Oil-source correlation study of the Paleogene red beds in the Boxing sag of the Dongying depression, eastern China

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ABSTRACT

We present a correlation study of the oil occurrence in the Paleogene red beds of the Boxing sag of the Dongying depression, eastern China. The reservoir includes the lower 4th Member of the Shahejie Formation (Es_4^l) and 1st Member of the Kongdian Formation (Ek_1). Sixteen source rock samples and 17 oil sand samples from the Boxing sag were collected and the biomarkers were analyzed to perform oil-source correlation. The results show that three oil types characterize the petroleum stored in the Paleogene red beds of the Boxing sag. The oil in Es_4^l is classified as Type A oil and is derived from the Es_3^l (lower 3rd Member of the Shahejie Formation) source rock, which was deposited in a freshwater-brackish lacustrine environment. The oil in Ek_1 of the eastern sag (well Bo-8) is originated from the Es_4^u (upper 4th Member of the Shahejie Formation) source rock, characterized by saline-hypersaline lacustrine environment, and classified as Type B oil. The oil within Ek_1 is a mixture of oil generated from both Es_3^l and Es_4^u source rocks and classified as Type C oil. The distribution of the different oil types in the Paleogene red beds in the Boxing sag is controlled by faults that connect the source rocks with the reservoir bed, which are here named "oil-source faults". The Paleogene red beds in the footwall blocks of these "oil-source faults" are the most promising oil and gas exploration target.

Key words: source rock, oil-source correlation, red beds, Boxing sag, Dongying depression, China.

RESUMEN

Presentamos un estudio de correlación de la presencia de petróleo en los lechos rojos del Paleógeno de la cuenca intracratónica (sag) Boxing en la depresión Dongying, este de China. El yacimiento incluye el cuarto miembro inferior de la Formación Shahejie (Es_4^l) y primer miembro de la Formación Kongdian (Ek_1). Se colectaron 16 muestras de roca fuente y 17 muestras de arena bituminosa de la cuenca Boxing y se analizaron los biomarcadores para establecer la correlación petróleo-fuente. Los resultados muestran que tres tipos de aceites caracterizan el petróleo almacenado en los lechos rojos del Paleógeno de la cuenca Boxing. El aceite en Es_4^l se clasifica como aceite del Tipo A y se deriva de roca fuente Es_3^l (tercer miembro inferior de la Formación Shahejie), la cual fue depositada en un ambiente lacustrino de agua dulce-salobre. El aceite en Ek_1 de la porción oriental de la cuenca (pozo Bo-8) se origina de roca fuente Es_4^u (cuarto miembro superior de la Formación Shahejie), caracterizada por un ambiente lacustre salino-hipersalino, y clasificado como aceite del Tipo B. El aceite en Ek_1 es una mezcla del aceite generado de las roca fuente Es_3^l and Es_4^u y se clasifica como aceite del Tipo C. La distribución de los diferentes tipos

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de aceite en los lechos rojos del Paleógeno en la cuenca Boxing está controlada por fallas que conectan las rocas fuente con los lechos que conforman el yacimiento, las cuales son llamadas en este trabajo "fallas de fuente de aceite". Los lechos rojos del Paleógeno en los bloques de piso de esas "fallas de fuente de aceite" son los blancos de exploración de aceite y gas más prometedores.

Palabras clave: roca fuente, correlación aceite-fuente, lechos rojos, cuenca intracratónica Boxing, depresión Dongying, China.

INTRODUCTION

The Dongying Depression is located in the south of the Bohai Bay basin (Figure 1) and has the most abundant oil and gas resources in the eastern China (Sun *et al*., 2006; Qiu *et al*., 2010). In the last 40 years, the petroleum exploration of the Dongying depression has been focused on the shallow Eocene Shahejie Formation. However, with the decreasing exploitation potential of former strata, the Paleogene red beds becomes the potential reservoir bed in the Dongying depression, where several wells with commercial oil production have been drilled since 2008.

The Paleogene red beds in the Dongying depression refers to the local deep Eocene strata –lower 4th Member of the Shahejie Formation (Es_4^l) and 1st Member of the Kongdian Formation (Ek_1). They consist of a series of continental clastic strata that show red color due to the oxidizing depositional environment. Since this is a new petroleum exploration target, the study on the source of the oil stored in the Paleogene red beds (red-bed oil) can directly help to understand the oil and gas accumulation pattern, as well as to understand the distribution of potential oil reservoirs in the Dongying depression.

Many earlier studies (Li *et al*., 2003, 2005, 2010; Zhang *et al*., 2003a, 2003b; Zhu and Jin, 2003; Zhang *et al*., 2004; Zhu *et al*., 2004, 2005; Pang *et al*., 2005; Liu, *et al*., 2006; Wang, *et al*., 2008; Meng *et al*., 2010, 2011) have demonstrated that there are two main source rocks in the Dongying depression: the lower 3rd and the upper 4th Members of the Eocene Shahejie Formation (Es_3^l and Es_4^u), respectively, and that oils from the Dongying depression are all associated to these two source rocks. However, scarce research has been conducted on the source of the red-bed oil in the Dongying depression, especially in the Boxing sag, a fact that hinder oil and gas exploration. As one of the main sags in the Dongying depression,

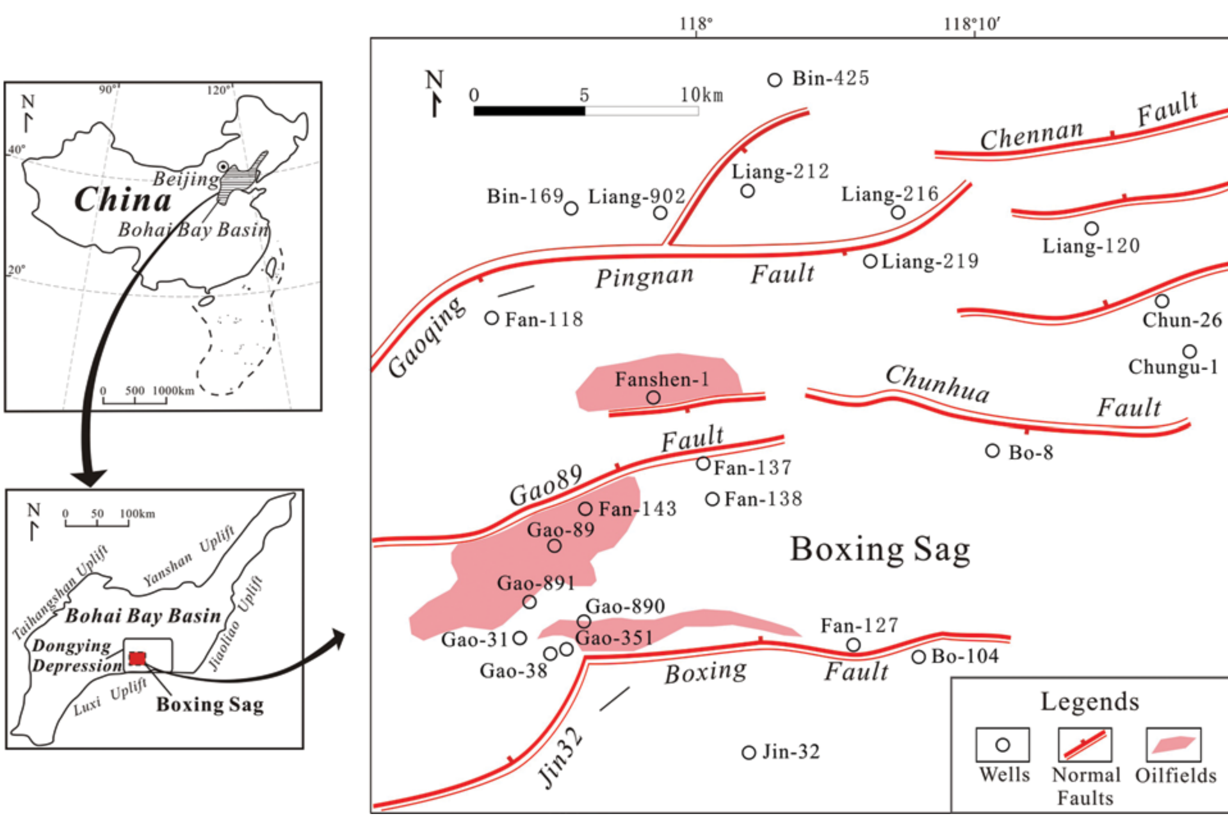

Figure 1. Geological location, and sample distribution, of the Boxing sag in the Dongying depression, eastern China.

the Boxing sag was chosen as a case to study the source of Paleogene red-bed oil in the Dongying depression by means of oil-source correlation according to biomarker signatures.

GEOLOGICAL SETTING

The Boxing sag is located in the southwestern portion of the Dongying depression, in the southern Bohai Bay basin, eastern China (Figure 1). According to the seismic and logging data, the study area is divided into four step-fault zones by three main normal faults with east-west strike, which were active at the time the Paleogene strata were deposited, namely Gaoqing-Pingnan, Gao89 and Jin32-Boxing faults, and the major part of Boxing sag is to the south of the Gaoqing-Pingnan fault (Figure 1). The Paleogene strata in the Boxing sag are represented from bottom to top by the Kongdian, Shahejie and Dongying formations (Figure 2). There are four source rocks in the Boxing area, namely Es_1 (1st Member of the Shahejie Formation), Es_3^m (middle 3rd Member of the Shahejie Formation), Es_3^l and Es_4^u. The two main source rocks are Es_3^l and Es_4^u shale, most of which were deposited in a semi-deep to deep lacustrine basin and the rest in a shallow lacustrine basin (Rong and Wang, 2004; Yang and Chen, 2004; Su *et al*., 2005; Xu and Wu, 2011). The Paleogene red beds (Es_4^l and Ek_1) are the favorable as well as the potential reservoir bed. Two regionally extensive units represent the cap rock: the thick Ed_3-Es_1 (3rd Member of the Dongying Formation and 1st Member of the Shahejie Formation) and the Es_3^l-Es_4^u dark mudstone. The study on the source of Paleogene red-bed oil in the Boxing sag has

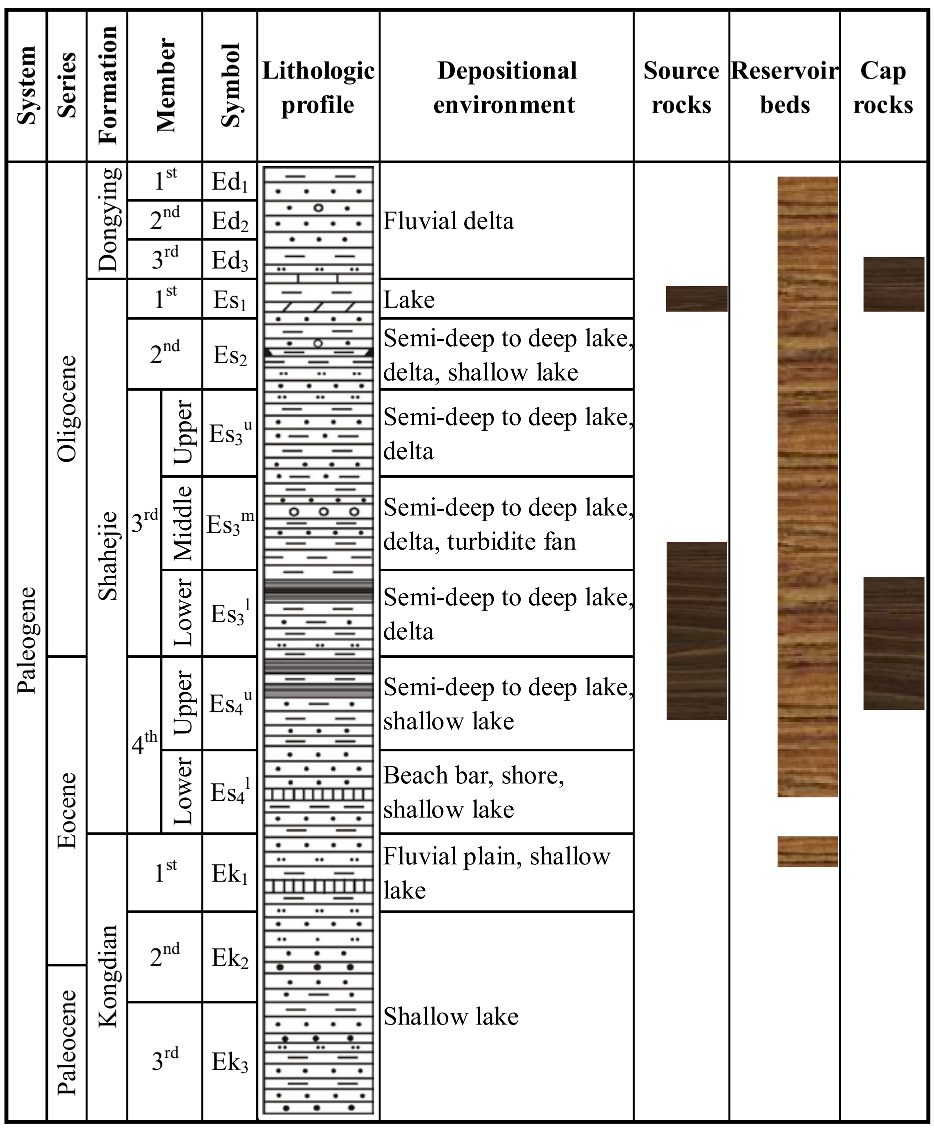

Figure 2. Paleogene stratigraphy in the Boxing sag of the Dongying depression, eastern China (according to the Research Institute of Geological Science, Shengli Oilfield Company Limited, 2000, 2007).

important geological significance for further oil and gas exploration in the Boxing area.

SAMPLES AND EXPERIMENTAL METHODS

In this research, 16 source rock samples and 13 oil sand samples were collected from Es_3^l, Es_4^u, Es_4^l and Ek_1 in the Boxing sag of the Dongying depression. Sampled wells are representative for the whole study area (Figure 1).

The oils were extracted from oil sand samples with chloroform ($CHCl_3$) for 24 hours under room temperature and the soluble organic matter were extracted from powdered source rock samples with chloroform in a Soxhlet apparatus for 72 hours. After solvent removal by rotary evaporation, the oils or rock extracts were further treated with chloroform for 12 hours under room temperature to precipitate asphaltenes. The filtrates were subsequently fractionated by using column chromatography (silica gel/alumina, 3:1) into saturated and aromatic hydrocarbons, and non-hydrocarbons. The used elution solvents were hexane, dichloromethane-hexane (7:3) and chloroform-methanol (1:1), sequentially (Wang *et al*., 2010). The saturated hydrocarbons of oils or rock extracts were analyzed by gas chromatography (GC) and gas chromatography-mass spectrometry (GC-MS).

Gas chromatography (GC) analysis was performed on an Agilent 6890N equipped with a 30 m × 0.25 mm × 0.25 µm HP-5 fused silica capillary column and the carrier gas was He at a constant flow of 1.0 mL·min^{-1}. The GC oven was programmed and the temperature was kept at 100 °C for 1 minute, then rose to 300 °C at a rate of 4 °C·min^{-1} and held at 300 °C for 25 minutes. The temperature of injector and flame ionization detector (FID) was 300 °C.

Gas chromatography-mass spectrometry (GC-MS) analysis was performed on an Agilent 6890GC/5975iMS equipped with a 60 m × 0.25 mm × 0.25 µm HP-5MS fused silica capillary column and the flow of carrier gas (He) was at a constant rate of 1.0 mL·min^{-1}. The GC oven was programmed to be hold at 50 °C for 1 minute, then rose to 120 °C at a rate of 20 °C·min^{-1} and continued to rise to 310 °C at a rate of 3 °C·min^{-1}, finally held at 310 °C for 25 minutes. The mass spectrometer was operated in both full scan and selected ion monitoring (SIM) modes with a ionization energy of 70 eV.

BIOMARKER SIGNATURES AND DEPOSITIONAL ENVIRONMENT OF SOURCE ROCKS IN THE BOXING SAG

The signatures of biomarkers of 16 samples from Es_3^l and Es_4^u source rocks are summarized in Table 1 and Figure 3 and are described in the following section.

Table 1. Biomarker parameters of Es_3^l and Es_4^u source rocks in the Boxing sag of the Dongying depression, eastern China.

Sample type	Well	Depth (m)	1	2	3	4	5	6	7	8	9	10	11
Es_3^l source rock	Fan-118	3032.20	22	1.22	0.47	0.37	1.07	0.03	0.12	5.42	0.72	0.39	0.23
	Liang-219	3009.00	25	1.05	0.63	0.60	1.01	0.07	0.20	6.25	0.91	0.30	0.08
	Fan-137	2851.85	23	1.28	0.63	0.46	1.15	0.02	0.11	7.15	1.41	0.41	0.15
Type 1 Es_4^u source rock	Fan-137	3214.50	23	0.30	1.57	4.81	1.10	0.79	5.03	9.09	1.41	0.39	0.16
	Fan-143	3112.00	25	1.27	1.95	1.52	1.26	0.35	1.40	3.75	0.81	0.41	0.19
	Fan-138	3072.90	25	0.74	2.33	2.83	1.16	0.69	3.77	6.60	0.29	0.40	0.23
	Gao-89	3016.50	23	0.48	1.28	2.56	1.19	0.13	0.81	4.29	0.50	0.42	0.16
	Gao-891	2813.00	23	0.94	1.72	1.71	1.32	0.07	0.62	5.25	0.81	0.35	0.13
Type 2 Es_4^u source rock	Liang-216	3064.00	20	0.37	1.01	2.13	0.94	0.19	1.55	8.24	0.55	0.39	0.06
	Liang-212	2684.80	24	0.36	2.99	6.50	0.78	0.05	2.10	21.41	0.96	0.30	0.02
	Gao-890	2610.00	25	0.37	1.54	3.40	1.10	0.14	1.16	7.49	0.69	0.26	0.02
	Gao-31	2501.26	18	0.32	0.70	1.59	0.84	0.09	8.10	10.07	1.31	0.25	0.03
	Gao-351	2440.15	14	0.25	2.01	7.04	1.26	0.14	1.99	4.84	0.88	0.18	0.01
	Fan-127	2391.60	25	0.47	1.46	3.19	1.02	0.07	3.78	7.49	0.62	0.12	0.02
	Gao-38	2396.66	16	0.36	1.60	3.72	1.11	0.07	0.37	7.08	0.35	0.17	0.01
	Bo-104	2153.30	17	0.16	2.46	24.85	1.59	0.08	2.99	3.50	0.63	0.11	0.02

1. Peak of *n*-alkanes; 2. Pr/Ph; 3. Pr/*n*-C_{17}; 4. Ph/*n*-C_{18}; 5. CPI= [(*n*-C_{25} + *n*-C_{27} + *n*-C_{29} + *n*-C_{31} + *n*-C_{33}) / (*n*-C_{24} + *n*-C_{26} + *n*-C_{28} + *n*-C_{30} + *n*-C_{32}) + (*n*-C_{25} + *n*-C_{27} + *n*-C_{29} + *n*-C_{31} + *n*-C_{33}) / (*n*-C_{26} + *n*-C_{28} + *n*-C_{30} + *n*-C_{32} + *n*-C_{34})] / 2; 6. tricyclic terpanes/17α-hopanes; 7. gammacerane/C_{31} homohopane = gammacerane / (22S 17α, 21β-homohopane + 22R 17α, 21β-homohopane); 8. C_{35} homohopane index = 100 × 17α, 21β-pentashomohopane (22S+22R) / [17α, 21β-homohopane (22S+22R) + 17α, 21β-bishomohopane (22S+22R) + 17α, 21β-trishomohopane (22S+22R) + 17α, 21β-tetrashomohopane (22S+22R) + 17α, 21β-pentashomohopane (22S+22R)]; 9. C_{27}/C_{29} sterane = 20R 5α, 14α, 17α-cholestane / 20R 24-ethyl-5α, 14α, 17α-cholestane; 10. ααα-C_{29} sterane 20S/(20S+20R) = 20S 24-ethyl-5α, 14α, 17α-cholestane / (20S 24-ethyl-5α, 14α, 17α-cholestane + 20R 24-ethyl-5α, 14α, 17α-cholestane) ααα-20R; 11 diasteranes/regular steranes.

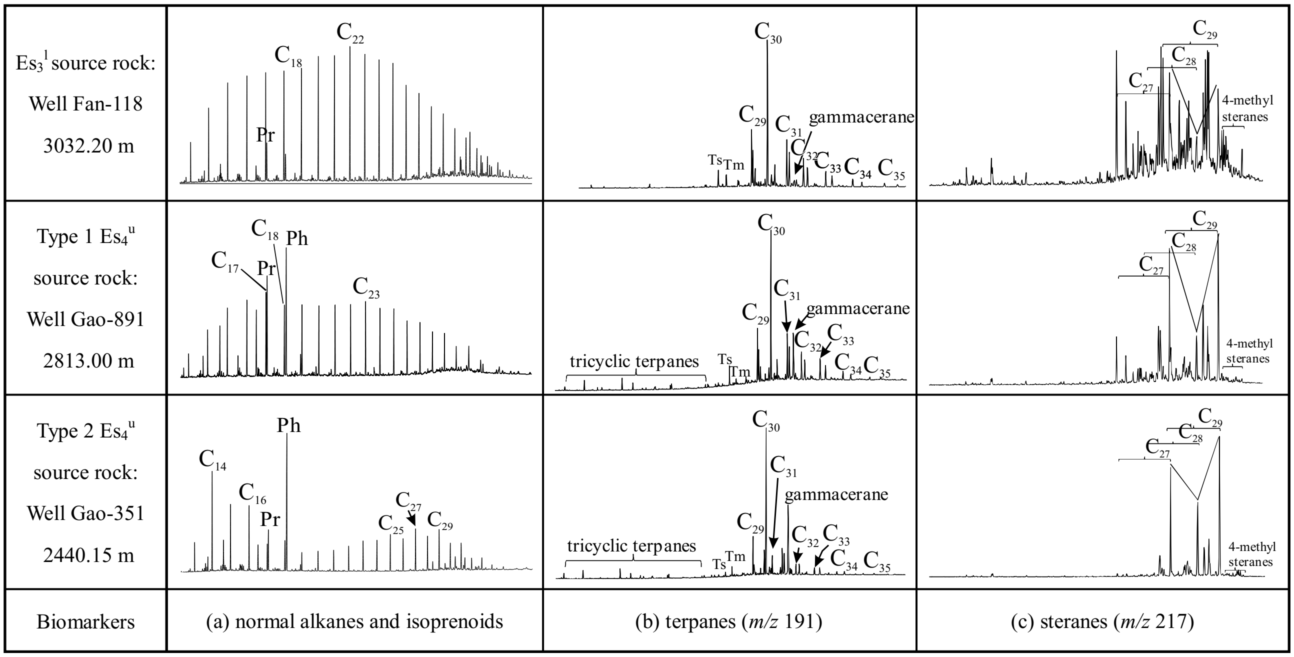

Figure 3. Gas chromatograms of saturated hydrocarbons (a) and mass chromatograms of terpanes (*m/z* 191) (b) and steranes (*m/z* 217) (c) of the source rocks in the Boxing sag of the Dongying depression, eastern China.

Es_3^l source rock

The *n*-alkanes show Gaussian distribution or weak double peak pattern and the peak is between n-C_{22}–n-C_{25}, carbon preference index (CPI) is 1.01–1.15 (Table 1). For example, the sample from well Fan-118 shows weak double peak pattern and n-C_{22} as the peak of *n*-alkanes (Figure 3a). The concentration of pristane is higher than that of phytane (Pr/Ph > 1), Pr/n-C_{17} is lower than 0.63 and Ph/n-C_{18} is lower than 0.6 (Table 1, Figure 3a).

Concentrations of tricyclic terpanes and gammacerane are very low, with tricyclic terpanes/17α-hopanes lower than 0.07 and gammacerane/C_{31} homohopane lower than 0.20 (Table 1, Figure 3b). The C_{35} homohopane index is between 5.42% and 7.15% (Table 1).

The ααα-20R C_{27}/C_{29} sterane is 0.72–1.41, ααα-20R C_{28} sterane shows lower concentration than that of ααα-20R C_{27} and C_{29} steranes, and the concentration 4-methly steranes is very high (Table 1, Figure 3c).

Es_4^u source rock

The Es_4^u source rock can be subdivided into two types according to the relative distribution of *n*-alkanes (Table 1, Figure 3a): Type 1 Es_4^u source rock extracts show Gaussian distribution centered between n-C_{23}–n-C_{25} (*e.g.*, well Gao-891, peak of *n*-alkanes is n-C_{23}); Type 2 Es_4^u source rock extracts show double peak pattern, namely n-C_{14}–n-C_{18} or n-C_{20}–n-C_{25} (*e.g.*, well Gao-351, peak of *n*-alkanes is n-C_{14}). The CPI is higher than 1 except for three samples (CPI = 0.78–1.32; Table 1). Pr/Ph is lower than 1 except for one sample, Pr/n-C_{17} is higher than 1 except for one sample, and Ph/n-C_{18} is higher 1.52 (Table 1, Figure 3a).

Concentration of tricyclic terpanes and gammacerane are higher than those of Es_3^l source rock samples (tricyclic terpanes/17α-hopanes = 0.05–0.79, gammacerane/C_{31} homohopane = 0.37–8.1). The C_{35} homohopane index is between 3.50% and 21.41%, half of which is bigger than that of the Es_3^l source rock samples (Table 1, Figure 3b).

Like the Es_3^l source rock samples, ααα-20R C_{28} sterane of Es_4^u source rock samples also shows obviously lower concentration compared to that of ααα-20R C_{27} and C_{29} steranes, and the ratio of ααα-20R C_{27}/C_{29} sterane is lower than 1 except for two samples (0.29~1.41). Unlike to the Es_3^l source rock samples, the concentration of 4-methly steranes of Es_4^u source rock samples is very low (Table 1, Figure 3c).

Depositional environments of Es_3^l and Es_4^u source rocks

Previous studies indicated that the main source rocks of the Boxing sag are Es_3^l (fresh-brackish or brackish lake) and Es_4^u (brackish-saline or saline lake) shales (Yang and Chen, 2004; Su *et al*., 2005; Han *et al*., 2007). However, these studies were based on few samples and their conclusions about the depositional environments of the two source rocks in the Boxing sag were essentially deduced from more general studies of the Dongying depression (*e.g.*, Zhu and Jin, 2003; Zhu *et al*., 2004, 2005). Thus, based on the biomarker signatures obtained in this work, the depositional environments of these two source rocks can be refined.

The Es_3^l source rock has biomarker signatures characterized by a dominance of pristane (Pr/Ph > 1), very low concentrations of tricyclic terpanes and gammacerane, and higher concentration of 4-methly steranes, which indicates that it was deposited in a freshwater-brackish lacustrine environment (Philp *et al.* 1989; Wang 1990; Fu *et al.* 1990, 1991).

The Es_4^u source rock has a clear phytane (Pr/Ph < 1 and Ph/n-C_{18} > 1.52) and gammacerane predominance, higher tricyclic terpanes/17α-hopanes ratio, moderately higher C_{35} homohopane index, and very low concentration of 4-methly steranes, indicating that it was deposited in a saline-hypersaline lacustrine environment (Philp *et al.* 1989; Wang 1990; Fu *et al.* 1990, 1991; Zhang *et al.* 1998).

Besides, concentration of diasteranes (0.01–0.06) and C_{29} sterane 20S/(20S+20R) value (0.11–0.39) of the Type 2 Es_4^u source rock samples are much lower than those of the Es_3^l source rock samples (0.08–0.23 and 0.30–0.41, respectively; Table 1). Concentration of diasteranes and C_{29} sterane 20S/(20S+20R) parameter increases with increasing thermal maturity (Seifert and Moldowan, 1978, 1986, respectively). Therefore, these biomarker parameters indicate that Type 2 Es_4^u source rock samples have lower thermal maturity than the Es_3^l source rock samples. This is because the Type 2 Es_4^u source rock samples (except the well Liang-216) have shallower burial depth (2153.30 m–2684.80 m) than that of the Es_3^l source rock samples (2851.85 m – 3032.20 m; Table 1) and the thermal maturity parameter (R_o) of source rock samples from the Dongying depression has a positive relation to the burial depth. Although there are many faults that affect the original burial depth of these samples, these are synsedimentary faults, which have not changed the relative burial relationship of these samples.

BIOMARKER SIGNATURES AND CLASSIFICATION OF RED-BED OIL IN THE BOXING SAG

In addition to source rocks, we studied 17 oil sand samples from 12 wells in the Boxing sag. Four samples from wells Bin-169, Liang-120, Chun-26 and Jin-32 only have gas and mass chromatograms but no specific data about concentration of each biomarker could be collected (Table 2, Figure 1). Biomarker signatures of the oil sand samples are summarized and shown in Table 2 and Figures 4 and 5.

The C_{31} homohopane 22S/(22S+22R) and C_{29} sterane 20S/(20S+20R) parameters of the oil sand samples are 0.53–0.59 and 0.37–0.52, respectively (Table 2), lower than or reaching the equilibrium values of these two parameters (0.57–0.62, Seifert *et al*., 1980, and 0.52–0.55, Seifert and Moldowan, 1986, respectively). These two parameters increase with increasing thermal maturity and the equilibrium values indicate that the main phase of oil generation has been reached or exceeded (Peters *et al*., 2005), which corresponds to the low thermal maturity of the local source rocks (R_o = 0.5% – 0.8%).

On the basis of the combined biomarkers characteristics of these oil sand samples, the red-bed oil in the Boxing sag can be divided into three types.

Type A oil

This oil type has *n*-alkanes with a Gaussian distribution with a *n*-C_{22}–*n*-C_{25} peak, CPI is 1.01–1.10; Pr/Ph is 0.55–0.89, Pr/*n*-C_{17} is 0.48–0.93 and Ph/*n*-C_{18} is 0.39–0.77 (Table 2, Figure 4a). The concentrations of tricyclic terpanes and gammacerane are low (tricyclic terpanes/17α-hopanes = 0.08–0.24, gammacerane/C_{31} homohopane = 0.14–0.27), and the C_{35} homohopane index is low (2.88%–5.65%) (Table 2, Figure 4b). The ααα-20R C_{27}/C_{29} sterane

Table 2. Biomarker parameters of the Paleogene red-bed oil in the Boxing sag of the Dongying depression, eastern China.

Sample type	Well	Member	Depth (m)	1	2	3	4	5	6	7	8	9	10	11
Type A oil	Fan-143	Es_4^l	3115.20	25	0.89	0.48	0.51	1.03	0.08	0.14	3.79	0.79	0.40	0.58
	Liang-902	Ek_1	2532.00	23	0.82	0.47	0.39	1.10	0.08	0.14	4.72	0.92	0.40	0.57
	Gao-891	Es_4^l	2804.10	22	0.62	0.64	0.77	1.06	0.22	0.25	2.88	0.94	0.46	0.57
	Gao-891	Es_4^l	2808.80	23	0.64	0.55	0.77	1.01	0.08	0.27	5.65	0.84	0.52	0.57
	Bin-425	Es_4^l	2607.80	23	0.55	0.93	0.74	1.07	0.24	0.26	3.60	0.90	0.47	0.55
Type B oil	Bo-8	Ek_1	2678.80	16	0.71	0.98	1.55	1.17	0.12	1.66	12.42	1.22	0.42	0.59
Type C oil	Fanshen-1	Ek_1	4056.20	18	1.00	0.86	0.75	1.10	0.64	0.51	5.46	0.95	0.41	0.53
	Fanshen-1	Ek_1	4057.70	18	0.98	0.88	1.01	1.45	0.85	0.63	5.18	1.04	0.37	0.53
	Bin-425	Ek_1	2769.50	16	1.06	0.93	0.73	0.93	0.14	0.28	6.94	0.73	0.42	0.56
	Bin-425	Ek_1	2700.90	16	0.95	0.89	0.69	1.13	0.22	0.51	6.08	0.88	0.39	0.54
	Chungu-1	Ek_1	2313.20	18	0.65	1.54	0.72	1.32	0.68	0.57	6.24	1.05	0.37	0.53
	Chungu-1	Ek_1	2319.50	16	0.77	0.52	0.69	1.16	0.53	1.03	5.72	0.68	0.37	0.57
	Gao-891	Ek_1	3234.90	25	0.87	1.01	1.28	1.06	0.33	0.51	6.91	0.85	0.38	0.54

1 to 10 are referred as those in Table 1; 11. C_{31} homohopane 22S/(22S+22R) = 17α, 21β-homohopane 22S/(22S+22R).

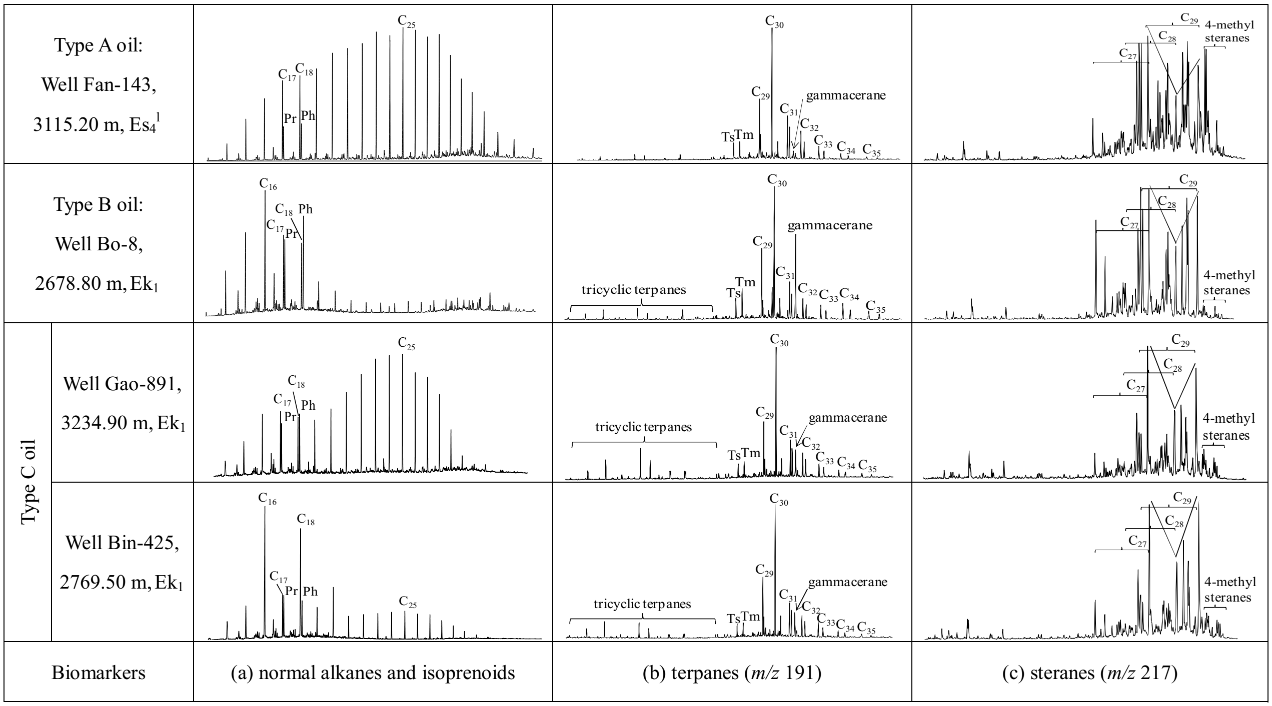

Figure 4. Gas chromatograms of saturated hydrocarbons (a) and mass chromatograms of terpanes (*m/z* 191) (b) and steranes (*m/z* 217) (c) of the Paleogene red-bed oil in the Boxing sag of the Dongying depression, eastern China.

is 0.79–0.94, ααα-20R C_{28} sterane shows notable lower concentration than that of ααα-20R C_{27} and C_{29} steranes, and diasteranes and 4-methly steranes concentrations are very high (Table 2, Figure 4c).

Type B Oil

This oil type is only found in well Bo-8. The *n*-alkanes display a double peak pattern with *n*-C_{16} as the main peak, CPI is 1.17; Pr/Ph is 0.71, Pr/*n*-C_{17} is 0.98 and Ph/*n*-C_{18} is 1.55 (Table 2, Figure 4a). The concentration of gammacerane and the C_{35} homohopane index are very high (gammacerane/C_{31} homohopane = 1.66, C_{35} homohopane index is 12.42%), tricyclic terpanes/17α-hopanes is 0.12 (Table 2, Figure 4b). The ααα-20R C_{27}/C_{29} sterane is 1.22, ααα-20R C_{28} sterane shows a significant lower concentration than that of ααα-20R C_{27} and C_{29} steranes (Table 2, Figure 4c). Diasteranes show less concentration than that of Type A oil, and 4-methly steranes are present in low concentration (Figure 4c).

Type C oil

In this oil type, the *n*-alkanes show a weak double peak pattern: sample from well Gao-891 plot mainly in the right part with *n*-C_{25} as the main peak (Figure 4a), whereas

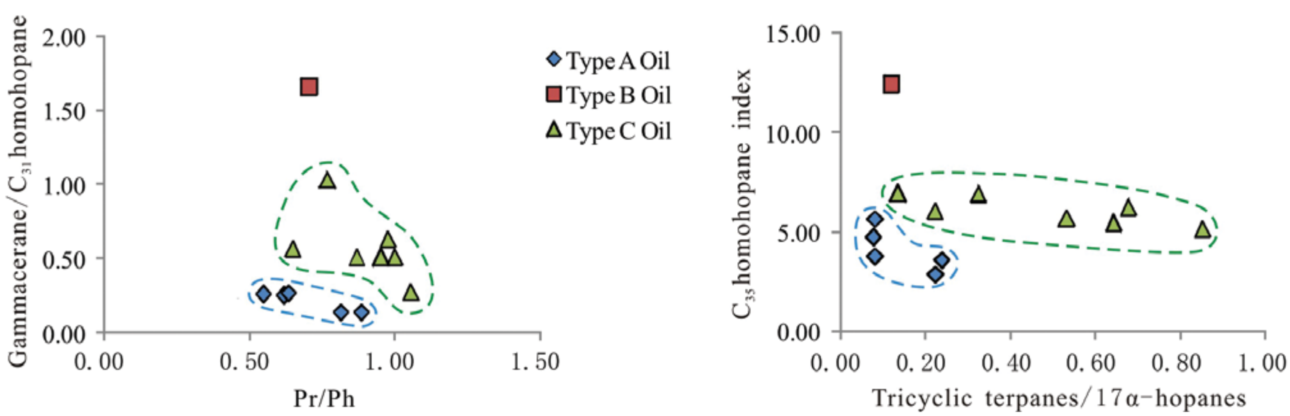

Figure 5. Biomarker scatter plots showing the classification of the Paleogene red-bed oil in the Boxing sag of the Dongying depression, eastern China.

the sample from well Bin-425 plot mostly in the left part with n-C_{16} as the main peak (Table 2, Figure 4a). CPI is 0.93–1.45, Pr/Ph is 0.93–1.45, Pr/n-C_{17} is 0.52–1.54 and Ph/n-C_{18} is 0.69–1.01 (Table 2). Tricyclic terpanes/17α-hopanes is 0.14–0.85, gammacerane/C_{31} homohopanes is 0.28–1.03, C_{35} homohopane index is 5.18% – 6.94% (Table 2, Figure 4b). The ααα-20R C_{27}/C_{29} sterane is 0.68–1.04 (Table 2), ααα-20R C_{28} sterane shows a lower concentration than that of ααα-20R C_{27} and C_{29} steranes, and a medium concentration of diasteranes and 4-methly steranes (Table 2, Figure 4c). In summary, the values of biomarker parameters of Type C oil are intermediate between those of Type A and Type B oils (Table 2).

Four of the biomarker parameters, namely Pr/Ph, gammacerane/C_{31} homohopane, tricyclic terpanes/17α-hopanes and C_{35} homohopane index, are very useful to study the redox conditions and salinity of lacustrine environments, and were chosen to illustrate the classification of the Paleogene red-bed oil in the Boxing sag (Figure 5). In the biomarker scatter plots of Figure 5, the three types of red-bed oil can be clearly distinguished.

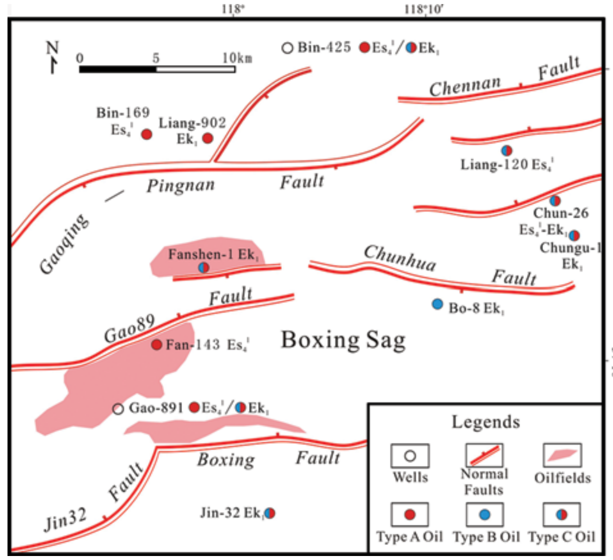

Figure 6. Distribution of the different oil types of the Paleogene red beds in the Boxing sag of the Dongying depression, eastern China.

DISCUSSION

Type A oil includes the samples listed in Table 2 and the sample from well Bin-169 shown in Figure 6. Due to the common biomarker signatures, such as pristane predominance (Pr/Ph > 1), very low concentrations of tricyclic terpanes and gammacerane, relatively low C_{35} homohopane index, and high concentrations of diasteranes and 4-methly steranes, we consider that Type A oil (*e.g.*, sample from well Fan-143, 3115.20 m) is derived from Es_3^l source rock (*e.g.*, sample from well Fan-118, 3032.20 m; Figures 3 and 4).

Only the sample from well Bo-8 is classified as Type B oil. It shows a clear phytane (Pr/Ph < 1, Ph/n-C_{18} > 1) and gammacerane predominance, relatively higher tricyclic terpanes/17α-hopanes ratio and C_{35} homohopane index, and very low concentrations of diasteranes and 4-methly steranes. Based on these features we propose that Type B oil (sample from well Bo-8, 2678.80 m) is originated from Type 2 Es_4^u source rock (*e.g.*, sample from well Gao-351, 2440.15 m; Figures 3 and 4).

Type C oil includes the samples listed in Table 2 and the samples from wells Liang-120, Chun-26 and Jin-32 shown in Figure 6. All the biomarker parameters values of Type C oil are between those of Type A and Type B oils, suggesting that it could be a mixed oil generated from both Es_3^l and Es_4^u source rocks. According to the distribution of n-alkanes, oil sand sample from well Gao-891 (3234.90 m) is a mixed oil generated from Es_3^l (*e.g.*, sample from well Fan-118, 3032.20 m) and Type 1 Es_4^u (*e.g.*, sample from well Gao-891, 2813.00 m) source rocks (Figures 3 and 4). While the other Type C oils (*e.g.*, sample from well Bin-425, 2769.50 m) are mixed oils generated from Es_3^l (*e.g.*, sample from well Fan-118, 3032.20 m) and Type 2 Es_4^u (*e.g.*, sample from well Gao-351, 2440.15 m) source rocks (Figures 3 and 4).

Figure 6 shows the distribution of different oil types of the Paleogene red beds in the Boxing sag. The Type A oil occurs within the Es_4^l red beds (except for well Liang-902) in the western part of the basin, mostly in the footwall block of the Gaoqing-Pingnan, Gao 89, and Jin 32 normal faults. The Type B oil is within the Ek_1 red beds in the eastern part of the basin, and the Type C oil mainly occurs within the Ek_1 red beds in the footwall blocks of other normal faults in the basin (Figure 6).

The results of our oil-source correlation indicate that the red-bed oil essentially move from the source rocks to the overlying strata along the faults. In fact, the red-bed reservoirs are in the footwall blocks and the source rocks in the hangingwall blocks, indicating that the main normal faults of the basin are providing the connection between the two. All found oilfields and collected oil sand samples occur along the faults and mostly in the uplifted blocks. Therefore, the distribution of the Paleogene red-bed oil in the Boxing sag is controlled by these “oil-source faults” and the Paleogene red beds in the footwall blocks are the most promising oil and gas exploration target of the area.

CONCLUSIONS

There are two main source rocks in the Boxing sag: Es_3^l source rock deposited in a freshwater-brackish lacustrine environment and Es_4^u source rock deposited in a saline-hypersaline lacustrine environment.

The oil stored in Paleogene red beds of the Boxing sag can be divided into three types: the oil in Es_4^l in the western part of the basin is classified as Type A oil, the oil in Ek_1 in the eastern part of the basin (well Bo-8) is classified as Type B oil, and the oil in Ek_1 in other places in the basin is classified as Type C oil.

The results of oil-source correlation indicates that Type A oil is derived from the Es_3^l source rock, Type B oil is originated from the Es_4^u source rock, and Type C oil is a kind of mixed oil generated from both Es_3^l and Es_4^u source rocks.

Distribution of the Paleogene red-bed oil in the Boxing sag is controlled by "oil-source faults" and the Paleogene red beds in the footwall blocks are the most promising oil and gas exploration target.

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