Sedimentary characteristics and hydrocarbon accumulation of glutenite in the fourth member of Eogene Shahejie Formation in Shengtuo area of Bohai Bay Basin, East China

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Sedimentary characteristics and hydrocarbon accumulation of glutenite in the fourth member of Eogene Shahejie Formation in Shengtuo area of Bohai Bay Basin, East China

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Abstract

The genetic type and hydrocarbon accumulation conditions of glutenite in Shengtuo Area have been studied based on cores, well-logs, and formation test data. During deposition of the fourth member of Eogene Shahejie Formation (Es4), Shengtuo Area was predominated by nearshore subaqueous fan and sublacustrine fan, controlled by the Chennan Fault and the Tuo-Sheng-Yong Fault. Nearshore subaqueous fan and sublacustrine fan were respectively developed on the downthrown of the Chennan Fault and the Tuo-Sheng-Yong Fault. Both of nearshore subaqueous fan and sublacustrine fan can be subdivided into three subfacies, including inner fan, middle fan and outer fan, from proximal to distal provenance. The braided channel within the middle fan, characterized by conglomeratic sandstones and sandstones with high secondary porosity and overpressured microfissures resulted from the effect of organic acid and reservoir overpressure, is the best reservoir among these three subfacies. Inner fan subfacies, consisted of thick-bedded, poorly-sorted and matrix-supported conglomerates, has low primary and secondary porosity, is the best sealing among this depositional system. Outer fan sediments, comprised of thick dark mudstones interbedded with thin sandstones in which overpressured microfissures developed very well, accounts for the migration pathway for oil and gas to enter braided channel reservoir from source rocks. In addition, the glutenite fans were developed near the Lijin Sag and the Minfeng Sag, which deposited two sets of high quality source rocks (Es4s (upper section of Es4) and Es4x (lower section of Es4) source rock). With regional cap rock and appropriate preservation conditions, the different subfacies in glutenite fans worked together and formed a “self-generation and self-storage” lithostratigraphic trap characterized by “migrating through outer fan, accumulating in middle fan and sealing by inner fan”. 
1. INTRODUCTION
Glutenites, especially those block-like massive deposits in rift basins, consist of sandstones and conglomerates, commonly include alluvial fan, fan delta, nearshore subaqueous fan and sublacustrine fan (Kong, 2000; Sui, 2003). These fans are generally developed during the late stage of initial subsidence and the early stage of accelerated subsidence (Wu et al., 2002), and formed on the escarpment of rift basins characterized by steep slope, proximal provenance, high relief topography and intense tectonic movement (Kneller and Branney, 1998; Dasgupta, 2002; Han et al., 2003; Lin et al., 2005). These glutenites interfingering with lacustrine mudstones and being near source rocks, can form multi-type reservoirs (Xie et al., 2002; Zouhri, 2004).

As the development of the major oil and gas bearing basins has been deeply matured in China, the focus of the onshore exploration objectives have turned to the litho-stratigraphic reservoirs (Jia and Chi, 2004; Jia et al., 2004; Jia et al., 2008; Sun et al., 2009). As an important type of litho-stratigraphic reservoirs, the exploration of glutenite reservoirs has made a great breakthrough in rift basins like Nanxiang Basin and Bohai Bay Basin in Eastern China recently (Jiang et al., 2003). For example, glutenite reservoirs with an approximate amount of $6 \times 10^8$ t account on 7.63% of the proven oil reserves in Bohai Bay Basin (Yuan and Qiao, 2002). The glutenite reservoirs have become key litho-stratigraphic reservoirs in rift basins of Eastern China (Sun, 2003; Lin et al., 2005; Qi, 2006).

Shengtuo Area is located on the northern escarpment of Dongying Depression in the Bohai Bay Basin (Fig. 1). Due to steep topography, proximal provenance, and intense structural activities (Yuan and Xu, 2003; Yan et al., 2005), the glutenites fans, including nearshore subaqueous fans and sublacustrine fans, developed widely in this area during deposition of the fourth member of Eogene Shahejie formation ($Es_4$), (Jiang et al., 2003; Sun, 2003). These glutenite fans have become important exploration targets in the Dongying Depression currently. For example, the formation test data indicated that Well FS1 produced 81.7 t/d of oil and $11.8 \times 10^4$ m$^3$/d of gas in braided channel sand bodies of nearshore subaqueous fan, and Well T764 produced 15.21 t/d of oil and 1043 m$^3$/d of gas in braided channel sand bodies of sublacustrine fan. However, due to the lacks of understanding of high-quality reservoir distribution and hydrocarbon accumulation patterns of glutenite, success rate of glutenite reservoir exploration is relatively low. At present, success rate of exploration well with over 5 t/d oil production is about only 10%. So, detail studying of sedimentary characteristics and hydrocarbon accumulation patterns of glutenite reservoirs in Shentuo Area is very important to increase the sucess rate of exploration of glutenite reservoir on the steep slope of fault basin or rift basins.

2. GEOLOGIC BACKGROUND
Dongying Depression is located on the southeast of Bohai Bay Basin, with escarpment structural belt controlled by the shovel-shaped Chennan Fault in north. Shengtuo Area
is located in the center of the escarpment structural belt, with Chenjiazhuang Bulge in north, Central Fault anticlinal zone in south, Lijin Sag in the southwest, and Minfeng Sag in southeast (Fig. 1). The exploration area of Shengtuo Area is about 230 km² (Zhang et al., 2004; Sun, 2006) (Fig. 1). Since 1960’s, seven oil-bearing strata have been discovered, including the fourth (Es4), the third (Es3), the second (Es2) and the first member (Es1) of Shahejie Formation, Dongying Formation (Ed), Guantao Formation (Ng) and Minghuazhen Formation (Nm) with total estimated oil reserves of over $5 \times 10^8$ t (Li et al., 2003). The discordogenic faults, such as Chennan Fault and Tuo-Sheng-Yong Fault together with their descendent faults in the central and northern part of Dongying Depression, controlled the development of the deposition of Shengtuo Area (Ren et al., 2004; Zhu et al., 2004). The study interval Es4 is in the early stage of the second chasmic stage of Dongying Depression (Yuan and Xu, 2003). The climate was semi-arid and muggy during Es4 (Wang et al., 1994; Sun, 2006) and it was in favour of mechanical weathering of mother rock and development of glutenite sediments. On the setting of the steep topography controlled by Chennan Fault and Tuo-Sheng-Yong Fault, gravity flows caused by surging flood, formed nearshore subaqueous fan and sublacustrine fan, which were closed to the source rock in the center of the Dongying Depression (Kong, 2000; Wang and Sui, 2003; Yan et al., 2005).

3. FACIES ASSOCIATIONS
Based on a comprehensive analysis, it concluded that the glutenites of Es4 in Shengtuo Area were primarily developed in two major sedimentary facies, nearshore subaqueous fan and sublacustrine fan. Nearshore subaqueous fan was developed on the downthrown of Chennan Fault being closed to the provenance, whereas sublacustrine fan was deposited on the downthrown of Tuo-Sheng-Yong Fault being far away from the provenance (Fig. 2).

Figure 1. (A) Location of Shengtuo Area in Dongying Depression of Bohai Bay Basin. (B) Structure map of Shengtuo Area. CN Fault-Chennan Fault; TSY Fault-Tuo-Sheng-Yong Fualt.
3.1. Nearshore subaqueous fan

During $Es^4$, nearshore subaqueous fans spread widely on the downthrown of Chennan Fault. The Nearshore subaqueous fan is mainly composed of matrix-supported conglomerates. The gravel is poorly-sorted and poorly-rounded, showing angular or subangular shape. Multiple phase fans are separated by dark mudstones, and single fan can be divided into inner, middle and outer fans from near source to distant source (Fig. 3a, Jiang, 2003).

Inner fan is dominated by main channel, which is characterized by matrix-supported conglomerates (Fig. 4A), grain-supported conglomerates (Fig. 4B), pebbled sandstones with dark mudstones. Matrix-supported conglomerates display boulder-like structure and musily even vertically distributing of gravel. The bottom scour structures are well developed in the main channel, whereas bedding or laminate structures are poorly developed. Middle fan is composed of braided channel sand bodies, which is the main component of nearshore subaqueous fan. The braided channel is mainly
comprised of pebbled coarse-grained sandstones, medium-grained sandstones, and a few conglomerates. Compared to the main channel, braided channel has fewer conglomerates and more sandstones. Various sedimentary structures are well developed and observed in the braided channel, such as scour surfaces, graded beddings and parallel beddings (Fig. 4C, D). In vertical section, braided channels present as multiple-phase sandstone beds superimposing together without mudstone interlayers. Outer fan is characterized by thick dark mudstones interbedded with thin siltstones and silt-fine-grained sandstones. Sedimentary structures in the outer fan include deformed structures such as ball-and-pillow structures, load cast (Fig. 4E), and sandstone dike structures. In vertical section, inner fan, middle fan and outer fan successively develop from bottom to top, showing a fining-upward sequence (Fig. 3a).

3.2. Sublacustrine fan

The concept of sublacustrine fan derived from submarine fan (Stow et al., 1984; Shanmugam and Moiola, 1988; Payros and Pujalte, 2008). In lacustrine basin, it
generally refers to the flood gravity flow fan with longer feeder channel (Prabir, 2002; Jiang, 2003). During Es4, sublacustrine fans mainly distribute on the downthrown of Tuo-Sheng-Yong Fault. Same as nearshore subaqueous fan, sublacustrine fan could be subdivided into inner, middle and outer fans (Fig. 3b).

Inner fan is dominated by feeder channel, which is comprised of matrix-supported conglomerates (Fig. 4F), grain-supported conglomerates and pebbled sandstones. The massive conglomerates are poorly-sorted and poorly-rounded. Middle fan, the main part of sublacustrine fan, is characterized by braided channel, which is consisted of conglomerates, pebbled sandstones, and sandstones with thin-beded mudstones. The sediments within a single sequence from the bottom to the top are conglomerates, pebbled sandstones, and sandstones (Fig. 4G), which reflect a gradual change from gravel to sandy high density turbidity. Graded bedding (Fig. 4G), mud chippings (Fig. 4H) and scour structure (Fig. 4I) are very common in braided channel. Incomplete Bouma sequence, ripple bedding, and contemporaneous deformation structures (Fig. 4J) are the common sedimentary structures in fine-grained sediments between braided channels, whereas large-scale cross bedding is rare. Outer fan consists of mudstones with thin-beded siltstones and fine sandstones showing characteristics of C, D and E sections of Bouma sequence. Parallel bedding is the main sedimentary structure in the argillaceous sediments.

Figure 4. Core photos showing different sedimentary structures in glutenite in Es4, Shengtuo Area. (A) Matrix-supported conglomerates, from well T165 at 3498.8 m. (B) Grain-supported conglomerates showing graded bedding, from well T166 at 3464.1 m. (C) Scour surfaces, from well T134 at 3197.58 m. (D) Graded beddings (down) and parallel beddings (up), from well T127 at 2826.43 m. (E) Load cast, from well T165 at 3219.9 m. (F) Matrix-supported conglomerates, from well T720 at 3673.3 m. (G) Graded beddings, from well T153 at 3546.9 m. (H) Mud chippings, from well T710 at 3604.5 m. (I) Scour surfaces, from well T762 at 3265.8 m. (J) Load cast and sandstone ball, from well T762 at 3493.9 m. Photos from A to E belong to nearshore subaqueous fan, and photos from F to J belong to sublacustrine fan. The diameter of core is 10 cm. See Figure 1 for well locations.
4. HYDROCARBON ACCUMULATION ELEMENTS AND MODEL

4.1. Source rock

Timing of source rock mature and expulsion is an important factor that controls the distribution of oil and gas (Magoon and Dow, 1994; Sun and Liu, 2009). Shengtuo Area has superior source rocks, as a result of being close to Lijin and Minfeng oil-generation sags where two sets of high quality source rocks developed during $Es4s$ and $Es4x$ (upper section and lower section of $Es4$) (Table 1).

<table>
<thead>
<tr>
<th>Format-Thickness(m)</th>
<th>TOC(%)</th>
<th>Chloroform bitumen “A”(%)</th>
<th>Ro</th>
<th>$S_1$(mg/g)</th>
<th>$S_2$(mg/g)</th>
<th>Kerogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Es4s$ 50 ~ 150</td>
<td>0.6 ~ 8.2</td>
<td>0.3 ~ 0.8</td>
<td>0.45 ~ 0.93</td>
<td>-</td>
<td>-</td>
<td>I, II</td>
</tr>
<tr>
<td>$Es4x$ 200</td>
<td>0.12 ~ 4.1</td>
<td>0.104 ~ 1.127</td>
<td>0.93 ~ 1.25</td>
<td>0.02 ~ 8.24</td>
<td>0.03 ~ 7.19</td>
<td>II</td>
</tr>
</tbody>
</table>

The lithology of source rock of $Es4s$ consists of mainly dark-gray mudstone and calcareous mudstone with oil shale, which developed in semi-deep to deep lake with semi-saline to saline water (Zhang et al., 2009). The source rock was characterized by higher accumulation thickness (50~150 m) and organic matter abundance (TOC: 0.6~8.2%, generally more than 2%; content of chloroform bitumen “A”: 0.3~0.8%, generally more than 0.6%). The kerogen is dominated by type I and type II, and Ro is between 0.45 and 0.93. In sum, the source rock of $Es4s$ is a set of excellent quality source rock.

The source rock of $Es4x$ occurs between and below the gypsolyte-salt rock layers, and the accumulation thickness is about 200 m. TOC is 0.12~4.1%, generally more than 0.5%. Content of chloroform bitumen “A” is 0.1041~1.127%. Potential hydrocarbon $S_1$ is 0.02~8.24 mg/g, and $S_2$ is 0.03~7.19 mg/g. Organic matter is mainly terrigenous high grade plant and low grade aquatic organism in the semi-saline to saline water. The kerogen is dominated by type II and few type I. Ro is between 0.93 and 1.25. From the top to the bottom of $Es4x$, the maturity of organic matter is from mature to highly mature. Source rocks of $Es4x$ generated oil condensate in mature phase and gas in highly mature phase (Wang, 2009).

4.2. Reservoir

Due to the difference in hydrodynamic force, location and diagenesis, the different subfacies of glutenite fans have different physical properties. Physical properties of inner and outer fan are relatively poor, with porosity being less than 5% and permeability being less than 1 md in general. Physical properties of braided channel in middle fan are much better, with porosity being between 10% and 25% and permeability being between 100 md and 1000 md (Fig. 3). Braided channel can be the reservoir for hydrocarbon accumulation. Several elements are responsible for braided channels to be favorable reservoirs. (1) The braided channel is mainly composed of pebbly sandstones, gritstones with superimposed scour structure and classic turbidites. Grain-supported glutenite has the characteristics of less matrix, moderate gradation and medium thickness. Consequently, the original physical property of braided channel is relatively good. (2) A lot of secondary pores (Fig. 5) can be produced when a large...
amount of organic acid generated and the acid got into braided channel glutenite in the process of organic material thermal evolution (Schmid and Mcdonald, 1979; Surdam, 1989; Meng et al., 2008). (3) Formation overpressure exiting widely in the Es4 of Shengtuo Area (Liu et al., 2009), which inhibited compaction and cementation, made reservoir spaces of braided channel preserve well (Wilkinson et al., 1997; Holm, 1998; Osborne and Swarbrick, 1999; Gao and Zhang, 2001; Chen et al., 2002). In addition, formation overpressure also made glutenite form a series of overpressured fractures (Fig. 5), which increased the permeability of glutenite greatly.

Figure 5. Reservoir space types of braided channel within the middle fan of glutenite in Es4, Shengtuo Area. (A) Dissolved pore of matrix (×100/-), from well T764 at 3956.10 m. (B) Intracrystal dissolved pore (×100/-), from well T720 at 3672.60 m. (C) Carbonate cement dissolution (×100/-), from well T720 at 3673.00 m. (D) Structural fracture (×40/-), from well T79 at 3407.41 m. (E) Over-pressured fracture (×100/-), from well T719 at 3562.30 m. (F) Shrinkage joint (×40/-), from well T166 at 3253.8 m. See Figure 1 for well locations.

4.3. Petroleum migration
The glutenites of nearshore subaqueous fan and sublacustrine fan of Es4 in Shengtuo Area are close to the source sags. The main migration style of hydrocarbon is episodic flow through the overpressured micro-fracture system. Due to uncompaction and generation of hydrocarbon, the pore fluid pressure of source rock increases gradually (Bradley, 1975; Sahay and Fertl, 1988; Cobbold et al., 2004). When the pressure exceeds formation breakdown pressure, the overpressured micro-fissures form, and the hydrocarbon and other fluid discharge along the micro-fissures by the way of flashy flow (Ghaith et al., 1990; Hunt, 1990; Ortoleva, 1994; Roberts and Nunn, 1995). With the discharging of fluid, the pore fluid pressure decreases to the level below the formation breakdown pressure, and micro-fissures are closed and overpressured fluid stops discharging (Cha et al., 2002; Gao et al., 2009). Based on the analysis of cores,
vertical mineral vein develops very well in the contact zone of mudstones and sandstones in overpressured zone. The deeper the depth is, the more the vein develops. It has been proved that flowing of micro-fissure is very common in overpressured zones (Liu and Xie, 2003). A mass of overpressured micro-fissures are found in the source rocks of Es4 in study area, for example, in dark mudstones, calcareous mudstones and thin-bedded sandstones in Well Li88 (Fig. 6A). Most of the fissures are filled with calcite, whereas crude oil is found in parts of open fissures in thin-bedded sandstones (Fig. 6B). These are the evidences of episodic flowing from source rock to reservoirs.

![Figure 6. Overpressured microfissure in cores of out fan in Es4, Shengtuo Area.](image)

(A) Overpressured fracture in mudstone of source rocks, from well L88 at 2985.1 m.
(B) Over-pressured fracture of thin-bed sandstone in outer fan, from well L88 at 2875.9 m. See Figure 1 for well locations.

### 4.4. Sealing and preservation conditions

A set of 80~200 m thick dark mudstones with calcareous mudstones and thin-bedded sandstones distribute consistently from the bottom to top of middle section of the Es3 in Dongying Depression. In addition, calcareous mudstones generated “tight shell” during compaction. The dark mudstone and “tight shell” could serve as favorable sealing layers (Hu, 1989), forming regional seal of glutenite reservoirs. The inner fan is mainly consisted of thick-bedded and poorly-sorted matrix-supported conglomerates interbedded with thin none lacustrine mudstones. Primary pores and secondary pores were poorly developed in the inner fan due to strong compaction. As a result, the physical property of inner fan is extremely poor (Fig. 3), so the inner fan can be an effective lateral seal bed for glutenite reservoirs in braided channel. In the later structural evolution, Es4 had experienced consistent subsidence in Shengtuo Area, and few faults were developed in Es4. Consequently, the glutenite reservoirs of Es4 in Shengtuo Area had been preserved in very good conditions.

### 4.5. Hydrocarbon accumulation model

Different subfacies act different roles in the hydrocarbon accumulation process of glutenite fans of Es4 in Shengtuo Area (Fig. 7).
Sedimentary characteristics and hydrocarbon accumulation of glutenite

Figure 7. Hydrocarbon accumulation model of glutenite in Es4, Shengtuo Area. This source-reservoir-seal assemblage, hydrocarbon generated by mature source rock got into braided channel reservoirs of middle fan through overpressured micro-fissures of outer fan, formed “self-generation and self-storage” litho-stratigraphic trap, which was characterized by “migrating through outer fan, accumulating in middle fan and sealing by inner fan”. See Figure 1 for section locations.

Inner fan is composed of thick and poorly-sorted matrix-supported conglomerates (Fig. 3). Primary pores and secondary pores are dramatically reduced due to the strong compaction in the inner fan. As the result, inner fan with extremely poor physical property (Fig. 3) contributes to the lateral seal. In addition, overlain dark mudstone and “tight shell” in middle section of Es3 could serve as favorable regional seal of glutenite reservoirs.

Braided channel in middle fan is characterized by pebbly sandstones and sandstones (Fig. 3) with abundant secondary pores and overpressured micro-fissures (Fig. 5) made by organic acid and reservoir overpressure. The braided channel with much better physical property (Fig. 3) could be favorable reservoirs.

Outer fan is comprised of thick-bedded dark mudstones interbedded with thin-bedded sandstones (Fig. 3) with overpressured micro-fissures (Fig. 6). Although being non-effective reservoir, the thin-bedded sandstones in the outer fan could be a good migration pathway for oil and gas entering into braided channel sand bodies from synsedimentary source rocks in basin ward direction (Lijin and Minfeng oil-generation sags (Es4s and Es4x)).

With regional seal and later preservation, the different subfacies worked together, and formed “self-generation and self-storage” litho-stratigraphic trap, which was characterized by “migrating through outer fan, accumulating in middle fan and sealing by inner fan” (Fig. 7). Based on the model of hydrocarbon accumulation, enhancing the sedimentary study of glutenite and then searching for the braided channel within middle fan is the effective method of increasing the success rate of exploration of glutenite reservoir on the steep slope of fault basin or rift basins.
5. CONCLUSION

Based on the depositional environment, hydrodynamic force, formation mechanism and depositional characteristics, the glutenite of \( Es4 \) in Shengtuo Area is developed in nearshore subaqueous fan and sublacustrine fan. Nearshore subaqueous fans were developed on the downthrown of Chennan Fault, whereas sublacustrine fans were deposited on the downthrown of Tuo-Sheng-Yong Fault. The inner fan of glutenite mainly consisted of massive conglomerates supported by matrix. Middle fan, the main part of glutenite, was characterized by braided channel and consisted of pebbly coarse sandstones and medium-sandstones. The lithology of outer fan was mainly dark mudstones with thin-bedded siltstones and fine-grained sandstones.

Glutenite of \( Es4 \) in Shengtuo Area have superior oil sources conditions, due to being close to Lijin and Minfeng sags which have two sets of high quality source rocks. Gluennites in braided channel of middle fan with abundant secondary pores and overpressured micro-fissures, have better physical properties, and can be favorable reservoirs. Dark mudstones and gypsum-salt rocks closed to glutenite and inner fan with extremely poor physical properties can be good seal for glutenite reservoirs. The thin-bedded sandstones plus a certain of overpressured micro-fissures in the outer fan, connecting the source rock in the basin ward and the reservoir (middle fan braided channel) in the coast ward, is the good pathway for oil and gas migration. This source-reservoir-seal assemblage, hydrocarbon generated by mature source rock got into braided channel reservoirs of middle fan through overpressured micro-fissures of outer fan, formed “self-generation and self-storage” litho-stratigraphic trap, which was characterized by “migrating through outer fan, accumulating in middle fan and sealing by inner fan” (Fig. 7).

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