Controls and Distribution Features of Petroliferous Belts of Subtle Traps in Paleogene Strata of Bohai Bay Basin, Eastern China*

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Abstract

Bohai Bay Basin is a Cenozoic petroliferous rift basin in eastern China. The most of the traditional and easy-to-find hydrocarbon traps have been located. Subtle traps are the dominant targets for hydrocarbon exploration in petroliferous depressions. Using interpretation of 3D seismic profiles, analysis of well logs, and observation of drill cores, organic geochemistry data, and analysis of stratal liquid pressure in the depressions, controls and distribution characteristics of petroliferous plays of subtle traps in Paleogene strata of Bohai Bay Basin were investigated. Distributing in source rocks of upper part of the fourth member to third member of Shahejie Formation, sand bodies within lowstand systems tracts comprising incised channels, sublacustrine fans, deltas controlled by valleys, syndepositional faults, and flexural slopes associated with syndepositional anticlines, deep seated faults and fault block tilting, and sand bodies of sandy debris, turbidites, beach bars controlled by prodelta slopes, normal faults, and paleorelief within transgressive systems tracts to early highstand systems tracts are good reservoirs of lithologic traps, and structural and lithologic combination traps. Mudstones of deep lake subfacies in transgression systems tracts of sequences in upper part of fourth member of Shahejie Formation to the third member are high quality source rocks. Abnormal high overpressure caused mainly by hydrocarbon generating developing in sequences of upper part of fourth members to third member is the main dynamic factor of hydrocarbon from source rocks to subtle traps. Normal faults and unconformities are conduit systems. Lowstand sand bodies controlled by valleys, syndepositional normal faults and flexural slopes, and sealed by high quality source rocks within transgressive systems tracts are petroliferous plays of lithologic traps, and structural and lithologic combination traps. Unconformities control distribution of petroliferous plays of stratigraphic traps. The sand bodies controlled by syndepositional faults and flexural slopes within lowstand systems tracts, high quality source rock in transgressive systems tracts and abnormal high overpressure control petroliferous plays of subtle traps.

Introduction

Within the mature basins that have been explored, most of the traditional and easy-to-find hydrocarbon traps have already been located (Halbouty, 1969). Subtle traps, such as lithologic, stratigraphic, and structural and lithologic combination traps, are now the dominant targets for hydrocarbon exploration in these mature basins. The Bohai Bay Basin, a typical Paleogene petroliferous rift basin, is located in the eastern China (Allen et al., 1997; Zong et al., 1999; Wan, 2004). Dongying and Zhanhua depressions in Jiyang subbasin, Qikou and Nanpu depressions in Huanghua subbasin, Western and Damintuo depressions in Liaohe subbasins, and Raoyang depression in Jizhong subbasin are the petroliferous depressions, which are abundant in hydrocarbon (Figure 1). Episodic extensional tectonic events, associated extensional structures and depositional fills have resulted in multiple source rocks, combinations of reservoirs and cap rocks, and hydrocarbon reservoirs of conventional and subtle traps. High density of exploration wells and proven hydrocarbon reserves exceeding 60% hydrocarbon potential provide good samples to study the distribution and controls of the hydrocarbon reservoirs of subtle traps in rift basins. The purpose of this study is to examine the conditions of hydrocarbon migration and accumulation in subtle traps, and the distribution characteristics and controls of petroliferous plays of subtle traps in a sequence stratigraphic framework for exploration of subtle traps in the petroliferous depressions, which are abundant in hydrocarbon.

Geological Setting

The Bohai Bay Basin is a Mesozoic and Cenozoic rifted lacustrine basin in Eastern China and has a total area of 200,000 km^2. Uplifted Precambrian basement blocks surround the Basin. These include the Mountain Taihang to the west, the Mountain Yanshan to the north, Luxi uplift to the south, and Jiaoliao uplift to the east. The rhombic shape of Bohai Bay Basin (Figure 1) was developed prior to Paleogene time because of Mesozoic rifting. Paleogene strata, typically with thicknesses of 4,000 to 7,000 m, rest unconformably on a variety of older pre-Paleogene strata (Yao, 1994; Allen et al., 1997). Four major internal uplifts or horsts (Chengning, Cangxian, Neihuang, and Xingheng) and NE-NNE and NW striking faults divide the basin into six major subbasins: the NE striking Liaohe subbasin in the northeast; the NE striking Jizhong subbasin in the west; the NE striking Huanghua and the NNE striking Jiyang subbasins.

In the southeast is the NE and NW striking Bozhong subbasin in the east and the NE striking Dongpu subbasin in the southwest (Figure 1). These subbasins are subdivided into numerous depressions and 'Rises' or highs (Figure 1). Similar to other rift basins, the tectonic history of the Bohai Bay Basin is complicated by multi-stage episodic rifting including block faulting that is associated with rapid tectonic subsidence and volcanism (Lin, et al 2004; Hsiao, et al., 2004). A two-stage evolution model is popularly accepted, with Paleogene syn-rifting and differential subsidence, and Neogene post-rift thermal subsidence (Allen et al., 1997). The Paleogene synrifting stage consists of four rifting episodes: (1) the early-initial rifting episode beginning in the Paleocene and ending in the early Eocene (65 - 50.4 Ma); (2) the late-initial rifting episode in the middle Eocene (50.4 - 42.5 Ma); (3) the rifting climax in the late Eocene (42.5 - 38 Ma); (4) the weakened rifting episode during the Oligocene (38 - 24.6 Ma) (Figure 2).

Stratigraphy and Sequence Classification

The Paleogene strata in the basin consists of the Kongdian Formation ($E_{1-2}k$) overlain by the Shahejie Formation (E_2s), which is overlain by the Dongying Formation (E_3d). The lithologies are shown in Figure 2. The strata of Paleogene synrift succession that are recognized as first-order sequence 1 (FS1) while the strata of the Neogene post-rift succession are first-order sequence 2 (FS2). Strata of the four rifting episodes in the syn-rift age correspond to four second-order sequences (SSq) (episodes 1 to 4 from bottom to top) respectively. SSq1, at the bottom of the syn-rift succession, corresponds to rifting episode 1, and roughly correlates to the Kongdian Formation ($E_{1-2}k$). Two third-order sequences (Sq1-1, Sq1-2) were identified. SSq2 corresponds to rifting episode 2 and rough boundaries are aligned with the fourth member of the Shahejie Formation (E_2s_4). Two third-order sequences (Sq2-1, Sq2-2) were also identified. SSq3 corresponds to rifting Episode 3 and roughly corresponds to the third (E_2s_3) and lower part of the second members ($E_2s_2^L$) of the Shahejie Formation. Four third-order sequences (Sq3-1, Sq3-2, Sq3-3, Sq3-4) were identified. SSq4, at the top of the synrift succession, aligns with rifting episode 4 and roughly equates to the section including the upper part of the second member ($E_3s_2^U$) of the Shahejie Formation to the Dongying Formation (E3d). Four third-order sequences (Sq4-1, Sq4-2, Sq4-3, Sq4-4) were also identified (Figure 2).

The three orders of unconformities identified in the Paleogene synrift succession in the Bohai Bay Basin represent three levels of sequence boundaries. First-order unconformities are angular unconformities at the top and bottom of the Paleogene synrift succession. Second-order unconformities are also angular unconformities, between two adjacent rifting episodes. Third-order unconformities are localized and relate to their correlative conformities (Embry, 1995, 2002). These sequence boundaries can be identified on seismic profiles, logging curves and drill cores (Feng, et al. 2013).

Sand Bodies for Subtle Traps and Their Controls

Based on the seismic data, well logs and cores, we identified the following sand bodies in the subtle traps in the sequence stratigraphic framework of the Paleogene strata in the Dongying, Zhanhua, Qikou, Western, and Raoyang petroliferous Depressions: (1) fluvial delta sand bodies that had developed in LSTs; (2) proximal fan-delta sand bodies adjacent to the faulted margin within LSTs; (3) shallow-lake beach-bar sand bodies along the ramp slopes of the Depression in transgressive system tracts (TSTs); (4) incised-channel fill and sub-lacustrine fan sand bodies at the hinged margin in LSTs; (5) turbidite and sandy debris sand bodies in transgressive to early highstand system tracts (HSTs). These sand bodies controlled by syndepositional faults, flexural slops, and paleorelief are reservoirs of subtle traps (Figure 3 and Figure 4). The distribution of sand bodies in the LSTs of the sequences in $E_2s_4^U$ to E_2s_3 strata was controlled by syndepositional faults (Feng et al., 2013). The sand bodies are good reservoirs for subtle traps (Feng et al., 2013). Steeply dipping parallel (Figure 3a), comb-shaped and cross-shaped syndepositional faults (Figure 3b) developed mostly at the faulted margins of Sq3-1 ($E_2s_3^L$) of Raoyang and Zhanhua depressions. The sand bodies of fan deltas and sublacustrine fans in LSTs were deposited on the down-dip (lakeward) side of the faults and were found along their length. In Sq3-3 ($E_2s_3^U$) of Dongying depression, broom shaped and gently dipping parallel syndepositional faults occurred at the southern-hinged margins of the depression (Figure 3c). LST sand bodies, such as sublacustrine fans and small deltas, were also deposited on the down-dip (lakeward) side of these faults, and were found along their length (Figure 3c).

Incised-channel fills were deposited on the up-dip (landward) side of the faults. In Sq2-2 ($E_2s_4^U$) of Western depression, antithetic parallel synsedimentary faults occurred at the western-hinged margin of the depression (Figure 3d). LST sand bodies of fan deltas were deposited on the down-dip side of these faults and were controlled by them. Flexural slopes controlled by syndepositional anticlines (Figure 4a), deep-seated faults (Figure 4b), and fault block tilting (Figure 4c), were developed at margins and slopes of structural highs in Zhanhua and Dongying depressions. They were able to control distribution of LSTs sand bodies in depressions.

These LSTs sand bodies distributed at down-dip sides of flexural zones. Sand bodies of beach bars were distributed on the ramp of a hinged margin in the TST of Sq2-2 ($E_2s_4^U$), on the ramps of a faulted margin in TSTs in Sq3-1 ($E_2s_3^L$), Sq3-2 ($E_2s_3^M$) and Sq3-3 ($E_2s_3^U$) of Dongying depression, and on the ramp of Kongdian High in TSTs in Sq3-2 ($E_2s_3^M$) to Sq3-3 ($E_2s_3^U$) of Qikou depression. They were controlled by subaqueous highs, such as low buried hills, subaqueous volcanoes, anticlines, and horsts, and were distributed along slopes of subaqueous highs (Song et al., 2012; Feng et al., 2013). Sand bodies of gravity flow deposits, such as sandy debris and low-density turbidity, had developed at prodelta slopes to lakebeds of TSTs to early HSTs in sequences of E_2s_3 and were controlled by the prodelta slopes and faults such as in Dongying depression (Feng et al., 1990, Zou et al., 2012).

Source Rocks

Based on boreholes and geochemistry data, two source rocks developed in the Paleogene strata: one in Sq2-2 ($E_2s_4^U$), one in Sq3-1 ($E_2s_3^L$) and another in Sq3-2 ($E_2s_3^M$). The Sq2-2 source rock has excellent potential to generate hydrocarbon and features of low Pr/Ph ratios (<1) and relatively high gammacerane contents (Zhang et al., 2004; Li et al., 2010). These features suggest that the source rocks of the $E_2s_4^U$ interval were deposited in saline water (Li et al., 2010) (Table 1). According to data of organic chemistry in well Niu38 of Dongying depression (Figure 5), the Sq3-1 and Sq3-2 source rocks are good source rocks and have higher Pr/Ph ratios (>1) (Figure 5), and relatively low gammacerane content (Zhang et al., 2004; Li et al., 2010). These features show that the Sq3-1 and 3-2 source rocks were deposited in fresh water.

Subtle Traps and Hydrocarbon Reservoirs

The Paleogene petroleum reserves of subtle traps in the petroliferous depressions occurred in two petroleum plays. One was in the source rocks of Sq2-2, Sq3-1 and Sq3-2, and the other in Sq3-3, Sq3-4 and SSq4. Out of the confirmed Paleogene petroleum reservoirs of lithologic, and lithologic and structural combination traps, almost 90% were found in the Sq2-2 to Sq3-2 source rock petroleum plays.

Almost all of the confirmed Paleogene petroleum reservoirs of stratigraphic traps, with the exception of buried hill traps, were found in the sequences of Sq3-4 and SSq4 at the margins of the depressions. Recently, many hydrocarbon reservoirs of subtle traps have been found in the Sq2-2 to Sq3-3 strata at the faulted and hinged margins, on the faults, and the gentle flanks of the structural highs, as well as on the sag areas of the depressions. As described below, three major trap types were identified in the two Paleogene petroleum plays of the Depressions.

The subtle lithologic traps formed by lithologic variation, such as lenticular sand bodies and up-dip sandstone pinch-out, are widespread in the strata from Sq2-2 ($E_2s_4^U$) to Sq3-2 ($E_2s_3^M$) (Figure 6). These traps developed in source rocks and, in particular, in sags. Based on a sedimentary study in Dongying and Qikou depressions, traps consist of sublacustrine fan or gravity flow deposits that developed in the Sq3-1 ($E_2s_3^L$) and Sq3-2 ($E_2s_3^M$) source rocks (Feng et al., 2013). Traps also consist of beach bar deposits that developed in Sq2-2 ($E_2s_4^U$) (Song et al., 2012) of Dongying depression and in Sq3-2 ($E_2s_3^M$) to Sq3-3 ($E_2s_3^L$) of the ramp of Kongdian High in Qikou depression. The lateral extent and quality of the reservoirs vary substantially because of diagenesis and facies variation. The porosity of the lenticular sand bodies of Dongying depression was approximately 1-15% with a permeability of approximately 1-50×10^{-3} μm^2. The up-dip sand bodies pinch-out developed along flanks of paleostructure highs on the margin in the depression, as well as on gentle slopes. The sand bodies forming up-dip and pinch-out were the dominant sand bodies of the sublacustrine fans and deltaic fronts. The porosity and permeability of the updip sand bodies was greater than that of the lenticular sand bodies. Hydrocarbon reservoirs of lenticular sand bodies did not have a unified oil-water contact and each hydrocarbon reservoir had an oil-water contact. They were distributed in the Sq3-2 ($E_2s_3^M$) source rock of Lijin and Niuzhuang sags of

Dongying depression, for example, in the hydrocarbon reservoir of the lenticular trap of the Ying 11 Well in the Lijin sag (Figure 6). Hydrocarbon reservoirs of up-dip sandstone pinch-out occurred mainly on the southern-hinged margin. Oil was found only near the top of the individual up-dip and pinch-out sand bodies (Figure 6).

Stratigraphic traps formed by stratigraphic truncation below unconformities or sequence boundaries, with an onlap above them, were widespread in the Paleogene strata at the hinged and faulted margins (Figure 6 and Figure 7). Beach bar and deltaic front sandstones were taken as reservoirs. The traps were capped by the unconformities and mudstones near them. The formation of such traps is controlled by a combination of stratigraphic, lithologic and structural factors. In the Western and Eastern Depressions of Liaohe subbasin, the hydrocarbon from Sq3-1, Sq3-2 ($E_2s_3^{L\text{ and }M}$) and Sq2-2 ($E_2s_4^{U}$) mature source rocks migrated along faults, sand bodies and unconformities to form stratigraphic reservoirs at hinged and faulted margins (Figure 7).

Lithologic and structural combination traps controlled by structural and lithologic factors were the main subtle traps in the depressions. The trap reservoirs were made of sandstones of sublacustrine fans, delta, and fills of incised channels in LSTs, capped by deep lacustrine mudstone and oil shale in TSTs. The traps were lateral pinch-out or facies change and were cut at up-dip by normal faults. They have the potential to form petroleum plays whose proven reserve can exceed 50 million tons (360 million bbl), such as the Liangjialou oilfield of Dongying depression, which is a typical example of subtle reservoirs of lithologic structural combination traps. Their reservoirs are sand bodies in LST3-3 of Sq3-3 (Figure 3c and Figure 8). These sand bodies belong to deposits of fills of incised channels and sublacustrine fans. They were capped by TST3-3 deep lake mudstone and cut at up-dip by normal faults. The geochemical properties of the oils have intermediate values between those observed in extracts from the lower Sq3-1 ($E_2s_3^{L}$) and Sq2-2 ($E_2s_4^{U}$) source rocks (Zhang et al., 2004; Hao et al., 2005; Li et al., 2010). Consequently, the oils in the subtle traps were most likely derived from mixed Sq3-1 ($E_2s_3^{L}$) and Sq2-2 ($E_2s_4^{U}$) source rocks, with a predominant contribution from the Sq2-2 ($E_2s_4^{U}$) source rocks. Hydrocarbon may have migrated along faults from Sq2-2 ($E_2s_4^{U}$) and Sq3-1 ($E_2s_3^{L}$) source rocks to these subtle traps (Figure 8). Another example is Liuxi hydrocarbon reservoirs of structural and lithologic combination traps at the eastern faulted margin of Raoyang depression (Figure 9). The reservoirs predominantly ranged from fan deltaic sandstone to conglomerate in the LST3-1 of Sq3-1 ($E_2s_3^{L}$) and in LST3-2 of Sq3-2 ($E_2s_3^{M}$) and were capped by deep TST3-1 and TST3-2 lake mudstone and cut by faults. Hydrocarbon from Sq3-1 ($E_2s_3^{L}$) and Sq3-2 ($E_2s_3^{M}$) migrated to the structural and lithologic traps along faults.

Distribution of Hydrocarbon Reservoirs and Conditions of Hydrocarbon Accumulation in Subtle Traps

Hydrocarbon reservoirs of subtle traps are important exploration targets in these abundant petroliferous Depressions (Li et al., 2004) and have special distribution characteristics. The sections of hydrocarbon reservoirs of stratigraphic traps occur near unconformities or sequence boundaries. First and second-order unconformities or sequence boundaries are favorable in particular for hydrocarbon reservoirs of stratigraphic traps (Figure 6 and Figure 7). This is because the margins of the depression were the dominant direction for the migration of hydrocarbon. The unconformities, normal faults and sand bodies are conduits along which hydrocarbon can migrate from source rocks. The up-dip direction of the stratigraphic traps was sealed by unconformities. The hydrocarbon reservoirs of lithologic traps were distributed in Sq3-1, Sq3-2 ($E_2s_3^{L\text{ and }M}$) and Sq2-2 ($E_2s_4^{U}$) source rocks at the center of sags of depression. For example, take the Dongying depression where the Ying 11 hydrocarbon reservoirs of the lithologic trap at the Lijin sag, and the Niuzhuang oilfield of the lithologic hydrocarbon reservoirs at the Niuzhuang sag (Figure 6).

The hydrocarbon reservoirs of lithologic and structural combination traps were distributed on the slopes of the sags, and near faults and flexural slopes associated with syndepositional anticlines, deep-seated faults and fault block tilting. In the sequence stratigraphic framework, the hydrocarbon reservoirs of lithologic and structural combination traps were located in LSTs. For example, the Lijialou oilfield of Dongying depression is a typical subtle hydrocarbon reservoir located in LST3-3 of Sq3-3 ($E_2s_3^U$) on the southern-hinged margin (Figure 8). Another example is the Liuxi hydrocarbon reservoirs of structural and lithologic combination traps in LST3-1 to LST3-2 of Sq3-2/E_2s_3 L to Sq3-2 /$E_2s_3^M$ at the faulted margin of Raoyang depression (Figure 9).

Take Jiyang subbasin as example, the distribution of the hydrocarbon reservoirs of subtle traps shows cyclic features around the kitchens of source rocks, such as the Lijing, Boxing, Niuzhuang, and Minfen sags in Dongying Depression; Bonan, Gubei, Gunan, sags in Zhanhua depression; Chexi and Dawangbei sags in Chezheng depression. The hydrocarbon reservoirs of the lithologic traps were distributed at the centers of sags while those of structural and lithologic combination traps were distributed on the slope zones of sags (Figure 10). Both types of hydrocarbon reservoirs were distributed in the overpressure zone of Sq3-1 and Sq3-2 ($E_2s_3^{M\text{ and }L}$), and Sq2-2 ($E_2s_4^U$) (Figure 10). Based on the DST data, hydrocarbon reservoirs in Sq3-1 and Sq3-2 ($E_2s_3^{M\text{ and }L}$) and Sq2-2 ($E_2s_4^U$) have overpressure and high oil-bearing saturation (Gao et al., 2010; Hao, 2013), for example, the Liangjialou and Niuzhuang oilfields in Dongying depression. Overpressure is a dynamic factor to overcome capillary resistance. The relationship between porosity and the pressure of sand bodies with oil-bearing saturation exceeding 80% in lithologic traps was studied by Li and Pang (2004). They found that porosity was the reverse ratio to liquid pressure in oil-bearing sandstone. Higher overpressure is favorable for hydrocarbon accumulation in the tight sandstones of lenticular lithologic traps in particular (Li and Pang, 2004). Hydrocarbon reservoirs of stratigraphic traps were distributed at the margins of source rock kitchens in normal liquid pressure systems containing high-viscosity oil.

Controls of Petroliferous Plays of Subtle Traps

Petroliferous plays of subtle traps are composed of hydrocarbon reservoirs of subtle traps. They develop in special regions controlled by source rocks, sand bodies, unconformities/sequence boundaries, conduits, and liquid overpressure. Based on exploration data and the above analysis, the sand bodies within LSTs of $E_2s_4^U$ to $E_2s_3^U$ sequences were controlled by syndepositional faults and flexural slopes and channels, capped by mudstone and shale in TSTs of the sequences, and consisted of petroliferous plays of structural and lithologic combination traps in the overpressure zone. The sand bodies within LSTs (Figure 3 and Figure 4) were reservoirs and traps of the petroliferous plays of the subtle traps. They were capped by deep lake mudstone and shale in TSTs and were made of source rock. Syndepositional faults not only controlled the sand bodies in LSTs, but were also conduits along which the hydrocarbon in the deep intervals migrated to the subtle traps. Liquid-bearing oil forced by overpressure in Sq2-2 to Sq3-1, and Sq3-2 ($E_2s_4^U$ to $E_2s_3^{L\text{ and }M}$) migrated along the faults and microfractures to the subtle traps. The relatively high paleogeothermal gradient anomalies in these areas, established by fluid inclusions, are strong evidence for the presence of overpressured hydrocarbon fluid migration (Feng et al., 2013).

Lenticular sand bodies (beach bars, small sublacustrine fans, gravity flow deposits of prodelta controlled by faults, slopes of prodelta, and slopes of paleorelief) developed in early HSTs to TSTs in $E_2s_4^U$ to E_2s_3 sequences. There were also lithologic traps distributed in mudstone and shale. Based on our research, hydrocarbon reservoirs in over 85% of the lenticular sand bodies have overpressure. None of the oil-bearing lenticular sand bodies had near-normal liquid pressure (Zhang et al., 2004). The overpressure favors hydrocarbon accumulation in the lithologic traps (Losh, 1998; Losh et al., 1999; Li and Pang, 2004). Correlation between the oil and source rocks shows that hydrocarbon in Sq3-1 and Sq3-2 ($E_2s_3^{M\ and\ U}$) lenticular sand bodies originated mainly from Sq3-1 ($E_2s_3^L$) and Sq2-2 ($E_2s_4^U$) source rocks. The faults and microfractures may act as conduit systems (Li et al., 2010). The microfractures may be related by hydrofracturing associated with episodic hydrocarbon expulsion in the overpressure zone of these depressions (Xie et al., 1998). Therefore, lenticular sand bodies, controlled by depositional slopes and slopes of paleorelief in the overpressure zone, were petroliferous plays of lithologic traps.

The hydrocarbon reservoirs associated with unconformities were petroliferous plays of stratigraphic traps. First- and second-order unconformities/sequence boundaries were distributed throughout the whole depressions and dominant stratigraphic traps were associated with them. The stratigraphic traps developed at margins of these depressions, which were the predominant directions of hydrocarbon migration. The traps were charged by hydrocarbon migrating from the overpressure source rock kitchens along faults, sand bodies, and unconformities (Figure 7 and Figure 8). The first- and second-order unconformities controlled the distribution of the petroliferous plays of stratigraphic traps in particular.

Conclusions

(1) The sand bodies in the LSTs in $E_2s_4^U$ to E_2s_3 sequences and the sand bodies in the TSTs to early HSTs of the sequences are good reservoirs of lithologic and structural combination, and lithologic traps.

(2) Two source rocks developed in the Paleogene strata of these Depressions: a source rock in Sq2-2 ($E_2s_4^U$) and a source rock in Sq3-1 and Sq3-2 ($E_2s_3^{M\ and\ L}$). The source rocks in Sq2-1 and Sq3-1 have excellent potential for hydrocarbon generation.

(3) Sand bodies distributed in the overpressure source rocks within LSTs in $E_2s_4^U$ and E_2s_3 sequences are controlled by syndepositional faults, covered by mudstone and shale in TSTs, and are petroliferous plays of lithologic and structural combination traps. The sand bodies in overpressure mudstones and shales of TSTs and early HSTs in $E_2s_4^U$ and $E_2s_3^{L\ and\ M}$ sequences are controlled by slopes of pro-delta and paleorelief, and are petroliferous plays of lithologic traps. Unconformities at the margins of the depression controlled the distribution of petroliferous plays of stratigraphic traps.

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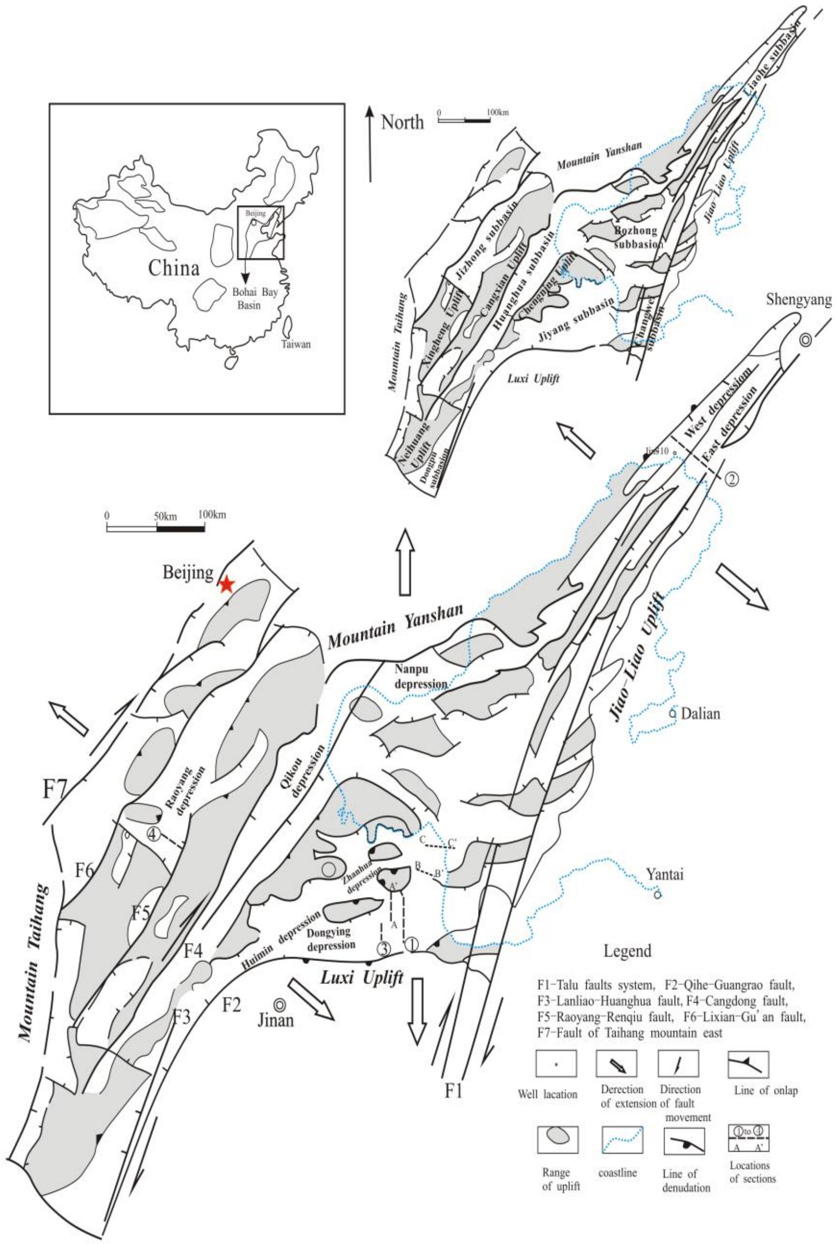

Figure 1. Schematic map of the structural units in the Bohai Bay Basin, Eastern China. The locations of sections in Figure 4, Figure 6, Figure 7, Figure 8, and Figure 9 are indicated in the map.

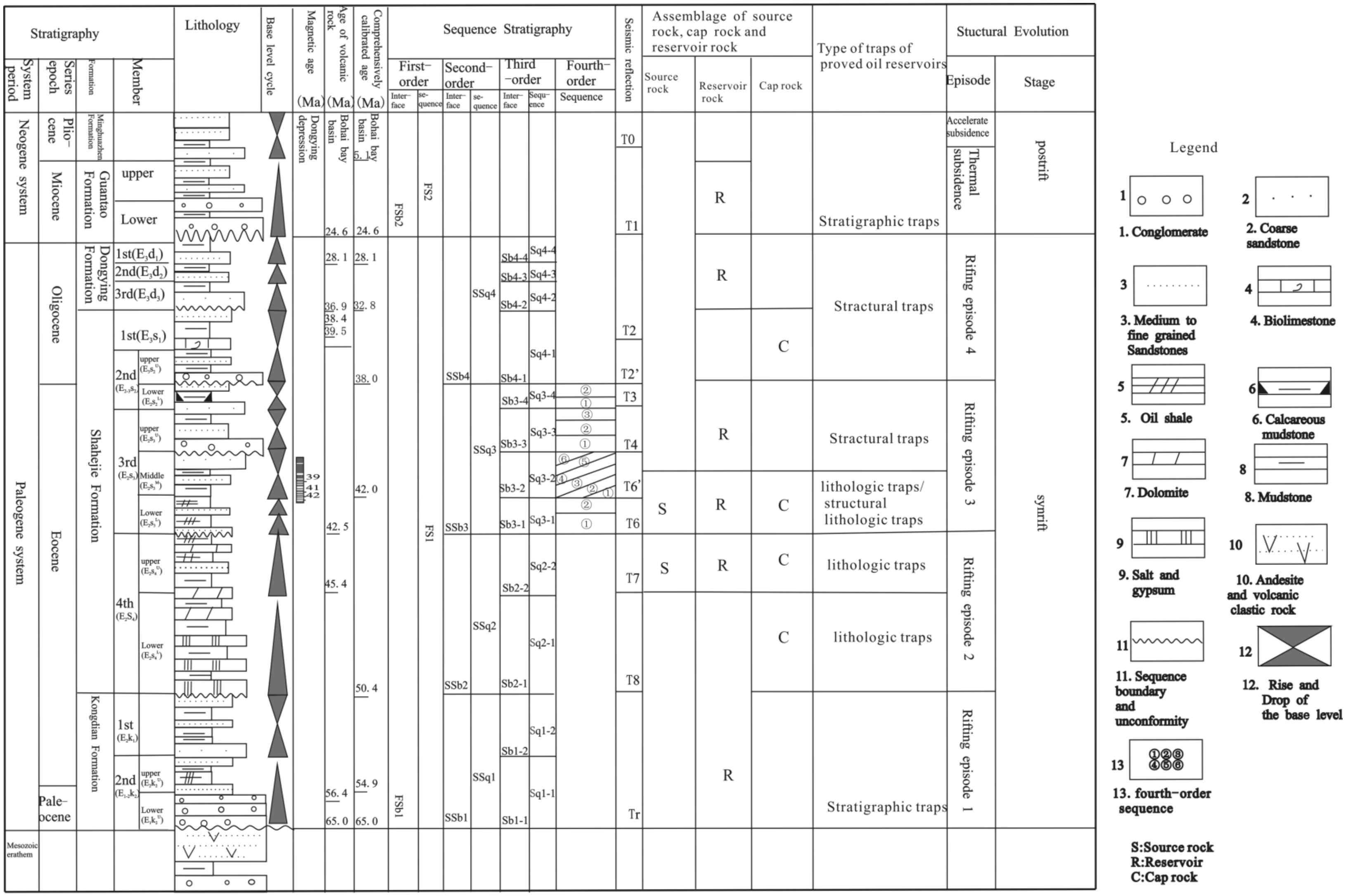

Figure 2. The general sequence stratigraphic charts and the factors for hydrocarbon accumulation of Paleogene strata in the Bohai Bay Basin (Feng, 1999). The classification of different order sequence stratigraphy is based on the changes in lake level, episodic tectonic activities, assemblage biozones, climate and detailed work of this paper. The ages of sequence boundaries are determined from micropaleontologic data e.g. ostracoda and palynologic data, palaeomagnetic dating and volcanic rocks dating (Chen and Peng, 1985; Li, et al, 1992; Yao, 1994; Feng, 1994). The S is source rock; R is reservoir, C is cap rock. FS: first-order sequence; SSq: second-order sequence; Sq: third-order sequence. Sq3-1 means first third-order sequence within second-order sequence 3.

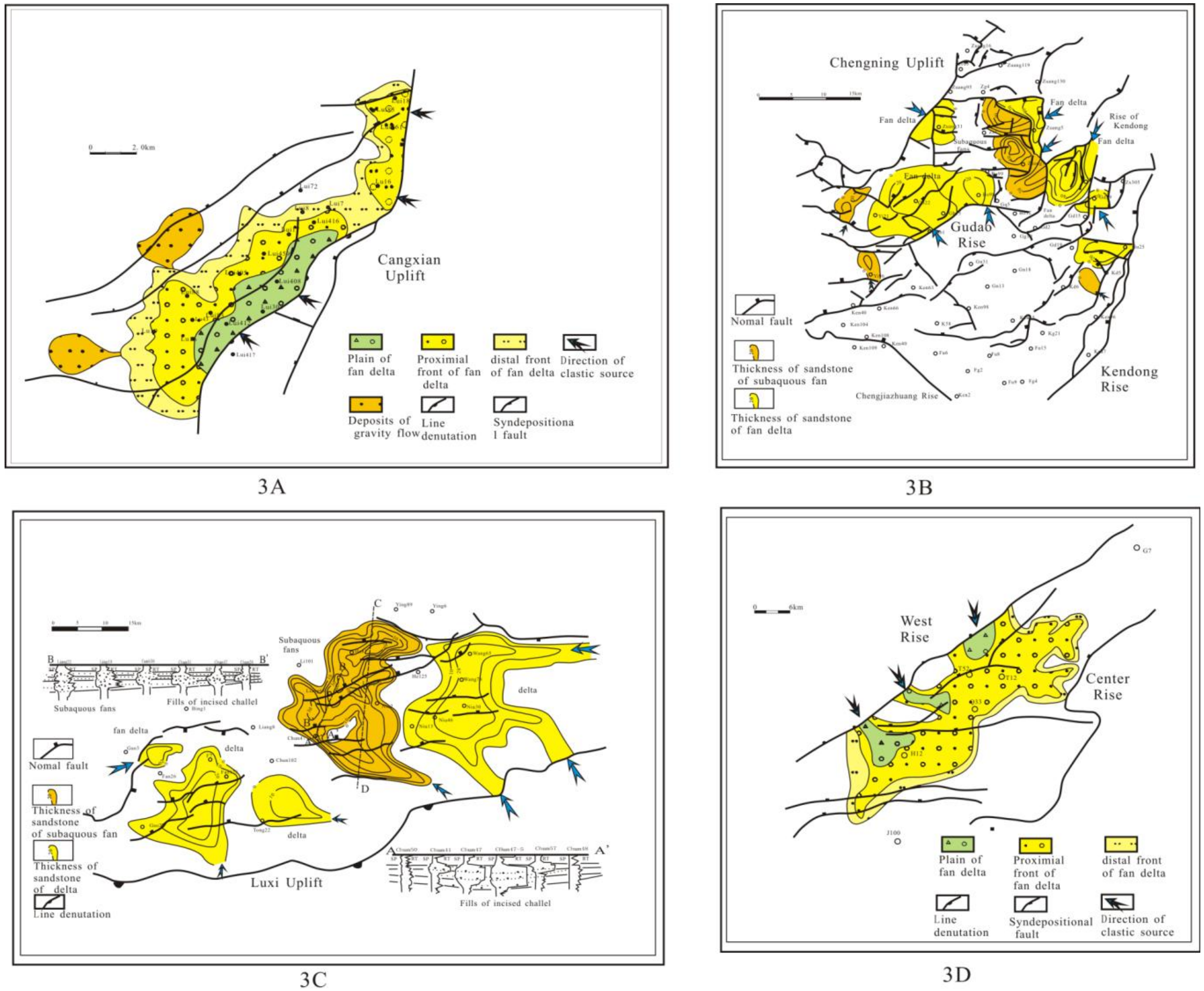

Figure 3. The sand bodies within lowstand systems tracts of sequences in Paleogene strata controlled by syndepositional faults. 3A shows lowstand fan delta controlled by steeply dipping parallel syndepositional faults of sequence Sq3-1 ($E_2s_3^L$) in faulted margin of Raoyang depression of Jizhong subbasin; 3B shows syndepositional faults and lowstand sand bodies of sequence Sq3-1 ($E_2s_3^L$) in Zhanhua depression of Jiyang subbasin; 3C shows the syndepositional faults controlling lowstand sand bodies of sequence Sq3-3 ($E_2s_3^U$) at hinged margin of Dongying depression of Jiyang subbasin. 3D shows lowstand fan deltas controlled by syndepositional antithetic faults of sequence Sq2-2 ($E_2s_4^U$) in the west depression of Liaohe subbasin.

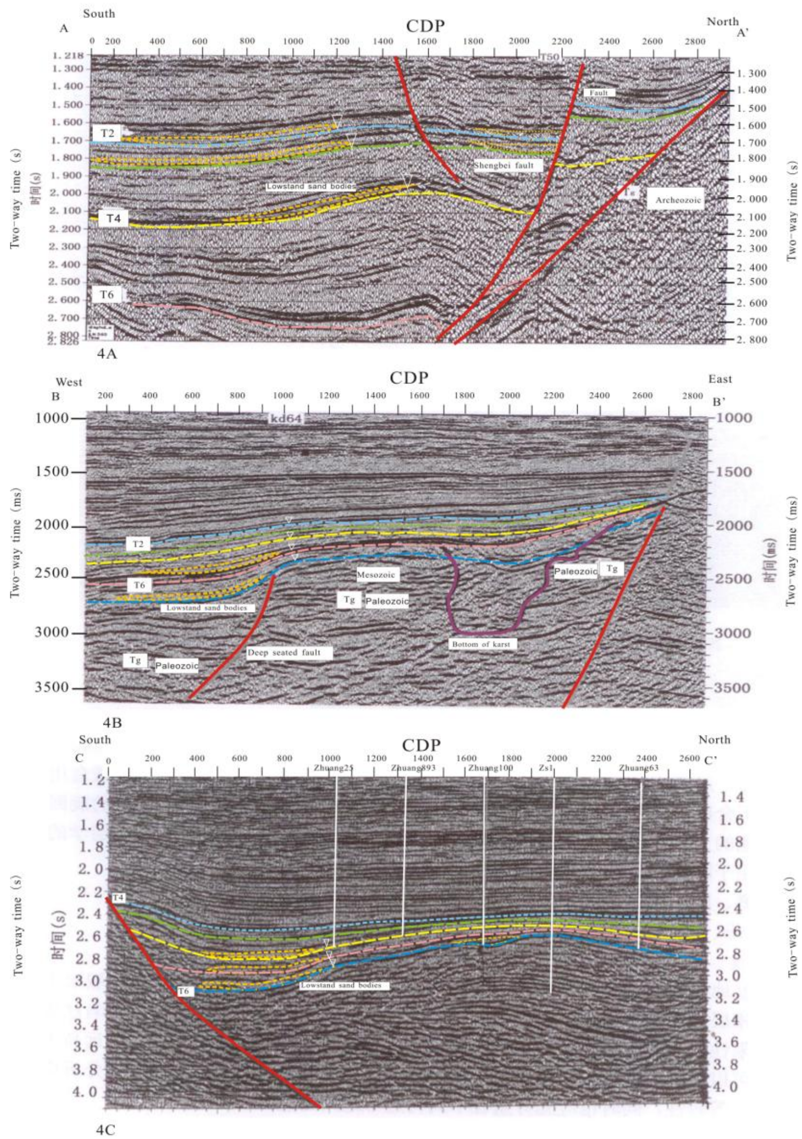

Figure 4. Sand bodies within LSTs controlled by flexural slopes associated with syndepositional anticlines, deep-seated faults, and fault block tilting. 4A: LST sand bodies controlled by flexural slope associated with syndepositional anticline at north faulted margin of Dongying depression. The location (AA') is shown in Figure 1. 4B: LST sand bodies controlled by flexural slope associated with deep-seated faults at Kendong buried hill of Zhanhua depression. The location (BB') is shown in Figure 1. 4C: LST sand bodies controlled by flexural slope associated with fault block tilting at Gubei sag of Zhanhua depression. The location (CC') is shown in Figure 1.

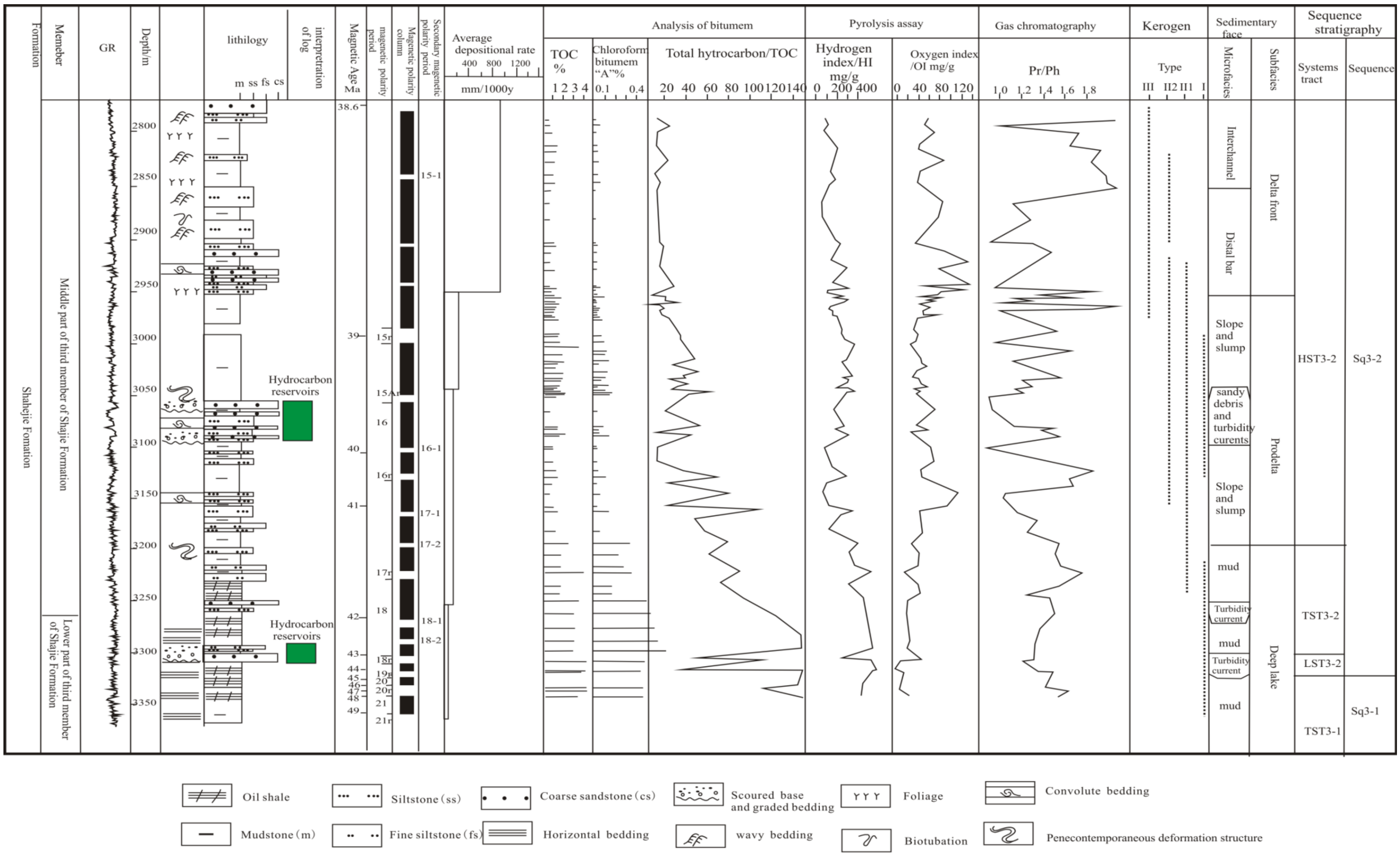

Figure 5. Lithologic and geochemical profiles of well Niu38 in Dongying depression of Jiyang subbasin.

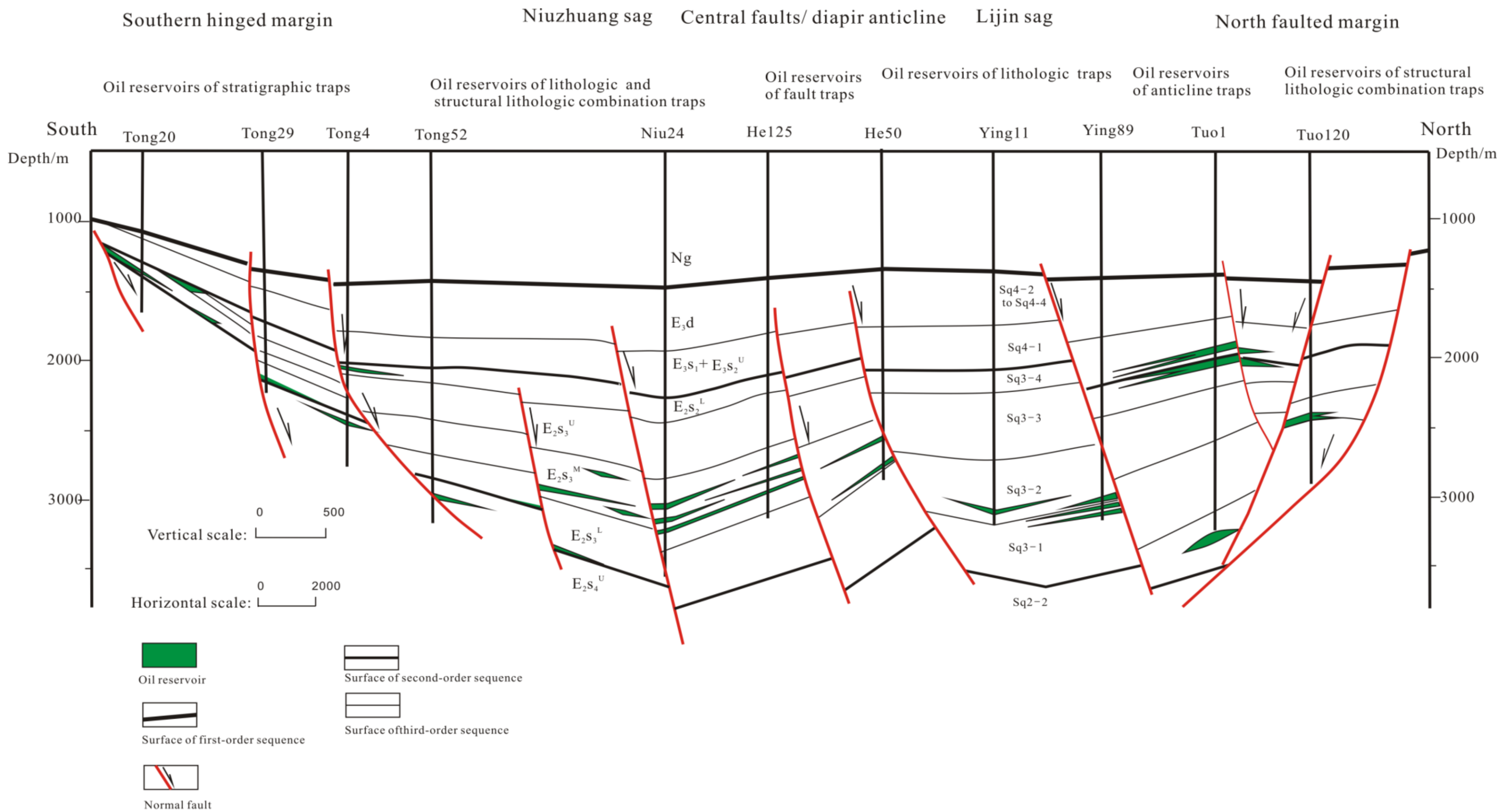

Figure 6. Hydrocarbon reservoirs profile of Dongying depression of Jiyang subbasin from North to South. The location of the profile (1) is indicated in Figure 1. Symbols of strata and sequences are shown on the profile same as Figure 2.

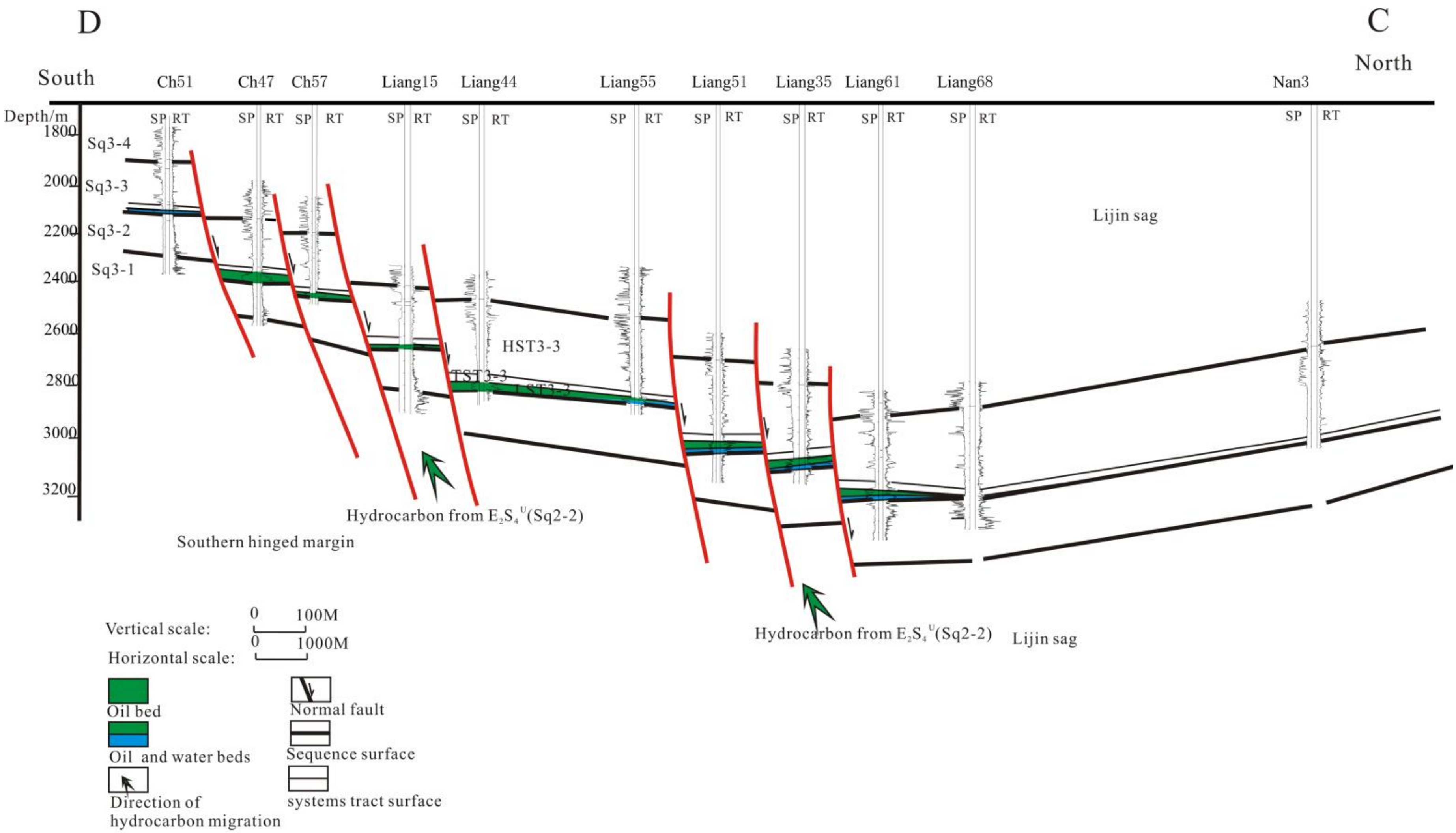

Figure 7. Hydrocarbon reservoir profile of Liaohe subbasin from East to West. The location of the profile (2) is indicated in Figure 1. Symbols of strata and sequences are shown on the profile same as Figure 2.

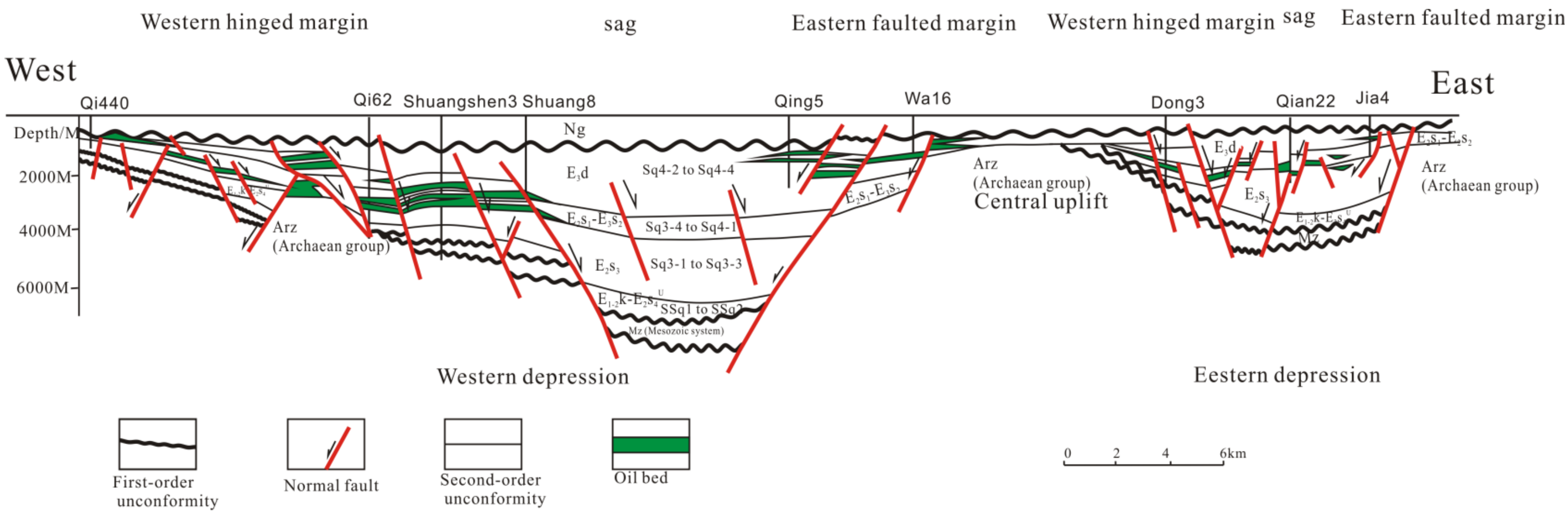

Figure 8. Well-tied hydrocarbon reservoir profile within systems tracts of sequence Sq3-3 ($E_2s_3^U$) from North to South at Liangjialou oil filed of Dongying depression. The location of the profile is indicated in Figure 1 (3) and Figure 3c (DC).

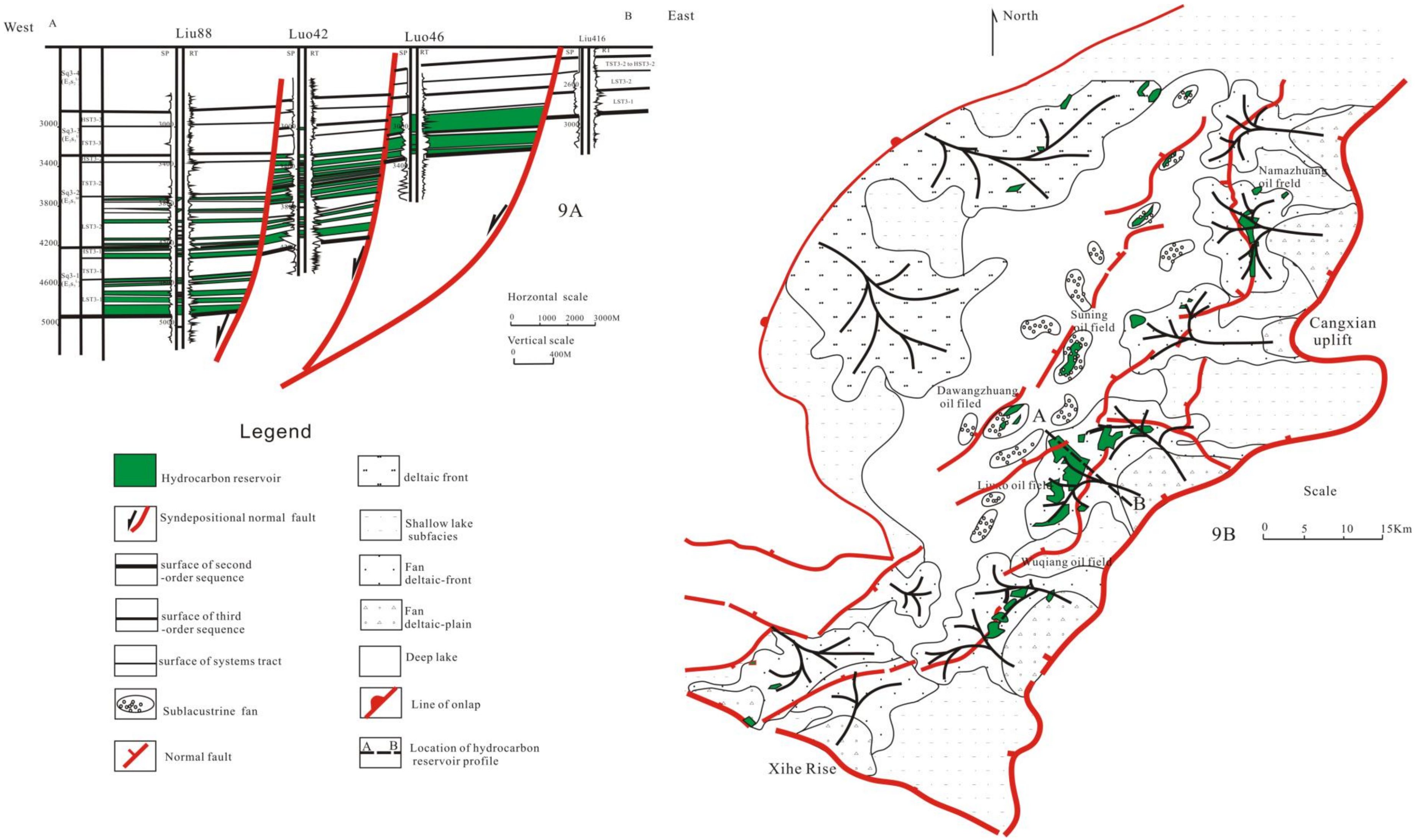

Figure 9. Hydrocarbon reservoir section (9A) and distribution map of hydrocarbon reservoirs and sedimentary facies (9B) at faulted margin of Raoyang Depression in Jizhong subbasin from East to West. The location of the profile (AB and (4)) is indicated in 9B and Figure 1 respectively. Symbols of strata and sequences are shown on the profile same as Figure 2.

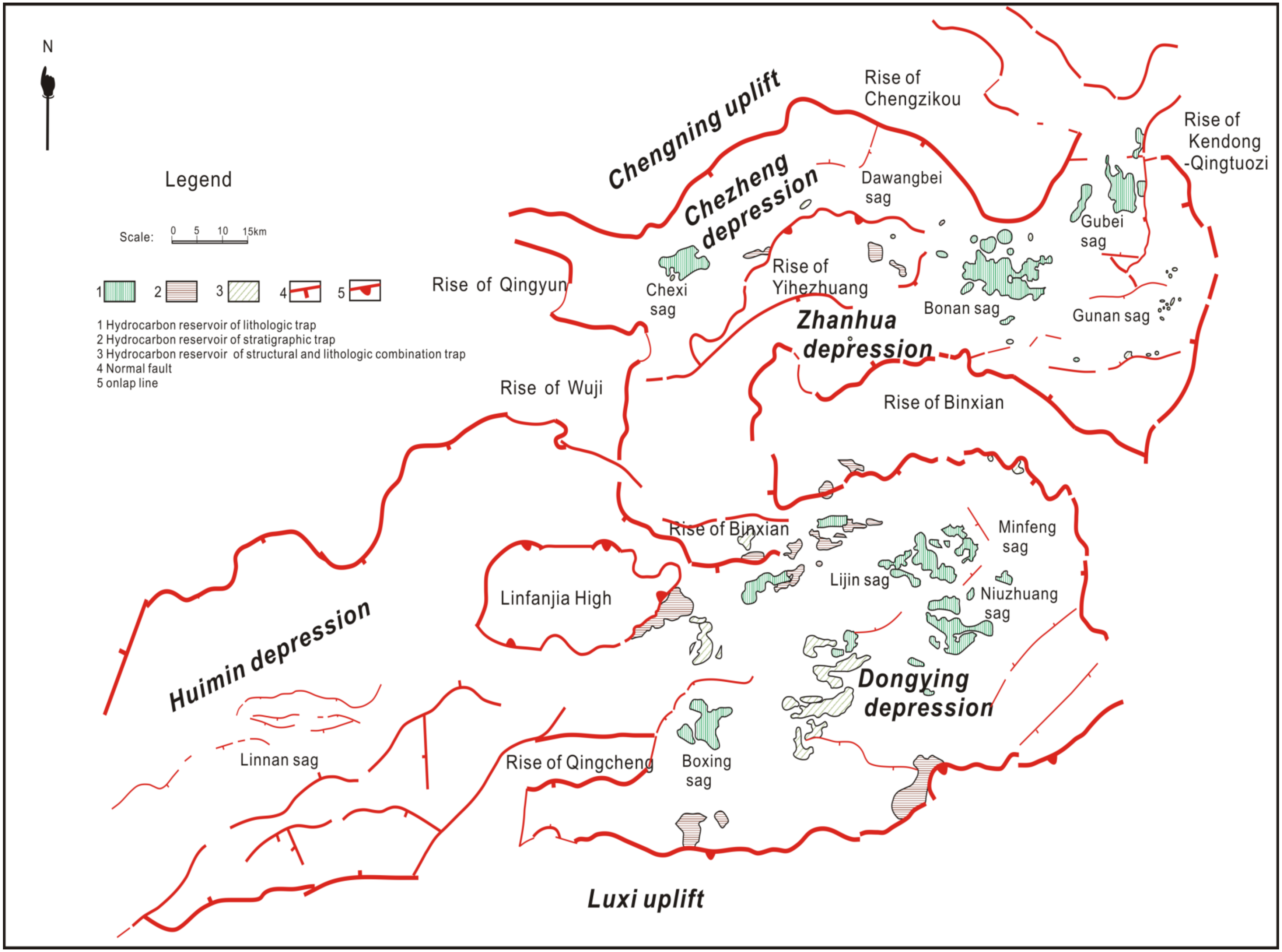

Figure 10. Distribution map of hydrocarbon reservoirs of subtle taps within Paleogene strata in the Jiyang subbasin.

Well	Depth/m	interval	lithology	Toc (%)	Chloroform bitumen"A" /Exact (%)	Hi(mg/g.TOC)	OI(mg/g.TOC)	PI(S1/(S1+S2)	S1+S2	Tmax	Pr(pristine)/ Ph(phytane)	Type of Kerogen
N11	3321.53	$E_2s_4^U$	Grey mudstone	0.87	0.089						0.84	I
	3602.03	$E_2s_4^U$	Oil shale	2.16	0.64	201	42	0.34	7.8	427	0.37	
W7	2707.5	$E_2s_4^U$	Grey mudstone	1.69	0.63	486	60	0.24	10.9	418	0.19	
	2803.0	$E_2s_4^U$	Grey mudstone	3.88	0.211						0.31	I
T39	2978.0-3016.0	$E_2s_4^U$	Grey mudstone	1.75	0.289							II_1
DF3	3066.0	$E_2s_4^U$	Brow to grey shale	7.32	2.855							
W125	2797.50	$E_2s_4^U$	Grey Calcareous mudstone	0.70	0.20	244	134	0.37	2.7	426	0.42	
Y8	2677.8-2788.5	$E_2s_4^U$	Grey mudstone	2.4	0.281						0.94	II_1
DF2	3940-4050	$E_2s_4^U$	Gray mudstone	1.25	0.434						0.09	
DF1	3450-3550	$E_2s_4^U$	Grey mudstone	3.01	0.950						0.57	
W78	2905.02	$E_2s_4^U$	Oil shale	1.72	0.74	219	38	0.52	8.5	437	0.62	
	3907.0	$E_2s_4^U$	Grey mudstone	4.83	1.1085						0.83	I

Table 1. Basic geochemical data of partial source rocks in upper part of 4th member ($E_2s_4^U$) of Shahejie Formation in Dongying depression.