation may have started in Es_4 and Es_3 during the deposition of the Neogene strata (Li Xin et al., 2008).

The stratigraphic reservoirs in the Raoyang depression (Liu Zhen et al., 2007; Wang Zhihong et al., 2005), which is located adjacent to the Baxian depression and shows high petroleum potential, should be able to be successfully explore for petroleum. The basic geological conditions for petroleum accumulation are present in deeply buried intervals of the Jizhong sub-basin. High heat flow easily accelerates the maturation of source rocks in a half-graben basin or depression. Meanwhile, the structures and fluid transportation performances of faults could affect hydrocarbon accumulation (Du Chunguo et al., 2014). Vertical hydrocarbon migration and multi-source hydrocarbon mixtures are possible due to the growth of a normal fault network (Liu Hefu et al., 2003). According to the rule of complementarity for hydrocarbon distribution in an oil-rich depression (Du Jinhu et al., 2004), the total quantity of hydrocarbons is constant; thus, stratigraphic reservoirs are often present where structural reservoirs rarely occur (Du Jinhu et al., 2004). Thus, the rule raises the following question: what are the favorable conditions for petroleum accumulation in stratigraphic reservoirs in deeply buried intervals (e.g., Es_4 and Es_3) in the study area?

We discussed the sedimentary facies characteristics and stratigraphic petroleum trap prospects in a half-graben in North China and indicated that economic hydrocarbon accumulations exist in the deeply buried intervals. The most important factor affecting the petroleum accumulation is the presence of perfect reservoirs in the deeply buried intervals in a half-graben basin. In particular, pinched-out turbidite sandbodies below transitional belts of grabens can form perfect stratigraphic petroleum traps. In addition, we should pay attention to the reservoir properties in the deeply buried strata.

10 Conclusions

Favorable stratigraphic petroleum accumulation conditions and various types of stratigraphic traps are found in deeply buried areas below the eastern and western slopes in the Baxian depression. The stratigraphic traps at the foot of the transitional belt in the east are particularly notable. These traps, mainly dominated by turbidite fans in front of delta fronts, have multiple layers composed of progradation, retrogradation, or turbidite channel superposition patterns. These stratigraphic traps may have accumulated hydrocarbons because they are surrounded by mature source rocks. The majority of reservoirs formed at burial depths exceeding 4500 m or even 5000 m in Es_4 and Es_3 are primarily gas or condensate-gas reservoirs. The results of this study suggest that when suitable petroleum accumulation conditions are present, deeply buried areas in similar half-graben basins or depressions may have considerable petroleum exploration potential, even at burial depths of more than 5000 m.

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